University of Alberta

Slo-pitch Placement Hitting Movement Analysis

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Physical Education and Recreation

Fall, 2010
Edmonton, Alberta

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Abstract

Many sports biomechanics research studies follow a traditional task analysis concept that there is only one best possible movement pattern and thus focus on the examination of kinematics and kinetics of movement without considering the influence of constraints that are imposed on it. This study developed an interdisciplinary approach by utilizing the principles of ecological task analysis and movement coordination from areas of motor leaning and biomechanics to examine the skill of placement hitting in slo-pitch softball. The choice of evaluating this slo-pitch batting skill to assess movement patterns is pragmatic because of its popularity of the sport and uniqueness of the batting movement. Therefore, the purpose of this study was to examine the influence of two task constraints (stride technique and designated field location) and an environmental constraint (pitched ball location) on the participants' batting performances, kinematics, and movement patterns. A three-way ANOVA of 2 fields (same and opposite) x 2 locations of pitch (inside and outside) x 3 strides (open, parallel and closed) repeated measure study was conducted in this study. The results showed that participants were more successful in placing the ball to the same field instead of the opposite field. The pitched ball location and stride techniques did not have a consistent impact on the results across the different hitting conditions. To achieve these batting performance results, participants demonstrated different joint movements and different coordination patterns. Hence, this

study supports the rationale of ecological task analysis but not traditional task analysis. Further, to understand the generalizability of the findings, a Euclidean distance analysis was conducted to evaluate the degree of dissimilarity between the individual and group mean results. The results indicated that participants generally showed a low degree of dissimilarity, so they were quite homogeneous as a group. Hence, the results from this study not only enable us to evaluate a human movement skill under the influence of different constraints but educators may apply the findings to other players. A similar interdisciplinary approach is warranted for future research studies in order to better understand the mechanics of human motion.

Acknowledgement

I would like to sincerely thank my advisor, Dr. Pierre Gervais, and the supervisory committee members, Dr. Pierre Baudin and Dr. Marcel Bouffard, for their support and mentorship during the doctoral program at the University of Alberta. They have been excellent role models, and it has been a privilege to receive guidance from an extremely well educated and experienced group of mentors. Further, I would also like to sincerely thank the chair of committee, Dr. Daniel Syrotuik, and the committee members, Dr. Loren Chiu and Dr. Jason Carey, for their help and support. Without their academic advice and research expertise, the completion of this dissertation would not have been possible. Moreover, I would like to thank Dr. Graham Caldwell from the University of Massachusetts-Amherst, for taking his time to evaluate my dissertation and provide insightful feedback.

Finally I am deeply thankful to all my family and friends for their endless love and support. They have been inspirational to my personal achievements and development. I will always love and cherish my family and friends, and I am truly grateful to have them in my life.

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Definitions

Apex: The highest vertical position in a ball's entire trajectory.

Centre field: Same as neutral field.

Closed stride: The batter strides toward the opposite field (right field) at an angle greater than 30° in a clockwise direction, Figure 1.1.

Control: Timing and sequencing between intra- or inter- body segmental movement to achieve a goal.

Coordination: Timing and sequencing between intra- or inter- body segmental movement.

Fly ball: A batted ball that lands in the outfield.

Ground ball: A batted ball that has an apex trajectory lower than the batter's height and lands in the infield.

Impact: This is a force that is created when a bat makes contact with a ball.

Infield: An area inside the diamond formed by the baselines.

Inside pitch: A pitched ball that lands on the inside portion of the strike zone mat.

Left field: Same as same field.

Neutral field: An area on the field formed by lines extending from home plate between 30° to 60° (β), Figure 1.1.

Open stride: The batter strides toward the same field (left field) at an angle greater than 30° in a counter-clockwise direction, Figure 1.1.

Opposite field: An area on the field formed by lines extending from home plate between 0° to 30° (α), Figure 1.1.

Outfield: An area beyond the baselines and within foul lines.

Outside pitch: A pitched ball that lands on the outside portion of the strike zone mat.

Parallel stride: The batter strides toward the pitching machine at an angle less than 30° in either a clockwise direction or a counter-clockwise direction, Figure 1.1.

Pop fly: A batted ball that has an apex trajectory higher than the batter's height and lands in the infield.

Propulsion phase: The time interval that is defined from the zero velocity or zero acceleration, if the zero velocity is not present, and speeds up to the maximum absolute joint velocity prior to ball contact.

Reversed shared positive contribution: The time when both proximal and distal joints are in a propulsion phase divided by the time when either joint is in the propulsion phase, and this movement is initiated by the distal joint followed by the proximal.

Right field: Same as opposite field.

Same field: An area on the field formed by lines extending from home plate between 60° to 90° (γ), Figure 1.1.

Sequential movement: A proximal segment reaches its peak velocity before a distal segment initiates its movement. This type of movement occurs when the focus of the task is on velocity, a light object is used, or it is an open kinetic chain movement (Kreighbaum & Barthels, 1996).

Shared positive contribution: The time when both proximal and distal joints are in a propulsion phase divided by the time when either joint is in the propulsion phase, and this movement is initiated by the proximal joint followed by the distal.

Simultaneous movement: All segments initiate and finish the movements at the same time. This is typically when the focus of the task is on accuracy, a heavy object is used, or it is a closed kinetic chain movement (Kreighbaum & Barthels, 1996).

Skill: Specific timing and sequencing between intra- or inter- body segmental movement that are required to achieve a goal successfully.

Chapter 1: Introduction

1.1 History of Slo-pitch

The origin of the sport of softball has been attributed to a group of Yale and Harvard alumni who gathered inside a gymnasium at Farragut Boat Club in Chicago on Thanksgiving Day, 1887 waiting to find out the score between a Harvard-Yale football game. After the news of a Yale victory was announced, a Yale fan got excited because his bets paid off and proceeded to pick up an old boxing glove and throw it at a Harvard fan who struck it back with a stick. George Hancock, who is known as the inventor of softball, saw this happen, and was inspired to develop a game of indoor baseball using the laces from boxing gloves as a ball and a broken broomstick as a bat. As the game increased in popularity, it moved outdoors in 1888, and in 1889 Hancock published the rules for indoor-outdoor baseball. Many different names were used for the sport at that time such as “Kitten Ball” and “Diamond Ball.” It was not until 1926 that Walter Hankanson, a Denver YMCA official, came up with the name of “softball.” In 1933 the Amateur Softball Association (ASA), the official governing body, was formed and the name of “softball” was officially adopted in 1934 (“Compton’s encyclopedia,” 1991; “Merit students encyclopedia,” 1991; “The newbook of knowledge,” 2000).

There are two types of softball, fast pitch and slo-pitch, and each softball game has their distinct rules. In fast pitch, the pitcher often throws the ball with a windmill technique at a high velocity; however, in slo-pitch, the ball is pitched in an arc at a moderate velocity. The game of slo-pitch softball emerged in the 1950s as a means to promote social interaction by creating more offence to maximize the players' involvement in the game (Blucker & Graf, 1984). Since then slo-pitch softball has had its own rules separated from fast pitch softball. The name of "slow pitch" is used in United States, but in Canada it is commonly known as "slo-pitch." There are approximately 40-56 million participants playing softball in the United States (Gellman, 2005), and the majority of them plays slo-pitch. Although slo-pitch is not a new sport, the popularity and competitiveness of the sport have grown significantly in recent years. Slo-pitch is now played at regional, national and international levels.

1.2 Slo-pitch Placement Hitting

In a game of slo-pitch, the ball is pitched at a speed of 10-15 m/s and takes approximately 1.5 s to reach home plate (Carriero, 1984; Wu & Gervais, 2006, 2008). Since the ball is pitched at a moderate velocity, the batter has a greater chance of hitting the ball successfully compared to fast pitch softball and baseball. A very important type of batting skill in slo-pitch is placement hitting (McIntyre & Pfautsch, 1982). Placement hitting is hitting a ball to a specific field either the "same" or "opposite" field (McIntyre & Pfautsch, 1982). For a right-handed batter, if a ball is hit to the same field, left field, the batter can hit the ball farther because the batter's left elbow can almost be fully extended at ball contact, which allows the batter to generate a higher bat linear velocity (Gelinas, 1988;

McIntyre & Pfautsch, 1982). An advantage of hitting the ball to the opposite field, right field, is that if there were a runner on the second base, the runner would have a greater chance of advancing to the third base because a right fielder would have a longer throw to the third base than a left fielder. Due to the slower speed of a pitched ball in slo-pitch, the skill of placement hitting can be executed by stepping toward the ball instead of the pitcher. The batter uses either an open, parallel or closed stride technique to place the ball to a specific field. This batting skill has become very popular and crucial as part of a team's main offensive strategy (Perry, 1979).

In order to execute this batting skill properly, a batter's movement is influenced by the location of the pitched ball. For example, a right-handed batter might have initially intended to stride toward the pitcher (using parallel stride) and swung the bat early to pull the ball to the same field (left field). However, if the pitcher throws the batter an inside pitch, the batter can quickly adapt to the situation by changing his stride to the open stride to avoid getting "jammed" in his swing which would allow him to still pull the ball to the same field. This shows the influence of a pitched ball's location to the batter's decision on field of ball placement and stride technique. The field of ball placement and stride technique (task goals), and location of pitched ball (environment) have an impact on the batter's (performer's) outcome (Newell, 1986). Similar types of interactions between the performer, task goal and environment factors can be observed in other sports skills such as executing a slap shot to score a goal in ice hockey or spiking a ball to score a point in volleyball. For example, an ice hockey player may initially intend to execute a slap shot toward an open net in an attempt to score a goal. However, at the last moment the player sees that the goaltender is covering the net and then quickly decides to execute a wrist shot instead, being the more accurate type of shot. This would allow the player to have a greater chance of scoring. Another example is that a volleyball player who may initially intend to spike the ball. However, upon preparing to spike the ball, the player notices that there are two blockers jumping up in an attempt to block their spike. The player then quickly changes his/her mind by tipping the ball over the blockers to score a point. From these above examples, it is clear that the relationship between the player (performer), task goal and environment variables interact very closely with each other. Therefore, in order to fully assess a sports skill and understand its mechanical movement patterns, all these three variables need to be taken into account (Davis & Burton, 1991).

1.3 Purpose

In this study the skill of placement hitting by slo-pitch softball batters was analyzed. The purpose of this study was to examine the influence of two task constraints and an environmental constraint on the experienced slo-pitch batters' ball placement performances, kinematics, and movement patterns. The two task constraints consisted of the stride technique of the batter and the desired landing location of the ball, and the environmental constraint consisted of the manipulation of the pitched ball location. The interaction between task goals (field of ball placement and stride technique) and environment (location of pitched ball) is inseparable because both of these constraints have an impact on the performer's outcome. Therefore, these constraints need to be taken into account and assessed collectively so that we can better understand the performer's outcome.

Further, a comparison of batting performances and techniques across participants was conducted. More specifically, each participant's results were compared to the mean to evaluate the degree of dissimilarity between the individuals and the group. These results enabled assessment of whether the group mean performance results could be used to generalize to all participants.

1.4 Statement of Problem

In baseball and fast pitch, the ball is thrown at a speed of 35-40 m/s and 20-25 m/s, respectively (Escamilla et al., 2001; Hay, 1978; Messier & Owen, 1985, 1986; Oliver, 2003). The batter only has approximately 0.5 s to hit the ball before it crosses the home plate (Hay, 1978). Hence, the batter has to adjust the timing of the swing rather than the stride direction in order to hit the ball to a specific field (Bennett & Yeager, 2000; Shapiro, 1974, 1979; Williams & Underwood, 1968, 1971). However, Pardee (1980) argued that a batter could not fully be effective if the stride direction was consistently in the same direction toward the pitcher. If a pitch was on the outside part of the home plate, the batter should stride toward the ball (a closed stride technique) and hit it to the opposite field. If a pitch was on the inside part of the home plate, the batter should still stride toward the ball (an open stride technique) to avoid getting “jammed” and hit it to the same field. This technique allows the batter to consistently strike the ball at the sweet spot[1] of the bat. However, due to the speed of the pitched ball and unknown location of the pitch in baseball and fast pitch, it is not possible for a batter to stride toward the ball when batting. On the other hand, in a game of slo-pitch, a batter has approximately 1.5 s to react to the ball (Carriero, 1984; Hay, 1978; Wu & Gervais, 2006, 2008), so the batter has more time to step toward the ball and hit it to a specific field (Osbone & Tullis, 1990; Perry, 1979). Hence, a slo-pitch player can execute this viable hitting skill known as slo-pitch placement hitting.

Messier (1982), Messier and Owen (1986) and LaBranche (1994) conducted research studies to examine three different striding techniques: open, closed and parallel. The authors found that there was no significant difference in the maximum linear bat velocity between the three stride techniques. However, a pitching machine threw balls at a fixed strike zone in the Messier (1982) and Messier and Owen (1986) studies, and the batters hit balls off a batting tee in LaBranche’s (1994) study. Therefore, the batters did not have to adjust their swing to the location of the pitch in

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[1] The sweet spot is also known as the center of percussion or center of oscillation. It is a point on a bat when struck with a ball produces zero net reaction force (vibration) at the pivot point.

either study. Also, the landing location of the batted ball was not recorded, so a right-handed batter could have hit an outside pitch to the left field instead of to the right field.

The objective of the skill of placement hitting is to place the ball into a specific field, and the execution of this skill is dependent on the interaction between the batter (performer), intended field of ball placement and stride technique (task goals) and location of pitched ball (environment). Due to the lack of empirical studies, it is yet unclear how different locations of pitch, intended fields of ball placement and stride technique factors might have influenced a player's performance outcomes, kinematics, and movement patterns. In order to better understand slo-pitch placement hitting, these factors must be examined collectively.

1.5 Hypotheses

Three main statistical analyses were conducted in this study. In the first analysis, it was hypothesized that the success rate and the percentages of fly balls in placement hitting performance for striding toward the ball would be significantly greater than for striding toward the pitcher and would also be significantly greater than striding away from the ball. It was further hypothesized that the percentages of ground balls and pop flies in placement hitting performance for striding toward the ball would be significantly less than striding toward the pitcher and would also be significantly less than striding away from the ball. In the second analysis, it was hypothesized that the kinematics variables of resultant linear and angular bat velocity at ball contact and bat swing time for placement hitting in striding toward the ball would be significantly greater than in striding toward the pitcher and would also be significantly greater than in striding away from the ball. It was further hypothesized that the lower body, trunk and upper body rotational angles for placement hitting in striding toward the ball would be significantly less than in striding toward the pitcher and would also be significantly less than in striding away from the ball. In the third analysis, it was hypothesized that percentage of shared positive contribution of lower body and trunk, and trunk and upper body for the movement pattern in striding toward the ball would be significantly less than in striding toward the pitcher and would also be significantly less than in striding away from the ball.

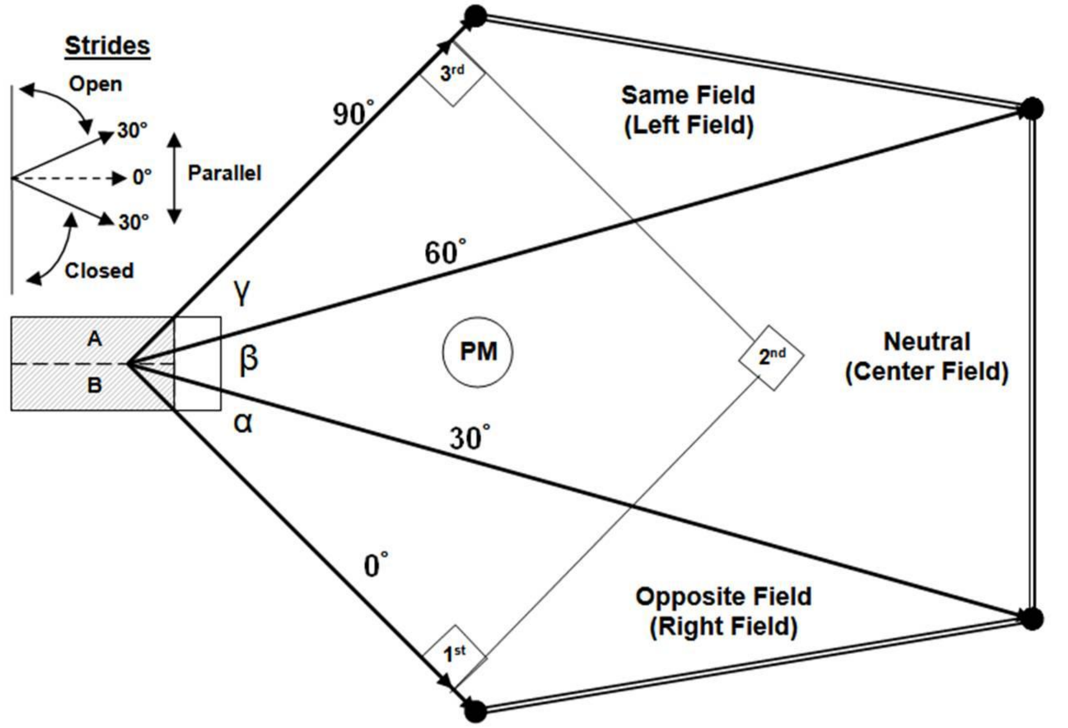

Figure 1.1 Three different types of stride techniques and different fields for ball placement (A = Inside strike zone, B = Outside strike zone, PM = Pitching Machine, α = 0° to 30°, β = 30° to 60°, γ = 60° to 90°).

1.6 Limitations

1. The player's experience in using the skill of placement hitting was not controlled in the study.
2. The psychological factors of the players during the testing were not controlled in the study.
3. Height and weight of each player were not controlled in the study.
4. The physical strength level of each player was not controlled in the study.

1.7 Delimitations

1. The placement hitting study was conducted in a field house.

2. Each participant hit three balls in each of 12 conditions for a total of 36 balls.
3. The order and the types of stride technique, strike zone location and field placement of the ball were randomized.
4. All participants used the same bat (Easton Cyclone SK37 0.78 kg and 0.86 m) for testing.
5. Indoor Jugs Lite-Flite 0.30 m (12”) softballs were used in the study.
6. Each participant gave their best effort to hit the ball hard while being able to place the ball to a designated field location.

1.8 Significance of the Study

First, the choice of using the skill of slo-pitch placement hitting to assess movement patterns is pragmatic. There are approximately 40-56 million softball players in the United States (Gellman, 2005), and the majority of the players are slo-pitch players. Although slo-pitch is not a new sport, the popularity and competitiveness of the sport have grown significantly in recent years. The number of players who play slo-pitch is far more than baseball and fast pitch. Understanding the fundamental mechanics in slo-pitch batting can be used in teaching practices and coaching strategies to develop skilled players.

Secondly, many researchers conducted their analysis simply by aggregating the entire group of performers’ data. Bouffard (1993) discussed the perils of averaging data and argued that patterns or results found by aggregating data might not necessarily apply to individuals, and individual data should be used as a unit of analysis. The author also pointed out that aggregating a group of performers' data can be conducted only if the homogeneity of the performers in a group is observed, or in other words, that all performers in a group must show a similar response to a treatment. This dissertation followed the approach suggested by Bouffard (1993). Each performer's performance was examined and compared to the group mean performance to examine if an individual performer showed a similar response as to the rest of group. This permitted evaluation of how applicable group mean performance was when generalized to other performers or populations.

Finally, many sports biomechanics research studies follow a traditional task analysis concept that there is only one best possible movement pattern, focusing on the examination of kinematics and kinetics of movement without consideration of the influence of constraints that are imposed on the movement (Burton & Davis, 1996; Nigg & Herzog, 1994). Hence, the evaluation of interactions between the performer, environment and task goal constraints are generally ignored (Burton & Davis, 1996). Further, most research studies have examined movement patterns in healthy population versus unhealthy population (Hamill et al., 1999; Heiderscheit & Hamill, 2002), able-body population versus disability population (Malone et al., 2002; Steenbergen et al., 2000), or skilled players versus unskilled players (Button et al., 2003; Temprado et al., 1997), so the research on examination of movement pattern in skilled players performing different sports task goals under the influence of various constraints is minimal.

