An Analysis of Trajectory Control Strategies in a Goal Oriented Throwing Task

by

Michael Timothy Gallivan

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Department of Physical Education

Division of Graduate Studies and Research
Faculty of Education
McGill University
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ABSTRACT

A simple analytical model was created in order to delineate the kinematic objectives of dart throws to targets located at various heights from the floor. The objective was defined as the specification of a constant wrist velocity at release, while performing corresponding adjustments in the dart's release height and trajectory with varying target heights. The purpose of the study was to investigate the kinematic variables reflecting the strategies of subjects of two ability levels performing a dart throwing task. A secondary concern was to delimit the parameters differentiating ability level. Two pairs of two male right handed subjects were classified as novice and expert dart players. A series of eight throws at each of three target locations (double twenty, bullseye and double three) were recorded cinematographically. The subjects' strategies, or self-imposed constraints upon the musculoskeletal and neuromuscular degrees of freedom were interpreted and discussed with respect to the movement objective. Analysis of the segment orientations at movement initiation and release revealed that subjects of both ability levels constrained their musculoskeletal degrees of freedom in a bid to increase the trial to trial consistency of segmental orientation, thereby reducing error at the target. Results also indicated the ability of the subjects to simultaneously control the velocity and path of the distal segments comprising the hand and dart. Subject of both ability levels demonstrated no significant differences in wrist resultant velocity at release across levels of target with concurrent alterations in release height, dart resultant velocity and dart angle of path at release

performed in order to hit the target. Skill level was delimited by the magnitude of the standard deviations of the segment trajectories and spatial orientations.

RESUME

Une modèle analytique a été crée pour delinéer les objectifs cinètique des lancées de darts aux cibles localisés a divers coordonées verticales. La spécification d'une velocité constante du poignet au point du relâche avec des ajustements correspondant en hauteur de relâche et trajectoire a été defini comme l'objectif du movement. La présente étude visait dans un premier temps a étudier les variables cinètiques qui reflètent les stratégies des sujets de deux niveaux d'habilité en exécutant une tâche de lancer des darts. Le deuxieme but de l'étude était de délimiter les paramêtres qui distinguaient entre les niveaux d'habilité. Deux paires de deux sujets droitiers masculins étaient classifiés comme joueurs novices ou experts. Un séries de huit lancés a chaqune de trois cibles (double vingt, centre et double trois) a été enregistré et analysée cinématographiquement. Les stratégies ou les contraintes voluntaires des sujets sur les degrés de liberté neuromusculaire et musculosquelettique ont été interpreté et discuté en considerant l'objectif du movement. Une analyse des orientations segmentaire au commencement du movement et au point de relâche a revelé que les sujets des deux niveaux d'habilité ont diminués leurs degrés de liberté musculoskeletale en assayent de regulariser leurs orientations segmentaire et de reduire l'erreur aux cibles. Les résultats ont indiqué la capacité des sujets de controller simultanément la velocité et trajectoire des segments comprennent la main et dart. Sujets des deux niveaux d'habilité ont demonstrés des altérations significantes en hauteur de relâche, velocité résultant et trajectoire du dart, mais aucune différence en velocité résultant de poignet entre les trois

niveaux de cibles. Les niveaux d'habilité ont été distingueé par la magnitude des déviations standardes des trajectoires et orientations spatiales.

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As for the significance of the results, read Chapters IV and V and weep. If you can somehow coordinate your motor system to eliminate the elbow-wrist synergy you have learned and practiced over the years, you may one day become number one ranked in the world. It would cost you a lot in beer money, let me tell you. There, I got the last word!

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CHAPTER I

INTRODUCTION

The upright stance and accompanying bipedal gait adopted by the early hominids has proven to be an un-paralleled evolutionary advance. Besides freeing the forelimbs from the task of quadruped locomotion, the erect bipedal stature permitted the simultaneous development and coordination of a complex visuo-motor system. The hand, comprised of four flexible digits and an opposable thumb, provided early humans with the capacity for prehension and the basis for various fine manipulatory skills such as tool making. It is reasoned that the advent of hunting game by throwing rocks contributed, in part, to the early (four to five million years ago) evolutionary success of the genus Homo by yielding larger and more variable quantities of food (Calvin, 1983). The ability to throw a rock at a moving target requires the parallel computation of the trajectories of both the stone and prey, which implies a highly organized brain and perceptual-motor ability (Calvin, 1983). Mastery of such a task demands movement planning with respect to the constraints of: 1) the geometry of the external world and 2) real-time (Hollerbach, 1985). Although the motor skill of throwing is no longer of vital importance to survival, the utilization of this particular highly skilled motor task still persists in many modern athletic endeavours.

1.1 Nature and Scope of the Study

One particular motor task requiring highly skilled throwing ability is competitive dart playing. The rules of the game stipulate that players must stand at a throwing line situated 2.37 meters from the circular board centered on a wall 1.73 meters from the surface of the floor. The nature of the game requires the capacity to throw a dart (three throws are permitted per throwing series) such that it flies to and sticks in the board. Both expert and novice level dart players have performed the throwing motion thousands of times and it is an easily repeatable skill.

Although contacting any of the numbered (from one to twenty) targets on the board earns the player a certain amount of points, the smaller double and triple bands earn the player twice and thrice the number of points, respectively. To complicate matters further, the numbered targets are situated at various heights and are randomly spread around the board in pie-chart fashion. In addition, a player must successfully strike the double of half the total of his/her remaining points in order to win the game. Expert players regularly hit the small, wire-encircled double and treble zones, which vary from three to four square centimeters in surface area, and rarely require more than three darts to "double out".

One of the requirements when learning to play the game of darts is an intuitive knowledge of the kinematics of projectile flight. The trajectory and horizontal range of the center of gravity of a dart are governed by the resultant velocity at release, height of release, horizontal distance from the release point to the board and the target height. Therefore, the prediction and control of the precise vertical and horizontal range are critical factors in determining consistency and success.

The problems of prediction and control are compounded by the necessity of producing accurate throws to the different targets situated at various vertical coordinates on the board. There exists an infinite combination of resultant release velocity, height of release and horizontal distance to the board which combine to produce a given vertical height at the board. The range of these variables is constrained by the height of the ceiling and by the anatomies and strategies of the players. In order to be consistent, a player must narrow the composite of the variables in such a fashion that only a small and easily effected alteration produces a successful flight trajectory to the desired target. Any dart player who can repeatedly produce accurate throws to the various targets previously mentioned must be considered a highly skilled thrower. The success rates of elite level dart players must be attributed to some other parameter than that of 'luck', as concluded by Anderson and Pitcairn (1986).

1.2 Statement of the Problem

Analysis of skilled motor performance involves the integration of the fields of biomechanics and motor control. The objectives of any particular physical movement are constrained by the neuromuscular inputs and the limitations of the musculoskeletal system and must be identified prior to the posing of a research question (Nelson, 1983). The task of throwing a dart to various targets on a board can be defined as a discrete motor skill with targeting constraints. According to the motor task taxonomy of Gentile, Higgins, Miller and Rosen (1975), this skill has been classified as one involving a stationary nature of environmental control with the presence of intertrial variability.

The goal or objective of dart throwing is the targeting requirement, yet this objective is insufficient in itself for the design of a research question. The strategies or patterns of muscular activation selected by the players to achieve the objective must also be examined. With the constraints mentioned by Hollerbach (1985) in mind, the goal of any dart throw to a target was defined as follows: To accelerate and release the dart at a consistent velocity and angle of path, from a consistent height from the floor such that the dart flies to and contacts the board at the specified target. Trajectory (or angle of path) has been defined by Morasso and Mussa Ivaldi (1982) as " ... one of the basic functions of the neuromotor controller, such as the compensation of loads, the pursuit of moving targets, the appropriate control of impacts (e.g. hitting), and the generation of contact forces (e.g. pushing)." The goal of dart throwing as defined above implies the simultaneous control of two parameters: 1) hand/dart velocity and path (trajectory) and 2) segment orientation.

The geometric constraints (Hollerbach, 1985) are related to the distance from the throwing line to the board (fixed), the target heights (fixed), and the height of release and horizontal distance of release from the target (variable, depending on segment lengths and degree of body lean). The real-time constraints are the resultant velocity of the dart at release (variable, depending on the vertical and horizontal velocity-time profiles of the hand/dart complex) and the actions occuring at release. The strategies selected by the players (as evidenced by the movement kinematics) may reflect an attempt by the nervous system to simplify the generation of movement patterns in order to optimize one of Nelson's (1983) costs of movement (Hasan, Enoka and Stuart, 1985).

The rationale for the selection of the objective of dart throwing, as well as the hypotheses of this study, was performed in the following manner. A simple BASIC program was written in an attempt to model throws to targets at three different vertical coordinates. The model's main shortcoming was related to the assumption that the dart was shot from a gun, therefore only hand velocity, release height and trajectory were modelled and release distance from the board was considered as a constant. The model permitted the manipulation of one of the following variables while holding the other two constant: release height, velocity at release and angle of projection. Values of 1.75 meters (release height for a 180 cm individual), 5 meters/second (which mimicks the approximate 0.2 second flight time) and five degrees (Anderson and Pitcairn, 1986) were chosen for release height, velocity and angle respectively. The horizontal distance from the board at release was ignored and held constant at 2.00 meters.

Analysis of the output data from a purely mathematical point of view demonstrated that two of the strategies were possible, while the third strategy (holding release angle and height constant) seemed to be unlikely. Manipulation of release angle necessitated release angles of +8.0, +6.5 and +2.1 degrees to hit targets at the top, center and bottom of the board. Manipulation of release height (at constant angle and velocity) required release heights of 1.86, 1.78 and 1.55 meters to hit the same targets. Altering release velocity required velocity values of 15, 9.5 and 8.1 meters/second to hit the specified targets.

Although such radical alterations in release velocity are not impossible, it is highly unlikely that the controller (at any level) could specify the necessary changes in release velocity in the consistent fashion demonstrated by elite dart players. Although these parameters could covary, a combination of manipulating release angle and release height while maintaining a constant release velocity seems to be a reasonable model of control. This model necessitates a constant wrist release velocity, with subtle changes performed at the hand sufficient to alter the dart release resultant velocity. Success in the task requires a consistent trajectory (path and velocity) of the hand at release while manipulating release height and angle of projection. Thus, the following research question has been identified: What are the kinematic strategies of the dart player and how are these strategies modified when the target height is altered?

In order to create hypotheses concerning the control mode utilized in such a task, certain assumptions must be made a priori due to the lack of specific research data. Firstly, a unimodal velocity profile of the elbow and wrist must be assumed (Schmidt, Zelaznik, Hawkins, Frank and Quinn, 1979). Secondly, the time from initiation of movement until the inflection point of the velocity profile must be assumed to be representative of the antagonist burst minus motor time (Wallace, 1981). This assumption seems to be viable since viscous forces could hardly overcome the inertia of the limb combined with the vertical component of gravitational force (after an absolute angle of 90 degrees). In light of the objectives and assumptions stated above the research hypotheses which follow were generated.

1.3 Purpose of the Study

The purpose of this study was to investigate the kinematic variables reflecting the variant and invariant aspects of the strategies of subjects of two ability levels performing a dart throwing task. The second concern of this study was to examine the kinematic variables which differentiated the level of skill of the subjects participating in the experiment.

1.4 Hypotheses

1) There will be no significant differences in the resultant velocity of the styloid process of the wrist at release (WRV) across levels of the independant variable.

2) There will be significant differences in the resultant velocity of the dart at release (DRV) across levels of the independant variable.

3) There will be significant differences in the angle of projection of the dart at release (DPATH) across levels of the independant variable.

4) There will be significant differences in the vertical coordinate of the dart at release (RH) across levels of the independant variable.

1.5 Limitations and Delimitations

The limitations of this study are:

1) All data was collected from the sagittal plane, therefore three dimensional analysis is precluded.

2) The analysis of the throwing action embraces the time span from movement initiation to release only.

3) Only two subjects of each ability level, performing eight trials each of three experimental conditions, participated in the study, thus generalization to larger populations is cautioned.

4) Each trial was assumed to be the subject's best effort.

The following delimitations apply to this study:

1) Only male expert and novice level dart players between the ages of 20 and 40 were employed as subjects.

1.6 Definitions and Abbreviations

The following definitions apply to this study:

Angle of projection: The angle (in degrees) from the horizontal of the path of the dart measured from the first frame following release.

Expert dart player: A player who (in 1986) competed in the "A" division in the Montreal Dart League.

Horizontal release distance: The distance (in meters) from the tip of the dart at release to the surface of the dartboard.

Inflection point: The time point corresponding to the film frame where the velocity profile changes sign.

Movement initiation: The time point (zero) corresponding to the film frame where the dart begins moving toward the board.

Novice dart player: A player who (in 1986) had not competed in any league and who possessed less than one year of non-competitive playing experience.

Release: The time point corresponding to the film frame where contact between the fingers and dart is broken.

Release height: The distance (in centimeters) from the dart to the floor at release.

Strategy: The self-imposed constraints in movement kinematics utilized by a subject performing goal-directed arm movements.

Trajectory: The path taken by the hand as it moves to a new position and the speed of the hand as it moves along the path (Abend, Bizzi and Morasso, 1982).

The following abbreviations apply to this study:

WRV - Wrist resultant velocity at release
WVH - Wrist horizontal velocity at release
WVV - Wrist vertical velocity at release
WPRO - Wrist angle of path at release
FRV - Finger resultant velocity at release
FVH - Finger horizontal velocity at release
FVV - Finger vertical velocity at release
FPRO - Finger angle of path at release
DRV - Dart resultant velocity at release
DVH - Dart horizontal velocity at release
DVV - Dart vertical velocity at release
DPRO - Dart angle of path at release
RH - Release height of the dart

CHAPTER II

REVIEW OF LITERATURE

Although dart playing has been investigated by many sport psychologists studying the effects of mental practice upon skill acquisition, biomechanical analyses of dart throwing have been overlooked in the literature. In this chapter, computer generated dart throwing strategies will be described and discussed within a review of the literature of goal-directed arm movements from the field of motor control.

2.1 Dart Throwing

Anderson and Pitcairn (1986) explored the underlying mechanism controlling the dart throw. A single subject, with no previous competitive experience, was selected as the subject for the study. The subject was instructed to throw darts at a dartboard from two distance conditions: 1) 8.5 and 2) 7.5 feet. The experimenters used a Selspot apparatus to measure the subject's kinematic pattern during 10 bullseye throws, 10 low misses (darts contacting the board below the bullseye) and 10 high misses (contacting above the bullseye). The subject required 114 throws to hit the bull ten times in the first condition (8.8% success rate) and 122 throws (8.2% success rate) in the second condition.

Anderson and Pitcairn (1986) attempted to discover the parameters of a throw which would predict success by comparing the kinematics of the hits and misses. They also examined how these parameters were adjusted by the subject when throwing at a new target created by changing the distance from the target. The vertical and horizontal coordinates of the hand position at the start of the throw and at release, the coordinates of the elbow at release, the wrist angle at the start of the throw and release, the vertical and horizontal hand velocity at release and the duration of the throw were selected as the dependant variables for statistical analysis. Anderson and Pitcairn (1986) analyzed the data utilizing four statistical techniques: 1) analyses of variance of the positional data, 2) discriminant analyses differentiating between high misses, hits and low misses, 3) correlational analyses for purposes of discovering the prediction parameters and 4) analyses of the hand trajectory.

Anderson and Pitcairn (1986) found no significant differences among the variance of the positional variables between the two conditions. The sole exception was a significant difference in the variance of the vertical coordinate of the shoulder at release in the 7.5 feet condition. The authors calculated the standard deviation (noise) of the x and y coordinates of the hand over time and illustrated a tendency for the variance to rise from movement initiation to release and the noise was greater for misses than hits. Anderson and Pitcairn reported the mean throw duration to be 0.120 second, a time shorter than the 0.135 seconds necessary for advantageous visuo-motor feedback (Carlton, 1981). It is also interesting to note that their subject released the dart while the hand moved along a fairly consistent trajectory. Extrapolation of the x and y hand velocity at release yielded hand velocity values between 26.3 and 30.4 Selspot units/second in condition 1 and 27.7 to 28.1 Selspot units/second in condition 2, and angle of path values between 7.9 and 11.6 degrees in condition 1 and 2.9 to 4.9 degrees for condition 2.

The discriminate analysis for the 8.5 feet condition identified the angle of wrist at release to discriminate low misses and hits as well as low misses and high misses. The analysis also demonstrated that the vertical velocity of the hand at release discriminated low misses and hits, hits and high misses, but not low misses and high misses. The vertical velocity was greatest for high misses and least for hits. The discriminate analysis for the 7.5 feet condition identified the vertical and horizontal position of the shoulder at release. The authors stated that since the discriminate analysis identified separate controllable parameters as predictors of success in the two conditions, they could not identify a controlled variable predicting success in the two conditions, as depicted by the different styles (kinematic patterns) characteristic of the two conditions.

Anderson and Pitcairn (1986) found strong correlations ($p < .01$) between the starting and release (x-x and y-y) positions of the hip, shoulder, elbow, wrist and hand, while weak correlations existed between the x and y starting and release (x-y) positions. It was concluded that these coordinates are "locked" and covary with changes in spatial location. Hand trajectory (vertical and horizontal position throughout the throw) was plotted for hits in both conditions.

Analysis of the hand trajectories for hits revealed a relatively small variance yet it was observed that large vertical and horizontal shifts existed from throw to throw. Second order polynomial equations were generated and the independant constants were correlated. Anderson and Pitcairn described a strong relationship between the initial position and trajectory slope regardless of throwing condition. The authors concluded that although throwing aptitude involves skill, the success of any particular throw by an individual of any skill level may be a matter of luck. Skill acquisition involves the reduction of noise (standard deviation) and more skilled players have a higher signal to noise ratio (Anderson and Pitcairn, 1986). Skill may therefore be acquired through efficient motor commands or gradual elimination of noise from the system.

2.2 Analytical Model of Dart Throwing

Although Anderson and Pitcairn (1986) stressed the necessity of a precise biomechanical model of the throw their analysis completely ignored the kinematics of the throw, especially the release variables which govern the vertical and horizontal range of the projectile. In the present study, a simple analytical model was created in order to determine the dependant variables and test the hypotheses of the study. The model does not include the effects of lift and drag forces upon the flight of the projectile.

The vertical distance (or board height, BH, as defined by the analytical model) travelled by a projectile is governed by the horizontal distance to the target (RD) and height of release (RH), the vertical (VV) and horizontal (VH) release velocity and the angle of release (PRO). Given the latter variables, the flight time (FT), time to peak vertical height (TUP) and peak vertical height (SUP) are calculated by the following equations:

$$FT = RD/VH \qquad (1)$$

$$TUP = VV/g \qquad (2)$$

$$SUP = (g * (TUP) \text{ squared})/2) \qquad (3)$$

where g = acceleration due to gravity (9.81 m/s/s)

The height (vertical peak) of the dart with respect to ground level (PHT) is calculated by adding the peak vertical height (SUP) to the vertical height of release (RH). The time spent in descent (TD) before contacting the target and the distance descended (SDOWN) are calculated by equations 5 and 6:

$$PHT = RH + SUP \qquad (4)$$

$$TD = FT - TUP \qquad (5)$$

$$SDOWN = (g * (TD) \text{ squared})/2 \qquad (6)$$

The vertical height at contact with the target (BH) is calculated by subtracting the distance descended from the peak height, as calculated by equation 7:

$$BH = PHT - SDOWN \qquad (7)$$

It is obvious that there exists an infinite combination of velocity, release height and distance which will produce the same height of contact on the board. The range of the geometric variables is narrowed or constrained by the thrower's stance and segment lengths (affecting RH and RD), and the ceiling height (affecting VV). The strategy of a particular thrower of any skill level must reflect an attempt to constrain their movement kinematics to produce a consistent release velocity and height.

As previously described in the introductory chapter, the model was utilized to generate feasible throwing strategies as well as the statistical hypotheses of the present investigation. A practical strategy for throwing darts to targets situated at various vertical board coordinates was demonstrated by the model. This strategy involved the manipulation of release height and angle while maintaining a constant release velocity. Release height is directly related to the spatial orientation of the body segments at release while release angle (path) is related to the trajectories of the distal segments at release.

From the initiation of the throwing movement until release, the dart and hand comprise a single segment due to the grip on the dart by the fingers. The trajectory of the hand/dart throughout the throw encompasses the vertical and horizontal velocity and the angle of path. The timing of release is vitally important since the height of contact at the board is solely dependant upon the dart's velocity, angle of path and vertical and horizontal release heights. The goal of the throw therefore requires the propulsion of the dart to a point in space where the trajectory produces a successful vertical coordinate at contact with the board. The question of how the nervous system may specify the variables necessary to accomplish this strategy involves a discussion of command hierarchy and goal-directed arm movements.

2.3 Theories of Movement Planning

The production of movement is integral to the survival of all higher life forms. From birth, humans develop the ability to coordinate a neuromuscular system which enables the production of skilled movement.

Movement is accomplished via a complicated controller (central nervous system) and effector (musculoskeletal) mechanism. The hierarchy of command postulated by Bernstein (1967) is organized such that the controller (highest center) specifies the bare outline of the movement, while the spinal cord (lowest center) furnishes the muscles with the movement particulars. Greene (1982) asserted that the spinal cord contains mechanisms for: 1) the selection of the involved musculature and 2) the commands to transmit to the selected muscles. Centrally initiated commands cause contractions in muscles or groups of muscles, which in turn create torques on the joints where they insert thereby creating movement of the limb at the particular joint. The degrees of freedom problem proposed by Bernstein (1967) states the potential limitations of the brain as the sole controller of coordinated, multiple joint movement.

The musculoskeletal degrees of freedom are equal to the number of coordinates required to designate the configuration of the articulating segments (Hasan, Enoka and Stuart, 1985). In other words, the degrees of freedom can be defined as the number of axes about which a joint can revolve. For example, the human arm possesses seven mechanical degrees of freedom: three at the shoulder joint, one at the elbow joint and three at the wrist. However, all three-dimensional hand orientations are made theoretically possible through six degrees of freedom. Hollerbach (1985) pointed out the kinematic redundancy of the design of the arm, stating that such redundancies are " ... useful for obstacle avoidance, for elimination of internal singularities, and for joint limit avoidance." The redundancy of the arm is also disadvantageous, since it makes an inverse kinematics solution (the transformation of segment positions and spatial orientations into a time sequence of joint coordinates) a very complex calculation indeed (Hollerbach, 1985).

Given these seven degrees of freedom there is an infinite number of paths a segment, or group of segments, may follow in order to accomplish a task (Hasan, Enoka and Stuart, 1985). A favoured path may suggest a relationship between the angles of the various joints involved in the production of the given movement. Due to such a preference it may be said that the nervous system has reduced the degrees of freedom (Hasan, Enoka and Stuart, 1985). The concept of coordination may be more precisely defined when related to this reduction of the degrees of freedom effected by the central nervous system (Bernstein, 1967).

Although Bernstein's theory (1967) of command hierarchy is considered plausible, it cannot satisfy questions concerning: 1) the mechanism whereby the position of the target object is specified (terminal values of joint angles versus a global coordinate system), 2) the level where the identity and timing of the involved musculature is selected and 3) how the adjustment of muscle activity is undertaken when movement is performed against a resistance (Hasan, Enoka and Stuart, 1985).

In order to produce a skilled movement of the hand to a target, computations must be performed concerning how to move the arm and hand while maintaining the center of gravity over the base of support (Hinton, 1984). For a movement to be computationally simple, the smallest number of degrees of freedom must be chosen such that the arm and hand can assume all possible three dimensional orientations (Greene, 1982). The initial position of the segments must determine the pattern of commands from the nervous system to the musculature (Hasan, Enoka and Stuart, 1985). Robotics research has also provided valuable insight into the problems encountered by the central nervous system prior to and during the control of skilled movement (van Dijk, 1978; Sakitt, 1980; Benati, Gaglio, Morasso, Tagliasco and Zaccaria, 1980).

A basic element of the organization of movement is known as the muscle synergy: a programmed combination of agonist and antagonist muscles which cooperate during the production of voluntary movement (Greene, 1982). Lee (1984) stated that synergies can be defined in the sense of goal-direction (the interaction of components to obtain an output goal) or morphology (taking into account the neural constraints imposed upon movement production). In studies of goal-directed arm pointing movements, Soechting and Lacquaniti (1981), Lacquaniti, Soechting and Terzuolo (1982) and Soechting (1984) have described coupling (synergy) of the shoulder and elbow joints, while the latter study demonstrated the independant control of the wrist. Such results suggest that individual joints can be split from the general synergy via an inhibitory process, permitting separate movement control (Greene, 1982). Indeed, Anderson and Pitcairn identified the wrist angle at release to discriminate between low misses and hits as well as low and high misses in condition 1. This result may suggest the presence of synergistic control of the individual segments comprising the arm in a dart throwing task.

Hollerbach (1985) outlined one possible level of movement planning to be trajectory planning. Trajectory (or endpoint) planning involves the specification of the position and orientation of the hand and the transformation (via inverse kinematics) into a time sequence of joint angles. Models utilizing the endpoint approach yield both straight-line and curved hand paths (Abend, Bizzi and Morasso, 1982). Evidence of hand trajectory planning (Morasso, 1981; Abend, Bizzi and Morasso, 1982; Lacquaniti, Soechting and Terzuolo, 1982) has described the possibility for the reduction in the degrees of freedom in the control of arm movements. It has also been demonstrated that movement trajectory is independant of velocity and load (Abend, Bizzi and Morasso, 1982; Lacquaniti, Soechting and Terzuolo, 1982). Thus, the path followed by any particular segment or group of segments may be specified regardless of movement velocity. This model of control is exemplified in various tasks and supports the viability of the strategies hypothesized in the present study. Trajectory planning is one of the goals of the dart throw and requires further elaboration.

Lacquaniti, Soechting and Terzuolo (1982) stated that "... one can expect to find concrete expressions of the rules governing the organization of the movement in the invariant characteristics of the movement's parameters ...". The existence of variant and invariant characteristics in discrete and cyclic motor tasks has been identified in human locomotion (Winter, 1983), posture (Nashner, 1977) and arm trajectory (Abend, Bizzi and Morasso, 1982; Lacquaniti, Soechting and Terzuolo, 1982; Soechting and Lacquaniti, 1981). Soechting and Lacquaniti (1981) attempted to identify the invariant aspects of a simple pointing movement through examination of joint angles and hand trajectory. Subjects were asked to execute pointing movements in the sagittal plane towards a target on a television screen and were given no further instructions regarding accuracy. The following criterion starting position was selected: upper arm in a vertical position, forearm in a horizontal position and index finger extended.

The nature of the experimental setup permitted two degrees of freedom, shoulder flexion and elbow extension, and did not require a specific hand orientation at target contact. Soechting and Lacquaniti (1981) found that the spatial trajectory was independant of the movement velocity and was invariant from trial to trial, which suggests that the planned variable was the trajectory and not the torques selected to produce the trajectory. The authors asserted that movement velocity changes do not simply reflect scalings in the torques acting at the shoulder and elbow since the net torques are a combination of inertial torques, Coriolis forces and gravitational torques. Soechting and Lacquaniti (1981) also found that the ratio of the maximal velocity at the elbow and at the shoulder was equal to the ratio of angular displacement at the same two joints, the two angular velocities reach their maxima at the same time and the slope of the angular velocities was independent of target location. Soechting and Lacquaniti (1981) postulated that the movement is organized and planned in terms of intrinsic coordinates (shoulder and elbow angle) rather than in terms of extrinsic coordinates (target position), which requires the existence of a transformation mechanism between the two sets of coordinates.

Soechting (1984) studied the effect of placing an accuracy constraints on finger pointing movements. Subjects were instructed to point to and touch targets with diameters of 2.2, 3.5 and 5.0 centimeters. Two target locations were utilized, with one target situated 25 centimeters above the other. Movement speed was varied from trial to trial while the starting position was maintained constant. Soechting found a tight coupling existed between shoulder flexion and elbow extension while the wrist moved independantly. The author stated that shoulder and elbow coupling is virtually a prerequisite due to the inertial coupling of the two joints and that their motion is co-regulated. Although motion at the wrist can be coordinated with the proximal joints, forearm pronation and supination is not inertially coupled to motion at the shoulder and elbow and can logically be regulated independantly. Soechting (1984) stated that two variables may designate the target: its spatial location and orientation. Hand location is primarily determined by excursion at the shoulder and elbow, while hand orientation is determined by wrist rotation. This finding does not imply that wrist motion cannot be coordinated with motion at more proximal joints when it is the goal of the movement, due to biomechanical constraints (Soechting, 1984).

Lacquaniti, Soechting and Terzuolo (1982) studied subjects performing pointing movements to targets while holding a 2.5 kilogram weight in their hands. The experimenters once again found that the trajectory was independant of the presence of the load and movement speed. A second experiment was performed with a rod strapped to the subject's forearm, effectively doubling its length. Upon examination of the results, the authors argued that movement control and organization must occur at two discrete hierarchical levels. A lower level compensates for parameters such as load, while a higher level plans the movement trajectory. The results led Lacquaniti, Soechting and Terzuolo (1982) to postulate that the extrinsic target coordinates were in fact mapped to intrinsic coordinates of joint angles and segment lengths.

Morasso (1981) investigated the spatial control of the arm trajectories of humans performing a targeting task. The subject's arms were strapped to a manipulandum and were constrained to perform movements comprised of two degrees of freedom in the horizontal plane. Although shoulder and elbow angular velocity curves exhibited single and double peak profiles, the tangential hand velocity curve was single peaked. Morasso (1981) hypothesized that the central command/s controlling the movements specified a spatial control of the hand. Such a mode of control requires the existence of a higher order mechanism which performs the transformation of spatial coordinates and commands into joint motion.

Previous research has focused on the underlying mechanism controlling the dart throw and ignored the movement kinematics controlling the success of the throw. The theory of trajectory planning encompasses both goals of the present investigation: the planning of movement trajectory and segment orientation. Trajectory planning of a movement may be organized either in terms of joint angular coordinates (Soechting and Lacquaniti, 1981) or the transformation of extrinsic spatial coordinates into a sequence of joint angles (Lacquaniti, Soechting and Terzuolo, 1982, Morasso, 1981). Segment orientation is a result of the coordinated reduction of the degrees of freedom of the moving joints which produces the favoured trajectory (Hasan, Enoka and Stuart, 1985). Regardless of the nature of the planned parameters, research has indicated that hand location and orientation may be controlled separately (Soechting, 1984) and that movement control and organization occurs at two distinct hierarchical levels (Lacquaniti, Soechting and Terzuolo, 1982). Research has therefore demonstrated the possible means whereby the goals of a successful dart throw, namely the control of hand trajectory and segment orientation, could be accomplished. A study of the kinematic strategies utilized by dart throwers was therefore warranted and undertaken.

CHAPTER III

METHODOLOGY

The following section contains a complete account of subject selection and preparation, cinematographical procedures, data measurement and analysis, research design and statistical methods. The purpose of this study was to investigate the kinematic variables reflecting the variant and invariant aspects of the strategies of subjects of two ability levels performing a dart throwing task. The second concern of this study was to examine the kinematic variables which differentiated the level of skill of the subjects participating in the experiment.

3.1 Subject Selection

Four male right-handed volunteers were enlisted through personal communication as subjects for the present study. Two expert subjects were recruited from the "A" division of the Montreal Dart League and the remaining two subjects were recruited on campus and classified as novice players. The expert subjects had recently competed in the Quebec provincial dart championships and had previously played matches against various world class dart players.