Chapter 2: Review of Literature

2.1 Coordination

Nicolas Bernstein (1967), a Russian physiologist, defined coordination as “the organization of control of the motor apparatus” (p. 127) and proposed the development of coordination as “the process of mastering redundant degrees of freedom of the moving organ, in other words, its conversion to a controllable system” (p. 127). Bernstein (1967) viewed the development of coordination as a result of a learner being able to utilize various methods “in order to reduce the number of degrees of freedom at the periphery to a minimum” (pp. 107-108), and the degrees of freedom was defined as the number of mechanical movements that the learner can use to achieve the task goal. Then the learner gradually releases all restrictions on the degrees of freedom of the movement control. This process is known as shifting from “freezing” to “freeing” in the number of biomechanical degrees of freedom in movement control. Finally the learner utilizes and exploits this movement control to execute the task successfully. For example, in slo-pitch, a novice batter holds the bat in a horizontal plane and only uses shoulder rotation and elbow extension when hitting the ball. The number of biomechanical degrees of freedom consists of only the shoulder and elbow joints and the horizontal movement of the bat, so the degrees of freedom are kept to a minimum. Once the novice slo-pitch batter has had more opportunities to practice the skill of batting, the slo-pitch batter begins to hold the bat in an upright position so the bat can travel in all three planes. Also, the novice begins to incorporate knee extension in the forward stride and hip rotation in the bat swing. Hence, the number of biomechanical degrees of freedom is increased because more body joints are involved in the skill and the movement of the bat travels in all three planes. As the slo-pitch batter becomes proficient in the skill of batting, the batter is then able to coordinate and control the joints efficiently and resulting in a greater bat swing velocity.

Kugler, Kelso and Turvey (1980) introduced a dynamical systems perspective, coordinative structure theory, in the area of movement sciences. Kugler et al. (1980) defined coordination from a mathematical point of view as a function that contains a set of free variables. For example, a mathematical equation contains several variables (i.e. x, y and z) which can be produced to describe the movement of the forearm in the skill of slo-pitch placement batting. The values that are assigned to these variables are referred to as control because these values can determine and dictate the outcome of the movement coordination. Skill is then referred to as the optimal values to achieve a task goal. For example, the exact values for the variables that are needed in order to produce a forearm movement that allows the batter to place the ball to a desired field location. Newell (1985) followed upon Kugler et al.’s (1980) definitions and defined coordination as the temporal and spatial relationship between the intra- or inter- body segmental movements, such as the timing between left forearm and hand and the angle that is formed by both segments in the skill of slo-pitch placement hitting. Control is referred to as the absolute magnitude of the segmental movement, such as the angular velocities of the left forearm and hand segments. The skill is referred to as the ability to successfully coordinate and control segmental movement to achieve the task goal such as the exact angular velocities of the left forearm and hand segments that are required in order to successfully place the ball over the infielder's head into the intended outfield in the skill of slo-pitch placement hitting. Newell (1985) indicated that angle-angle diagram could be used to assess coordination pattern qualitatively, and Sparrow, Donovan, van Emmerik, and Barry (1987) proposed the use of the cross-correlation function technique to assess movement coordination pattern quantitatively. Cross-correlation function (CCF) is a method to evaluate the degree of similarity between the two sets of time series data. A positive sign indicates a direct relationship between the two data sets, and a negative sign indicates an inverse relationship between the two data sets. A correlation value close to +1 indicates a strong in-phase coordination; a correlation value close to -1 indicates a strong anti-phase coordination. A correlation value of zero indicates an independency between the data sets.

In the area of sports biomechanics, Northrip et al. (1983) defined coordination as a proper sequence of force production to produce an optimal outcome to achieve a task goal, and the examination of timing and sequencing of the movement can provide a fundamental understanding in coordination. Hudson (1986) developed a shared positive contribution (SPC) technique to assess coordination by examining the timing and sequencing of a movement. The shared positive contribution shows the degree to which two segments operate either simultaneously or sequentially. A SPC of 0% indicates a sequential type of movement coordination pattern, and a SPC of 100% indicates a simultaneous type of movement coordination pattern.

2.2 Ecological Task Analysis

The development of coordination is one of the key research areas in motor development and learning. Traditionally, theories about development of coordination have emphasized either maturation or learning. Motor development research has primarily focused on the patterns of coordination in phylogenetic activities (Ames, 1937; Gesell, 1929). Phylogenetic activities are fundamental human activities that are needed for survival such as walking, sitting and standing. In contrast, ontogenetic activities tend to be short term social-driven activities such as playing softball or volleyball. The early work of Ames (1937) and Gesell (1929) charted developmental movement sequences of infants and young children in various phylogenetic activities, and they explained that the progression of development movement sequence is due to the maturation process.

In the area of motor learning, research suggests that learning is an adaptation of behaviour that is due to training procedures or environmental factors. Schmidt (1975) developed the schema theory of motor learning. The schema theory explains that learning is achieved through construction of generalized motor programs. People learn a new skill by exploring different movements within a class and understand how these different movements are related to each other. For example, the skill of placement hitting is a type of batting skill. A slo-pitch batter can learn this new skill of placement hitting by exploring different joint movements and utilizing their knowledge and experience that they already have acquired from batting in general to assist them in developing this new skill. Kugler, Kelso and Turvey (1980, 1982) proposed another perspective that is called coordinative structure theory. These authors argued that the development of coordination emerges as a result of constraints that are imposed on movement. Constraints are defined as boundary conditions that limit the motion of the system and can also be viewed as the limitation of the degrees of freedom in the development of constraints (Kugler, Kelso & Turvey, 1980). For example, a pitcher throws an inside pitch to a slo-pitch batter. The location of pitched ball is considered as an environmental constraint which limits the batter's choice of movement solution on how to strike the ball successfully. Hence, this constraint may have an impact on the batter's performance outcome. Kugler, Kelso and Turvey (1980, 1982) indicated that the constraints eliminate certain configurations of response dynamics, so the result of the movement pattern of coordination is self-organized in order to achieve an optimal task goal. Constraints can be found in all levels of biological systems; from the cellular level to the whole body organism level. Newell (1986) defined two types of constraints: structural constraints (relatively time independent) and functional constraints (relatively time dependent). The influence of a structural constraint has a very slow rate of change with development, and the rate of impact to the movement pattern of coordination is a slow process. A softball players' talent in batting is an example of a structural constraint. The influence of functional constraints has a faster rate of change, and the rate of impact to the movement pattern of coordination is immediate. The bat swing velocity is an example of a functional constraint.

Newell (1986) proposed three categories of constraints (organismic, environmental and task) that interact closely with each other and have an influence on the development of coordination and control. Organismic constraints are those internal to the biological system, and they are found at each level of analysis such as chemical and neural. In the field of human movement research, the organismic constraint is related to the performer, and examples of this type of constraint are the performer's height, weight, strength, and skill level. Environmental constraints are those external to the biological system. This category of constraints can be classified as structural or functional. An example of an environmental constraint that is a structural constraint is temperature, and an example of an environmental constraint that is a functional constraint is manipulating the environment in which the activity takes place (such as moving the location of the activity to space in order to remove the influence of gravity). Task constraints are those related to the goal of the task with specific rules to constrain the dynamics of movement pattern coordination. This category of constraint can have more than one dimension such as time and space, and often task rules are specified and imposed on the movement pattern in the context of task goal achievement for the performer.

Davis and Burton (1991) developed ecological task analysis based on the approach taken by Newell (1986). Ecological task analysis (ETA) examines a movement skill performance outcome by evaluating the influence of task, performer and environment constraints collectively (Davis & Burton, 1991). Ecological task analysis is a type of analysis that uses a dynamic system approach to examine the stability and change of the performer's movement form as a result of dynamic interactions between the three major constraints/categories as proposed by Newell (1986) (Balan & Davis, 1993; Davis & Burton, 1991). The three major constraints are the performer, the environment and the task. In sport settings, the performer constraint is the characteristics of the performer (player) such as strength and skill levels (Balan & Davis, 1993; Burton & Davis, 1996; Davis & Burton, 1991). Environmental constraint is the environmental condition in which the performer performs the task. This includes the performer's surrounding environmental conditions such as the field of play, sun, wind, and temperature and also those related to the opposing team such as location of the pitched ball to the batter and defensive players' positions on the field. Task constraint is establishing and identifying specific task goals for the performer such as hitting a ball to the same field with an open stride technique.

In ecological task analysis, the performer's movement patterns are based on the results of the dynamic interactions between the performer, environment and task constraints. Therefore, if one of the constraints is changed, the performer's performance outcome will be changed as well (Balan & Davis, 1993; Burton & Davis, 1996; Davis & Burton, 1991). For example, if a pitcher threw an inside pitch to a batter, the batter could use an open stride to hit the ball to the same field. However, if the pitcher threw an outside pitch to the batter instead, the batter could then change his stride to the closed stride and still be able to accomplish the same task goal of hitting the ball to the same field. Hence, there is more than one movement pattern to accomplish the task (Balan & Davis, 1993; Burton & Davis, 1996; Davis & Burton, 1991). This type of analysis provides an intrinsic motivation to the performer and uses a performer-oriented approach (Burton & Davis, 1996). Conversely, in traditional task analysis, the instructor describes and identifies the components of the task, and the performer is instructed to accomplish the task in a sequence of specific steps and movements (Davis & Burton, 1991). The instructor directs the performer to accomplish the task with only one best possible biomechanical movement pattern, so the traditional task analysis uses a teacher-oriented approach (Balan & Davis, 1993).

Ecological task analysis has four major steps. The first step is to structure the physical and social environment and to present task goals to the performer. Task goals are presented to the performer in a clear and concise manner, and these goals are structured and specified by the physical and social environment rather than by traditional verbal and physical demonstration from the instructor (Burton & Davis, 1996). For example, in slo-pitch placement hitting, a coach would ask a player to use a closed stride and place a ball to the opposite field. The second step of ecological task analysis is to allow the performer to have multiple movement solutions to achieve task goals. For example, the coach would not instruct the player on how to swing the bat for an optimal performance outcome. The player would have a number of choices on how they would swing the bat, and this decision might be based on the location of the pitched ball. Hence, there might be multiple performance outcomes for a specific task goal. The third step of ecological task analysis is to identify the performer's optimal performance outcome by examining task, environment and performer variables. In ecological task analysis the performer, task goals and environmental factors should be assessed over a range of control variables or task dimensions in order to determine a critical value that may show a change in the performer's movement pattern (Kugler et al., 1980; Kugler et al., 1982). The manipulation of control variables or task dimensions can enable instructors to obtain information on 1) what critical value will elicit a new movement pattern, 2) what range of values in which the movement pattern can be seen as stable or unstable, 3) the optimal movement pattern, and 4) the boundary conditions of the task goals for the emergence of new movement patterns. In ecological task analysis, the critical value of the control variables is preferably in a performer scale measure that is a dimensionless number or a ratio between a control metric and a performer metric (such as diameter of ball/hand width or VO^2/kg/stride) (Burton & Davis, 1996). The fourth step of ecological task analysis is to provide instruction on different movement solutions to the performer (Davis & Burton, 1991). The role of instructors is to provide a range of possible movement solutions concisely to assist performers to achieve the task goals. For example, instructors may instruct players to either increase or decrease a joint angle during the swing of the bat to place the ball to right field in the skill of slo-pitch placement hitting.

2.3 Segmental Movement Patterns

In the area of biomechanics there are two general types of body segmental movement: sequential and simultaneous (Kreighbaum & Barthels, 1996). A sequential type of movement occurs when a proximal segment reaches its peak velocity before a distal segment initiates its movement. This type of movement occurs when the focus of the task is on velocity, a light object is used, or when it is an open kinetic chain movement. The open kinetic chain movement is defined by the end segment of a sport skill movement that can move freely in space. A simultaneous type of movement occurs when all segments initiate the movements at the same time. This type of movement occurs when the focus of the task is on accuracy, a heavy object is used, or when it is a closed kinetic chain movement. The closed kinetic chain movement in a sport skill is defined by an end segment movement that experiences a resistive force. Hence, the free motion of the end segment in space is restricted or constrained (Kreighbaum & Barthels, 1996; Luttgens & Wells, 1982; Morehouse & Cooper, 1950). A sport skill movement sometimes cannot be classified as entirely sequential (SEQ) or entirely simultaneous (SIM). The skill movement may be a combination of both types, so it falls in a continuum ranging from the sequential to simultaneous (Hudson, 1986; Kreighbaum & Barthels, 1996). Hudson (1986) and Malone et al. (2002) adapted a shared positive contribution (SPC) technique in an attempt to classify the body segmental movement pattern objectively, so comparison can be made between different sports skills. The shared positive contribution is determined as the time when both proximal and distal segments are in a propulsion phase divided by the time when either segment is in the propulsion phase. The propulsion phase of a segmental movement is the time when the segment speeds up from the zero velocity or zero acceleration, if the zero velocity is not present, to its maximum.

In baseball and fast pitch pitching, studies have shown that the segments of the arm show a sequential movement pattern (Atwater, 1979; Alexander & Haddow, 1982; Feltner & Dapena, 1986; Hudson, 1986; Barrentine, 1999; Barrentine et al., 1998; Hong et al., 2001; Oliver, 2003). For placement hitting, McIntyre and Pfautsch (1982) identified left hand, left lower arm, and left upper arm segments as the essential variables for evaluating placement hitting mechanics. However, placement hitting in slo-pitch enables the batter to use different stride techniques. Therefore, both upper body and lower body segments need to be examined collectively in order to understand the movement pattern of this skill.

2.4 Baseball, Fast Pitch and Slo-Pitch Batting Mechanics

A batting skill is considerably different from a pitching skill. Batting requires a batter to anticipate a pitched ball and strike it with a bat accurately. Research studies on baseball batting mechanics have either focused on the mechanics of body motion or the characteristics of bat swing motion. Race (1961) conducted one of the earliest scientific studies to focus on mechanics of body motion in baseball batting. Seventeen professional baseball players participated in the study. A 16 mm movie camera was placed anteriorly to the batters to record their batting mechanics. The author concluded that striding, hip rotation, and wrist action movements were important factors in batting. Shapiro (1974) further examined the batting mechanics motion and described the motion as being initiated by the hip rotation followed by the shoulder rotation. Prior to ball contact, the hip rotation could be observed between 0.17 s to 0.30 s with the shoulder rotation occurring between 0.16 s to 0.26 s. Later Hirano (1987) conducted a kinematics comparison between five skilled and two unskilled right-handed Japanese baseball players. A 16 mm cine camera was placed 10 m above the batter's head and collected the trials at 200 Hz. A celluloid plate (0.03 m wide and 0.06 m long) was attached on both sides of the iliac crest to clearly identify the movements at the hip joint. Hirano (1987) concluded that the unskilled group showed a greater and an earlier increase of hip joint angle with respect to the bat angle than the skilled group. Also, the angular velocity of the hip in the unskilled group showed a lower and an earlier maximum value than the skilled group. This study further supported the importance of hip rotation in baseball batting mechanics. Further, Welch, Banks, Cook, and Draovitch (1995) conducted a baseball bat swing study with seven professional baseball players to obtain a comprehensive understanding of the skill for training and rehabilitation purposes. The authors conducted a full body 3D kinematics analysis with six cameras operated at 200 Hz. A total of 23 reflective markers were placed on various joints on the batter, the bat and the ball. Each subject hit a ball off a batting tee, and the three best hits were collected for analysis. The authors were able to report that the maximum hip, shoulder, and arm angular velocities were 714°/s, 937°/s, and 1160°/s, respectively. The sequential mechanics in the baseball swing began with maximum hip rotation, followed by maximum shoulder rotation and then maximum arm rotation. A fast pitch batting swing is thought to be different from a baseball swing because the pitching distance in fast pitch is shorter than in baseball. Thus, the batters in fast pitch have less time to react to the ball than in baseball (Lopiano, 1978). Spragg and Noble (1987) compared the hitting technique between female fast pitch batters and male baseball batters. The authors concluded that the males reached peak velocities in a sequence of hips (0.096 s prior to ball contact), trunk (0.077 s prior to ball contact) and left arm (0.073 s prior to ball contact); whereas the females showed a left arm (0.097 s prior to ball contact), hips (0.074 s prior to ball contact) and trunk (0.071 s prior to ball contact) sequence. The male baseball players showed a proximal to distal sequential body segment movement sequence (hips, trunk and left arm), but this was not observed among the female fast pitch players (left arm, hips and trunk). The authors believed that these differences might be due to the physical differences between the two genders.

Baseball and fast pitch batting mechanics are not limited to focusing on hip, shoulder and arm rotational movements since the batter must also have a proper stance and stride towards the pitcher to hit the ball. Therefore, a couple of research studies have examined different batting stances at ball contact. LaBranche (1994) examined the influence of three different batting stances (open, closed, and parallel) on linear bat velocity, response time, and ground reaction forces in baseball hitting. Seventeen varsity baseball players participated in the study. Each player stood on a force plate and hit a ball off a tee. A light stimulus was used as a starting signal, and two successful hits were collected for each type of stance. LaBranche (1994) found no significant difference in the linear bat velocity for all three stances. No significant differences were found in the reaction forces and response time between parallel and closed stances. However, the reaction forces in the parallel and closed stances were greater than in the open stance. Also, the response time in the parallel and closed stances was less than in the open stance. Hence, the author concluded that it was less ideal to assume an open stance since it produced a slower and less forceful swing. Messier and Owen (1986) examined the effects of stride techniques (open, parallel and closed) on ground reaction forces and bat velocities in fast pitch softball. Seven intercollegiate fast pitch softball players participated in the study, and each player stood on a force plate during the data collection. A pitching machine was used to deliver the softballs, and two Locam cameras operated at 100 Hz to record the swing of the bat. Messier and Owen (1986) concluded that there was no statistical significance difference between the three stride conditions in the resultant maximum linear bat velocity. In terms of ground reaction forces, the players showed a lower ground reaction force in y-direction (anterior-posterior direction) with an open stride than in the parallel and closed strides. The authors suggested that this information may be used for softball shoes development.

Another research focus on batting mechanics has been the evaluation of the characteristics of the bat swing. Shapiro (1979) examined the kinematics and kinetics of a baseball bat swing with a 3D cinematographic method. A varsity baseball player was the only participant in the study. Instead of using a pitching machine, a former varsity pitcher threw baseballs toward the batter at approximately 25 m/s. Two Locam cameras were placed along the first baseline to capture the front view of the batter. The batter hit several balls, and the three best hits were chosen for analysis. Shapiro (1979) reported that, from the starting position, the movement of the bat started in a downward motion and then, prior to ball contact, the bat started to move in an upward motion. This bat swing motion is supported by several former baseball players, coaches, and scientists (Williams, 1968; Hames, 1975; Lopiano, 1978; Koike et al., 2003). In addition, the total swing time from the beginning of the bat swing to ball contact was 0.25 s, and the maximum linear bat velocity ranged from 26.0 m/s to 34.7 m/s at ball contact. The bat basically started to accelerate from the starting ready position and reached its peak acceleration at 0.06 s before the ball contact. The bat then experienced a period of deceleration until approximately 0.01 s prior to ball contact, and then the bat started to accelerate again. Koike, Kimura, Kawamura, et al. (2003) followed a different approach and examined the kinetics of the upper body movement in a baseball swing. Five varsity players participated in the study, and each subject hit a ball off a batting tee. The body segmental movements were captured by a VICON motion analysis system at 120 Hz, and the impact of the ball was videotaped by two high-speed cameras at 250 Hz. Several strain gauges were inserted inside a bat's handle and sampled at 500 Hz to measure the forces exerted by the hands. The authors concluded that the baseball swing started with a phase of downswing followed by a level phase to strike the ball. When the ball was struck by the bat, the bat was in an upward position. From the movement pattern depicted in the force graph of the shoulder joint, the authors concluded that the bottom arm was used mainly to accelerate the bat, and the top arm was used to modify the bat motion, which had an important implication for the ball's flight direction. In fast pitch, Messier and Owen (1985) conducted the first fast pitch softball hitting mechanics study using 3D analysis. Eight female varsity softball players participated in the study, and each player performed two successful hits against a pitching machine that propelled balls at 23.7 m/s. Two Locam cameras operated at 100 Hz and were positioned approximately 10 m away from the batter. From the results Messier and Owen (1985) described that the bat started a downward motion for approximately 0.020 s prior to ball contact. Then the bat changed into an upward motion to strike the ball. The maximum resultant bat velocity was 19.08 m/s and occurred at 0.032 s prior to ball contact. The authors suggested that because of the shorter pitching distance, slower response time and bat's linear velocity, there might be an optimal softball bat swing that should be different from a baseball bat swing.