3.2 Subject Preparation

The subjects reported to the Arthur Currie Gymnasium prior to the cinematography session, whereupon their body mass, height and the lengths of the body segments were recorded. The subject's darts were weighed on a Mettler calibrated scale accurate to 0.1 grams. The dart lengths and the location of the center of gravity (as measured by a balancing technique) were also recorded. The subjects then changed into athletic shorts and an assistant placed indelible black dots over the following anthropometric landmarks:

1 - the base of the fifth metatarsal: FINGER MARKER
2 - the ulnar styloid process at the right wrist: WRIST MARKER
3 - the lateral epicondyle of the right elbow: ELBOW MARKER
4 - 2.5 cm below the acromion process of the right shoulder: SHOULDER MARKER
5 - the third cervical vertebra: C3 MARKER
6 - the right iliac crest: ILIAC MARKER

The experimenter verbally explained the test protocol to the subjects and any questions were answered without explaining the precise nature of the study. Advised consent forms were completed by each individual. The subjects were permitted to warm up in a draftless conference room which had been previously set up. There was a one half hour period during which the subjects were encouraged to warm up as they would prior to a match or competition.

3.3 Cinematographical Procedures

The filming session took place in a draftless conference room located in the Arthur Currie Gymnasium. A WINMAU dart board was secured to the wall such that the bullseye was 173 centimeters from the surface of the floor. The double twenty and double three were located 17 cm above and below the bullseye, respectively. The inside of the bullseye was composed of a radius of 1.6 cm (area = 8.04 square cm), while the doubles were 0.8 cm by 5 cm (4 square cm) as measured from the inside wires. A section of white masking tape marked the throwing line, set 237 centimeters from and parallel to the wall. The subjects were permitted to place positional markers on the floor to facilitate consistent foot placement. These markers were subsequently utilized in the filming of a two dimensional matrix prior to the actual data collection.

A high speed Redlake Locam camera (Model 51-003), outfitted with a wide angle lens, was set up 2.81 meters perpendicular to the throwing plane of action, in order to film the sagittal plane. The Locam was loaded with Kodak 4-X reversal /colour film (type 7250) and was set to film at 150 frames per second, necessitating an exposure time of 1/675 and an F-stop of 2.6. A bank of three 1000 watt lights illuminated the plane of action. A timing light generator was connected to the Locam and was set to flash 100 times per second. The flashes appeared as red dots on the side of the processed film and were used to compute the film speed during each individual trial. A two dimensional matrix (1.00 m by 0.40 m) was placed level to the toe marker of each subject and filmed. The subjects' trials were identified by two numbered markers (target and trial) which were placed in the lower right corner of the plane of action. The exposed film was developed by Mount Royal Film in Montreal, Quebec.

3.4 Data Measurement and Analysis

The subjects performed eight trials at each of the three pseudo-randomized levels of the target condition:

1 - Double Twenty (top) - D1 (190 cm above floor)
2 - Bullseye (center) - D2 (173 cm above floor)
3 - Double Three (bottom) - D3 (156 cm above floor)

The selection of the target location about the vertical line bisecting the dart board through the bullseye was performed in an attempt to restrict the movement to the sagittal plane. The order of trials at the targets was generated by a BASIC program and the subjects were informed of the target location prior to each series of throws. After assuming their throwing posture, the subjects threw three darts at the target, while only the third throw was recorded cinematographically. The expert subjects chose to throw only the third dart at the target after having thrown the first two darts to the left or right lateral side of the target, in order to reduce the chance of a deflection.

The camera was started during the end of the aiming action and was stopped after the dart contacted the board. After each throw, an assistant recorded the horizontal distance between the inside (center side) of the tip of the dart and the inside of the closest wire of the target for the purpose of predicting the contact point on the board. The angle of the dart from the horizontal was also measured to the nearest degree using a protractor. Trials where the dart contacted the wire of the target and fell to the floor were considered successful and were not repeated. Any trial was repeated when the subject or the experimenter felt that the movement was not representative of the participant's ability level. After each subject completed the eight trials in each of three target conditions, the next subject warmed up until he felt ready for the filming to commence.

3.5 Data Analysis

One trial each of Subject 2 (at D3) and Subject 3 (at D1) were impossible to analyze due to an internal problem with the Locam. The remaining trials (n=94) at each of the three target conditions were selected for analysis. Prior to digitizing, the film was inspected and the initiation of the throwing movement was marked as the time point corresponding to the film frame where the dart-hand began moving toward the board. The release was marked as the time point corresponding to the film frame where contact between the fingers and dart was broken. The processed film was projected by a L-W pin-registered stop-action projector onto a Summagraphics digitizing board. A Watfiv digitizing program (D.E) program facilitated the digitizing process by prompting the user with the frame number and name of each body marker. The D.E program prohibitted the loss of any digitized data and insured the correct order of digitization throughout. The horizontal (x) and vertical (y) coordinates of the body landmarks, tip and flight of the dart and reference points were registered using a handheld cursor and stored as a file by the digitizing program on the McGill MUSIC-A system.

A Watfiv (DATAPROG) program adjusted the vertical and horizontal coordinates of the origin to a common reference point in order to compensate for any movement of the projector or film frame during advancing the film. Subsequently, the digitized coordinates of all trials during which the Locam was operating above or below the criterion 150 frames per second film speed were further adjusted by a cubic spline Watfiv program (SPLINE). The raw x,y coordinates were smoothed by a low-pass recursive digital filter (Wood, 1983).

The selection of the cutoff frequencies was performed by running a trial of each subject through the entire gamut of Kinematic and modelling programs at increments of 0.5 Hz. The following cutoff frequencies were selected for the toe line marker (4.0), the tip of the dart (6.0), the flight of the dart (6.0), the base of the fifth metatarsal (6.0), the ulnar styloid process at the right wrist (6.0), the lateral epicondyle of the right elbow (6.0), 2.5 cm below the acromion process of the right shoulder (6.0), the third cervical vertebra (5.0), the right iliac crest (5.0). The first and second order derivatives of displacement of the markers and joints as well as absolute and relative joint angles were calculated by the McGill University Biomechanics laboratory Kinematic programs. The output of each run of the Kinematic program was stored as a MUSIC file from the operating system and a hard copy was also obtained.

The stored output files were transferred from the MUSIC system by the PCWS software package to the 10 mB fixed disk of a Sperry microcomputer via a Signalman modem. Two programs (written in Microsoft BASIC) were utilized to: 1) input the data output by the Kinematic program and 2) write the dependant variables to sequential files for statistical and graphical analysis. The first program computed the vertical and horizontal coordinates of the dart tip at release, the velocity and angle of path of the dart during each frame analyzed and created a file containing the computed data.

The purpose of the second program was to verify the frame containing the dart release and the selection of the smoothing cutoff frequencies. The program input the smoothed x and y data for a particular trial and calculated the vertical coordinate of contact with the wall or board for each analyzed film frame. This program enabled the prediction of the horizontal contact coordinate of the dart at the board had the dart been released during any frame prior to the actual release frame.

3.6 Statistical Methods

Subjects were divided into two levels of ability (expert and novice) and were distinguished by their present level of play. Due to the nature of the design of the study, no statistical comparisons were performed between ability level although differences were discussed. The independant variable chosen for the present study was target height and was comprised of three levels: top (D1), center (D2) and bottom (D3). The dependant variables were the vertical coordinate of release, the angle of projection of the dart, the resultant velocity of the styloid process of the wrist at release and the resultant velocity of the dart at release.

The Statistical Package for the Social Sciences (SPSSX) package was selected to conduct all statistical analyses. Descriptive statistics of all measured variables were obtained via the CONDESCRIPTIVE procedure. Four parametric oneway analyses of variance (ONEWAY) were conducted to detect statistically significant differences (alpha = 0.01) among the three levels of the independant variable for research hypotheses one through four. The absence of one trial for subjects two and three necessitated OPTION 10 (utilizing the harmonic mean) in statistical analyses. A non-parametric correlational procedure (NONPAR CORR) was used to obtain the Spearman Rank correlation between release frame and the frame containing the inflection point of the forearm angular velocity profile. A parametric analysis (PEARSON CORR) was applied in order to obtain correlations between the shoulder, elbow and wrist absolute angles across levels of target height. Student Newman-Keuls post hoc comparisons (RANGES subcommand) were performed if the probability of the F ratio was less than 0.01.

CHAPTER IV

RESULTS

The purpose of this study was to investigate the kinematic variables reflecting the variant and invariant aspects of the strategies of subjects of two ability levels performing a dart throwing task. The second concern of this study was to examine the kinematic variables which differentiated the level of skill of the subjects participating in the experiment. Results are presented in the following sections: subject description, comparison of kinematic strategies and additional observations.

4.1 Subject Description

A total of four subjects, two of each ability level, volunteered to participate in the study. The categorization of ability level was performed solely upon their present level of competitive dart playing experience. Based on this criterion, two pairs of subjects were classified as expert and novice players respectively.

The subjects' eight series of throws at each of the three levels of target height were recorded cinematographically. All trials of the film were visually inspected and the frames containing the initiation and release of the throw were marked in order to facilitate digitizing. Movement initiation was defined as the time point (zero) corresponding to the film frame where the dart began moving toward the board while the release was defined as the frame where contact between the fingers and dart was broken. The developed film was subsequently projected onto a digitizing board and all landmarks appearing in each film frame were digitized. The digitizing procedure commenced eight frames prior to the movement initiation and terminated eight frames following release to allow for warmup and warmdown of the smoothing operation. The digitized coordinates were stored on-line by the D.E. program into separate MUSIC files and were later submitted to the Biomechanics Laboratory Kinematics programs for analysis. Eight trials at each target were submitted for analysis, with the exception of subject two (Double three, n=7) and subject three (Double twenty, n=7).

4.1.1 Biometric Data of the Subjects

A description of the anthropometric data, including the darts used, pertaining to each subject appears in Table 1. The subjects differed in height (171.7 cm to 188.0 cm) and possessed similar segment lengths. Subjects 3 and 4 (novice players) used the same darts during the filming session.

Table 1 Anthropometric Data by Subject

Level	Subject	Height	Trunk	Shoulder	Upper arm	Lower arm	Hand	Dart	Mass
E	1	175.3	42.0	22.5	29.0	23.0	9.5	14.1	22.8
	2	188.0	38.0	22.5	32.0	28.5	9.0	14.7	23.5
N	3	171.7	43.0	25.0	30.0	26.0	9.0	15.2	22.0
	4	183.0	39.5	24.0	30.0	26.0	11.0	15.2	22.0

UNITS: segment lengths (centimeters)
dart mass (grams)

4.2 Comparison of Kinematic Strategies

Table 2 presents statistics describing the results of all trials of each subject. Mean error was calculated by dividing the sum of the absolute values of the distance from the target (mm) by the number of trials. The expert players each hit the target in 50.0% of all filmed trials while the novice players each hit the target in only 20.8% of the trials. A comparison of the total number of hits and the mean error and standard deviation clearly establishes the differences in skill level between the expert and novice players.

The success rate at the bullseye (D2) was 75% and 25% for the expert and novice level players respectively. This percentage was much greater than that reported by Anderson and Pitcairn's (1986) study where the success rate was 8.8% (10 hits in 114 trials) and 8.2% (10 hits in 122 trials) for the two distance conditions. The success rate of the four subjects in the present study is indicative of a higher level of skill than that of the novice subject who participated in the Anderson and Pitcairn study.

A comparison of the mean errors and standard deviations of the two ability levels reflected a greater variation in error made by the novice players. The angle of the dart at contact with the board tended towards 20 degrees for the expert players and 0 degrees for the novice players. It is possible that the angle of the dart at contact is indicative of the finger position in relation to the center of mass of the dart at release or the actions performed by the fingers while releasing the dart.

Table 2 Descriptive Statistics of Trials across Levels of Target

Level	Subject	Target	Hits	Mean Error	S.D.	Min	Max	Mean Angle	S.D.
E	1	D1	3/8	9.8	11.0	-26	10	19.0	2.4
		D2	6/8	1.6	3.9	- 2	11	16.5	4.6
		D3	3/8	2.8	3.4	-25	5	26.7	5.6
E	2	D1	2/8	8.0	6.3	-16	16	20.0	1.3
		D2	6/8	2.1	5.3	-15	2	21.4	5.3
		D3	4/8	6.8	11.6	-34	4	25.1	8.6
N	3	D1	1/8	11.9	12.8	-40	9	1.2	5.8
		D2	2/8	7.4	7.7	-24	11	0.0	1.9
		D3	2/8	9.3	9.0	-20	22	2.3	6.9
N	4	D1	2/8	24.1	25.0	-62	50	-1.3	4.7
		D2	2/8	10.3	13.5	-40	0	-3.5	4.0
		D3	1/8	11.9	10.4	-30	10	3.5	6.4

Units:
- D1 Double twenty
- D2 Double bull
- D3 Double three
- Error (millimeters)
- Angle (degrees from horizontal)
- Min (largest error below the target in millimeters)
- Max (largest error above the target in millimeters)

4.2.1 Comparison of Absolute Segment Orientations

Tables 3 and 4 illustrate the initial and release segment absolute spatial orientations over the three levels of target for all subjects respectively. The three levels of target were: D1 - Double twenty, D2 - Double bull and D3 - Double three. Angles are measured from the horizontal (0 degrees) and increase in a counter-clockwise fashion.

Dart players commonly assume one of many possible stances beginning with the placement of the foot at the throwing line. Subjects one and three placed their right toe on and perpendicular to the throwing line, while subjects two and four placed their entire right foot on and parallel to the line. With respect to the initial segment orientations, Table 3 demonstrates the existence of tendencies for all subjects regardless of skill level.

A trend existed where all subjects leaned (TS) further, depressed the shoulder complex (SS) and lowered the upper arm (US) with decreases in target height. A trend also existed where all subjects began the propulsive movement with less flexion of the forearm segment (FS) and more flexion of the hand segment (HS) corresponding with decreases in target height. All subjects tended to reduce the absolute angle of the dart (DS) with decreases in target height, with the exception of subject one.

Table 3 Segment Absolute Spatial Orientations across Levels of Target at Movement Initiation

		TARGET					
		D1		D2		D3	
	Subject	Mean	S.D.	Mean	S.D.	Mean	S.D.
TS	1	15.8	(0.5)	18.7	(0.2)	22.6	(0.4)
	2	24.6	(0.7)	28.4	(1.0)	31.0	(0.5)
	3	31.8	(2.4)	35.0	(1.3)	39.1	(1.7)
	4	13.7	(0.6)	16.8	(0.4)	19.7	(0.4)
SS	1	-52.5	(0.5)	-56.8	(0.8)	-60.5	(0.3)
	2	-52.8	(0.7)	-56.9	(0.4)	-61.6	(0.6)
	3	-60.0	(2.8)	-67.3	(3.2)	-70.8	(2.0)
	4	-55.5	(0.6)	-60.6	(0.7)	-65.0	(0.4)
US	1	-35.4	(1.9)	-37.3	(1.1)	-42.1	(1.3)
	2	-23.8	(3.0)	-27.9	(1.4)	-31.6	(3.0)
	3	-23.1	(5.1)	-32.2	(3.0)	-34.3	(2.1)
	4	-18.8	(2.0)	-21.5	(1.8)	-24.4	(1.2)
FS	1	109.1	(8.7)	108.5	(1.5)	101.1	(0.9)
	2	103.4	(3.1)	100.5	(1.4)	93.4	(3.7)
	3	117.7	(4.8)	112.6	(3.8)	109.5	(2.7)
	4	112.4	(4.6)	110.7	(2.5)	108.2	(1.7)
HS	1	26.8	(1.4)	31.8	(1.6)	35.4	(0.9)
	2	32.1	(2.6)	35.2	(1.4)	39.6	(2.4)
	3	39.2	(2.2)	41.2	(2.7)	41.5	(1.7)
	4	36.9	(6.2)	41.3	(6.7)	45.0	(6.0)
DS	1	8.0	(1.3)	8.5	(2.7)	- 2.4	(2.1)
	2	12.3	(2.8)	11.1	(2.0)	8.5	(2.4)
	3	27.9	(4.7)	28.5	(2.7)	27.2	(3.1)
	4	38.6	(17.0)	53.3	(2.9)	49.7	(1.8)

Note: D1 Double twenty, D2 Double bull, D3 Double three
TS (trunk), SS (shoulder), US (upper arm), FS (forearm),
HS (hand), DS (dart)
all angles are absolute and measured in degrees

Table 4 depicts the subjects' tendencies with respect to the segment absolute spatial orientations at release. The trend of increased angle of trunk lean (TF) and depression of the shoulder complex (SF) with decreases in target height persisted for all subjects. No such trend existed for the angle of the upper arm (UF), forearm (FF) or hand (HF) for any of the throwers, with the exception of subject 1 (FF). The expert players exhibited a tendency to decrease the absolute angle of the dart at release with decreases in target height. Subject 3 followed the same trend as the expert players, while subject 4 actually increased the dart angle with decreasing target height.

Table 4 Segment Absolute Spatial Orientations across Levels of Target at Release

		TARGET					
		D1		D2		D3	
Subject		Mean	S.D.	Mean	S.D.	Mean	S.D.
TF	1	13.8	(0.6)	16.9	(0.4)	20.8	(0.7)
	2	17.7	(2.0)	21.6	(1.2)	25.1	(0.6)
	3	25.8	(1.7)	30.7	(1.2)	35.4	(2.1)
	4	12.7	(0.8)	16.1	(0.2)	19.6	(0.4)
SF	1	-43.4	(3.5)	-48.6	(2.7)	-53.4	(1.7)
	2	-52.6	(1.0)	-57.0	(0.5)	-61.5	(0.5)
	3	-44.1	(4.1)	-51.7	(3.2)	-55.7	(3.8)
	4	-47.1	(2.5)	-51.9	(2.2)	-61.2	(2.2)
UF	1	-21.0	(10.5)	-25.3	(7.0)	-25.1	(5.6)
	2	-13.9	(6.8)	-20.8	(5.6)	-25.1	(4.8)
	3	-32.3	(6.1)	-26.2	(5.6)	-32.2	(8.9)
	4	-25.7	(7.7)	-30.9	(6.0)	-40.9	(8.8)
FF	1	73.7	(17.0)	69.3	(10.1)	67.5	(7.4)
	2	72.6	(10.3)	76.1	(7.8)	84.9	(10.6)
	3	82.3	(11.2)	70.8	(10.8)	75.0	(19.6)
	4	76.0	(14.1)	75.1	(15.1)	49.8	(14.3)
HF	1	154.3	(8.7)	149.8	(5.7)	148.9	(3.3)
	2	111.7	(7.0)	113.4	(6.0)	85.6	(2.4)
	3	134.8	(9.1)	130.9	(8.1)	142.2	(14.9)
	4	133.2	(9.4)	145.0	(11.5)	122.2	(10.8)
DF	1	-1.4	(2.3)	- 3.6	(2.4)	-15.1	(3.1)
	2	0.5	(2.7)	- 0.8	(3.3)	- 2.3	(3.3)
	3	6.5	(4.6)	3.1	(3.5)	1.1	(3.5)
	4	6.0	(2.5)	9.1	(21.7)	12.9	(8.1)

Note: D1 Double twenty, D2 Double bull, D3 Double three
TF (trunk), FF (shoulder), UF (upper arm), FF (forearm),
HF (hand), DF (dart)
all angles are absolute and measured in degrees

The initial and release absolute segment spatial orientations for the expert and novice players are depicted graphically in Figures 1 and 2. The graphs are of successful trials (hits), are typical of the subject's segment orientations across the three levels of target and are drawn to scale. Moving from proximal to distal, the triangles, diamonds and squares represent the iliac, c3, shoulder, elbow, wrist and finger markers. The graphs clearly display the trend made by all subjects of lowering the elbow with decreases in target height via the depression of the shoulder complex and an increased angle of trunk lean. This trend persists from movement initiation to release.

Figures 1 and 2 also also provide the opportunity to examine the musculoskeletal degrees of freedom used by each of the subjects. Subject 1 reduced the propulsive motion to the shoulder, elbow, wrist and finger, eliminating movement of the trunk. Subject 2 further reduced the action to motion at the wrist and finger markers only, with all movement taking place about the virtually motionless elbow joint. Subject 3, like Subject 1, restricted the motion to the shoulder, elbow, wrist and finger, yet moved the elbow through a greater range of motion. Subject 3 also tended to move both trunk markers in the vertical direction, especially in D1. Subject 4, reduced the throwing action to motion at the elbow, wrist and finger markers only and propelled the forearm through a greater range of motion than the expert players. The graphs distinctly illustrate the greater range of motion at the wrist (the angle formed between the forearm and hand) of the novice players when compared to the expert players.

EXPERT SEGMENT ORIENTATIONS

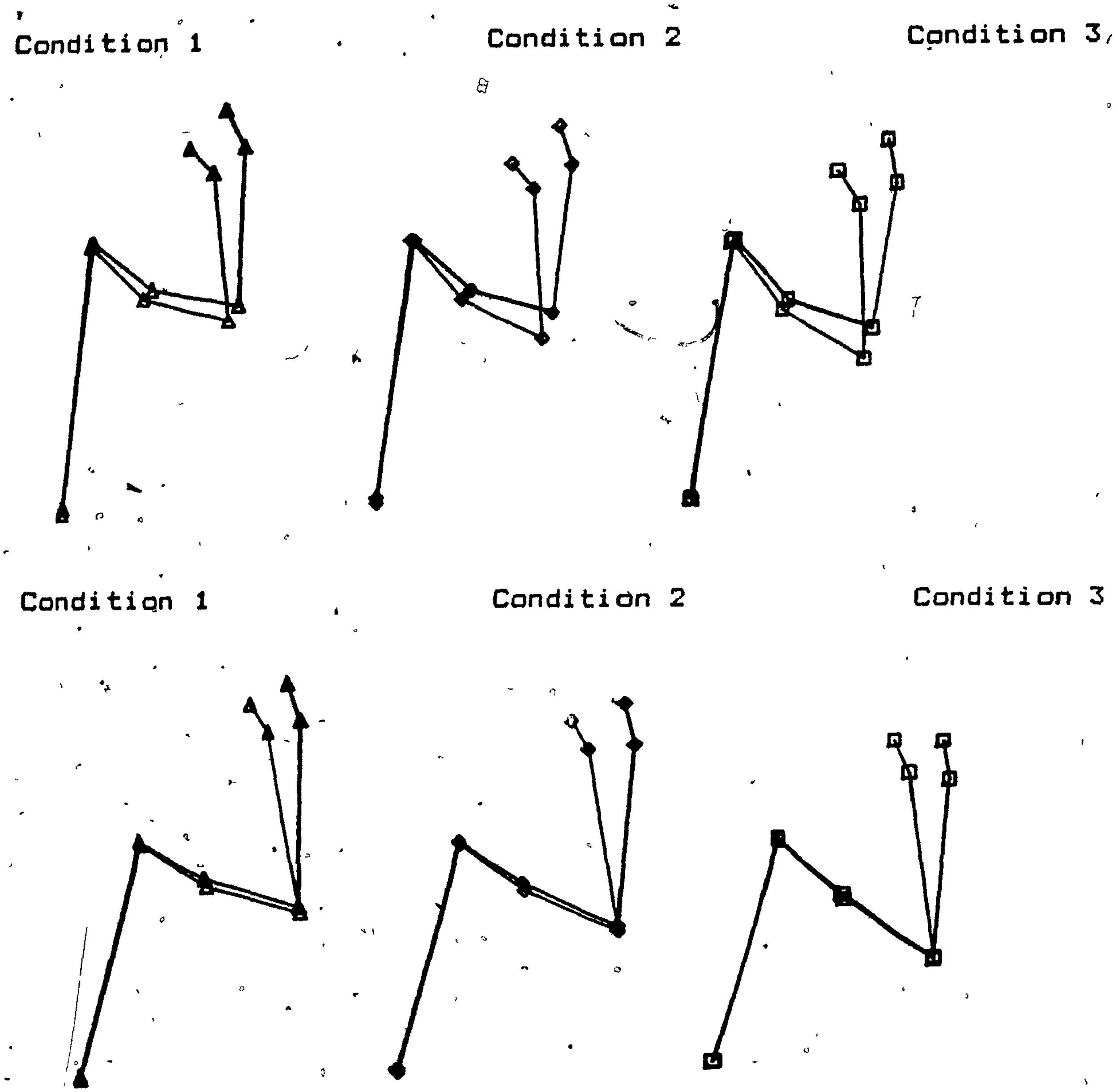

Figure 1: Expert segment orientations selected from typical trials at movement initiation and release. Condition 1 = Double Twenty, Condition 2 = Bullseye, Condition 3 = Double Three.

NOVICE SEGMENT ORIENTATIONS

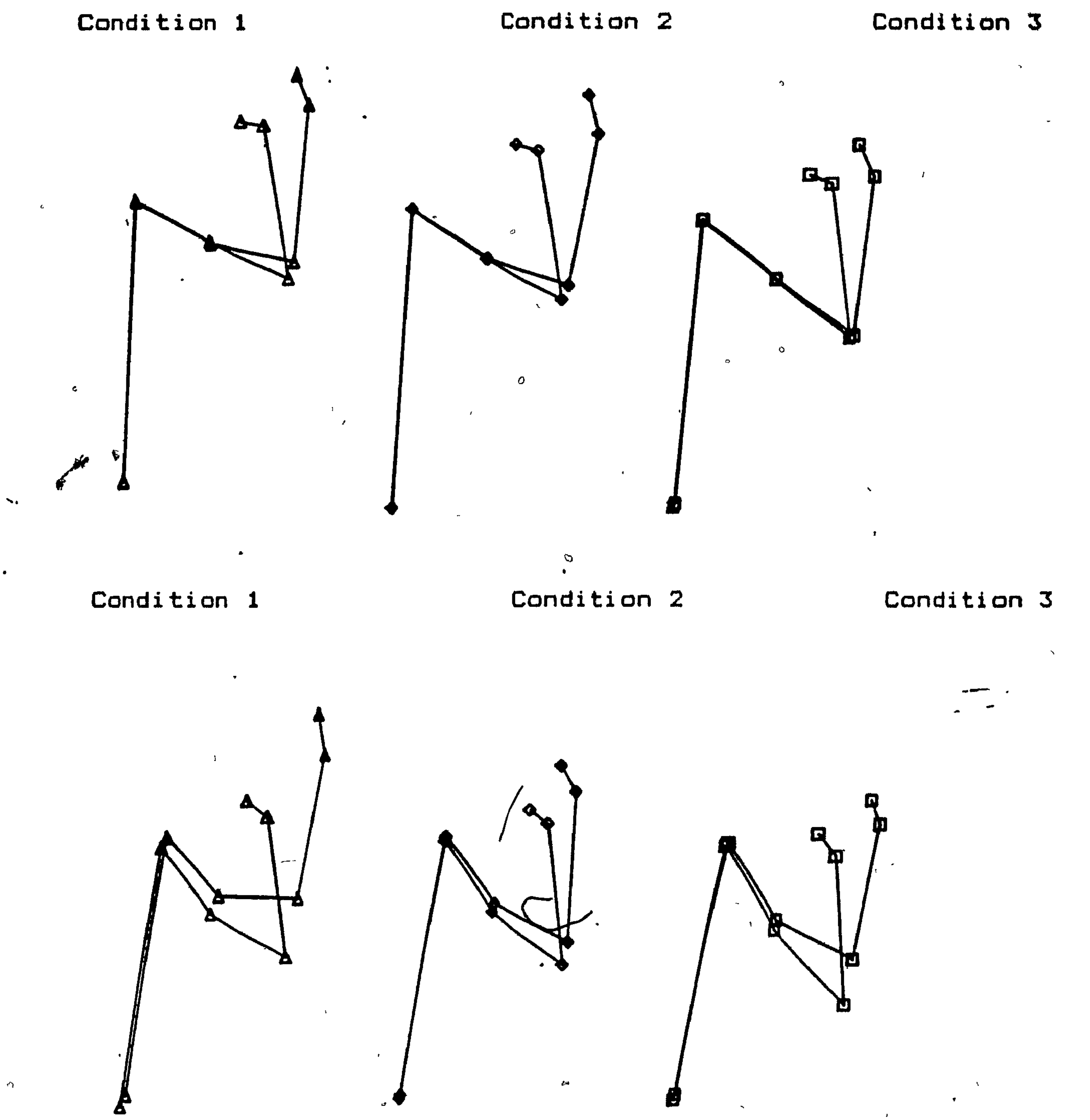

Figure 2: Novice segment orientations selected from typical trials at movement initiation and release. Condition 1 = Double Twenty, Condition 2 = Bullseye, Condition 3 = Double Three.

4.2.2 Comparison of Release Kinematics

The dependant variables selected in this study were: 1) the resultant velocity of the styloid process of the wrist at release, 2) the resultant velocity of the dart at release, 3) the angle of projection of the dart at release and 4) the vertical coordinate of the dart at release. Hypothesis one concerned the differences in the resultant velocity of the styloid process of the wrist at release (WRV) across levels of target height. The second hypothesis involved the differences in the resultant velocity of the dart at release (DRV) across levels of target height. The third hypothesis was related to the differences in the angle of projection of the dart at release (DPATH) across levels of the independant variable. Hypothesis four concerned the differences in the vertical coordinate of the dart at release (RH) across levels of target height.

During the analysis, it was deemed necessary to fully analyze the trajectories of the wrist, finger and dart at release. The analysis was extended to include the finger and wrist markers in order to demonstrate differences between the strategies of the expert and novice players. The absence of one trial necessitated performing ANOVA's adjusted for unequal sample sizes utilizing the harmonic mean in all statistical analyses for subjects two and three. Full ANOVA tables for each dependant variable are presented in Appendix B. Alpha was set at 0.01 for the testing of significance.

Table 5 contains descriptive statistics of the kinematic parameters pertaining to the wrist marker and demonstrates the consistency in the resultant velocity of the wrist at release across levels of target for all subjects. There were no significant differences in the resultant velocity of the wrist at release (WVR) for any of the four subjects and hypothesis one was therefore accepted. However, the histogram presented in Figure 3 demonstrates a slight trend of reduction in wrist velocity with decreasing target height existed for subjects one through three, while subject four actually increased WVV with decreases in target height.