One of the batting skills in baseball and fast pitch is placement hitting. The skill of placement hitting requires the batter to place the ball to a desired field location, either right field or left field, and this allows the offensive team to incorporate different team strategies such as hit and run or sacrifice fly ball. Two scientific studies have examined the characteristics of bat swing on the skill of placement hitting in baseball. McIntyre and Pfautsch (1982) conducted a study to examine the batting mechanics in hitting balls to the same field versus opposite field in baseball. A total of 20 right-handed varsity baseball players participated in the study, and the participants were either assigned to the group skilled in hitting balls to the opposite field or the group unskilled in hitting balls to the opposite field. Assignment to the two groups was based on the evaluations of their coach. The entire baseball field was divided into three fields: same field (left field), centre field, and opposite field (right field). Any ball hit to the centre field was excluded from the study. The reason was that the authors believed that those hits contained the batting characteristics from both the same and opposite fields, so the difference in batting techniques was not observable. In this study each player performed three successful hits from a pitching machine to both same and opposite fields. A camera was placed above the batter's head and pointed perpendicular to the ground to record the batter's upper body movement because the authors assumed that the body movements occurred mainly on a horizontal plane. The results showed no significant difference between the two groups in all the dependent variables examined. This indicated that the unskilled opposite field batters showed similar hitting mechanics as the skilled opposite field batters. Significant differences were observed between the same and opposite field conditions. The authors reported a significant difference between the mean time from the starting bat position to ball contact for the same field hitting group (0.142 s) and opposite field hitting group (0.125 s). Interestingly, with different contact times, the authors did not find any significant difference in the linear bat velocity between the same and the opposite field hitting groups. The authors also reported that, prior to ball contact, the angular displacement of the bat, left hand, and left forearm in hitting the ball to the opposite field were significantly less than in hitting the ball to the same field. Further, the angular velocities of the bat, left hand, and left forearm in hitting the ball to the opposite field were significantly greater than hitting the ball to the same field. Gelinas (1988) followed the same methodological approach as McIntyre and Pfautsch (1982) and added the inside and the outside pitch locations in the study to evaluate the batting mechanics in the same and opposite field hitting. A professional baseball player was the only participant in the study. The velocity of the pitching machine was set at 33.5 m/s, and the participant performed 12 hits to each of the two fields (same or opposite field) for each type of pitch location (inside or outside). A total of 48 hits were collected in the study. However, due to the difficulty of hitting an inside pitch to the opposite field; this condition was excluded from the data analysis. Gelinas (1988) concluded that in the opposite field hitting the batter showed a smaller bat angle, which was related to a smaller forearm angle and a limited shoulder and hip rotation movement. Also, the author indicated that the batter's stride direction was relatively consistent towards the pitcher because the velocity of the pitched baseball was just as fast as having a pitcher pitching in a real game.

Previous baseball and fast pitch softball research studies have provided a fundamental understanding on the mechanics of body motion and characteristics of bat swing (Gelinas, 1988; Hirano, 1987; Koike et al., 2003; LaBranche, 1994; McIntyre & Pfautsch, 1982; Messier & Owen, 1985; 1986; Race, 1961; Shapiro, 1974; 1979; Spragg & Noble, 1987; Welch et al., 1995). It is evident that hip, shoulder and arm rotational movements are critical when hitting a baseball or softball (Hirano, 1987; Messier & Owen, 1985; Race, 1961; Shapiro, 1974; Spragg & Noble, 1987; Welch et al., 1995). Also, the bat generally travels in a downward direction in the beginning of the swing and then changes to an upward direction to strike the ball, and, in fact, the bat reaches its maximum velocity prior to contact with the ball (Koike et al., 2003; Shapiro, 1979). Both skills of baseball and fast pitch hitting require the batter to focus on timing accuracy of a pitched ball (De Lucia & Conchran, 1985; Molstad, et al., 1994; Shank & Haywood, 1987). In baseball and fast pitch, the ball is thrown at a speed of 35-40 m/s and 20-25 m/s, respectively (Escamilla et al., 2001; Hay, 1978; Messier & Owen, 1985, 1986; Oliver, 2003). The batter only has approximately 0.5 s to hit the ball before it crosses the home plate (Hay, 1978). Lee et al., (1983) indicated that the human visual-motor system to process information for time-to-contact depends on the task, but in general the process time is approximately 0.10 s to 0.15 s. Lee et al., (1983) further indicated that in baseball the batter requires at least 0.15 s to process the information of pitched ball. Schmidt (1982) showed that the time from the beginning of bat movement until the bat crosses home plate is approximately 0.16 s. Therefore, the decision time for the batter to swing the bat is only approximately 0.19 s. However, in slo-pitch softball the ball is thrown in a parabolic arc towards the batter at a speed of 10-15 m/s, and the batter has approximately 1.5 s to hit the pitched ball (Carriero, 1984; Wu & Gervais, 2006, 2008). The decision time for the slo-pitch batter is increased to 1.19 s. The timing accuracy and trajectory of the pitched ball in slo-pitch are quite different from baseball and fast pitch softball; therefore, the slo-pitch batting technique may be uniquely different from baseball and fast pitch.

To date, only one scientific research study has examined slo-pitch batting mechanics. York (1995) conducted a study to evaluate the timing accuracy of the pitched ball and the anaerobic power in slo-pitch batting performance. A total of 19 division class “C” players participated in the study. Each player performed a Wingate Anaerobic Test and a Bassin Anticipation Timer to assess the timing accuracy. The test results were correlated to players’ 10-game batting average performance during their 1994 summer season. York (1995) concluded that the absolute peak and the mean powers were significantly correlated to the batting average but not the timing accuracy scores. Hence, the author suggested that the slo-pitch players who wished to improve their batting average should focus on increasing anaerobic power. However, several important questions regarding the skill of slo-pitch placement hitting remain unanswered. The skill of slo-pitch placement hitting not only requires the batter to focus on anaerobic power but also on accuracy of ball placement to the desired field location. Therefore, what are the body motion mechanics and characteristics of the bat swing in the skill of slo-pitch placement hitting that requires the batter to use both bat velocity and accuracy successfully? What is the sequence of body motion between hip, shoulder and arm rotational movements when the batter needs to focus on both bat velocity and accuracy? Further, previous baseball and fast pitch research studies have examined the influence of different stride techniques on bat velocity. Both LaBranche (1994) and Messier and Owen (1986) have indicated that there was no significant difference in the linear bat velocity between different stride techniques. However, for the skill of slo-pitch placement hitting, the batter has more time to stride toward the ball than in baseball and fast pitch, so perhaps different stride techniques may have an impact on bat velocity. The skill of slo-pitch placement hitting has fundamental mechanical similarities to baseball and fast pitch, but it presents to be uniquely different. Therefore, it is important that this skill be studied, so we can better understand mechanics of human body motion.

2.5 Summary

In a game of slo-pitch, the ball is pitched at a speed of 10-15 m/s and takes approximately 1.5 s to reach home plate (Carriero, 1984; Wu & Gervais, 2006, 2008). Due to the slower speed of the pitched ball in slo-pitch, the skill of placement hitting can be executed by stepping toward the ball instead of toward the pitcher. The batter can use either an open, parallel or closed stride technique to place the ball to a specific field. This viable batting skill has become very popular and crucial as part of a team's main offensive strategy (Perry, 1979). The question of whether or not striding toward the ball could produce better performance outcomes than striding toward the pitcher or even striding away from the ball remained unknown. In order to examine this question, it is important to understand that this batting skill involves the dynamic interactions of the performer (batter), task goals (where to hit the ball and with what kind of stride technique) and environmental (location of pitched ball) constraints. It is critical that all these constraints are assessed collectively. Many sports biomechanics research studies follow the traditional task analysis concept that there is only one best possible performance, and the dynamic interactions between the performer, environment and task goal constraints are not evaluated (Burton & Davis, 1996). In the area of biomechanics the focus of assessing movement outcome is typically on the performer alone (e.g. body segmental movement pattern between a proximal body segment and a distal body segment) while in the area of adapted physical education, specifically with ecological task analysis, the focus of assessing movement outcome is not only on the performer exclusively but also on the task goals and environmental factors. A sports skill requires a player to coordinate body segments in a proper sequence in order to execute a skill effectively. However, in sports settings, often these sports skills are performed in a dynamic environment rather than in an isolated or static one. When a sports skill, such as the basketball free-throw, takes place in a fixed and unchanging environment, it is known as a closed skill. On the other hand, when a sports skill, such as the slo-pitch batting, takes place in an unstable and changing environment, it is known as an open skill (Schmidt & Wrisberg, 2000). Therefore, in order to evaluate an open skill fully, the task goals and environmental factors need to be taken into account. Very few research studies have combined both approaches to evaluate an open sports skill. Therefore, the results from this study would enable us to gain valuable insights on how different environmental and task constraints have influenced the performer's performance outcomes and movement patterns.

Chapter 3: Methodology

3.1 Participants

Ten right-handed skilled (class A/B division) male slo-pitch players were recruited to participate in the study. The class A/B divisions are the most competitive divisions in the Edmonton and surrounding city leagues. Participants who play in the class A/B divisions have at least 8 years of ball playing experience. The skill of placement hitting is a popular batting technique that players from A/B divisions often use as an offensive strategy. Participants had a mean age of 33.7 years, height of 1.80 m, weight of 93.50 kg and had a mean ball playing experience of 12.7 years. The number of participants was estimated from a three-way (2 fields x 2 locations x 3 strides) repeated measure ANOVA design that was conducted in the study. Using statistical software, inputting the same effect size (f) of 1.0 as the previous research work by Messier (1982) and given the power of 0.80 for main effects and 0.70 for two-way interaction effects with a medium correlation of 0.50 at $\alpha = 0.05$, the total number of participants required was estimated to be 10 (Hintze, 2006). Participants from division A/B were randomly selected and recruited through personal contact. Their skill level and experience in using the skill of placement hitting were considered similar to other players in division A/B. Their height, weight, and years of experience in the league were recorded, Appendix A. Potential participants were excluded from the study if they were currently injured or had a history of chronic injuries related to their training. Written informed consent was obtained from the participants before participation in the study. This study was approved by the institutional research ethics review board.

Twenty-two reflective markers were placed on each participant at the following body locations: top of the head (marker A), bottom of the chin (marker B), right and left acromio-clavicular joints (marker C and L, respectively), right and left medial epicondyles of the humerus (marker E and N, respectively), right and left lateral epicondyles of the humerus (marker D and M, respectively), upper back (Thoracic 1, marker U), lower back (Lumbar 3, marker V), right and left distal radioulnar joints (marker F and O, respectively), right and left anterior superior iliac spines (marker G and P, respectively), right and left medial epicondyles of the tibia (marker I and R, respectively), right and left lateral epicondyles of the tibia (marker H and Q, respectively), right and left lateral malleoli (marker J and S, respectively), right and left 1st distal phalanges (marker K and T, respectively), Figure 3.1. Only body markers C, D, E, G, L, M, N, P, R and Q were used in the three dimensional analysis. The rest of markers were used for model identification purpose.

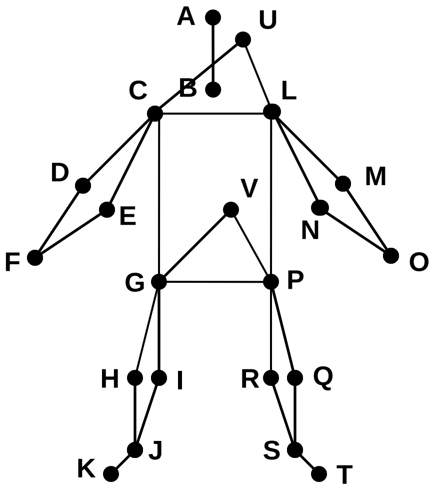

Figure 3.1 A total of 22 different body marker placements.

3.2 Participants Protocols and Experimental Set Up

This study took place in an indoor field house to control the influence of air forces. Two reflective markers were placed on an Easton Cyclone SK37 0.78 kg and 0.86 m (28 oz and 34”) bat at the top and bottom of the bat, respectively. A Jugs Lite-Flite pitching machine (Jugs Softball, Jug Inc., Tualatin, OR) was placed 14.44 m away from the participant. Wu and Gervais (2006, 2008) reported that the pitcher’s stride length was approximately equal to 0.80 m. Therefore, the actual distance between the batter and pitching machine was calculated as 15.24 m – 0.80 m = 14.44 m. From the pilot study conducted on the Jugs Lite-Flite pitching machine, the pitching machine was found to have a precision of ± 0.11 m in pitched ball landing location. Twenty-four Jugs Lite-Flite indoor softballs, 0.30 m (12”), were used in the study. Small strips of reflective tape were placed on the surface of the balls in order to track the speed of batted balls, and the total weight of the Jugs Lite-Flite softball with the reflective tape was 0.07 kg. The balls were thrown at a speed of approximately 13.55 ± 0.77 m/s with an arc trajectory of 2.72 ± 0.22 m. The balls were pitched to two different strike zone locations (inside or outside), and the field were divided approximately 30° apart into three different fields (same, neutral and opposite). A blue mat was placed in front of the pitching machine so that the batter could not see where the balls were pitched to him. The 1st, 2nd, and 3rd base were placed 21.34 m (70 ft) apart as in official slo-pitch Canadian rules for senior men. The baselines were marked with white tape, and a screen was placed behind the bases and baselines to stop all batted balls, Figure 3.2.

Participants performed their regular warm-up routine and took batting practice until they were ready for testing. Each participant stood at their own comfortable location in the batter's box with their own natural stance. Participants were instructed to use either a closed, open or parallel stride technique and hit the ball either to the same field or opposite field. The participant was not informed about the location of the pitched ball. Each participant hit three balls in each of 12 conditions to ensure reliability of each participant's performance (Hopkins, 2000), Table 3.1. The participant had 30 s to rest between each ball, and one minute to rest between each condition. The influence of fatigue and the risk of injury were minimal in this study. Since there were a total of three different stride techniques (open, parallel or closed), two different fields (same or opposite), and two different strike zone locations (inside or outside), a total of 36 balls were hit by each participant. Hence, a total of 360 trials were collected in this study.

Table 3.1 Task (field location and stride technique) and environmental (pitch location) requirements in each of twelve placement hitting conditions

Conditions	Testing requirements	Conditions	Testing requirements
1	Same field Inside pitch Open stride	7	Opposite field Inside pitch Open stride
2	Same field Inside pitch Parallel stride	8	Opposite field Inside pitch Parallel stride
3	Same field Inside pitch Closed stride	9	Opposite field Inside pitch Closed stride
4	Same field Outside pitch Open stride	10	Opposite field Outside pitch Open stride
5	Same field Outside pitch Parallel stride	11	Opposite field Outside pitch Parallel stride
6	Same field Outside pitch Closed stride	12	Opposite field Outside pitch Closed stride

Each result for a batted ball was recorded regardless if the attempt was performed successfully or not. The stride angle from the Qualisys data and video images were used to examine if the participants had performed the requested stride technique. Each batted ball was recorded as a fair ball or a foul ball. Also, the types of hit (pop fly, fly ball or ground ball) and ball’s landing field (same, neutral or opposite) were recorded as well. In this study a pop fly was recorded when a batted ball that was higher than the participant’s height landed before the bases; a ground ball was recorded when a batted ball that was lower than the participant’s height landed before the bases. A fly ball was recorded when a batted ball landed beyond the bases, Appendix A. Two experienced slo-pitch umpires determined and recorded types of hit and ball's landing field for each batted ball. The order of the stride technique, designated field placement, and strike zone location were randomized to reduce any order effect.

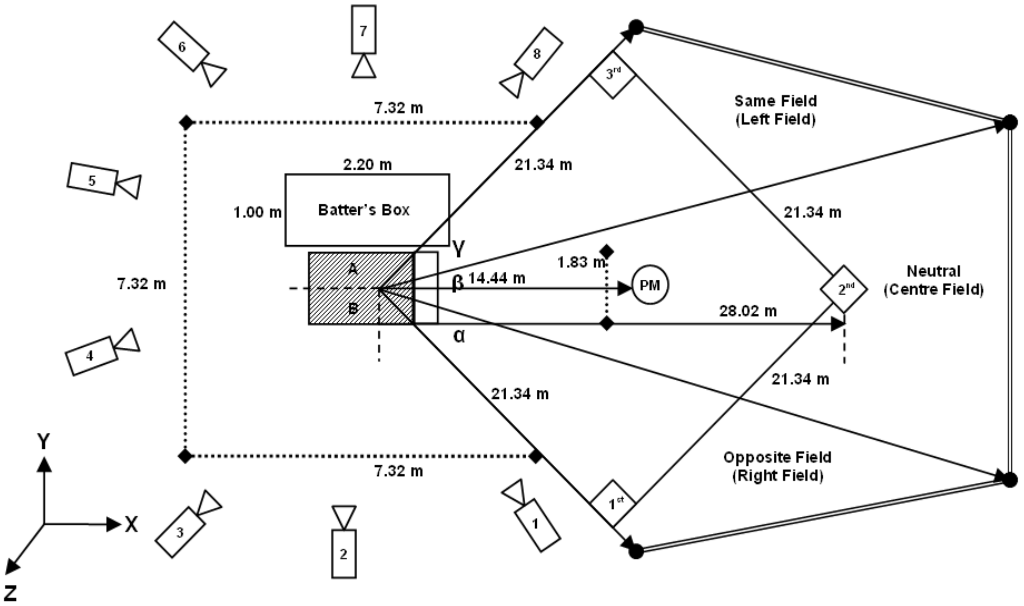

Figure 3.2 Placement hitting performance experimental set up (A = Inside strike zone, B = Outside strike zone, PM = Pitching Machine, Camera = #1 to #8, α = 0° to 30°, β = 30° to 60°, γ = 60° to 90°).

3.3 Instrumentation and Filtering

An 8-camera Qualisys motion capture system (ProReflex MCU 240, Qualisys AB, Sweden) was operated at 240 Hz (680 x 500 pixel image sensor resolution). The Qualisys motion capture system had a precision of 1.5 x 10^{-3} m/pixel. A three-dimensional (3D) analysis was conducted, and the cameras were placed approximately 60° apart around the participant. The size of calibration volume was 2.5 m (X-direction) x 2.5 m (Y-direction) x 2.5 m (Z-direction). A wand calibration technique was used to calibrate the volume. The 3D coordinate data points were determined by Bundle adjustment which is a nonlinear transformation technique from the Qualisys Track Manager computer program (Triggs et al., 2000). A 0.750 m wand stick with a marker at each end was placed inside the calibrated volume to validate the accuracy of the calibrated volume and the experiment set up. The results of the accuracy test showed that the experiment set up with the Qualisys system had a 0.04 % error in the 0.750 m wand stick testing.

The data were smoothed with 4th order Butterworth filter and, the optimal cut-off frequency was determined for each coordinate using residual analysis (Wells & Winter, 1980). The cut-off frequency for the x-coordinate ranged from 6.3 to 12.2 Hz; the y-coordinate ranged from 6.1 to 11.6 Hz, and the z-coordinate ranged from 6.3 to 10.8 Hz.

3.4 3D Body Joint and Linear and Angular Bat Velocities Calculations

Welch, Banks, Cook, and Draovitch (1995) examined baseball hitting mechanics and indicated that baseball hitting was a kinetic chain movement starting when the stride foot was planted on the ground. The sequence of segmental movement to execute a hitting skill starts with the stride foot contact followed by the hip rotation then the shoulder rotation (trunk rotation) concluding with the arm rotation (Bennett & Yeager, 2000; Hay, 1978; Pardee, 1980; Shapiro, 1974; Welch et al., 1995). Since the hitting skill is a kinetic chain movement, the sequence of body movement is from the lower body segments to the upper body segments. Hence, in this study the proximal segment was defined as the segment that was closest to the fixed point (i.e. ground) of the kinetic link system, and the distal segment was defined as the segment that was furthest away from the fixed point of the kinetic link system. Three relative joint angular velocities were determined: lower body, trunk and upper body. The lower body joint rotational angle was formed between the z_1 axis and z_2 axis of the local coordinate systems; the trunk joint rotational angle was formed between the z_2 axis and y_3 axis of the local coordinate systems; the upper body joint rotational angle was formed between the y_3 axis and y_4 axis of the local coordinate systems.

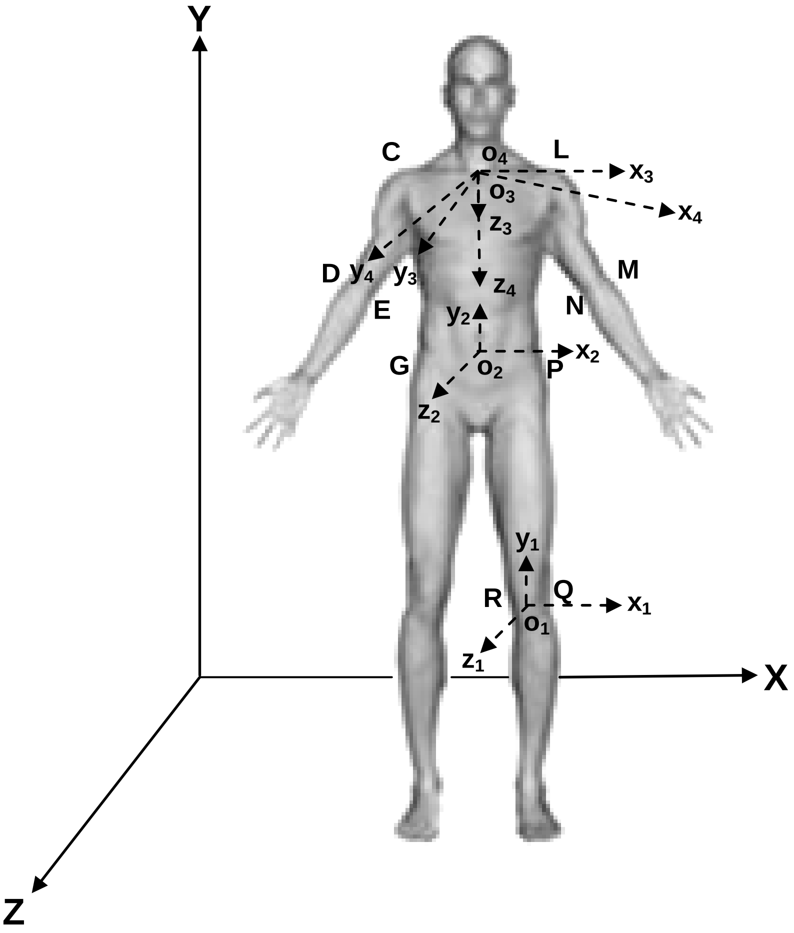

Figure 3.3 Four different local coordinate systems (1 to 4) with origins located at 1) the centre of the left knee joint for the left thigh rotation (o_1), 2) the mid-centre of the hips for the hip rotation (o_2), 3) the mid-centre of the shoulders for the shoulder rotation (o_3), and 4) the mid-centre of the arms for the arm rotation (o_4) (x_i, y_i and z_i represents the local coordinate vectors (i, j, and k) of the respective body segment.).