Table 5 Kinematic Parameters of the Wrist Marker at Release for Expert and Novice Players across Levels of Target

Level of Play	Ss	Target	WRV (m/sec)	WPATH (degrees)	WVV (m/sec)	WHV (m/sec)
E	1	D1	3.14	11.20	0.93	3.00
			.16	2.94	.19	.13
		D2	3.13	11.49	0.63	3.06
			.19	2.81	.16	.18
		D3	3.07	9.39	0.51	3.03
			.15	4.31	.17	.13
				*	*	
E	2	D1	3.29	− 3.22	−0.18	3.28
			.17	3.16	.17	.18
		D2	3.17	− 6.68	−0.36	3.15
			.13	2.95	.15	.15
		D3	3.10	−11.67	−0.62	3.03
			.16	2.66	.12	.18
				*	*	
N	3	D1	2.92	11.27	0.58	2.86
			.24	4.15	.23	.21
		D2	2.78	15.74	0.76	2.67
			.19	2.71	.16	.16
		D3	2.67	6.46	0.34	2.64
			.38	7.72	.33	.38
				*		
N	4	D1	2.59	2.90	0.18	2.50
			.20	4.39	.23	.15
		D2	2.59	− 1.39	−0.03	2.58
			.56	4.15	.21	.55
		D3	2.67	0.85	0.05	2.65
			.25	4.18	.21	.25

* : $p < .01$
WRV : resultant velocity of wrist at release
WPATH: angle of path of wrist from horizontal at release
WVV : vertical velocity of wrist at release
WHV : horizontal velocity of wrist at release

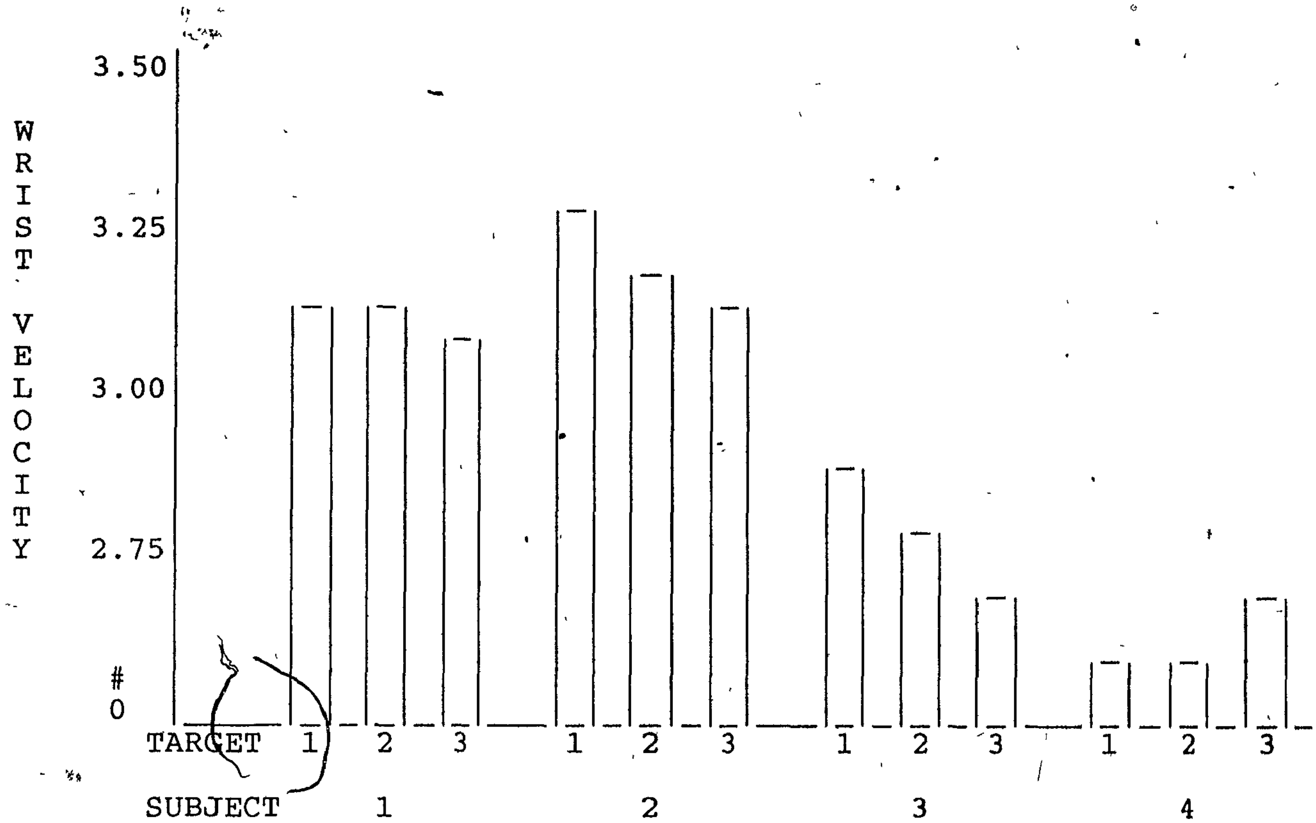

Figure 3: Resultant velocity (meters/second) of the wrist marker at release for four subjects over three conditions.

Significant differences were evident in the wrist vertical velocities (WVV) for the expert players only (Table 5). No differences were found in the horizontal velocity of the wrist (WVH) for any subject. Significant differences in the angle of path of the wrist at release (WPATH) were found for subjects one, two and three. The standard deviations of the kinematic variables relating to experts' wrist markers were generally smaller than those of the novices, reflecting the greater amount of noise in the nervous systems of the novices.

Table 6 demonstrates the absence of any statistically significant differences in the resultant velocity of the finger at release (FRV) with the exception of subject two. Subject two also displayed significant differences in the horizontal velocity of the finger marker

1

at release (FVH), while the remaining subjects did not. Significant differences in the vertical velocity of the finger (FVV) and path of the finger at release (FPATH) were in evidence for the expert players was only. The standard deviations of the kinematic variables describing the experts' finger markers, especially FPATH, were once again smaller than those of the novices.

Table 6 Kinematic Parameters of the Finger Marker at Release for Expert and Novice Players across Levels of Target

Level of Play	Ss	Target	FRV (m/sec)	FPATH (degrees)	FVV (m/sec)	FHV (m/sec)
E	1	D1	4.53	20.08	1.55	4.24
			.16	4.32	.31	.21
		D2	4.55	13.95	1.09	4.40
			.23	5.08	.37	.27
		D3	4.38	11.71	0.89	4.28
			.10	3.27	.25	.10
				*	*	
E	2	D1	4.36	1.38	0.11	4.34
			.14	4.58	.35	.14
		D2	4.27	- 1.42	- 0.11	4.26
			.09	3.58	.27	.09
		D3	4.10	- 6.84	- 0.48	4.08
			.10	3.83	.26	.15
			*	*	*	*
N	3	D1	4.17	12.64	0.93	4.05
			.33	5.48	.43	.28
		D2	3.85	16.58	1.10	3.68
			.15	3.87	.27	.13
		D3	3.63	4.15	0.35	3.52
			.53	15.36	.88	.56
N	4	D1	3.82	12.47	0.81	3.71
			.21	5.77	.34	.28
		D2	3.93	6.67	0.49	3.87
			.46	7.24	.57	.38
		D3	3.52	13.20	0.80	3.42
			.16	4.50	.26	.19

* : $p < .01$
FRV : resultant velocity of finger at release
FPATH: angle of path of finger from horizontal at release
FVV : vertical velocity of finger at release
FHV : horizontal velocity of finger at release

Table 7 illustrates the statistically significant alterations in the height of release (RH) made according to target height by all subjects, thereby verifying hypothesis four. The increased angle of trunk lean (TS and TF) and depression of the shoulder complex (SS and SF) served to lower the elbow and hand correspondingly with decreases in the height of the target. Tukey comparisons (Table 8, Appendix C) revealed the existence of significant differences between each level of target for both expert and novice subjects.

Only subject four displayed significant differences in the dart's horizontal velocity (DHV) at release. All subjects, excluding subject two, released the dart at significantly different resultant velocities (DRV), lending support to hypothesis two. Tukey comparisons (Table 9, Appendix C) revealed that subjects one and four exhibitted differences in DRV between D2-D3 only, while subject three demonstrated differences between D1-D2 and D1-D3.

Significant differences in the dart vertical velocity (DVV) and dart angle of path (DPATH) at release were established for all subjects. This angle was calculated as the arctangent of the release vertical velocity divided by the release horizontal velocity, verifying hypothesis three. Subjects of all levels of ability altered the projection angle by significantly changing the dart's vertical velocity at release. Once again, the standard deviations of the kinematic variables relating to the experts' darts were generally smaller than those of the novices. Tukey comparisons revealed the existence of significant differences between each level of target for subject two and between D1-D2 and D1-D3 for subjects one and four. Subject three exhibitted differences between D1-D3 and D2-D3.

Table 7 Kinematic Parameters of the Dart at Release for Expert and Novice Players across Levels of Target

Level of Play	Ss	Target	RH (meters)	DRV (m/sec)	DPATH (degrees)	DVV (m/sec)	DHV (m/sec)
E	1	D1	1.89	5.25	19.94	1.78	4.93
			.01	.20	2.81	.19	.26
		D2	1.85	5.36	13.90	1.28	5.20
			.01	.24	2.59	.18	.29
		D3	1.79	5.04	12.90	1.13	4.92
			.01	.09	1.29	.11	.10
			*	*	*	*	
E	2	D1	1.94	4.88	20.32	1.69	4.58
			.02	.11	1.76	.13	.13
		D2	1.88	4.78	16.17	1.33	4.59
			.01	.10	2.02	.14	.13
		D3	1.84	4.71	11.45	0.93	4.62
			.01	.14	1.43	.11	.14
			*		*	*	
N	3	D1	1.86	4.90	21.95	1.82	4.54
			.02	.24	2.39	.12	.29
		D2	1.80	4.52	22.11	1.70	4.18
			.02	.08	2.08	.14	.12
		D3	1.75	4.52	17.21	1.34	4.31
			.03	.33	2.60	.21	.32
			*	*	*	*	
N	4	D1	1.97	4.67	21.84	1.73	4.32
			.03	.10	4.09	.27	.21
		D2	1.92	4.89	12.86	1.07	4.77
			.01	.55	3.09	.18	.59
		D3	1.87	4.27	16.37	1.20	4.09
			.01	.22	2.99	.22	.22
			*	*	*	*	*

* : $p < .01$
RH : release height
DRV : resultant velocity of dart at release
DPATH: angle of projection of dart from horizontal at release
DVV : dart vertical velocity
DHV : dart horizontal velocity

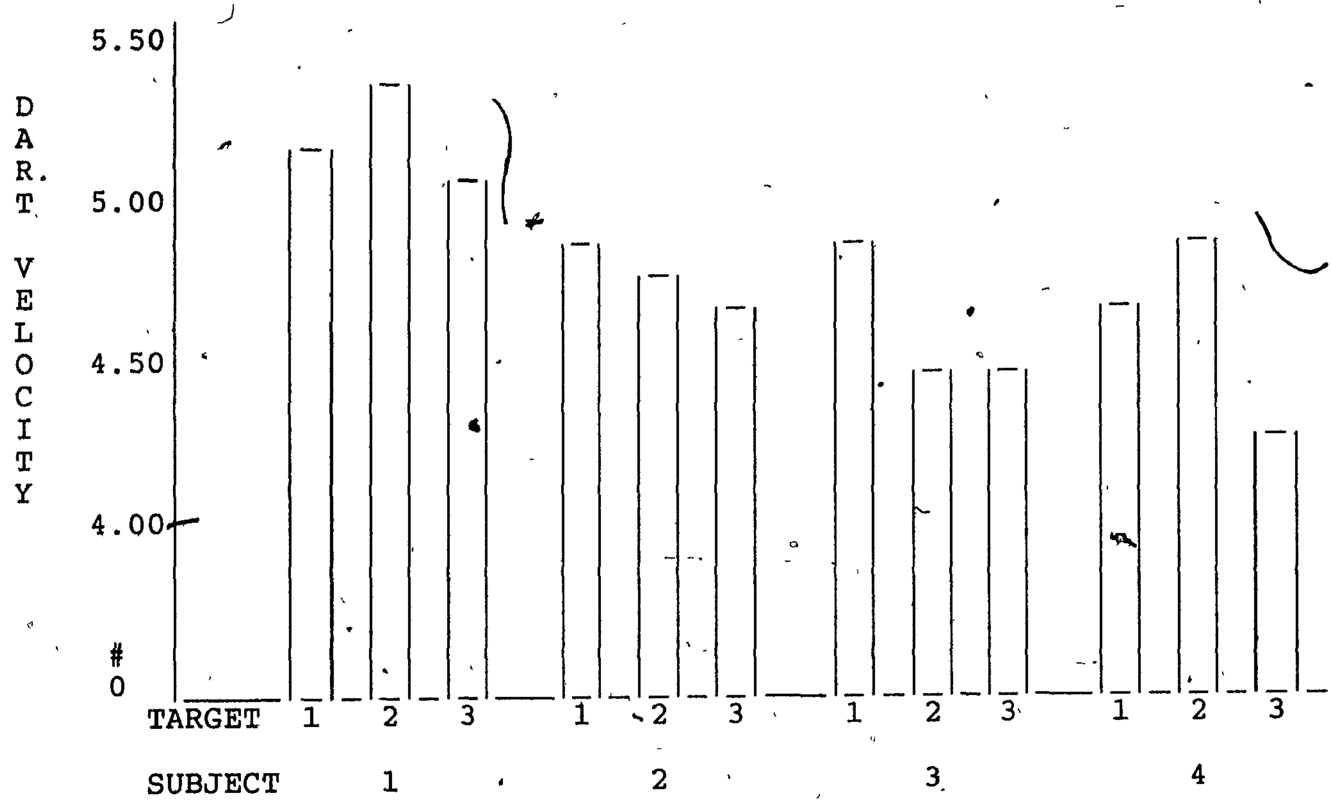

Figure 4: Resultant velocity (meters/second) of the dart at release for four subjects over three conditions.

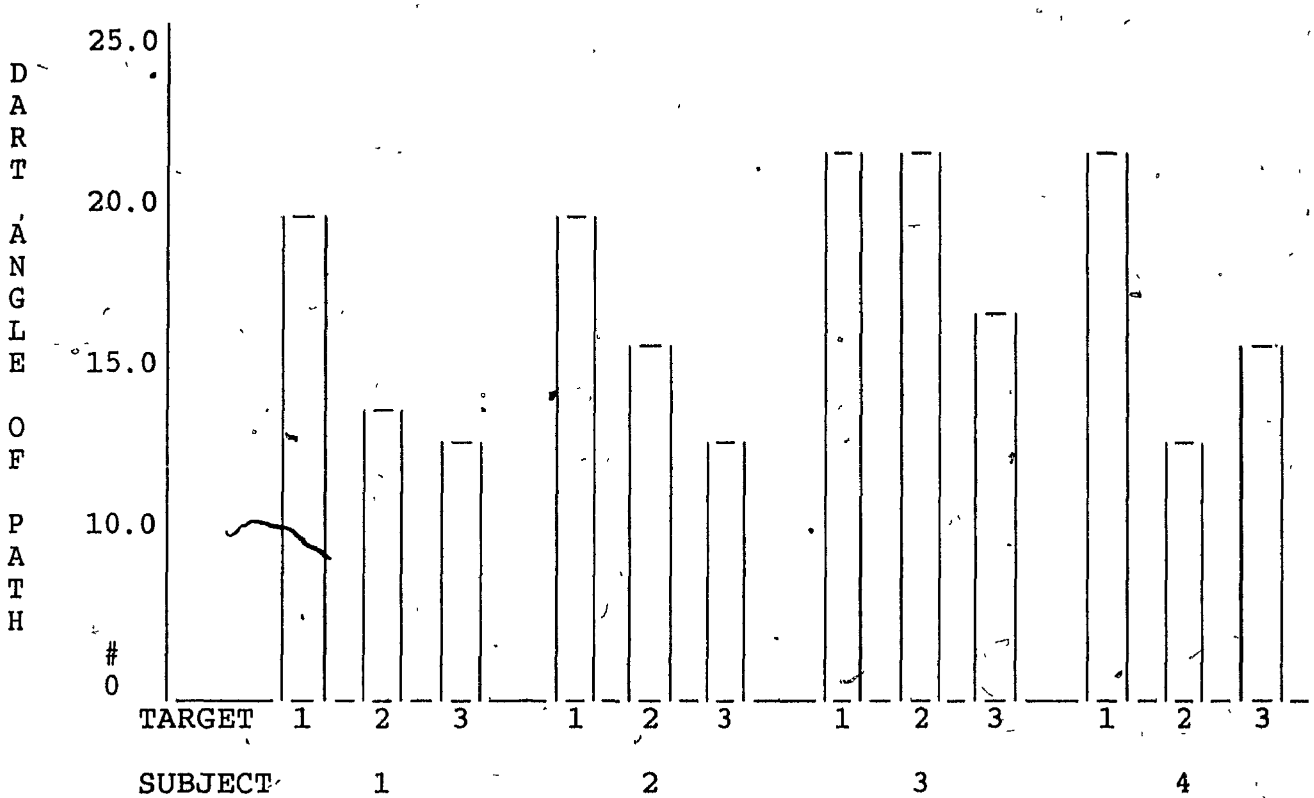

Figure 5: Angle of path (degrees) of the dart at release for four subjects over three conditions.

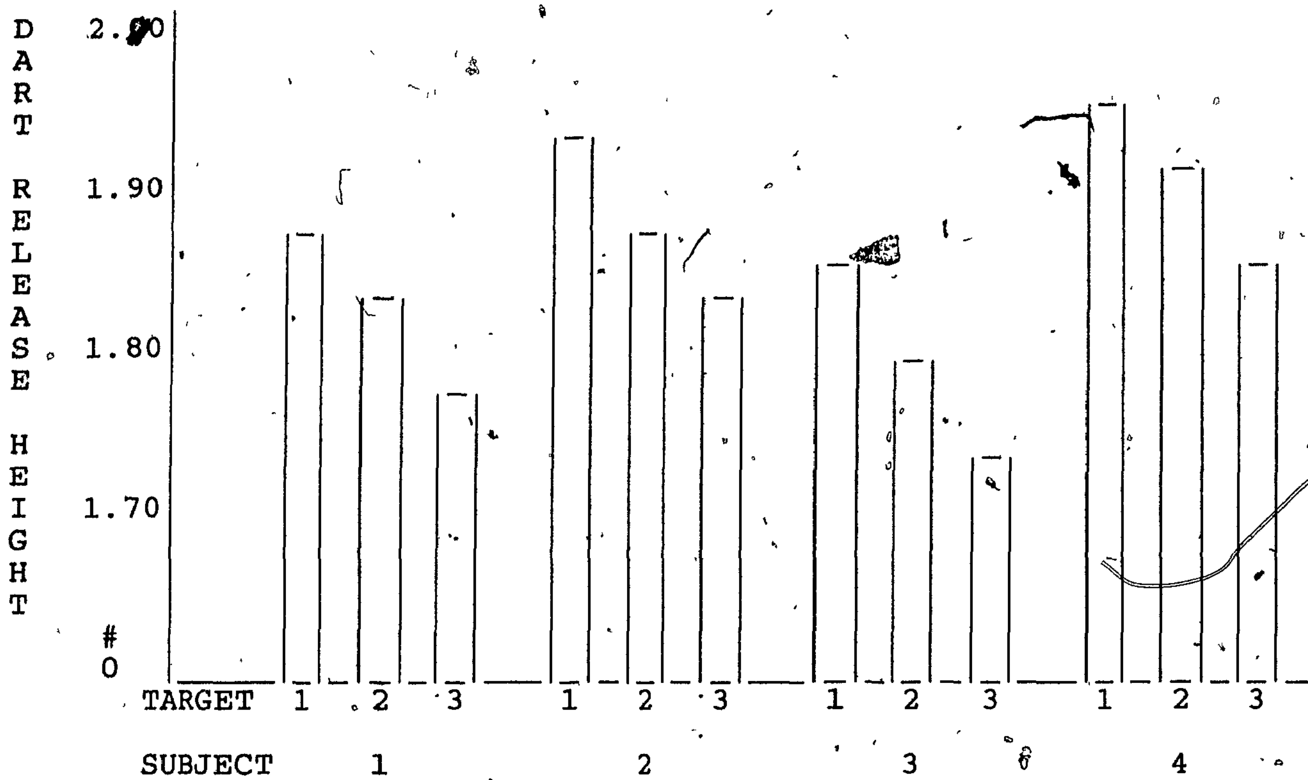

Figure 6: Dart release height (meters) for four subjects over three conditions.

4.3 Additional Observations

During the analysis of the data, observations were made which were regarded as pertinent towards a more complete understanding of the strategies of the players and are presented here.

4.3.1 Analysis of Segment Absolute Angles

A correlative analysis was carried out in an endeavour to ascertain the relationships between the shoulder, elbow and wrist absolute angles throughout the throw. Table 11 presents the results of this analysis and must be examined with the segment orientations of figures one and two in mind.

Table 11 Correlation Coefficients among Shoulder, Elbow and Wrist Absolute Angles across Levels of Target

Level of Play	Subject	Target		Elbow r	Elbow R	Wrist r	Wrist R
E	1	1	Shoulder	-.47	.22	-.35	.12
			Elbow			.95	.90
		2	Shoulder	-.60	.36	-.47	.22
			Elbow			.96	.92
		3	Shoulder	-.84	.71	-.82	.67
			Elbow			.97	.94
E	2	1	Shoulder	.31	.10	.31	.10
			Elbow			.96	.92
		2	Shoulder	-.03*	.00	.07*	.00
			Elbow			.96	.92
		3	Shoulder	.40	.16	.31	.10
			Elbow			.92	.84
N	3	1	Shoulder	-.31	.10	-.14*	.02
			Elbow			.90	.81
		2	Shoulder	-.76	.58	-.74	.55
			Elbow			.91	.83
		3	Shoulder	-.47	.22	-.27	.07
			Elbow			.91	.83
N	4	1	Shoulder	-.81	.66	-.45	.20
			Elbow			.63	.37
		2	Shoulder	-.97	.94	-.74	.55
			Elbow			.74	.55
		3	Shoulder	-.75	.56	-.11*	.01
			Elbow			.43	.18

* $p > .01$
r = Pearson Correlation Coefficient
R = Coefficient of Determination
p = probability of r, with 22 (subjects 2 and 3) and 23 df

Of the expert players, subject one displayed significantly (p<.01) negative correlations of the shoulder-elbow (r = -0.47 to -0.84) and shoulder-wrist (r = -0.35 to -0.82) and significantly positive correlations between the elbow and wrist (r = 0.95 to 0.97). Correlative results for subject two demonstrated positively significant correlations of the shoulder-elbow (r = 0.31 to 0.40) and shoulder-wrist (r = 0.31) and between the elbow and wrist (r = 0.92 to 0.96). However, in the D2 the correlation between the shoulder and elbow and the shoulder and wrist of subject two were not significant. Between ninety and 94 percent and 84 to 92 percent of the variance in the wrist angle was explained by the elbow angle of subjects one and two respectively.

With regard to the novice players, subject three displayed significantly negative correlations between the shoulder-elbow (r = -0.31 to -0.76) and shoulder-wrist (r = -0.27 to -0.74) with the exception of the shoulder-wrist in D1, and a significantly positive correlation between the elbow-wrist (r = 0.90 to 0.91). Subject four also displayed significantly negative correlations between the shoulder-elbow (r = -0.75 to -0.97) and shoulder-wrist (r = -0.45 to -0.74) with with the exception of the shoulder-wrist in D3, and a significantly positive correlation between the elbow-wrist (r = 0.43 to 0.74).

4.3.2 Analysis of Release Timing

It was noticed during the computer analysis that the film frame marked by the experimenter during the digitization process as the release frame often coincided with the first frame where the forearm angular velocity turned negative. Since it had been previously assumed that the inflection point in the forearm velocity profile was indicative of the onset of the movement of the antagonist musculature a correlative analysis was performed, the results of which are presented in Table 12.

Table 12 Correlation Coefficients between the Release Frame and the Frame Containing the Inflection Point of the Forearm Velocity Profile

Level of Play	Subject	Target	n	r	p	
E	1	1	8	1.00	.000	*
		2	8	.99	.000	*
		3	8	1.00	.000	*
		Total	24	.98	.000	*
E	2	1	8	1.00	.000	*
		2	8	.96	.000	*
		3	7	.97	.000	*
		Total	23	.97	.000	*
N	3	1	7	.90	.003	*
		2	8	.87	.002	*
		3	8	.84	.004	*
		Total	23	.93	.000	*
N	4	1	8	.98	.000	*
		2	8	.52	.091	
		3	8	.94	.000	*
		Total	24	.93	.000	*

* $p < .01$
r = Spearman Rank Correlation Coefficient
p = probability of r

Spearman Rank correlation coefficients between 0.96 and 1.00 were found for the expert players, while coefficients ranging from 0.52 to 0.98 were found for the novice players. Significant correlations ($p<.01$) were found for all subjects in all levels of target, with the exception of subject 4 in D2. Although no cause and effect relationship can be established between the onset of antagonist braking and release, it is possible that the timing of release is somehow coupled with that of the braking action.

CHAPTER V

DISCUSSION OF RESULTS

The purpose of this study was to investigate the kinematic variables reflecting the variant and invariant aspects of the strategies of subjects of two ability levels performing a dart throwing task. The second concern of this study was to examine the kinematic variables which differentiated the level of skill of the subjects participating in the experiment. Two pairs of expert and novice players were filmed from the sagittal plane during a dart throwing task. In this chapter, the results of the investigation will be discussed in the following manner. Each subject's kinematic data will be interpreted and the self-imposed constraints or strategies will be discussed with respect to task-related, musculoskeletal and neuromuscular degrees of freedom. Also, the two ability levels will be contrasted throughout this discussion.

The research question posed in Chapter I was: What are the kinematic strategies of the dart player and how are these strategies modified when the target height is altered? An analytical computer model was developed and permitted the examination of the feasibility of three possible dart throwing strategies. The most viable strategy for contacting targets located at various target heights involved the maintenance of a constant wrist resultant velocity at release, while manipulating release height as well as dart resultant velocity and path at release.

Four hypotheses concerning alterations in wrist and dart velocity, path and release height associated with throws to three levels of target height (D1 - double twenty, 190 cm above the floor, D2 - bullseye, 173 cm above the floor, D3 - double three, 156 cm above the floor) were constructed and statistically tested. Hypothesis one concerned the differences in the resultant velocity of the styloid process of the wrist at release (WRV) across levels of target height. The second hypothesis involved the differences in the resultant velocity of the dart at release (DRV) across levels of target height. The third hypothesis was related to the differences in the angle of projection of the dart at release (DPATH) across levels of the independant variable. Hypothesis four concerned the differences in the vertical coordinate of the dart at release (RH) across levels of target height. The research hypotheses were upheld in 15 of 16 cases, with the sole exception being subject two's dart resultant velocity at release.

5.1 Levels of Degrees of Freedom

When the degrees of freedom associated with arm movements are discussed in the literature (Hasan, Enoka and Stuart, 1985; Hollerbach, 1985), references are made with respect to the musculoskeletal system only. However, in any well defined, goal oriented task it can be stated that there are four levels of the degrees of freedom: 1) task related degrees of freedom or the combination of kinetic and kinematic parameters necessary to achieve the movement goal, 2) cognitive degrees of freedom or the subject's perception of the task's goal, 3) musculoskeletal degrees of freedom related to the geometry of joint articulation and the force-time characteristics of the muscle contraction and 4) the neuromuscular degrees of freedom reflected by the movement kinematics of the individual.

The available task related degrees of freedom have been well defined in the movement goal of the investigation: A dart player can effect variations in the release height (RH), release velocity (DRV) and angle of projection of the dart (DPRO) to achieve a successful throw to a specified target. The variations may be performed on any one or a combination of these kinematic variables. As previously stated in Chapter I, the dart throwing paradigm utilized in this study requires the subject's simultaneous control of two kinematic parameters: 1) hand-dart velocity and path (trajectory) and 2) segment orientation.

A reduction in musculoskeletal degrees of freedom must be a result of the individual's cognitive attempt at constraining the throwing motion, including the parameters of stance and joint motion. In the present investigation, this reduction is due to two factors. The first factor is related to the experimental paradigm whereby movement was restricted to the sagittal plane by selecting targets along a vertical line bisecting the dart board through the bullseye. Although movement was not physically limited in any way and a one camera setup could not measure action occuring along the 'z' axis, movements along that axis were not observed during the data collection session.

The second factor involves the individual's self-imposed constraints on both the available musculoskeletal and neuromuscular degrees of freedom. These constraints must be organised by the player in such a fashion as to achieve the movement goal. The musculoskeletal degrees of freedom of the trunk, shoulder, wrist and finger markers were restrained by both the experimental design as well as a cognitive constraint. The subject's strategy is composed of these self-imposed constraints made upon the musculoskeletal and neuromuscular degrees of freedom. In fact, given the movement goal and the strategy of the subject, the neuromuscular degrees of freedom are the nervous system's output or kinematics. In discussing the results of the present investigation, the subject's strategies will be discussed with respect to this division of the levels of degrees of freedom.

5.2 Musculoskeletal Degrees of Freedom

Since it has been demonstrated that the musculoskeletal degrees of freedom reflect a cognitive effort to constrain joint motion, an analysis of the subject's strategies at this level was deemed of interest.

5.2.1 Stance and Aiming

Dart players begin preparation for their series of throws by assuming their stance on the throwing line. The importance of a consistent stance (foot placement) and posture (segment orientations) is intuitively known to the expert dart players. A small lateral displacement of the feet from the habitual location of the positional marker placed on the throwing line would require compensatory adjustments at the trunk, shoulder, elbow and wrist in order to contact the target. The three dimensional position of the center of gravity must also be maintained in a stationary position over the base of support prior to and during the throw. Any displacement of the center of gravity would also require an adjustment in either/or release velocity, height and angle of projection during the throw. Although the role of visual proprioceptive information was not a concern of this investigation, it's function in the aiming process is important and must be discussed.

Vision must also play a paramount role in preparation for, and execution of the throw and it seems logical to assume that the visual system guides the orientation of the entire body as well as the dart during the aiming action. After placing the foot or feet at the marker on the throwing line, players of both ability levels lined up the dart with the target prior to flexing at the elbow joint and moving to the initiation position. This act of lining up the dart with the desired target allowed for the adjustment of the vertical height of the dart before it was drawn back to the movement initiation position. During that time span, visual proprioceptive information was likely used to correct any positional errors input to the system prior the drawback phase of the movement. Once the dart was lined up with the specified target, the segments comprising the trunk, arm and hand were also oriented in their favoured positions. It is therefore likely that release height was planned during the aiming phase.

Regardless of target height, each subject drew the dart back to the level of the eye in all filmed trials, although the actual height of the dart from the floor varied with the angle of lean of the trunk and the absolute angles at the shoulder and upper arm. During digitization, it was noticed that subject one ceased all movement prior to the initiation of the propulsive movement for approximately 0.17 seconds (10 frames). Subject two stopped the movement for one or two frames while the novice players performed a continuous movement from drawback to movement initiation. The act of aiming continued over a longer duration for the expert players compared to the novices and the movement initiation position was also maintained over a longer period of time. The aiming phase of the throw, which was not accounted for in the present study, is of vital importance to throwing accuracy since the duration of the throwing movement is too short to permit advantageous use of any visual feedback (Carlton, 1981). Therefore, it is during the time span between aiming and movement initiation that any errors may be corrected and release height must be planned. However, if the trajectory was planned using vision alone (i.e. as a straight line joining the eye and target), a release velocity equalling the speed of light would be required to contact the target. Thus, the aiming process explains the planning of release height yet it does not entirely account for the trajectories of the wrist, finger and dart.

5.2.2 Joint Motion

The stick figures presented in Figures 1 and 2 are representative of the subjects segmental orientations at movement initiation and release for throws to the three targets and enabled the calculation of the musculoskeletal degrees of freedom along two axes (x and y). By far the most experienced and talented dart player, subject one's trial results corroborated all four research hypotheses. Of the available two-dimensional degrees of freedom, two at the ilium, C3, shoulder and elbow (eliminating the wrist and finger), it may be stated that subject one coordinated his throw with a 50 percent (4/8) reduction in the potential degrees of freedom in all levels of target, through the elimination of movement at the two trunk markers. A highly skilled, yet less experienced player than subject one, subject two's trial results sustained three of the research hypotheses, save hypothesis two. Figure 1 displays a 75 percent (6/8) reduction in the degrees of freedom of throws in all levels of target through stationary trunk markers, and vertical motion only at the shoulder and elbow markers.

Although he was the least experienced of all participators in the study, subject three's trial results corroborated all research hypotheses. An examination of the typical segment orientations at the movement initiation and release of subject three discloses no reduction in the potential degrees of freedom in D1, and a 37.5 percent (3/8) reduction in D2 and D3 (Figure 2), via elimination of horizontal trunk and shoulder motion. A slightly more experienced player than subject three, subject four's trial results also supported all research hypotheses. Figure 2 displays a 75 percent (6/8) reduction in the potential degrees of freed shoulder markers.

It is evident that players of both ability levels reduced the potential degrees of musculoskeletal freedom in an attempt to constrain joint motion and increase consistency, thereby reducing error. Although the novice players constrained their joint motion to virtually the same extent as the experts, the mean error of dart contact at the board (Table 2) illustrates the inability of the novices to constrain their movement kinematics or neuromuscular degrees of freedom. Finally, the experimental design did not permit an extended analysis of the degrees of freedom of the fingers and thumb, the digits controlling the dart's release.