The 3D calculations of the joint angles were based on the technique presented by Robertson et al. (2004), pages 42-48. For the purposes of determining joint angles, four local coordinate systems were defined on the participant, Figure 3.3. For the left thigh rotation, the local coordinate system (x_1, y_1, and z_1) was located with its origin (o_1) at the centre of the left knee joint between right and left epicondyles of the femur. For the hip rotation, the local coordinate system (x_2, y_2, and z_2) was located with its origin (o_2) at the mid-centre between right and left anterior superior iliac spines. For the shoulder and arm rotations, the local coordinate systems (x_3, y_3, z_3 and x_4, y_4, z_4, respectively) were located with the origins (o_3 and o_4, respectively) at the mid-centre between right and left acromio-clavicular joints, Figure 3.3. The left thigh segment rotation was the rotation around the y_1 axis of the local coordinate system, and similarly the hip segment rotation was the rotation around the y_2 axis of the local coordinate system. The shoulder segment rotation was the rotation around the z_3 axis of the local coordinate system, and the arm segment rotation was the rotation around the z_4 axis of the local coordinate system. The unit vectors for the left thigh, hip, shoulder and arm segment rotations were calculated as follows:

The left knee joint centre location was determined by

$$\vec{o}_1 = \frac{\vec{Q} + \vec{R}}{2} \tag{1}$$

where Q and R were the marker locations of the lateral and medial epicondyles of the tibia of the left knee, respectively.

The left thigh segment was determined by

$$\vec{i}'_{thigh} = \frac{\vec{Q} - \vec{o}_1}{\left\| (\vec{Q} - \vec{o}_1) \right\|} \tag{2}$$

where P was the marker location of the left anterior superior iliac spine.

The local coordinate system with its origin at the left knee joint centre to determine the left thigh segment rotation was the following:

$$\vec{k}'_{thigh} = \frac{(\vec{Q}-\vec{o}_1)\times(\vec{P}-\vec{o}_1)}{\left\|(\vec{Q}-\vec{o}_1)\times(\vec{P}-\vec{o}_1)\right\|} \tag{3}$$

$$\vec{j}'_{thigh} = \vec{k}'_{thigh}\times\vec{i}'_{thigh} \tag{4}$$

The hip joint centre location was determined by

$$\vec{o}_2 = \frac{\vec{G}+\vec{P}}{2} \tag{5}$$

where G and P were the marker locations of the right and left anterior superior iliac spine, respectively.

The hip segment was determined by

$$\vec{i}'_{hip} = \frac{\vec{P}-\vec{o}_2}{\left\|(\vec{P}-\vec{o}_2)\right\|} \tag{6}$$

The local coordinate system with its origin at the hip joint centre to determine the hip segment rotation was the following:

$$\vec{o}_3 = \frac{\vec{C}+\vec{L}}{2} \tag{7}$$

where C and L were the marker locations of the right and left acromio-clavicular joints, respectively.

$$\vec{k}'_{hip} = \frac{(\vec{P}-\vec{o}_2)\times(\vec{o}_3-\vec{o}_2)}{\left\|(\vec{P}-\vec{o}_2)\times(\vec{o}_3-\vec{o}_2)\right\|} \tag{8}$$

$$\vec{j}'_{hip} = \vec{k}'_{hip}\times\vec{i}'_{hip} \tag{9}$$

The shoulder segment was determined by

$$\vec{i}'_{shoulder} = \frac{\vec{L}-\vec{o}_3}{\left\|(\vec{L}-\vec{o}_3)\right\|} \tag{10}$$

The local coordinate system with its origin at the shoulder joint centre to determine the shoulder segment rotation was the following:

$$\vec{j}'_{shoulder} = \frac{(\vec{o}_2 - \vec{o}_3) \times (\vec{L} - \vec{o}_3)}{\left\|(\vec{o}_2 - \vec{o}_3) \times (\vec{L} - \vec{o}_3)\right\|} \tag{11}$$

$$\vec{k}'_{shoulder} = \vec{i}'_{shoulder} \times \vec{j}'_{shoulder} \tag{12}$$

The arm segment was determined by

$$\vec{o}_{R.elbow} = \frac{\vec{D} + \vec{E}}{2} \tag{13}$$

where D and E were the marker locations of the lateral and medial epicondyles of the humerus of the right elbow, respectively.

$$\vec{o}_{L.elbow} = \frac{\vec{M} + \vec{N}}{2} \tag{14}$$

where M and N were the marker locations of the lateral and medial epicondyles of the humerus of the left elbow, respectively.

$$\vec{a}_{arm} = \frac{\vec{o}_{R.elbow} + \vec{o}_{L.elbow}}{2} \tag{15}$$

$$\vec{j}'_{arm} = \frac{\vec{a}_{arm} - \vec{o}_3}{\left\|(\vec{a}_{arm} - \vec{o}_3)\right\|} \tag{16}$$

The local coordinate system with its origin at the shoulder joint centre to determine the arm segment rotation was as the following:

$$\vec{i}'_{arm} = \frac{(\vec{a}_{arm} - \vec{o}_3) \times (\vec{o}_2 - \vec{o}_3)}{\left\|(\vec{a}_{arm} - \vec{o}_3) \times (\vec{o}_2 - \vec{o}_3)\right\|} \tag{17}$$

$$\vec{k}'_{arm} = \vec{i}'_{arm} \times \vec{j}'_{arm} \tag{18}$$

The unit coordinate vectors of each calculated local coordinate system formed a transformation matrix from the global coordinate system, respectively. This transformation only altered the components but not the unit vectors.

$$[T_R] = \begin{bmatrix} i'_x & i'_y & i'_z \\ j'_x & j'_y & j'_z \\ k'_x & k'_y & k'_z \end{bmatrix} \tag{19}$$

The joint angle calculations were calculated using the following:

$$[T_R] = [T_{Distal}]\,[T_{Proximal}]^T \tag{20}$$

Each $[T_R]$ matrix was calculated from a Cardan angles matrix to obtain the joint angles (Robertson et al., 2004, page 42-48). Three joint rotational angles were calculated (lower body, trunk, and upper body). The lower body joint angle was formed by the left thigh and hip segments. The trunk joint angle was formed by the hip and shoulder segments, and the upper body joint angle was formed by the shoulder and arm segments. A zero degree joint angle was defined when the participant was in the anatomical position with arms at shoulder-width apart and parallel to the ground at shoulder height and the local axis that represented the rotational movement of the proximal segment was aligned with the local axis that represented the rotational movement of the distal segment From the batter's batting position, a positive joint angle indicated that the local axis that represented the rotational movement of the proximal segment was rotated in front of the local axis that represented the rotational movement of the distal segment and behind for a negative joint angle. After each joint angle was calculated, a central difference technique was used to calculate the joint angular velocity.

For calculations on type of movement pattern, a shared positive contribution (SPC) or a reversed shared positive contribution (RSPC) was calculated for each trial for each pair of joint rotational angles (lower body and trunk, and trunk and upper body). The shared positive contribution was defined as a proximal to distal pattern where movement was initiated by the proximal joint followed by the distal, and the reversed shared positive contribution was defined as a distal to proximal pattern where movement was initiated by the distal joint followed by the proximal. Both shared positive contribution and reversed shared positive contribution were determined as the time when both proximal and distal joints were in a propulsion phase divided by the time when either joints was in the propulsion phase. The propulsion phase was the time interval defined from the zero velocity or zero acceleration, if the zero velocity was not present, and sped up to maximum absolute joint velocity prior to ball contact (Hudson, 1986; Malone et al., 2002), see Figure 3.4 for an illustration of the propulsion phase based on these discrete time points. The selections of the time scale points were determined in a reversed direction from the ball contact to zero velocity or zero acceleration if zero was not present. The instant of ball contact was located first and then the instant of maximum absolute joint velocity with its corresponding zero velocity or zero acceleration, if zero velocity was not present, were determined accordingly.

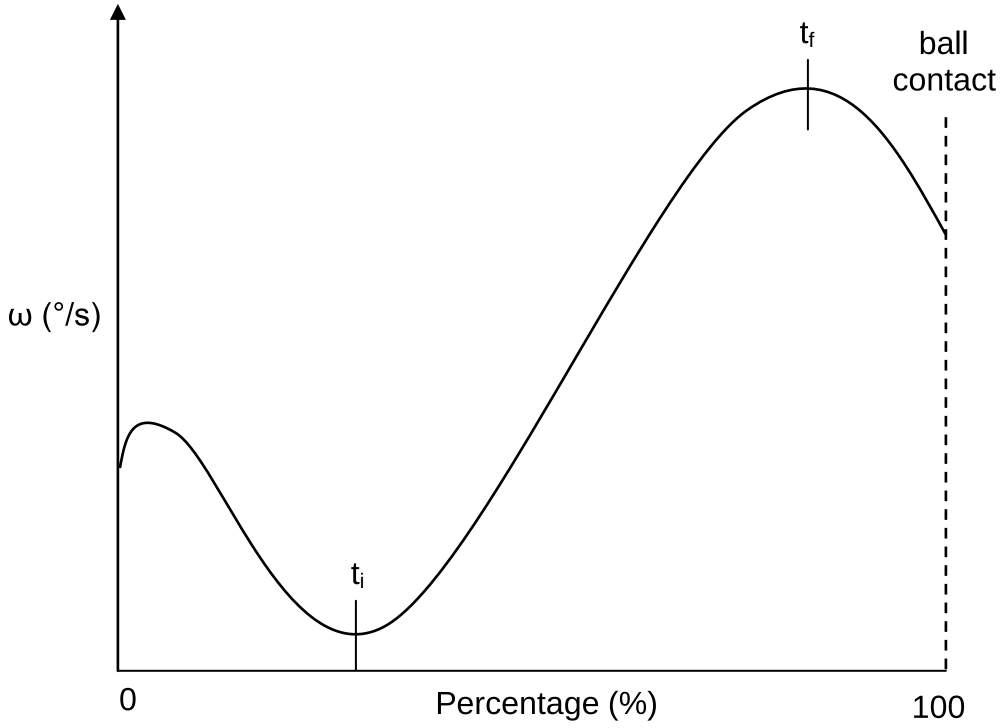

Figure 3.4 Normalized for time on the abscissa (0 % is the start of front foot striding toward the ball and 100 % is at ball contact.). The propulsion phase was defined from t_i that corresponds to zero velocity or zero acceleration, if the zero velocity was not present, with increasing speed to t_f that corresponds to the maximum absolute angular velocity prior to ball contact. The selections of the time points (t_i and t_f) were determined in a reversed direction from the ball contact to zero velocity or zero acceleration if zero was not present. The instant of ball contact was located first and then the instant of maximum absolute joint velocity with its corresponding zero velocity or zero acceleration, if zero velocity was not present were determined accordingly. The propulsion phase (t_p) was equal $t_f - t_i$ with both t_i and t_f correspond to the original non-normalized time scale points (i.e. seconds).

The shared positive contribution (SPC) and the reversed shared positive contribution (RSPC) were calculated as the following (see Figure 3.5 and Figure 3.6 for an illustration of the SPC and RSPC, respectively).

$$\% \text{ SPC} = [(t_b - t_c) / (t_d - t_a)] \times 100 \qquad (21)$$

$$\% \text{ RSPC} = [(t_d - t_a) / (t_b - t_c)] \times 100 \qquad (22)$$

where in both % SPC and % RSPC calculations, t_a, t_b, t_c and t_d correspond to the original non-normalized time scale points (i.e. seconds). The t_a and t_c correspond to the zero velocity or zero acceleration, if zero velocity was not present, for the proximal and distal joints, respectively. The t_b and t_d correspond to the maximum absolute joint angular velocity for the proximal and distal joints, respectively.

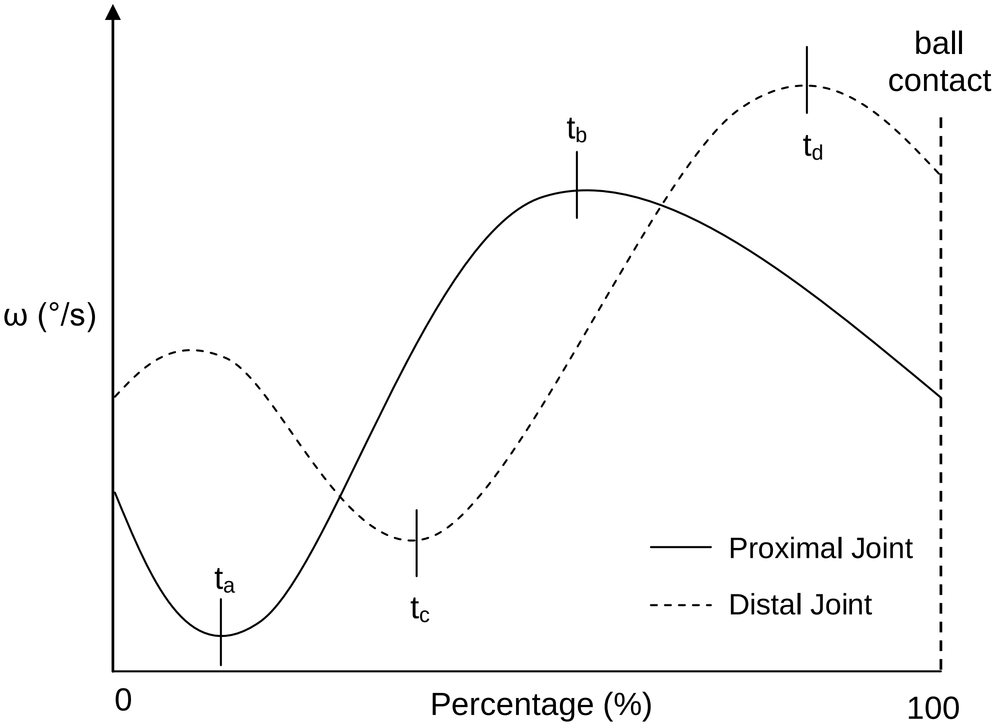

Figure 3.5 Normalized for time on the abscissa (0 % is the start of front foot striding toward the ball and 100 % is at ball contact.). Percentage of shared positive contribution (% SPC) was defined as the proximal to distal pattern where movement was initiated by the proximal joint followed by the distal. t_a and t_c correspond to the zero velocity or zero acceleration, if the zero velocity was not present, for the proximal and distal joints, respectively, and sped up to t_b and t_d which correspond to the maximum absolute angular velocity for the proximal and distal joints prior to ball contact, respectively. In the % SPC calculation, t_a, t_b, t_c and t_d correspond to the original non-normalized time scale points (i.e. seconds).

Based on a sampling rate of 240Hz and using the normalized time on the abscissa, it is estimated that the consequences of a one frame error in locating t would correspond to 0.0042 seconds in the non-normalized time scale or an error equal to 0.42%.

The marker that was placed on the top of the bat was used to calculate the linear displacement of the bat. For the angular displacement of the bat, the bat segment was determined as the displacement between the marker that was placed on the top of the bat and the marker that was placed on the bottom of the bat. Then, the dot product method was used to determine the angular displacement of the bat. The resultant linear and angular bat velocities at ball contact were both calculated using central difference.

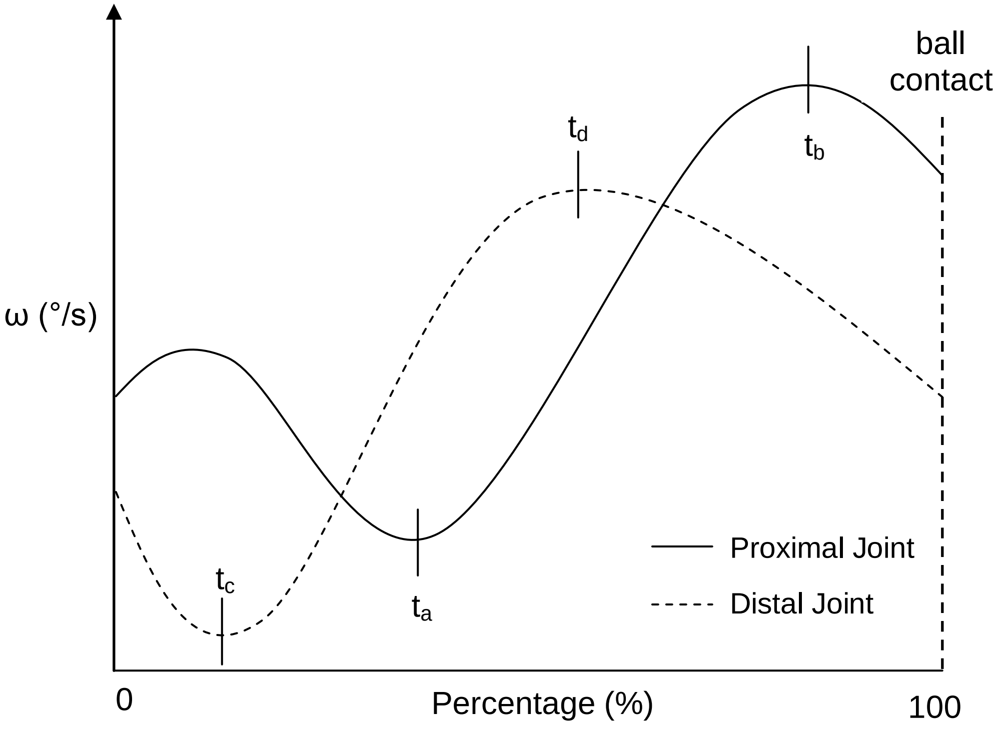

Figure 3.6 Normalized for time on the abscissa (0 % is the start of front foot striding toward the ball and 100 % is at ball contact.). Percentage of reversed share positive contribution (% RSPC) was defined as the distal to proximal pattern where movement was initiated by the distal joint followed by the proximal. t_a and t_c correspond to the zero velocity or zero acceleration, if the zero velocity was not present, for the proximal and distal joints, respectively, and sped up to t_b and t_d which correspond to the maximum absolute angular velocity for the proximal and distal joints prior to ball contact, respectively. In the % RSPC calculation, t_a, t_b, t_c and t_d correspond to the original non-normalized time scale points (i.e. seconds).

3.5 Experimental Design and Statistical Analysis

This study contained three major statistical analyses in an attempt to examine the difference in performance outcomes, kinematics, and movement patterns of the skill of placement hitting. The SPSS version 16.0 statistical analysis software was used for all statistical analyses.

1st analysis (Part A): placement hitting performance

A three-way ANOVA (2 fields x 2 locations of pitch x 3 strides) repeated measure study was conducted at $\alpha = 0.05$ on success rate of placement hitting performance. The success rate of placement hitting performance was calculated as the number of successful hits divided by the total number of trials (3) and then multiplied by 100. If a significant difference was found in the ANOVA test, pairwise comparisons were conducted using a *t*-test with the Bonferroni adjustment at $\alpha = 0.05 / c$, where c was the number of contrasts (Maxwell & Delaney, 1990). The same statistical analysis was conducted on percentage of hitting a fly ball, ground ball and pop fly.

1st analysis (Part B): individual performance VS group performance

In each of 12 conditions, a rescaled Euclidean distance analysis was conducted on the success rate of placement hitting, percentage of hitting a fly ball, ground ball and pop fly between each participant and the group mean performance. The rescaled Euclidean distance analysis was the measure of distance between dependent variables for individual performance versus group mean performance. The steps to obtain rescaled Euclidean distance (EuD) were as follows:

1st step: Participant vs Group mean - summed across variables

For condition i = 1 to 12

For participant j = 1 to 10

$$EuD_{mean} = \sqrt{\sum_{k=1}^{n} \left(\frac{x_{i,j,k} - \bar{x}_{i,k}}{max.(x_{i,k})}\right)^2} \tag{23}$$

where k = number of variables (e.g. n = 4 in the 1st analysis)

Therefore, for each condition, one EuD_{mean} per participant was calculated for a total of 12 conditions x 10 participants = 120 EuD_{mean}.