5.3 Neuromuscular Degrees of Freedom

The neuromuscular (or kinematic) degrees of freedom are measures of the nervous system's output given the task goal, musculoskeletal constraints and the subject's strategy. The measured kinematic variables include the segment spatial orientations at movement initiation and release, and the marker kinematics. The variant and invariant aspects of these variables and the differences delimitting the level of skill will be discussed in this section.

5.3.1 Segment Orientation

The statistical design of the investigation permitted analyses of variance using the means of eight trials at each target, permitting the contemplation of both the means and standard deviations of all the measured variables under study. The magnitude of the standard deviation reflects the noise of the nervous systems of the throwers (Anderson and Pitcairn, 1986). Although Anderson and Pitcairn's definition of noise was applied to the increase in the positional (x and y) standard deviations measured from movement initiation to release, the standard deviations of the variables measured in the present study reflect the trial to trial noise occuring at release.

At movement initiation, all subjects leaned further towards the target and lowered the angles of the shoulder complex and upper arm with decreases in target height and the trend persisted up to release (Table 3). The adjustment in the orientation of the more proximal segments enabled the thrower to line up the dart with the target while aiming. The subjects' standard deviations of the trunk, shoulder and elbow segments at both movement initiation and release were relatively low in comparison to those of the more distal segments, suggesting that the initiation positions were consistently attained by all subjects. At release, the subjects' standard deviations of the segment orientations were greater for all segments than at movement initiation. Thus, the movement initiation position was less noisy than the release positions due to the utilization of visual proprioceptive information by the throwers.

Table 4 depicts a trend whereby the standard deviations of the novice's segments were higher than those of the experts (especially the hand angle, HF), signifying the presence of a greater amount of noise. It is of interest to note that Anderson and Pitcairn's (1986) analysis identified the angle of the wrist at release to discriminate low misses and hits as well as low misses and high misses. The wrist angles of the novice subjects were 'noisier' than those of the experts, suggesting that the novice throwers' hand orientations at release were less consistent than the expert players and this factor must have contributed to the greater mean error of the dart at contact with the board.

5.3.2 Interrelationship of Shoulder, Elbow and Wrist Angles

Although the motion of the shoulder and elbow joints were significantly correlated for all subjects, excepting for one case, the correlations were likely influenced by the inertial coupling of the two joints (Soechting, 1984). Since no biomechanical coupling of the shoulder and wrist joints exists, it was no surprise that such correlations of shoulder-wrist were also of a low order. These findings were also influenced by the cognitive constraints made upon the musculoskeletal degrees of freedom of shoulder motion by the subjects.

Research by Soechting (1984) has demonstrated that wrist motion can be regulated independantly from that of the more proximal joints. During the planning stage of this study, it was assumed that the subjects' wrist motion would be independant of the elbow in order to achieve the selected dart trajectory. In examining the results of the expert players, however, the expert players displayed highly significant correlations between the elbow and wrist absolute angles throughout throws to the three targets. These findings suggest the existence of a goal-directed elbow-wrist synergy independant of target location (Table 11). Although the elbow-wrist correlations of the novice subjects were significantly correlated, they were of a lower order than those of the expert players. This also implies the existence of a goal-directed synergy similar to that of the experts, yet the coupling of elbow and wrist angle was not quite as tight as that of the expert players. An inhibitory process must have been responsible for the splitting of the shoulder from the general synergy (Greene, 1982). The existence of such a synergy reflects a further attempt made by the nervous system to simplify the movement.

5.3.3 Marker Kinematics

EXPERT SUBJECTS

Subject 1

Table 5 demonstrates that subject one exhibited no significant differences in wrist resultant velocity (WRV) across levels of target, supporting hypothesis one. The extended analysis of the wrist path, vertical and horizontal velocity revealed no significant differences in the horizontal velocity at release. The alteration of the path of the wrist (WPATH) was achieved through a significant and proportional alteration of wrist vertical velocity (WVV) with changes in target height. An identical pattern persisted for subject one's finger marker where significant differences were found in FPATH and FVV and no significant differences were found in FRV and FVH (Table 6).

Subject one released the dart at significantly different resultant velocities, angles of path and release heights among the targets, lending credence to hypotheses two, three and four (Table 7). The changes in DPATH were attained through a corresponding decrease in DVV with target height. Note that the differences in the marker paths became more marked at the finger, where FPATH attained virtually the same values as DPATH. While the DPATH for D2 and D3 varied by only one degree (12.90 versus 13.90 degrees), DHV was increased for target D2 in order to contact the bullseye. D1 was marked by virtually the same DHV as D3, yet it had a significantly higher DPATH than for D2 and D3 was selected.

Post hoc comparisons (Tables 8, 9 and 10, Appendix C) revealed that: 1) RH's were significantly different among D1, D2 and D3, 2) DRV was different between D2 and D3 only and 3) DPATH was different between D1-D3 and D2-D3. Subject one's strategy for creating trajectories to three different target heights was therefore one of creating enduring changes in DRV and DPATH through alterations in WVV and WPATH, and FVV and FPATH. In so doing, subject one constrained the hand (comprising the wrist and finger markers) and dart to act as a unit, thereby following a similar spatial trajectory at release. Although differences existed among the marker paths, no significant differences were found in the wrist, finger or dart resultant velocity, implying that the marker velocities were independant of the marker paths.

It appears that rather than 'throwing' the dart, subject one permitted the dart to slip out of his fingers. This finding is supported by two further findings. Firstly, the similarity in the magnitude of FPATH and DPATH suggests that no finger extension took place prior to release. Secondly, the correlation between the release frame and the frame containing the inflection point of the forearm velocity profile was 0.98. Given a sufficiently small grip force, the sudden onset of antagonist breaking would permit the dart to slip from the thrower's fingers. This method of release could reduce the trial-to-trial variation (noise) in DPATH given a consistent WPATH and FPATH.

Subject 2

Subject two demonstrated no significant differences in WRV, backing hypothesis one. Analysis of WPATH, WVV and WHV (Table 5) revealed the pattern followed by subject one, yet it did not persist at the finger marker. It is interesting to note that both WVV and WPATH were negative, signifying that the wrist was moving in a downward direction at release. The cause of the downward movement is likely due to the subject's height (188.0 cm) and large range of motion of the wrist angle (Tables 3 and 4).

Subject two displayed significant differences in FRV, FPATH, FVV and FHV (Table 6), with corresponding changes in the magnitude of the measured variable with target height. The alterations in FPATH were achieved through changes in both FVV and FHV and produced significant differences in FRV. FPATH was also below the horizontal in D2 and D3 (-1.42 and -6.84 degrees) and only slightly positive (1.38 degrees) in D1. This result signifies that the wrist and finger markers were constrained to act together as a functional unit.

The dart was released at significantly different RH's, DPATH's and DVV's, verifying hypotheses three and four, however hypothesis two was not accepted (Table 7). Subject two did not release the dart at significantly different resultant velocities, although a trend of decreasing DRV with target height was observed. Although WPATH and FPATH were below the horizontal or slightly above, all DPATH's were positive and much greater (18 to 19 degrees) than WPATH and DPATH. This finding suggests that subject two utilized his fingers to achieve the selected dart trajectory.

Post hoc comparisons (Tables 8, 9 and 10, Appendix C) revealed that DPATH's and RH's were significantly different among D1, D2 and D3. Although no differences existed in WHV and DHV, FHV was significantly different across levels of target. Subject two's strategies for contacting the three targets was to perform changes in DPATH across all levels of target, beginning with alterations in WVV and WPATH, and FRV (FVV and FHV) and FPATH. Subject two constrained the hand markers to act as a unit, yet finger extension must have caused the non-significance in DRV and the great increase in angle from FPATH to DPATH. Alterations in the paths of all markers were achieved through corresponding changes in their vertical velocity with target height. A non-significant trend of reducing DRV with decreasing target height was observed and the changes made in DPATH via DVV were sufficient to attain the specified target.

NOVICE SUBJECTS

Subject 3

Subject three sustained hypothesis one, exhibiting no significant differences in WRV across the levels of target. Although significant differences were displayed in WPATH, no differences were revealed in WVV or WHV and no trend of decrease in angle existed with decreasing target height (Table 5). In fact, WPATH was greater for D2 and D1. No significant differences were found for any of the variables pertaining to the finger marker at release (FRV, FPATH, FVV or FHV), although FPATH followed the same trend as WPATH (Table 6).

Subject three released the dart at significantly different RH, DRV, DPATH, and DVV across levels of target height, sustaining hypotheses two, three and four (Table 7). Post hoc comparisons (Tables 8, 9 and 10, Appendix C) demonstrated that: 1) RH's were significantly different among D1, D2 and D3, 2) DRV was different between D1-D2 and D1 and D3 and 3) DPATH was different between D1-D3 and D2-D3.

Subject three's strategy for hitting the differing targets was more difficult to recount due to the lack of significance of the finger variables and the pattern of marker paths at release. The trend of higher angles of path in D2 than D1 persisted from the wrist through the finger to the dart. The marker paths were due to a trend towards decreasing vertical velocity from D2-D1-D3 and a trend of reducing wrist and finger horizontal velocity correspondingly with target height. In order to hit the bullseye (D2), subject three released the dart at a higher DPATH (due to the contribution of a higher DVV) than in D1, with a lower DRV and DVH.

It is obvious that subject three 'lobbed' the dart at the bullseye with a DPATH greater than that for the double twenty and a DRV near to that of the double three. There is some evidence lending credence to the coordination of the hand markers to act as a unit. Although the significant differences in WPATH did not endure at FPATH and reappeared in DPATH, a non-significant trend similar to that of the expert subjects existed. A difference of 6 to 13 degrees between FPATH and DPATH was evident, suggesting the presence of finger extension prior to release. Although non-significant trends existed in the marker paths across target height, the standard deviations of the vertical velocities and paths were too large to allow for statistical significance. This finding signifies a greater amount of noise in the neuromuscular output of subject three, causing a lack of consistency in the segment and marker kinematics and contributing to the mean error about the specified target.

<u>Subject 4</u>

Subject four exhibited no significant differences in WRV, sustaining hypothesis one (Table 5). No differences were found in any of the remaining wrist variables at release, nor were differences found in any of the finger variables (Table 6), although a trend existed with respect to WPATH and DPATH. The negative WPATH and WVV were lower for the bullseye than the double three, as were the positive FPATH and FVV. A trend also existed whereby the horizontal velocity at the wrist tended to increase and the horizontal velocity of the finger tended to diminish with decreasing target height.

The dart was released at a significantly different RH, DRV, DPATH, DHV and DVV, backing hypotheses two, three and four (Table 7). Since no significant changes were made at either WPATH or FPATH, the significant alterations in DPATH must have been attained through an extension of the fingers, as with subjects two and three. Post hoc comparisons (Tables 8, 9 and 10, Appendix C) disclosed that 1) RH's were significantly different among D1, D2 and D3, 2) DRV was different between D2-D3 only and 3) DPATH was different between D1-D2 and D1-D3.

Subject four's strategy for throwing the dart to the different target heights was also unclear, owing to the non-significance of the wrist and finger kinematic variables and the pattern of marker paths at release. The trend of a lower path elevation for the wrist marker in D2 than in D3 endured through the finger and dart. A similar trend involving the marker horizontal and resultant velocities at release was also disclosed. It is plain to see that subject four utilized a higher release velocity and flatter path to hit the bullseye, while selecting a lower DRV and higher DPATH to hit the double three.

There is some evidence suggesting that subject four constrained the hand markers to act as a unit, due to the trend of marker path variation with target height. The large change in path from the wrist and finger to the dart implies finger extension prior to release. As with subject three, the standard deviations of the vertical velocities and paths did not allow for statistical significance. The standard deviations of the marker variables implies a lack of trial to trial consistency which contributed to the error at the target.

5.3.4 Release Timing

The instant of release is of vital importance to throwing accuracy since the dart's release trajectory and height combine to produce the flight to the target. A question arises as to how a thrower controls this vital aspect of release timing. Table 12 presented the results of a correlative analysis of two distinct events: the frame containing release and the frame containing the inflection point of the forearm velocity profile. Highly significant correlations were found in all but one case (Subject 4 in D2) and the correlations were of a higher order for the experts than the novices. Regardless of target height, players of all levels of ability released the dart at virtually the same frame as the onset of antagonist braking.

It was assumed in Chapter I that the inflection point of the forearm velocity profile is representative of the onset of antagonist braking action minus motor time. The results presented in Table 12 demonstrated that release occurs coincidentally with antagonist braking, yet a causal relationship could not be established within the boundaries of the analysis. The question of interest becomes: Is the onset of antagonist braking contingent upon the instant of release or is release controled utilizing the onset of braking?

It is intuitively known that dart throwers must make use of a light grip force in order to release the dart in a consistent fashion. It is possible that the deceleration of all segments distal to and including the forearm segment combined with the minimal grip force on the dart could cause the dart to slip from the thrower's fingers. If release occurs in this fashion then release timing is controled by the onset of the braking action and such timing must be pre-set by the nervous system. In such a well learned task, it would be expected that the expert players would exhibit higher correlations between the two events.

5.4 Comparison of Expert and Novice Results

Players of both levels of ability released their darts at significantly different vertical coordinates (Table 7) and in all cases these RH's were significantly different among D1, D2 and D3 (Table 8, Appendix C). This finding, along with the results concerning the analysis of the wrist marker presented in Table 5, suggests that the subjects utilized the simplest method of achieving the movement goal. Throws to the three levels of target were made by effecting subtle changes in the distal segment trajectories in the vertical plane. The segment path and velocity modifications made by the subjects may reflect a relationship between the joint angles of the shoulder, elbow and wrist joints and, thus, the individual, self-imposed constraints upon the musculoskeletal and neuromuscular degrees of freedom (Hasan, Enoka and Stuart, 1985).

It is evident that players of both ability levels were able to hold WHV and WRV constant (Table 5) while altering WPATH with changes in target height. This finding indicates that the components comprising trajectory, namely resultant velocity and path, can be controled simultaneously and independantly. The expert players displayed significantly different and proportional changes in WPATH with decreasing target height. Although the novice player's WPATH results were non-significant in the case of subject 4, they followed a similar trend except for target D2.

Since WHV was constant across target height, any changes in WPATH at release were due to changes made in WVV. The expert players demonstrated significant differences in WVV across levels of target and although the novices followed a similar trend, the magnitude of the WVV standard deviations did not permit statistical significance. This finding is also of interest since the movement was planned with respect to the geometry of the external world, i.e. velocity held constant in the horizontal plane and varied in the vertical plane.

The expert players also performed statistically significant alterations in FPATH through changes in FVV. Once again, the magnitude of the novice subjects' FVV and FVH standard deviations did not permit statistical significance in FPATH. At the level of the dart, the players altered DPATH via changes in DVV. All subjects released the dart at significantly different heights and DPATH's among the three target conditions. Only subject one's FPATH was virtually the same as DPATH, indicating the use of the fingers to guide the dart prior to release. All subjects' standard deviations were smaller for DPATH than FPATH, which signifies that the fingers must act to 'smooth' any trajectory noise perceived by the subjects at the muscular level.

5.5 Comparison of Expert and Novice Strategies

The expert subjects lowered DPATH with decreases in target height. The novice players, however, used different strategies involving the manipulation of dart velocity and angle of projection to launch the dart at the various targets. Subject 3 used the same angle of projection combined with a lower dart velocity to hit the bullseye (target 2) as for the double twenty (target 1). Subject 4 selected a lower angle of projection to hit the bullseye (combined with a higher release velocity) than for the double three (target 3). In fact, the novice subjects performed kinematically different throws to the three targets. The expert players alterated the dart's angle of path beginning by adjustments at the wrist, constraining the hand complex (wrist and finger markers) to act as a unit thereby reducing the potential musculoskeletal degrees of freedom.

Although the novice players did not significantly alter the path of the wrist (except subject three) or finger markers, the dart's angle of path was significantly different across levels of target. It is obvious that their modifications in DPATH were made at the level of the fingers. These results explain the differences in the mean error reported in Table 2. The coordination of the expert players is evidenced by their constraint of the hand and fingers to act as a unit, a tighter elbow-wrist synergy and a smaller trial to trial standard deviation.