2nd step: Participant vs Participant - summed across variables

For condition i = 1 to 12

For participant j = 1 to 9 (for 10 participants)

$$EuD_{ind} = \sqrt{\sum_{k=1}^{n} \left(\frac{x_{i,j,k} - x_{i,j+1,k}}{max.(x_{i,k})}\right)^2} \tag{24}$$

where k = number of variables (e.g. n = 4 in the 1st analysis)

Therefore, for each condition, 45 EuD_{ind} were calculated per condition for a total of 12 conditions = 540 EuD_{ind}.

3rd step: Rescaled Euclidean distance

For condition i = 1 to 12

For participant j = 1 to 10

$$EuD_{rescaled} = \frac{EuD_{mean_{i,j}}}{max.EuD_{ind_i}} \tag{25}$$

Therefore, for each condition, one $EuD_{rescaled}$ per participant was calculated for a total of 12 conditions x 10 participants = 120 $EuD_{rescaled}$ The rescaled Euclidean distance ($EuD_{rescaled}$) ranged between a value of 0 for no dissimilarity to a value of 1 for maximum dissimilarity. Due to the total lack of empirical studies that have used Euclidean distance analysis to evaluate the generalizability of data in the area of biomechanics, no specific cut-off point (e.g. 0.20 or 0.50) was ever established or reported on the rescaled Euclidean distance. Therefore, the results from the rescaled Euclidean distance analysis, ranging from 0 to 1, were categorized into five different groups (0-0.20, 0.21-0.40, 0.41-0.60, 0.61-0.80 and 0.81-1.00) in an attempt to understand the degree of dissimilarity of the data set which enabled us to assess if the group mean performance could be generalized to all participants (Pallant, 2007).

2nd analysis (Part A): Kinematics variables

A three-way ANOVA (2 fields x 2 locations of pitch x 3 strides) repeated measure study was conducted at $\alpha = 0.05$ on six different kinematics variables, Table 3.2. If a significant difference was found in the ANOVA test, pairwise comparisons were conducted using a *t*-test with the Bonferroni adjustment at $\alpha = 0.05 / c$, where c was the number of contrasts (Maxwell & Delaney, 1990).

Table 3.2 Kinematic variables at ball contact

Resultant linear bat velocity (m/s)
Resultant angular bat velocity (°/s)
Bat swing time (front foot stride to ball contact) (s)
Lower body rotational angle (°)
Trunk rotational angle (°)
Upper body rotational angle (°)

2nd analysis (Part B): individual performance VS group performance

In each of 12 conditions a Euclidean distance analysis was conducted on all six kinematics variables between each participant and group mean performance. The degree of dissimilarity enabled us to assess if the group mean performance could be generalized to all participants.

3rd analysis (Part A): movement patterns analysis

In this study each participant hit three balls in 12 different conditions (2 fields x 2 locations of pitch x 3 strides). Each participant performed a total of 36 hits (2 fields x 2 locations of pitch x 3 strides x 3 trials). A three-way ANOVA (2 fields x 2 locations of pitch x 3 strides) repeated measure study was conducted at $\alpha = 0.05$ on the combined % SPC and % RSPC for two different pairs of joints (lower body and trunk, and trunk and upper body). If a significant difference was found in the ANOVA test, pairwise comparisons were conducted using a *t*-test with the Bonferroni adjustment at $\alpha = 0.05 / c$, where c was the number of contrasts (Maxwell & Delaney, 1990). The results enabled us to determine if there was a significant difference in movement patterns.

3rd analysis (Part B): individual performance VS group performance

In each of 12 conditions, a rescaled Euclidean distance analysis was conducted on the combined % SPC and % RSPC for two different pairs of joints between each participant and group mean performance. The degree of dissimilarity enabled us to assess if the group mean performance could be generalized to all participants.

Chapter 4: Results

In a game of slo-pitch, the ball is pitched at a speed of 10-15 m/s and takes approximately 1.5 s to reach home plate (Carriero, 1984; Wu & Gervais, 2006, 2008). The skill of slo-pitch placement hitting is unique because it allows the batter to have time to adjust their stance, stride and swing the bat before hitting the ball. Generalizing on hitting mechanics from this study the skill of slo-pitch placement hitting began with the batter standing in the batter's box in their own comfortable stance with knees slightly bent. The bat was held in front of the back shoulder with the bottom of the bat positioned approximately at the shoulder level, Figure 4.1(A), Figure 4.2 (A), and Figure 4.3 (A).

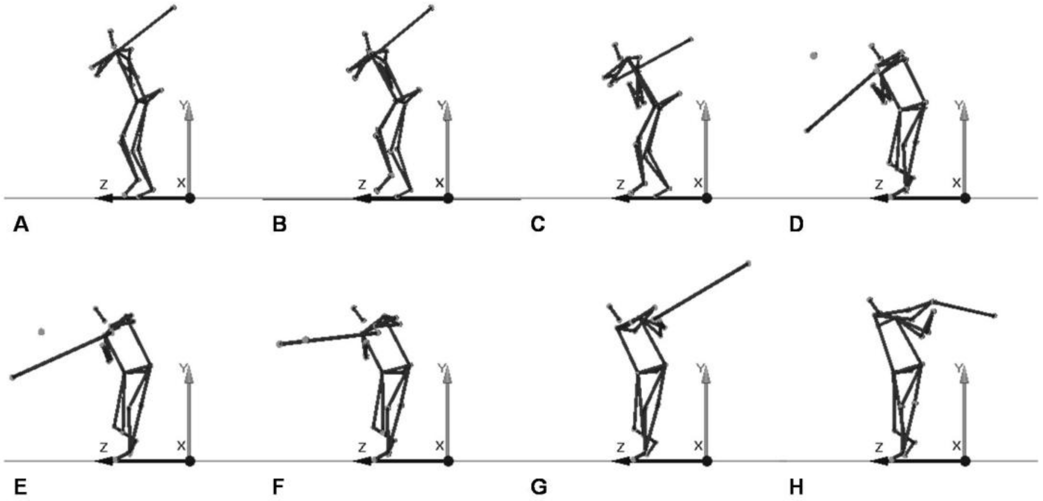

Figure 4.1 An example of a frontal view of the skill of slo-pitch placement hitting for participant #7 in condition #2. (A) natural stance, (B) front foot off the ground and striding forward, (C) lowering the back elbows and beginning of downward swing of the bat, (D) beginning of upward swing of the bat, (E) maximum linear and angular velocities of the bat, (F) ball contact, (G) follow through, and (H) finish.

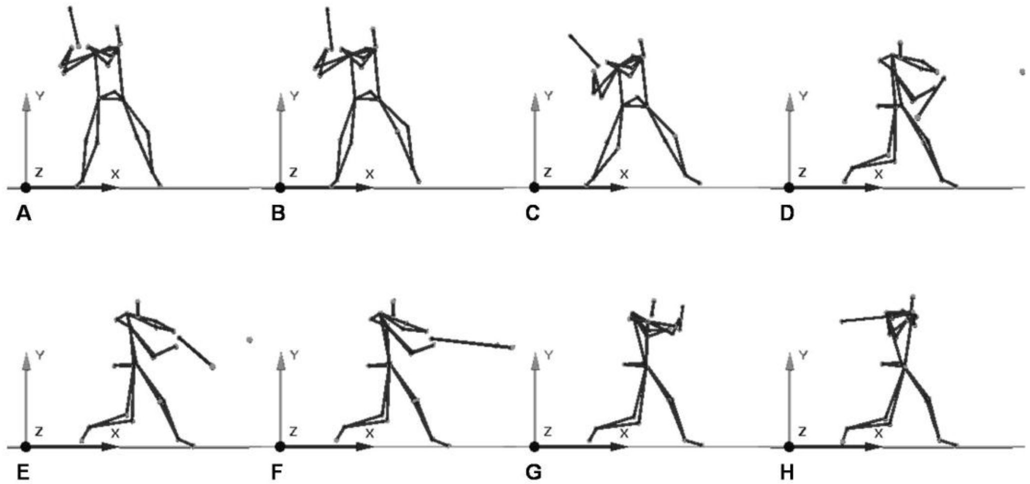

Figure 4.2 An example of a sagittal view of the skill of slo-pitch placement hitting for participant #7 in condition #2. (A) natural stance, (B) front foot off the ground and striding forward, (C) lowering the back elbows and beginning of downward swing of the bat, (D) beginning of upward swing of the bat, (E) maximum linear and angular velocities of the bat, (F) ball contact, (G) follow through, and (H) finish.

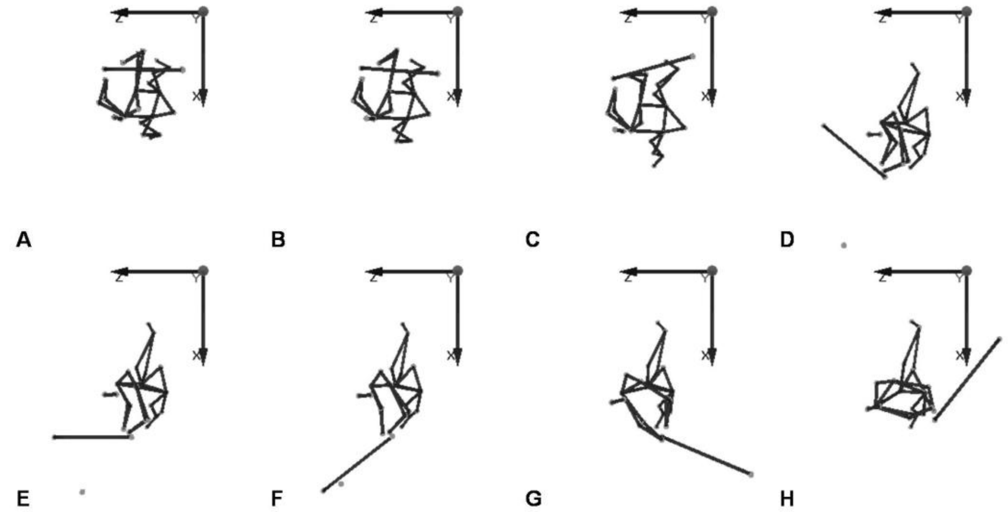

Figure 4.3 An example of a transverse view of the skill of slo-pitch placement hitting for participant #7 in condition #2. (A) natural stance, (B) front foot off the ground and striding forward, (C) lowering the back elbows and beginning of downward swing of the bat, (D) beginning of upward swing of the bat, (E) maximum linear and angular velocities of the bat, (F) ball contact, (G) follow through, and (H) finish.

Once the ball was pitched by the pitching machine, the batter then raised the front foot momentary to shift their body weight to the back foot. Then the front foot started to stride forward to initiate the beginning of the bat swing, Figure 4.1(B), Figure 4.2 (B), and Figure 4.3 (B). Depending on the stride instruction that was provided to the batter, the batter used either an open or a closed stride technique to stride toward the ball, Figure 4.4 (A & C), or they used a parallel stride technique to stride toward the pitching machine, Figure 4.4 (B).

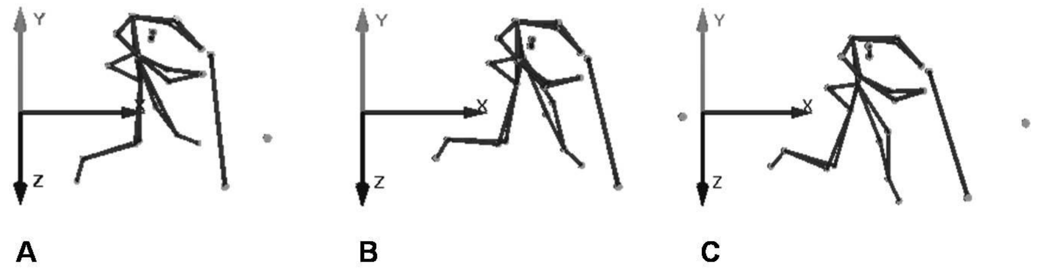

Figure 4.4 Three different stride techniques: A) open, B) parallel, and C) closed.

From the results of the study, on average, the heel of the front foot was planted on the ground approximately at 0.37 s (65 % of bat swing time). The back elbow (right elbow) began to drop to the hip level which allowed the bat to accelerate downward. Figure 4.1(C), Figure 4.2 (C), and Figure 4.3 (C). At this time the lower body, trunk and upper body joint angles and velocities began to increase or decrease depending on type of joint movement and coordination pattern. In this study one of the main movement coordination patterns that were observed in the batter was a distal to proximal type of joint movement with a sequential type of coordination pattern between the lower body and trunk joints, and a proximal to distal type of joint movement with a sequential type of coordination pattern between the trunk and upper body joints, Figure 4.5.

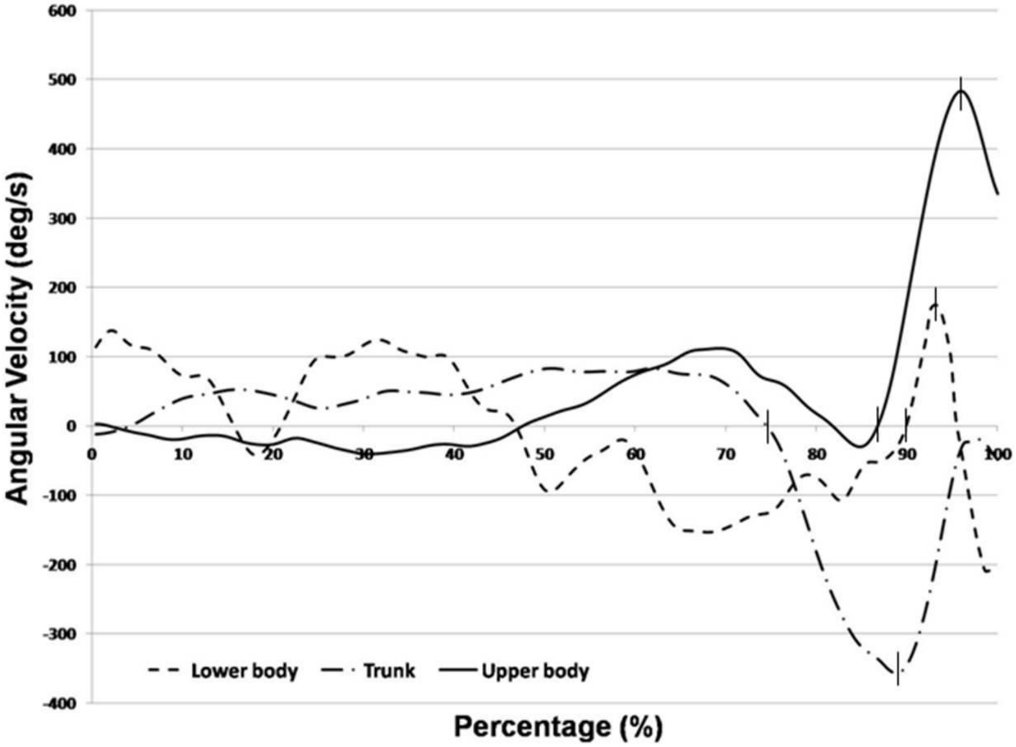

Figure 4.5 Normalized for time on the abscissa (0 % is the start of front foot striding toward the ball and 100 % is at ball contact.). The graph is an example of movement coordination pattern for participant #7 in condition #2 (same field, inside pitch and parallel stride). The lower body and trunk joints show a RSPC of -14 % in a sequential movement coordination pattern while the trunk and upper body joints show a SPC of 2 % in a sequential movement coordination pattern. The vertical lines indicate the beginning and end of the propulsion phase prior to ball contact.

Examples of other types of joint movement and coordination pattern that were observed in the study are as follows. Figure 4.6 shows a distal to proximal type of joint movement with a sequential type of coordination pattern between the lower body and trunk joints and a simultaneous type of coordination pattern between the trunk and upper body joints.

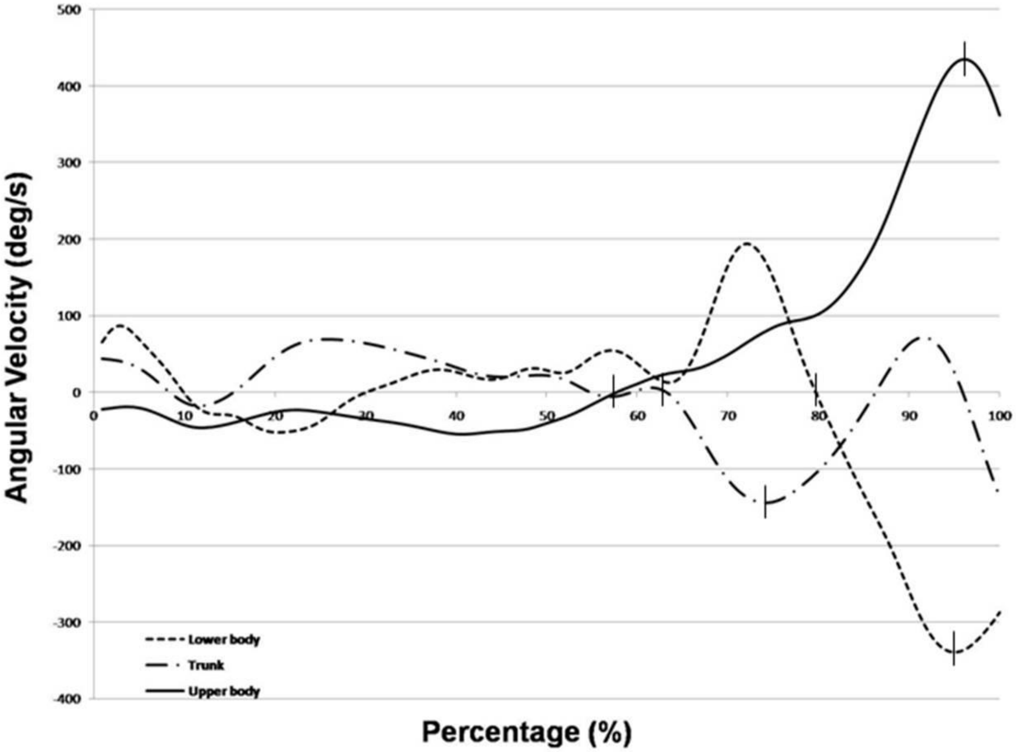

Figure 4.6 Normalized for time on the abscissa (0 % is the start of front foot striding toward the ball and 100 % is at ball contact.). The graph is an example of movement coordination pattern for participant #7 in condition #5 (same field, outside pitch and parallel stride). The lower body and trunk joints show a RSPC of - 21 % in a sequential movement coordination pattern while the trunk and upper body joints show a RSPC of 222 % in a simultaneous movement coordination pattern. The vertical lines indicate the beginning and end of the propulsion phase prior to ball contact.

Figure 4.7 shows a distal to proximal type of joint movement with a sequential type of coordination pattern between the lower body and trunk joints while a proximal to distal type of joint movement with a sequential type of coordination pattern was observed between the trunk and upper body joints. Figure 4.8 shows a proximal to distal type of joint movement with a sequential type of coordination pattern between the lower body and trunk joints while a distal to proximal type of joint movement with a sequential type of coordination pattern was observed between the trunk and upper body joints.

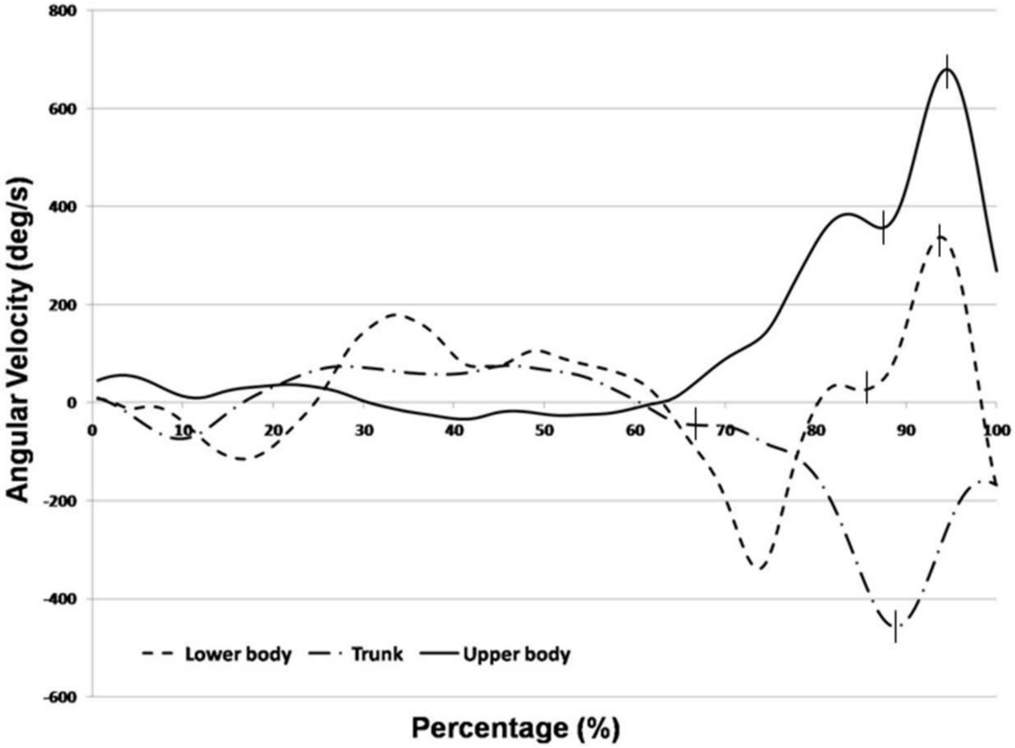

Figure 4.7 Normalized for time on the abscissa (0 % is the start of front foot striding toward the ball and 100 % is at ball contact.). The graph is an example of movement coordination pattern for participant #6 in condition #2 (same field, inside pitch and parallel stride). The lower body and trunk joints show a RSPC of 3 % in a sequential movement coordination pattern while the trunk and upper body joints show a SPC of 2 % in a sequential movement coordination pattern. The vertical lines indicate the beginning and end of the propulsion phase prior to ball contact.

In this study on average approximately at 0.49 s (85% of the bat swing time), the bat began to accelerate upward, Figure 4.1(D), Figure 4.2 (D), and Figure 4.3 (D), and then the upper body joint velocity reached its peak velocity approximately at 0.54 s (95% of bat swing time). On average the bat then reached its maximum linear and angular velocities approximately at 0.55s (96 % of the bat swing time). Figure 4.1(E), Figure

4.2 (E), and Figure 4.3 (E). At ball contact the mean lower body, trunk and upper body joint angles of all placement hitting conditions were at -1.53 ± 3.88 °, 2.14 ± 4.71 °, and 0.30 ± 3.52 °, respectively and the mean resultant linear and angular bat velocities at ball contact were 30.54 ± 0.60 m/s and 2010.44 ± 50.07 °/s, respectively, Figure 4.1(F), Figure 4.2 (F), and Figure 4.3 (F).

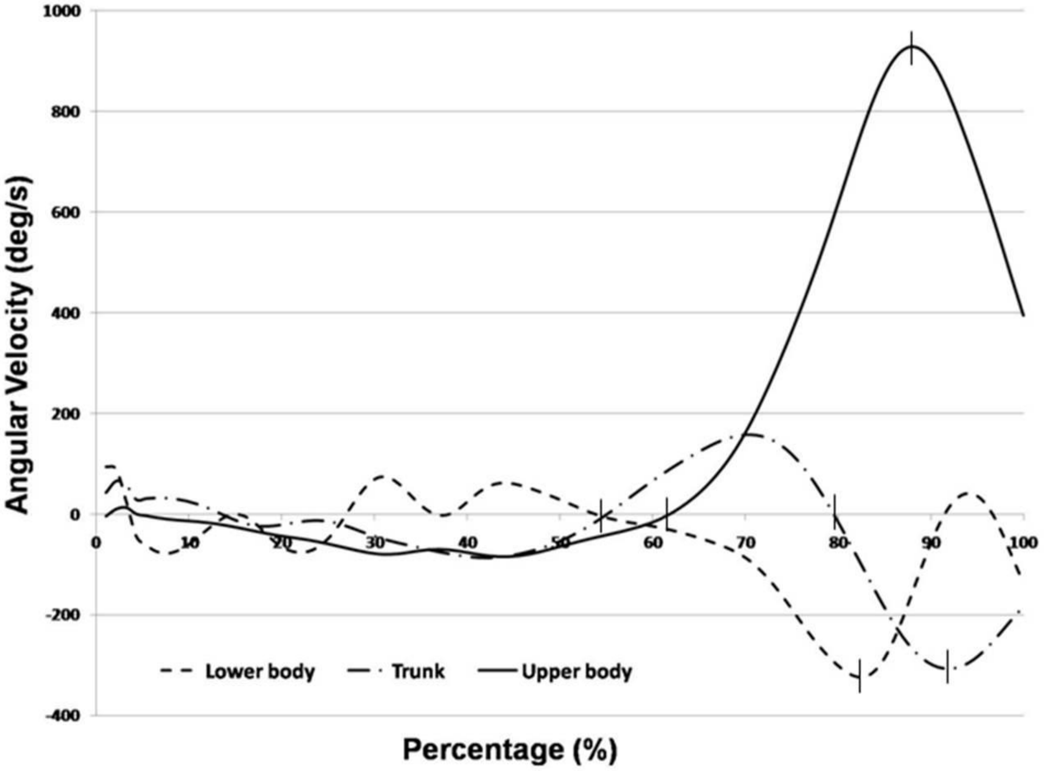

Figure 4.8 Normalized for time on the abscissa (0 % is the start of front foot striding toward the ball and 100 % is at ball contact.). The graph is an example of movement coordination pattern for participant #7 in condition #7 (opposite field, inside pitch and open stride). The lower body and trunk joints show a SPC of 8 % in a sequential movement coordination pattern while the trunk and upper body joints show a RSPC of 30 % in a sequential movement coordination pattern. The vertical lines indicate the beginning and end of the propulsion phase prior to ball contact

The mean duration of bat swing time was approximately 0.57 ± 0.04 s, and it was determined from the time the front foot started stride toward the ball or the pitching machine until ball contact. After ball contact the body and the bat continued to rotate to complete the follow through movement, Figure 4.1(G-H), Figure 4.2 (G-H), and Figure 4.3 (G-H).

Statistical analyses

Three major statistical analyses were conducted to examine the difference in performance outcomes, kinematics, and movement patterns of placement hitting. In each major statistical analysis an individual result was compared to the group mean result to evaluate the generalizability of the study.

1st analysis (Part A): placement hitting performance

Each participant was asked to use a specific stride technique and placed the ball to a designated field. If a participant was able to perform these two task constraints correctly, specific stride technique and placed the ball to a designated field, this trial was considered as a successful trial. The results showed that not all participants were able to perform this requirement. Table 4.1 shows the number of participants that were able to perform this requirement in at least one of three trials.

Table 4.1 Number of successful participants that were able to perform with a correct stride and placed the ball to a designated field.

	Conditions (Same field)	number of successful participants	Conditions (Opposite field)	number of successful participants
Inside pitch	1 (Open)	5	7 (Open)	5
	2 (Parallel)	9	8 (Parallel)	3
	3 (Closed)	9	9 (Closed)	7
Outside pitch	4 (Open)	7	10 (Open)	5
	5 (Parallel)	10	11 (Parallel)	7
	6 (Closed)	9	12 (Closed)	3

To further understand the participants' performance success results, a three-way ANOVA (2 fields x 2 locations of pitch x 3 strides) repeated measure study was conducted at $\alpha = 0.05$ on success rate of placement hitting performance. The success rate of placement hitting performance was calculated as the number of successful hits divided by the total number of trials (3) and then multiplied by 100. Statistical significant differences were found between the same and opposite fields on the success rate of placement hitting and percentage of hitting a ground ball, Appendix B. Participants showed a success rate of 48.34 ± 3.62 % when they hit the ball to the same field (left field). However, when participants hit the ball to the opposite field (right field), their success rate was only 22.70 ± 3.26 %. Further, the percentage for hitting a ground ball to the same field (23.89 ± 4.15 %) was found to be significantly greater than the percentage for hitting a ground ball to the opposite field (2.22 ± 0.91%); however, no significant differences were found in the percentage for hitting a fly ball and pop fly, Table 4.2. Figure 4.9 illustrates that both success rate and percentage of hitting a ground ball were higher in the same field condition than the opposite field condition.

Table 4.2 Placement hitting performance outcomes

Performance outcomes	**Same field**	**Opposite field**	***p***
Success rate (%)	48.34 ± 3.62	22.70 ± 3.26	0.00*
Fly ball (%)	21.66 ± 3.56	19.44 ± 2.78	0.65
Ground ball (%)	23.89 ± 4.15	2.22 ± 0.91	0.00*
Pop fly (%)	2.77 ± 1.24	1.11 ± 0.74	0.30

* Statistical significant at $p < 0.05$

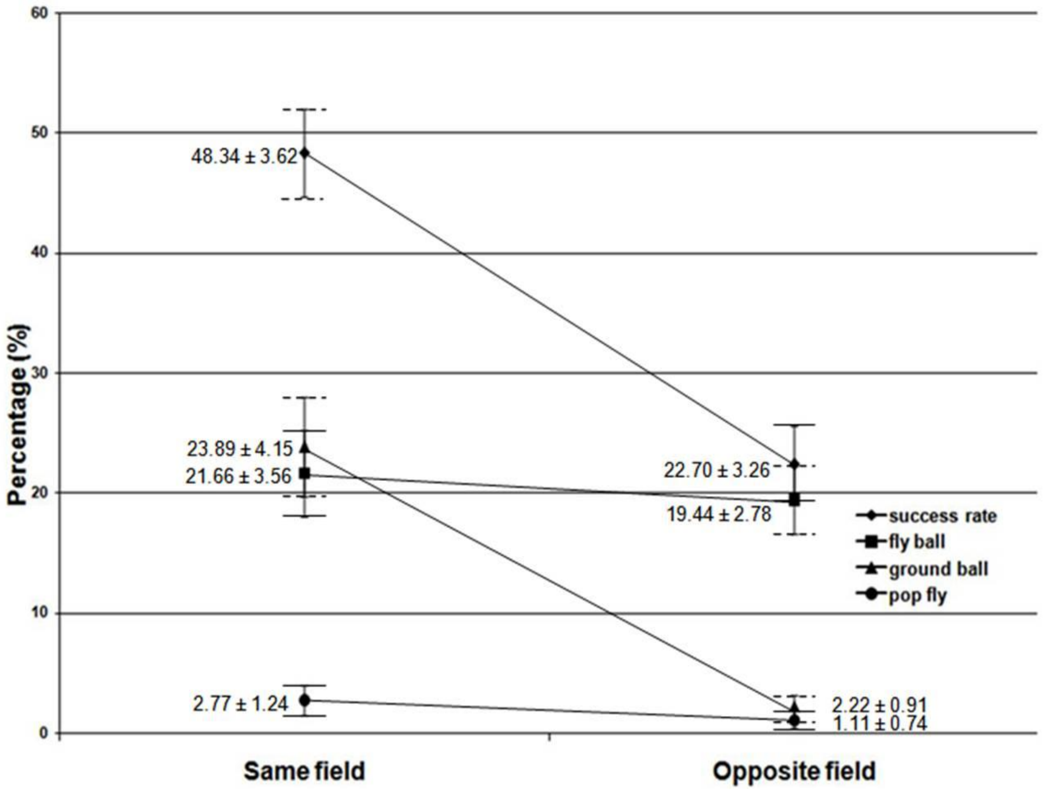

Figure 4.9 The mean and standard deviation (Mean ± SD) for the percentage of placement hitting performance outcome variables (% success rate, % fly ball, % ground ball and % pop fly) between the same and opposite field conditions.

No statistical significance was observed in the three-way interaction, so the research hypotheses that the success rate and the percentages of fly balls in placement hitting performance for striding toward the ball would be significantly greater than for striding toward the pitcher and would also be significantly greater than striding away from the ball were rejected in this study. In addition, the research hypotheses that the percentages of ground balls and pop flies in placement hitting performance for striding toward the ball would be significantly less than for striding toward the pitcher and would also be significantly less than striding away from the ball were also rejected in this study.

1st analysis (Part B): individual performance VS group performance

A Euclidean distance analysis was conducted on the percentages of success rate, fly ball, ground ball and pop fly in each of 12 conditions, Appendix C. Figure 4.10 illustrates the participants who had the lowest and highest degrees of dissimilarity to the group mean. These participants were identified by a between subject comparison of the Rescaled Euclidean distance averaged over the 12 conditions.

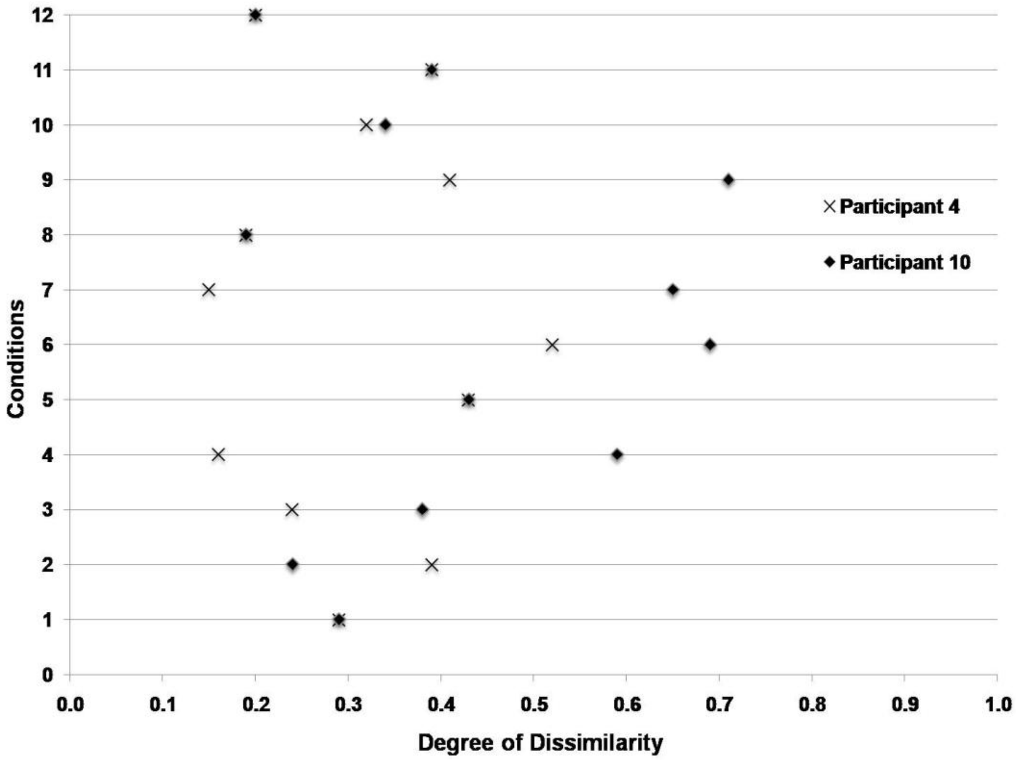

Figure 4.10 Participant #4 had the lowest degree of dissimilarity to the group mean, and participant #10 had the highest degree of dissimilarity to the group mean. (Participants were identified based on the averaged Rescaled Euclidean distance across the 12 conditions)

The results also indicated that across 12 different placement hitting conditions 24.2 % of participants showed a degree of dissimilarity between 0 and 0.20, and 46.7 % of participants showed a degree of dissimilarity between 0.21 and 0.40. Further, 16.7 % of participants showed a degree of dissimilarity between 0.41 and 0.60, and 11.7 % of participants showed a degree of dissimilarity between 0.61 and 0.80, Figure 4.11. Cumulatively, over 70 % of participants illustrated a degree of dissimilarity below 0.40, and over 85 % of participants illustrated a degree of dissimilarity below 0.60. Hence, generally, participants showed their individual performance results were similar to the group mean performance results.

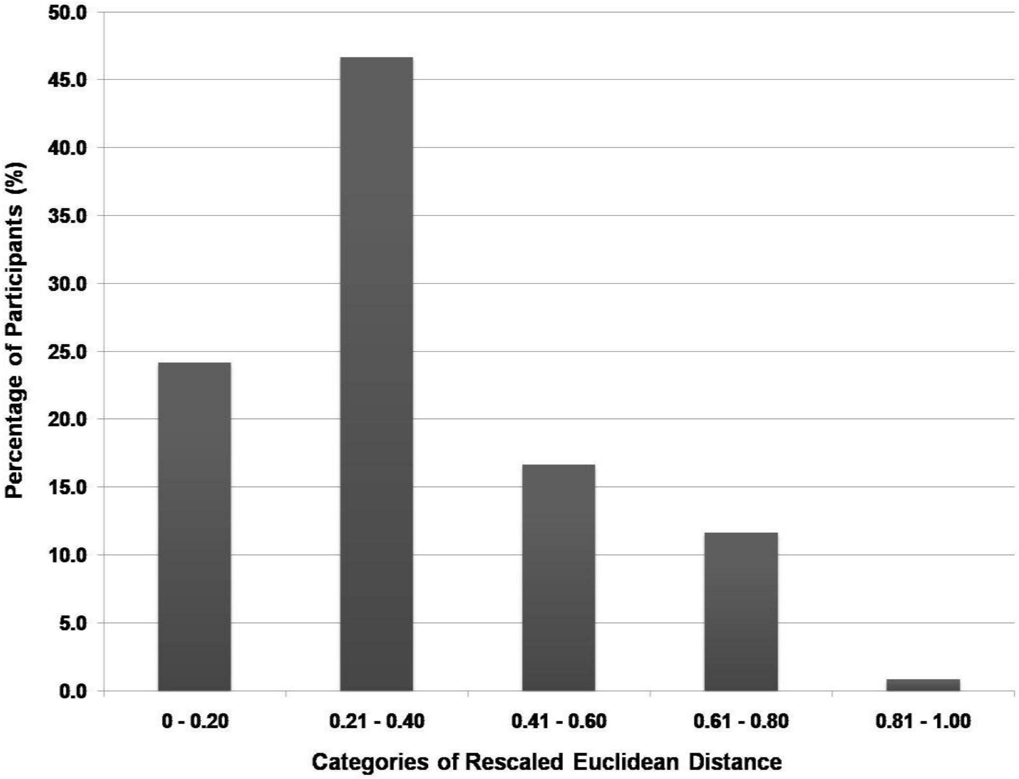

Figure 4.11 Percentage of participants across 12 different placement hitting conditions in each rescaled Euclidean distance category that was conducted on individual performance results versus group mean performance results.

2nd analysis (Part A): Kinematic variables

A three-way ANOVA (2 fields x 2 locations of pitch x 3 strides) repeated measure study was conducted at $\alpha = 0.05$ on kinematics variables, Appendix D. From the results of 1st analysis on performance, it was revealed that in a couple of conditions (i.e. condition 8 and 12) there were only three participants whom were able to perform the trials successfully, satisfying both task constraint requirements of correct stride technique and designated ball placement location. The objective of the study was guided by the rationale of ecological task analysis and to examine the influence of different constraints on the participants. Therefore, even though in some trials participants were only able to satisfy one task constraint, performing with a correct stride technique, but not the other task constraint, designated ball placement location, the findings would still provide important insights to our understanding of the influence of constraint on the kinematics of human movement. Hence, the average of the participant's trials that were performed with a correct stride and a fair ball with intended ball placement location in each condition was calculated and used for statistical analyses. From the results participants showed a linear bat velocity at ball contact of 31.47 ± 0.63 m/s when hitting the ball to the same field, and this was significantly greater than the linear bat velocity at ball contact of 29.62 ± 0.52 m/s when hitting the ball to the opposite field, Table 4.3. Figure 4.12 illustrates that significant difference was observed in the linear bat velocity but was not explicitly evident in the bat's angular velocity. This showed that the mechanics of the bat movement was not purely rotational around a fixed axis, but in fact it consisted of both linear and rotational movements. Moreover, the linear bat velocity was found to be significantly greater when participants used a parallel stride technique (31.14 ± 0.50 m/s) than an open stride technique (29.80 ± 0.51 m/s).