The much larger standard deviations of the novice player's segment and marker variables when compared to those of the experts reflects a less repeatable selection of segment orientation and trajectory. These two components form the movement goal of the investigation and along with the mean error at the target (Table 2), delimit the level of skill between the ability levels.

The results of the marker and dart velocities and paths indicate that the trajectory of the movement is indeed one of the planned variables in a dart throwing task. When trajectory is resolved into the velocity and path vectors, it is evident that wrist resultant velocity is maintained virtually constant by the individual while the release height and segment paths are altered with target height. Also, the subject's strategies for contacting the targets can be discriminated through a trajectory analysis.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The purpose of this study was to investigate the kinematic variables reflecting the variant and invariant aspects of the strategies of subjects of two ability levels performing a dart throwing task. The second concern of this study was to examine the kinematic variables which differentiated the level of skill of the subjects participating in the experiment. The hypotheses of the study were designed to compare the movement kinematics of a dart throw to three different targets. Hypotheses concerned: 1) the trajectory (angle of path and velocity) of the wrist and dart and 2) segment orientation (release height) at release.

6.1 Methodology

Two pairs of two novice and expert dart players were selected as subjects. The task consisted of a series of eight dart throws to targets situated at three different heights on a regulation size dartboard. A Locam camera filmed the throwers from the sagittal plane at 150 fps. Target height, the independant variable, was divided into three levels: double twenty (top), bullseye (center) and double three (bottom). Following an adequate warmup period, eight throws at each target were recorded cinematographically. All landmarks were digitized and analyzed using the McGill Biomechanics Laboratory's analysis programs. The hypotheses were evaluated for each subject through analyses of variance (alpha was set at 0.01) comparing the dependant variables across the three levels of target.

6.2 Findings

Data analysis and statistical testing of the hypotheses revealed the following results:

1) No significant differences in WRV were found for any subjects across levels of target and all throwers released the dart at a constant wrist resultant velocity. There was a trend for decreasing wrist resultant velocity at release (WRV) with decreases in target height for subjects one through three.

2) All subjects exhibited a trend for reducing RH with decreases in target height. Release height was altered through increases in the angle of trunk lean and a lowering of the shoulder complex. Release height was statistically different across levels of target for all subjects.

3) Dart resultant velocity (DRV) at release differed for three of four subjects across levels of target. Owing to the contribution of vertical and horizontal velocities, all subjects released the dart at significantly different resultant velocities across levels of target, with the exception of subject two.

4) All subjects released the dart at different angles of path across levels of target. The alterations performed in dart vertical velocity contributed to the angle of path at release. Differences were statistically significant for all subjects.

All subjects exhibited no significant differences in the wrist horizontal velocity (WVH) at release. Only the expert players released the dart at significantly different wrist vertical velocities, which contributed to the significances in wrist path. The novice players WVV's were too inconsistent to allow for statistical significance, yet they followed a similar trend to the experts. In the case of the expert players the trend of altering WPATH endured at FPATH and DPATH, whereas no such trend existed for the novice players.

6.3 Conclusions

The limitations, delimitations and methodology of the study must be kept in mind when interpreting the results. Based upon the results, evidence has been presented supporting the following conclusions:

1) The subjects recognized the task related degrees of freedom and all subjects cognitively perceived the task in a similar fashion.

2) Joint musculoskeletal degrees of freedom were reduced in an attempt to constrain joint motion and increase trial to trial consistency.

3) Movement initiation segment orientations were more consistently attained than release orientations by all subjects.

4) A goal-directed synergy of elbow and wrist joint angular excursion independant of target location existed for all subjects.

5) The instant of release was timed with the onset of the antagonist breaking action for all subjects.

6) The dart was released at significantly different vertical coordinates for each target for all subjects.

7) The dart was released at a constant WHV and WRV, while alterations in WPATH were performed via changes in WVV for each level of the independant variable.

8) The standard deviations of the measured variables delimits the level of skill of the subjects.

9) Joint velocity and path, the components comprising trajectory, can be regulated simultaneously and independantly.

6.4 Implications of the Study

The precise role of higher order centers in the production and ongoing control of human movement has not yet been firmly established. Evidence from the fields of motor control and robotics research has demonstrated the limitation of the brain as the sole controller of coordinated movement, given the sheer number of computations necessary to produce even a simple two joint movement (Raibert, 1978; Hinton, 1984). One question deemed tantamount in the realm of motor control research is, "How does the effector or musculoskeletal system diminish the degrees of freedom (independant ways of moving) to a level which can be more easily handled by the controller or higher centers?".

Movement consistency and repeatability is a critical element of dart throwing. Evidence presented in this study suggests that dart players, regardless of their knowledge of the physical laws governing projectile flight, follow a very simple strategy to launch the dart at the different targets on the board. The basic strategy involves the manipulation of release height and the dart's angle of path at release with changes in target height. The trajectory of the dart is governed by the the trajectories of the wrist and finger joint markers as well as the action of the fingers themselves. Joint marker velocity and path, the components forming trajectory, can be regulated simultaneously and independantly.

The skill of the players who participated in the study combined with the well defined task related degrees of freedom to produce low standard deviations for all measured variables. This made possible the delimitation of skill level through the examination of mean error at the target as well as the amount of trial to trial noise. The findings indicate that success in dart throwing is not a matter of chance, a great amount of practise and control are required to precisely control the trajectory of the segments comprising the arm and hand.

6.5 Suggestions for Further Research

An inspection of the results of the present investigation reveals various future research possibilities. A replication of this study, including the collection of electromyographical data could permit an examination of the timing of the agonist and antagonist musculature of the arm and hand. A similar experimental paradigm designed to assess the action of the fingers in three dimensions prior to and at release could shed light on the mechanics of the fingers at release. A third study could involve the physical restriction of the thrower's musculoskeletal degrees of freedom in order to investigate the adjustments in the subject's strategy. Finally, an experimental setup examining the decrease in trial to trial noise associated with the learning of such a simple, well defined task could provide valuable information pertinent to motor skill learning.

In the various fields comprising motor control, there is a need to define the task more precisely in terms of the levels of degrees of freedom expanded upon in this study. The relationship between the subject's perception of the task related degrees of freedom and the subject's constraint of the musculoskeletal and neuromuscular degrees of freedom is important and should also be examined. This relationship between the task and the movement kinetics and kinematics must affect the motor control strategy selected by the particular subject.

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APPENDICES

APPENDIX A

INFORMED CONSENT FORM

NAME (please print): ______________________________

The study that you have been asked to participate in is designed to compare the strategies you employ while throwing darts at selected targets on the board. You will be asked to wear a pair of shorts and will consent to the placement of markers over three bony landmarks. You will be asked to perform 24 throws while being filmed by a high speed camera, so that I may later analyze your performance and compare it with other players of your calibre.

At any time during the filming session, you may decide to discontinue participating in the study by asking to do so. Once the study is concluded, you may ask to see the high speed recordings of your performance. All data collected today is the property of the McGill University Department of Physical Education and will be used for research and instructional purposes only.

In signing below, you are indicating your consent to participate in this study, your awareness of the nature of the research, and that you have read and understood this informed consent form.

Date: ____________________

Signature: ____________________

APPENDIX B

Complete ANOVA Tables for Marker Kinematics

Tables are included for the following measures:

Wrist resultant velocity
Wrist horizontal velocity
Wrist vertical velocity
Wrist angle of path
Finger resultant velocity
Finger horizontal velocity
Finger vertical velocity
Finger angle of path
Dart resultant velocity
Dart horizontal velocity
Dart vertical velocity
Dart angle of path
Dart release height

Table B1

Variable: WRIST RESULTANT VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0216	0.0108	0.3842	0.6857
Within	21	0.5914	0.0282		
Total	23	0.6130			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.1408	0.0704	2.9723	0.0741
Within	20	0.4738	0.0237		
Total	22	0.6146			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.2369	0.1185	1.4620	0.2555
Within	20	1.6207	0.0810		
Total	22	1.8576			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0354	0.0177	0.1279	0.8807
Within	21	2.9065	0.1384		
Total	23	2.9419			

* $p < .01$

Table B2

Variable: WRIST HORIZONTAL VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0169	0.0085	0.3992	0.6759
Within	21	0.4451	0.0212		
Total	23	0.4620			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.2317	0.1158	4.0485	0.0334
Within	20	0.5722	0.0286		
Total	22	0.8039			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.2112	0.1056	1.4768	0.2522
Within	20	1.4304	0.0715		
Total	22	1.6416			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0957	0.0478	0.3672	0.6971
Within	21	2.7366	0.1303		
Total	23	2.8323			

* $p < .01$

Table B3

Variable: WRIST VERTICAL VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.7818	0.3909	13.2653	0.0002 *
Within	21	0.6188	0.0295		
Total	23	1.4006			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.7343	0.3672	17.6861	0.0001 *
Within	20	0.4375	0.0219		
Total	22	1.1718			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.7176	0.3588	5.6690	0.0112
Within	20	1.2659	0.0633		
Total	22	1.9835			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.1835	0.0918	2.0045	0.1597
Within	21	0.9614	0.0458		
Total	23	1.1449			

* $p < .01$

Table B4

Variable: WRIST ANGLE OF PATH

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	261.5910	130.7955	16.5597	0.0000 *
Within	21	165.8673	7.8984		
Total	23	427.4583			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	267.4202	133.7101	15.4249	0.0001 *
Within	20	173.3687	8.6684		
Total	22	440.7889			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	344.2501	172.1251	6.0233	0.0090 *
Within	20	571.5343	28.5767		
Total	22	915.7844			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	73.9672	13.9836	2.0589	0.1526
Within	21	377.2154	17.9626		
Total	23	451.1826			

* $p < .01$

Table B5

Variable: FINGER RESULTANT VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.1329	0.0665	2.2616	0.1290
Within	21	0.6171	0.0294		
Total	23	0.7500			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.2599	0.1299	9.8283	0.0011 *
Within	20	0.2644	0.0132		
Total	22	0.5243			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	1.0807	0.5404	3.9298	0.0364
Within	20	2.7502	0.1375		
Total	22	3.8309			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.7195	0.3597	3.8468	0.0377
Within	21	1.9638	0.0935		
Total	23	2.6833			

* $p < .01$

Table B6

Variable: FINGER HORIZONTAL VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.1085	0.0542	1.2942	0.2951
Within	21	0.8800	0.0419		
Total	23	0.9885			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.2682	0.1341	8.1541	0.0026 *
Within	20	0.3289	0.0164		
Total	22	0.5971			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	1.0946	0.5473	3.9055	0.0370
Within	20	2.8028	0.1401		
Total	22	3.8974			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.8446	0.4223	4.8292	0.0188
Within	21	1.8364	0.0874		
Total	23	2.6810			

* $p < .01$

Table B7

Variable: FINGER VERTICAL VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	1.8184	0.9092	9.1669	0.0014 *
Within	21	2.0828	0.0992		
Total	23	3.9012			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	1.3386	0.6693	7.5698	0.0036 *
Within	20	1.7683	0.0884		
Total	22	3.1069			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	2.4343	1.2172	3.4751	0.0507
Within	20	7.0050	0.3503		
Total	22	9.4393			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.5314	0.2657	1.5938	0.2268
Within	21	3.5009	0.1667		
Total	23	4.0323			

* $p < .01$

Table B8

Variable: FINGER ANGLE OF PATH

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	300.5450	150.2725	8.1718	0.0024 *
Within	21	386.1730	18.3892		
Total	23	686.7180			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	258.1950	129.0975	7.9538	0.0029 *
Within	20	324.6174	16.2309		
Total	22	582.8124			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	644.0314	322.0157	3.3273	0.0566
Within	20	1935.5970	96.7798		
Total	22	2579.6280			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	204.9647	102.4823	2.8999	0.0773
Within	21	742.1302	35.3395		
Total	23	947.0949			

* $p < .01$

Table B9

Variable: DART RESULTANT VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.4039	0.2020	5.7895	0.0099 *
Within	21	0.7326	0.0349		
Total	23	1.1365			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.1098	0.0549	4.0829	0.0326
Within	20	0.2689	0.0134		
Total	22	0.3787			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.7134	0.3567	6.3069	0.0075 *
Within	20	1.1311	0.0566		
Total	22	1.8445			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	1.5701	0.7850	6.4605	0.0065 *
Within	21	2.5518	0.1215		
Total	23	4.1219			

* $p < .01$

Table B10

Variable: DART HORIZONTAL VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.4053	0.2027	3.7328	0.0410
Within	21	1.1401	0.0543		
Total	23	1.5454			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0070	0.0035	0.1877	0.8303
Within	20	0.3726	0.0186		
Total	22	0.3796			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.4967	0.2484	3.7288	0.0420
Within	20	1.3321	0.0666		
Total	22	1.8288			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	1.8718	0.9359	6.3277	0.0071 *
Within	21	3.1060	0.1479		
Total	23	4.9778			

* $p < .01$

Table B11

Variable: DART VERTICAL VELOCITY

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	1.8743	0.9372	35.9239	0.0000 *
Within	21	0.5478	0.0261		
Total	23	2.4221			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	2.1496	1.0748	63.3444	0.0000 *
Within	20	0.3394	0.0170		
Total	22	2.4890			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.9804	0.4902	18.3226	0.0000 *
Within	20	0.5351	0.0268		
Total	22	1.5155			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	1.9526	0.9763	18.7458	0.0000 *
Within	21	1.0937	0.0521		
Total	23	3.0463			

* $p < .01$

Table B12

Variable: DART ANGLE OF PATH

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	231.4599	115.7299	21.3879	0.0000 *
Within	21	113.6311	5.4110		
Total	23	345.0910			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	293.4115	146.7058	46.9972	0.0000 *
Within	20	62.4317	3.1216		
Total	22	355.8432			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	121.1056	60.5078	10.7974	0.0007 *
Within	20	112.0788	5.6039		
Total	22	233.1844			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	327.8588	163.9294	13.9751	0.0001 *
Within	21	246.3317	11.7301		
Total	23	574.1905			

* $p < .01$

Table B13

Variable: DART RELEASE HEIGHT

SUBJECT 1

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0358	0.0179	124.1365	0.0000 *
Within	21	0.0030	0.0001		
Total	23	0.0388			

SUBJECT 2

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0369	0.0184	99.9293	0.0000 *
Within	20	0.0037	0.0002		
Total	22	0.0406			

SUBJECT 3

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0481	0.0241	38.6310	0.0000 *
Within	20	0.0125	0.0006		
Total	22	0.0606			

SUBJECT 4

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between	2	0.0441	0.0221	58.5949	0.0000 *
Within	21	0.0079	0.0004		
Total	23	0.0520			

*. $p < .01$

APPENDIX C

Complete Tables for Tukey Post Hoc Comparison Tests

Tables are included for the following measures:

Dart height of release
Dart resultant velocity
Dart angle of path

Table 8 Results of Tukey Post Hoc Comparisons of Dart Height of Release

	Subject 1				Subject 2		
	1	2	3		1	2	3
2	*			2	*		
3	*	*		3	*	*	

	Subject 3				Subject 4		
	1	2	3		1	2	3
2	*			2	*		
3	*	*		3	*	*	

* significant at 0.05 level
n non-significant

Table 9 Results of Tukey Post Hoc Comparisons of Dart Resultant Velocity at Release

	Subject 1			Subject 2		
	1	2	3	1	2	3
2	n			n		
3	n	*		n	n	

	Subject 3				Subject 4		
	1	2	3		1	2	3
2	*			2	n		
3	*	n		3	n	*	

* significant at 0.05 level
n non-significant

Table 10 Results of Tukey Post Hoc Comparisons of Dart Angle of Path at Release

	Subject 1				Subject 2		
	1	2	3		1	2	3
2	*			2	*		
3	*	n		3	*	*	

	Subject 3				Subject 4		
	1	2	3		1	2	3
2	n			2	*		
3	*	*		3	*	n	

* significant at 0.05 level
n non-significant