Table 4.3 Placement hitting kinematic variables at ball contact

Kinematics variables	Same field	Opposite field	*p*
Linear bat velocity (m/s)	31.47 ± 0.63	29.62 ± 0.52	0.00*
Angular bat velocity (°/s)	2029.27 ± 45.49	1991.60 ± 41.88	0.27
Bat swing time (s)	0.58 ± 0.03	0.59 ± 0.05	0.87

* Statistical significant at $p < 0.05$

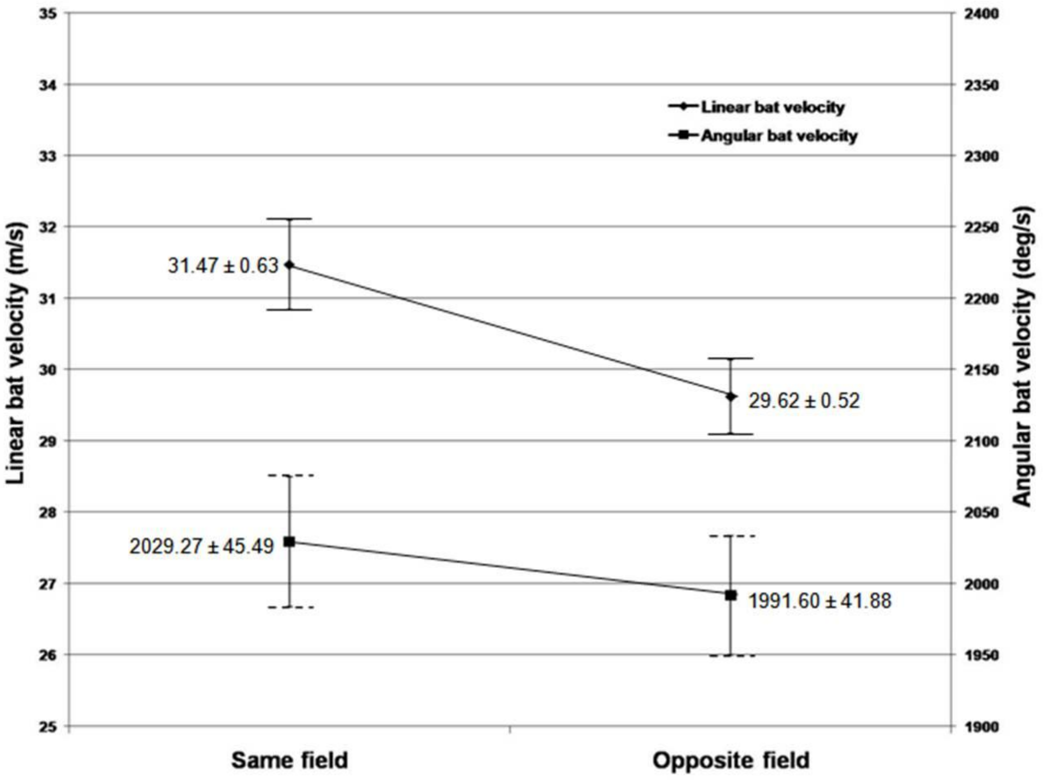

Figure 4.12 The mean and standard deviation (Mean ± SD) for the comparison of kinematics variables in the linear bat velocity (primary vertical axis) and angular bat velocity (secondary vertical axis) between the same and opposite field conditions.

Further statistical analyses revealed that the overall three-way interaction (2 fields x 2 locations of pitch x 3 strides) was found to be significant at $\alpha = 0.05$ on both linear and angular bat velocities at ball contact, Table 4.4 and Table 4.5.

Table 4.4 The overall three-way interaction (2 fields x 2 locations of pitch x 3 strides) for the linear bat velocity (m/s) at ball contact, mean (S.D.).

Stride	**Open**		**Parallel**		**Closed**	
Field\Pitch	**Inside**	**Outside**	**Inside**	**Outside**	**Inside**	**Outside**
Same	31.70	30.53	31.71	32.21	31.09	31.58
	(2.40)	(2.92)	(2.37)	(1.32)	(2.44)	(3.09)
Opposite	28.04	28.93	30.70	29.95	30.46	29.62
	(1.57)	(1.63)	(2.33)	(1.47)	(2.56)	(2.84)

Table 4.5 The overall three-way interaction (2 fields x 2 locations of pitch x 3 strides) for the angular bat velocity (°/s) at ball contact, mean (S.D.).

Stride	**Open**		**Parallel**		**Closed**	
Field\Pitch	**Inside**	**Outside**	**Inside**	**Outside**	**Inside**	**Outside**
Same	2045.62	1923.21	2056.77	2029.47	2052.63	2067.93
	(156.90)	(179.75)	(240.60)	(199.38)	(226.02)	(283.35)
Opposite	1883.96	1927.67	2074.26	2026.32	2076.43	1960.99
	(126.77)	(152.98)	(231.08)	(118.54)	(214.05)	(228.48)

Three limited three-way interactions ((2 fields x 2 locations of pitch x 2 strides (open and parallel, open and closed, or parallel and closed)) at $\alpha = 0.05$ were conducted in an attempt to understand the overall three-way interaction on linear and angular bat velocities, respectively. For the linear bat velocity the results showed that the limited three-way interaction effect was significantly different between open and parallel stride techniques and between open and closed stride techniques but not between parallel and closed stride techniques. The graph profile of each stride technique can be compared with each other to evaluate the overall three-way interaction effect.

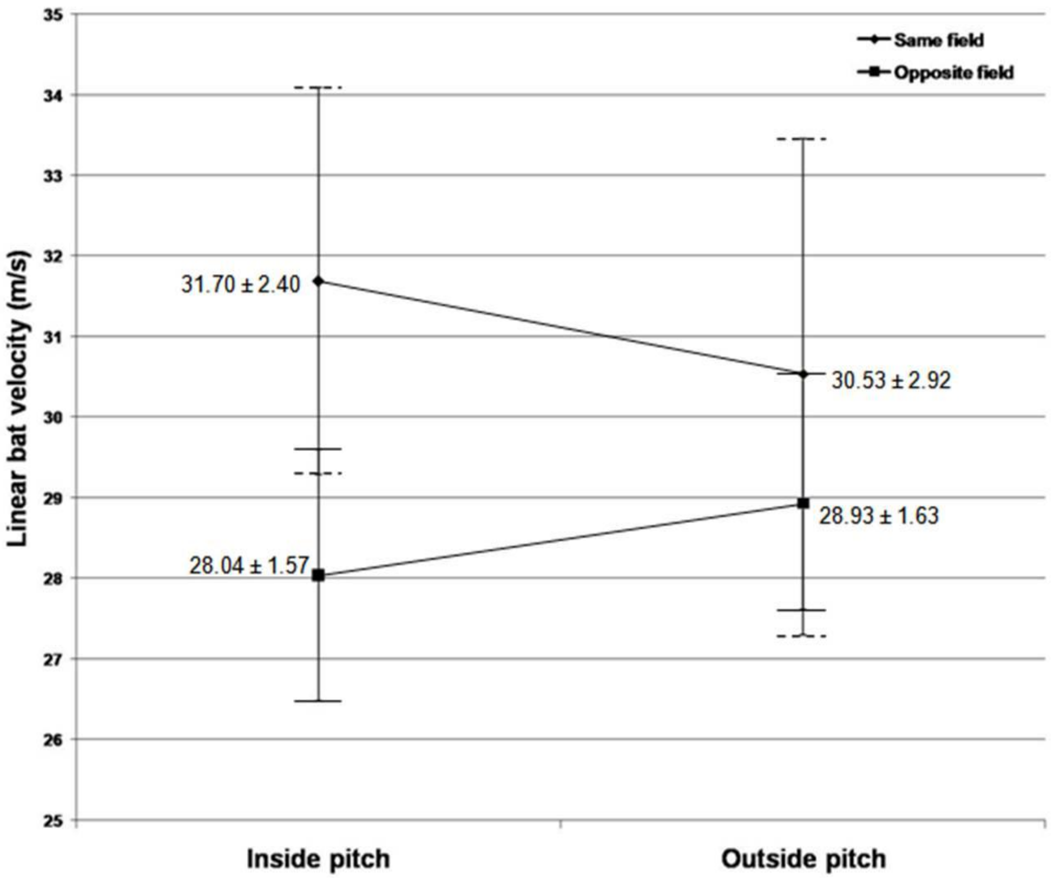

Figure 4.13 The mean and standard deviation (Mean ± SD) for the significant two-way interaction effect (2 fields x 2 location of pitches) for open stride technique on linear bat velocity.

Figure 4.13 shows a different graph profile when compared to Figure 4.14 or Figure 4.15. Figure 4.14 and Figure 4.15 show a similar graph profile with each other. This indicates that the limited three-way interaction effect was mainly due to the influence from the interaction between the type of designated field and location of pitch in the open stride technique (Figure 4.13). The two-way interaction (2 fields x 2 locations of pitch) with the use of $MS_{overall}$ error term from the overall three-way interaction at $\alpha = 0.05$ was conducted for each stride technique on linear bat velocity, and the results indicated the significant difference in each stride technique, Figure 4.13 to Figure 4.15.

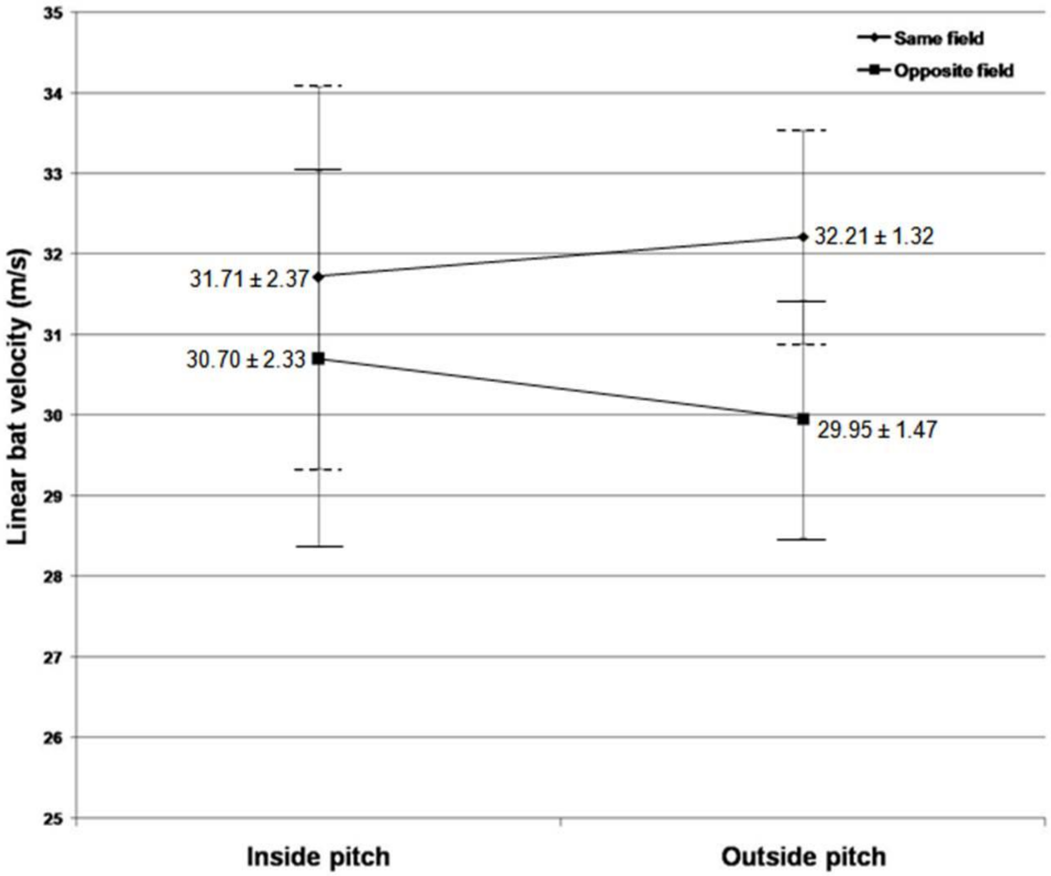

Figure 4.14 The mean and standard deviation (Mean ± SD) for the significant two-way interaction effect (2 fields x 2 location of pitches) for parallel stride technique on linear bat velocity.

With the use of *t*-test with Bonferroni adjustment at $\alpha = 0.05 / 2 = 0.025$ in each stride technique, the significant difference was found on the inside pitch between the same and opposite fields for the open stride technique, and on the outside pitch between the same and opposite fields for the parallel technique. Participants showed a linear bat velocity of 31.70 ± 2.40 m/s when they placed the ball toward the same field with an open stride on the inside pitch ball location, and this is statistically significantly greater than a linear bat velocity of 28.04 ± 1.57 m/s when they placed the ball toward the opposite field with an open stride. Similar results were observed on the outside pitch between the same (32.21 ± 1.32 m/s) and opposite (29.95 ± 1.47 m/s) fields for the parallel technique. For the closed stride technique, the significant difference was found on the outside pitch between the same (31.58 ± 3.09 m/s) and opposite (29.62 ± 2.84 m/s) fields at α = 0.05 level but not at α = 0.025.

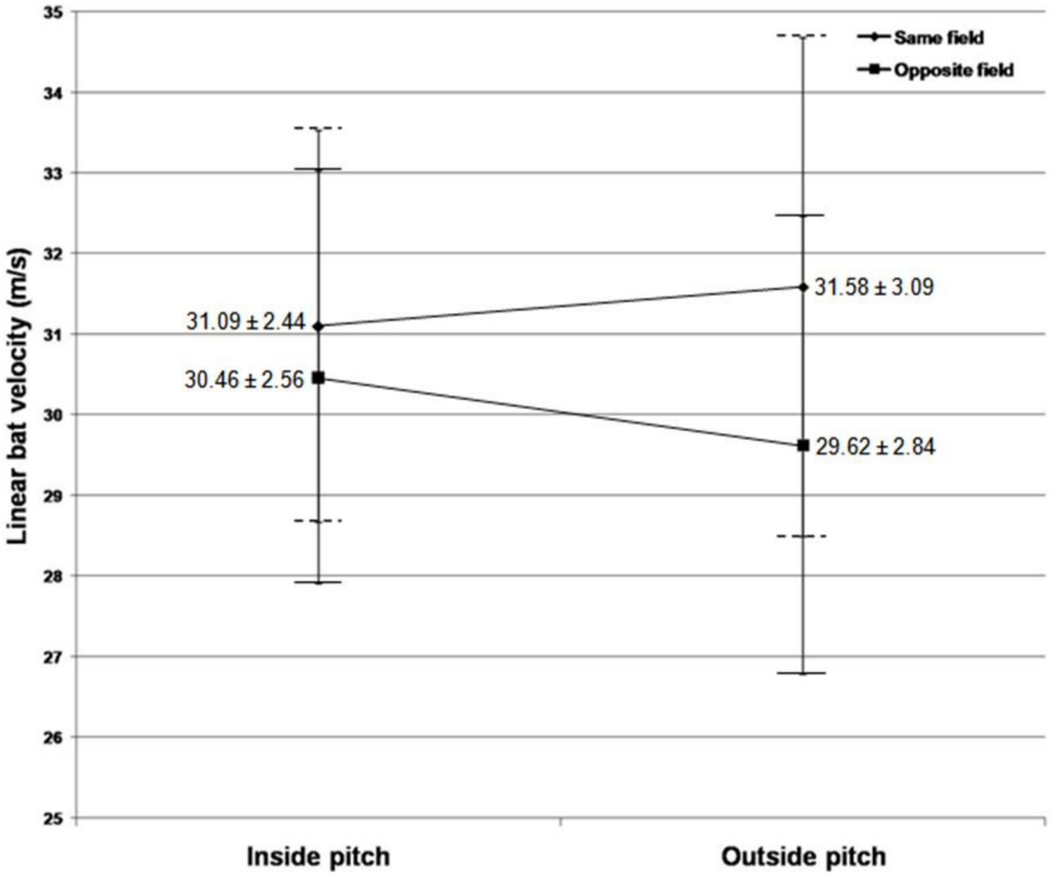

Figure 4.15 The mean and standard deviation (Mean ± SD) for the significant two-way interaction effect (2 fields x 2 location of pitches) for closed stride technique on linear bat velocity.

For the angular bat velocity the results showed that the limited three-way interaction effect was significantly different between the open and closed stride techniques only, and this can be observed by comparing the graph profile between Figure 4.16 and Figure 4.18. The parallel stride technique did not show any statistical significant difference when comparing to other stride techniques, Figure 4.17.

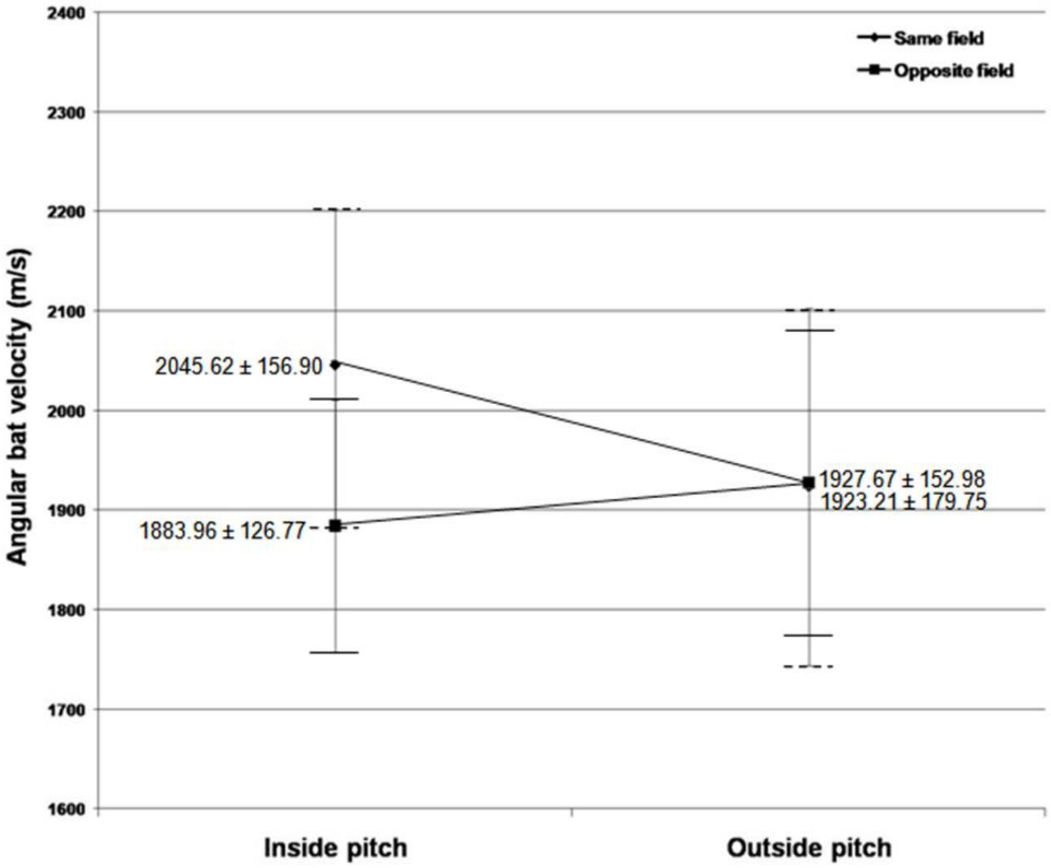

Figure 4.16 The mean and standard deviation (Mean ± SD) for the significant two-way interaction effect (2 fields x 2 location of pitches) for open stride technique on angular bat velocity.

The two-way interaction (2 fields x 2 locations of pitch) with the use of $MS_{overall}$ error term from the overall three-way interaction at α = 0.05 was conducted for each stride technique on angular bat velocity, and the results indicated that the significant difference was found on the open stride technique. With the use of *t*-test with Bonferroni adjustment at α =

0.05 / 2 = 0.025 on the open stride technique, the significant difference was found on the inside pitch between the same (2045.62 ± 156.90 °/s) and opposite (1883.96 ± 126.77 °/s) fields.

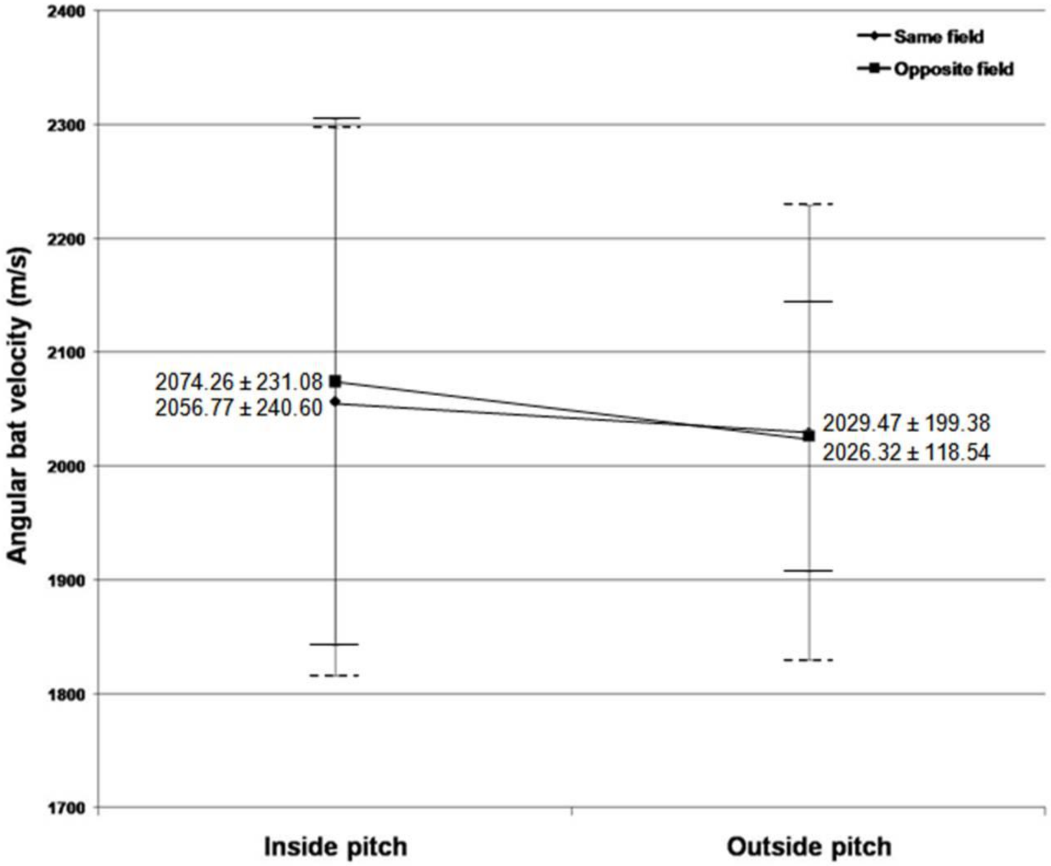

Figure 4.17 The mean and standard deviation (Mean ± SD) for the non-significant two-way interaction effect (2 fields x 2 location of pitches) for parallel stride technique on angular bat velocity.

To further evaluate the research hypotheses of the study, pairwise comparisons were conducted using a *t*-test with the Bonferroni adjustment at α = 0.05 / 12 = 0.004 on linear and angular bat velocities. No statistical significant differences were found in the 12 pairwise comparisons that were conducted, Appendix D. No statistical significant difference was found in the bat swing time in all statistical analyses. Therefore, the research hypotheses that the resultant linear and angular bat velocities at ball contact and bat swing time in placement hitting performance for striding toward the ball would be significantly greater than for striding toward the pitcher and would also be significantly greater than striding away from the ball were rejected in this study.

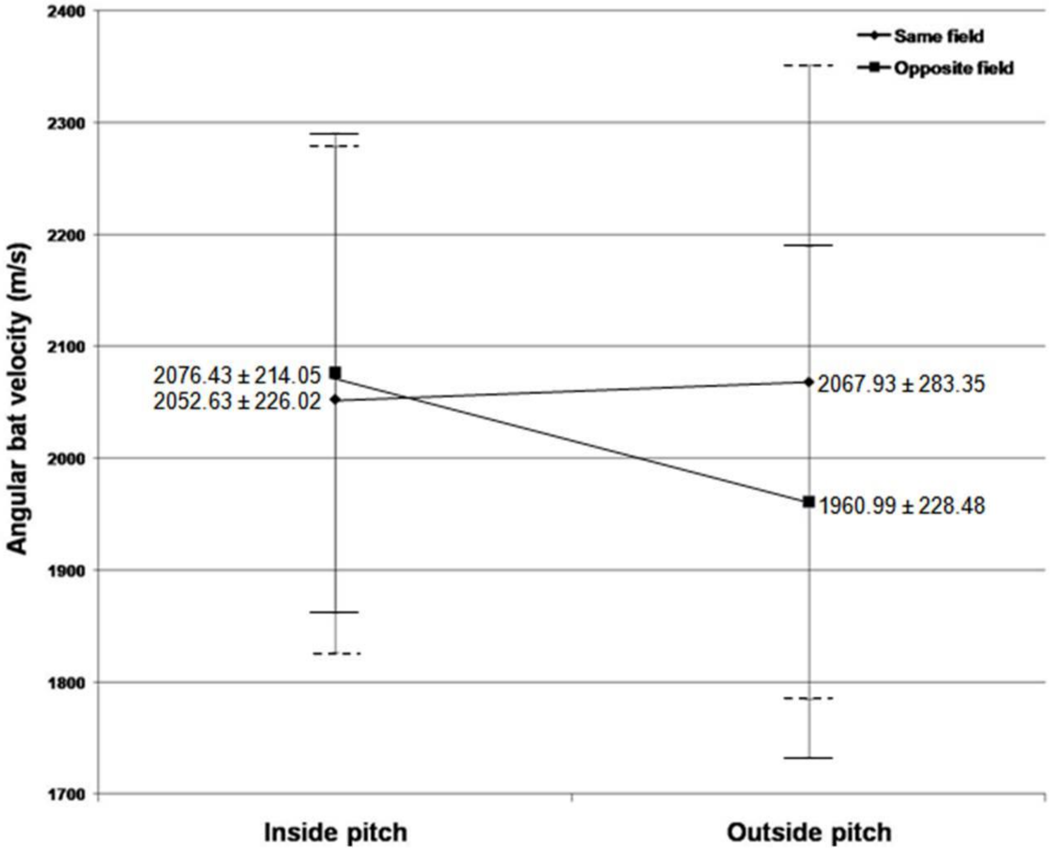

Figure 4.18 The mean and standard deviation (Mean ± SD) for the significant two-way interaction effect (2 fields x 2 location of pitches) for closed stride technique on angular bat velocity.

Statistical analyses were also conducted on body joint kinematic variables to better understand the skill of slo-pitch placement hitting movement mechanics. When participants used an open stride technique, they showed a significant difference in the lower body, trunk and upper body angles than using a closed stride technique, Table 4.6. The negative values of the lower body and trunk angles in the closed stride technique showed that the hips rotated more toward the ball than the left thigh segment, and the shoulders rotated more toward the ball than the hips. The open stride technique was also found to be significantly different from the parallel stride technique in the upper body angle, and this indicated that the elbows rotated more toward the ball than the shoulders.

No statistical significance was observed in the three-way interaction of lower body, trunk and upper body angles. Hence, the research hypotheses that the lower body, trunk and upper body rotational angles for placement hitting performance for striding toward the ball would be significantly less than for striding toward the pitcher and would also be significantly less than striding away from the ball were rejected in this study.

Table 4.6 Placement hitting body joint kinematic variables at ball contact

Body kinematics variables	**Open stride**	**Closed Stride**	***p***
Lower body angle (°)	2.85 ± 1.91	-6.40 ± 3.74	0.01*
Trunk (°)	2.03 ± 5.23	-8.06 ± 3.89	0.01*
Upper body angle (°)	-9.28 ± 2.34	6.67 ± 2.68	0.00*

* Statistical significant at $p < 0.02$

2nd analysis (Part B): individual performance VS group performance

A Euclidean distance analysis was conducted on the resultant linear bat velocity, resultant angular bat velocity, bat swing time, lower body rotational angle, trunk rotational angle and upper body rotational angle in each of 12 conditions, Appendix E. Figure 4.19 illustrates the participants who had the lowest and highest degrees of dissimilarity to the group mean.

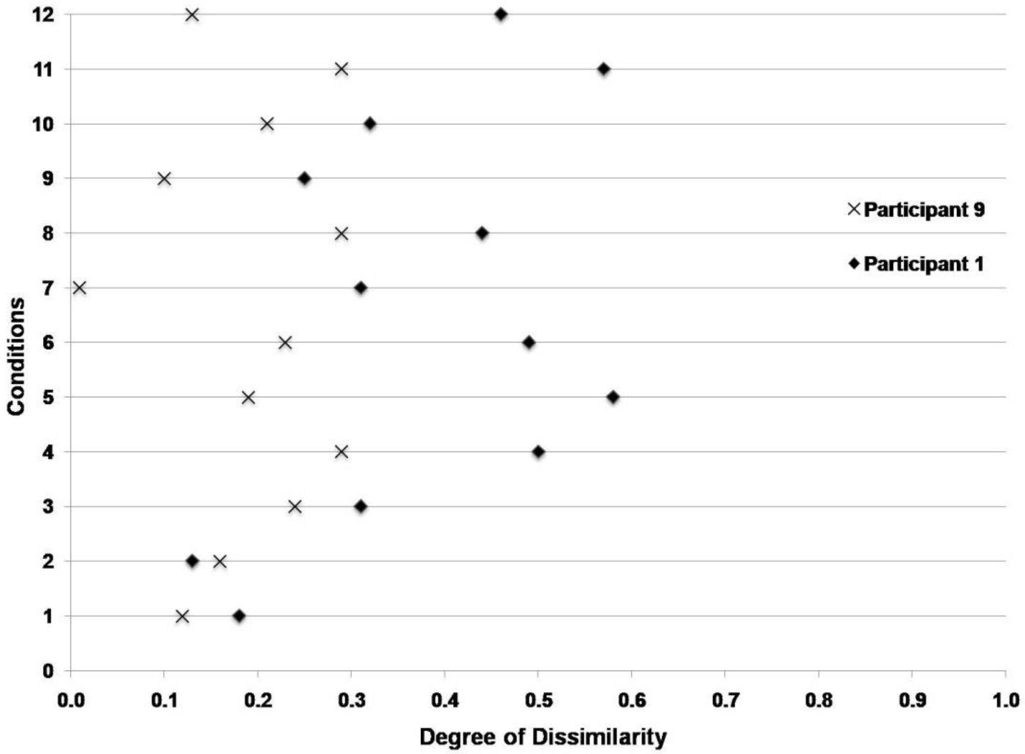

Figure 4.19 Participant #9 had the lowest degree of dissimilarity to the group mean, and participant #1 had the highest degree of dissimilarity to the group mean. (Participants were identified based on the averaged Rescaled Euclidean distance across the 12 conditions)

The results further indicated that across 12 different placement hitting conditions 40.8 % of participants showed a degree of dissimilarity between 0 and 0.20, and 34.2 % of participants showed a degree of dissimilarity between 0.21 and 0.40. Further, 23.3 % of participants showed a degree of dissimilarity between 0.41 and 0.60, and 1.7 % of participants showed a degree of dissimilarity between 0.61 and 0.80, Figure 4.20. Cumulatively, approximately 75 % of participants illustrated a degree of dissimilarity below 0.40, and 98 % of participants illustrated a degree of dissimilarity below 0.60 Hence, generally, participants showed their individual kinematic results were quite similar to the group mean kinematic results.

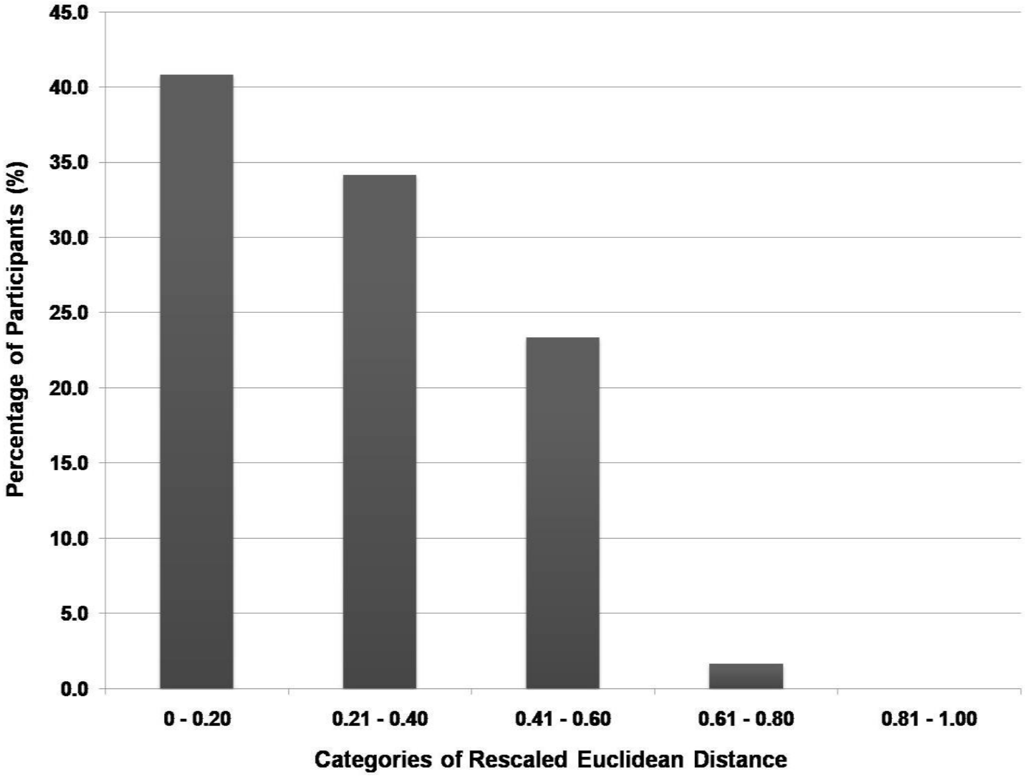

Figure 4.20 Percentage of participants across 12 different placement hitting conditions in each rescaled Euclidean distance category that was conducted on individual kinematic results versus group mean kinematic results.

3rd analysis (Part A): movement patterns analysis

A three-way ANOVA (2 fields x 2 locations of pitch x 3 strides) repeated measure study was conducted at $\alpha = 0.05$ on movement pattern coordination. From the results of 1st analysis on performance, it was revealed that in a couple of conditions (i.e. condition 8 and 12) there were only three participants whom were able to perform the successful trials, satisfying both task constraint requirements of correct stride technique and designated ball placement location. The objective of the study was guided by the rationale of ecological task analysis and to examine the influence of different constraints on the participants. Therefore, even though in some trials participants were only able to satisfy one task constraint, performing with a correct stride technique, and not the other task constraint, designated ball placement location, the findings would still provide important insights on the influence of constraint on human movement coordination. Hence, the average of the participant's trials that were performed with a correct stride and a fair ball with intended ball placement location in each condition was calculated and used for statistical analyses. The dependent variable was the combined percentage value for both SPC and RSPC measures for movement pattern coordination. No significant difference was found in both pairs of joints (lower body and trunk, and trunk and upper body) in the statistical analyses, Appendix F. Table 4.7 and Figure 4.21 illustrate that no significant difference was found in the combined % SPC and % RSPC of both lower body and trunk, and trunk and upper body joints between the same and opposite field conditions.

Table 4.7 Combined % SPC and % RSPC of movement pattern coordination

Movement pattern coordination	**Same field**	**Opposite field**	***p***
Lower body and trunk (%)	23.63 ± 7.78	31.60 ± 7.35	0.47
Trunk and upper body (%)	24.45 ± 5.48	41.07 ± 6.02	0.08

* Statistical significant at $p < 0.05$

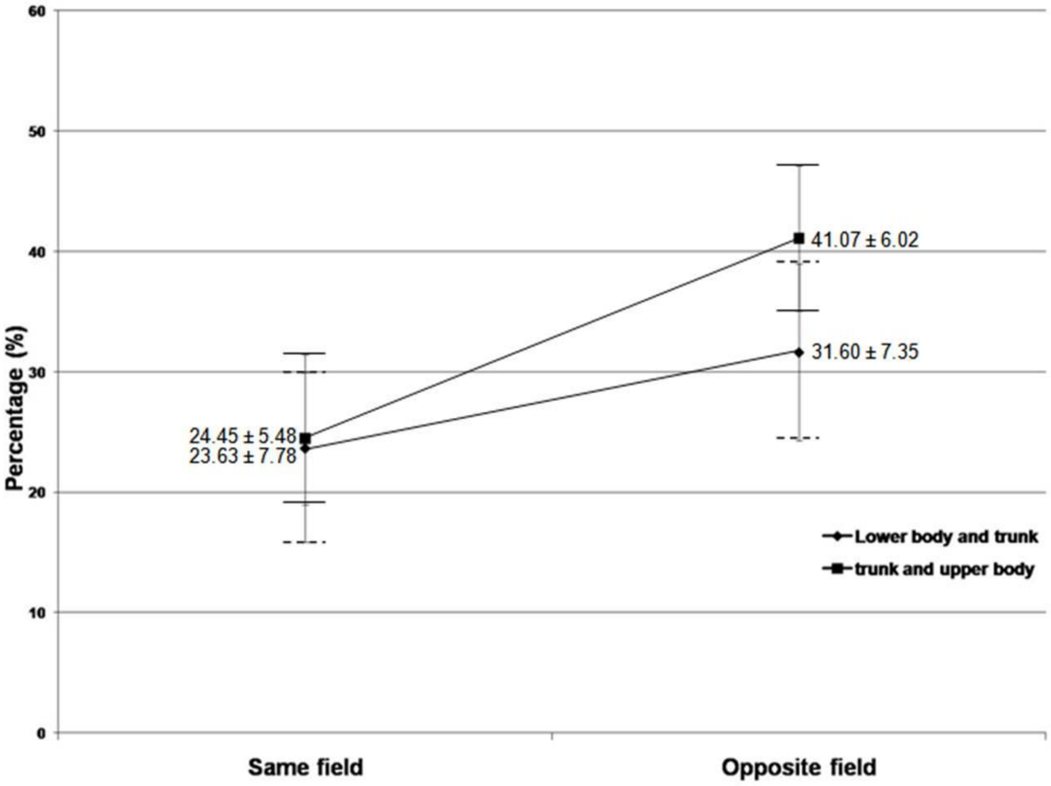

Figure 4.21 The mean and standard deviation (Mean ± SD) for the combined % SPC and % RSPC of both lower body and trunk, and trunk and upper body joints between the same and opposite field conditions.

Since no statistical significance was observed in the three-way interaction for the combined % SPC and % RSCP of both lower body and trunk, and trunk and upper body joints, the research hypotheses that the percentage of positive contribution of lower body and trunk, and trunk and upper body of the movement pattern coordination for striding toward the ball would be significantly less than for striding toward the pitcher and would also be significantly less than striding away from the ball were rejected in this study.

3rd analysis (Part B): individual performance VS group performance

A Euclidean distance analysis was conducted on combined percentages of SPC and RSPC for both lower body and trunk, and trunk and upper body joints in each of 12 conditions, Appendix G. Figure 4.22 illustrates the participants who had the lowest and highest degrees of dissimilarity to the group mean.

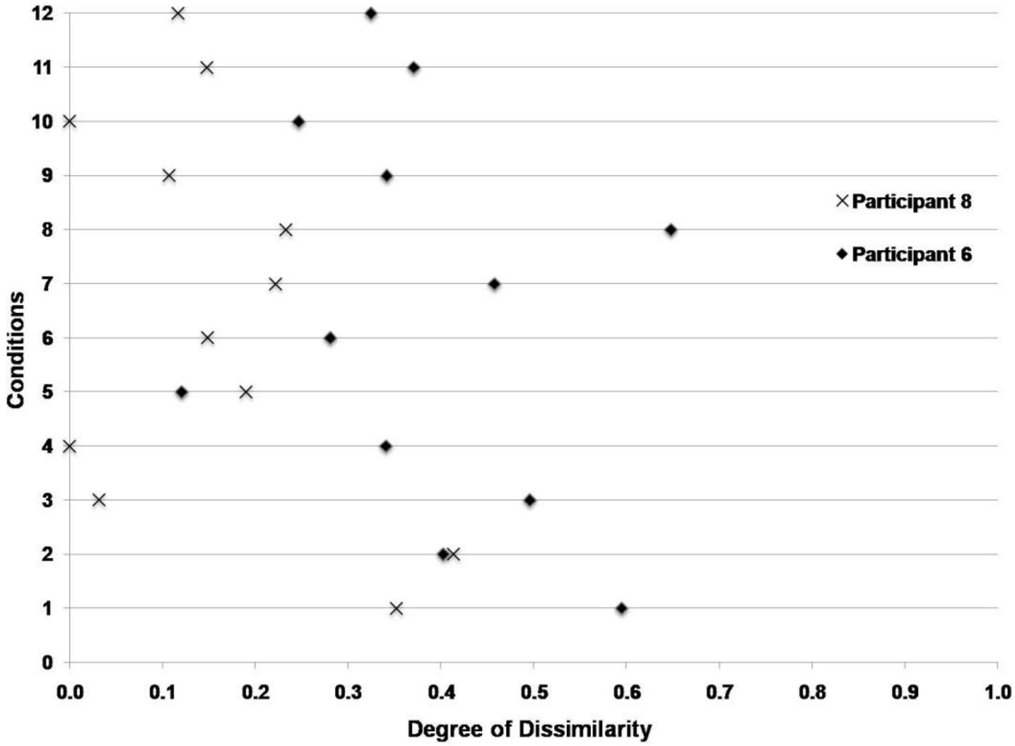

Figure 4.22 Participant #8 had the lowest degree of dissimilarity to the group mean, and participant #6 had the highest degree of dissimilarity to the group mean. (Participants were identified based on the averaged Rescaled Euclidean distance across the 12 conditions)

The results also indicated that across 12 different placement hitting conditions 34.2 % of participants showed a degree of dissimilarity between 0 and 0.20, and 35.0 % of participants showed a degree of dissimilarity between 0.21 and 0.40. Further, 28.0 % of participants showed a degree of dissimilarity between 0.41 and 0.60, and 2.8 % of participants showed a degree of dissimilarity between 0.61 and 0.80, Figure 4.23. Cumulatively, approximately 70 % of participants illustrated a degree of dissimilarity below 0.40, and 97 % of participants illustrated a degree of dissimilarity below 0.60. Therefore, participants generally showed that their individual combined percentages of SPC and RSPC results were quite similar to the group mean combined percentages of SPC and RSPC results.

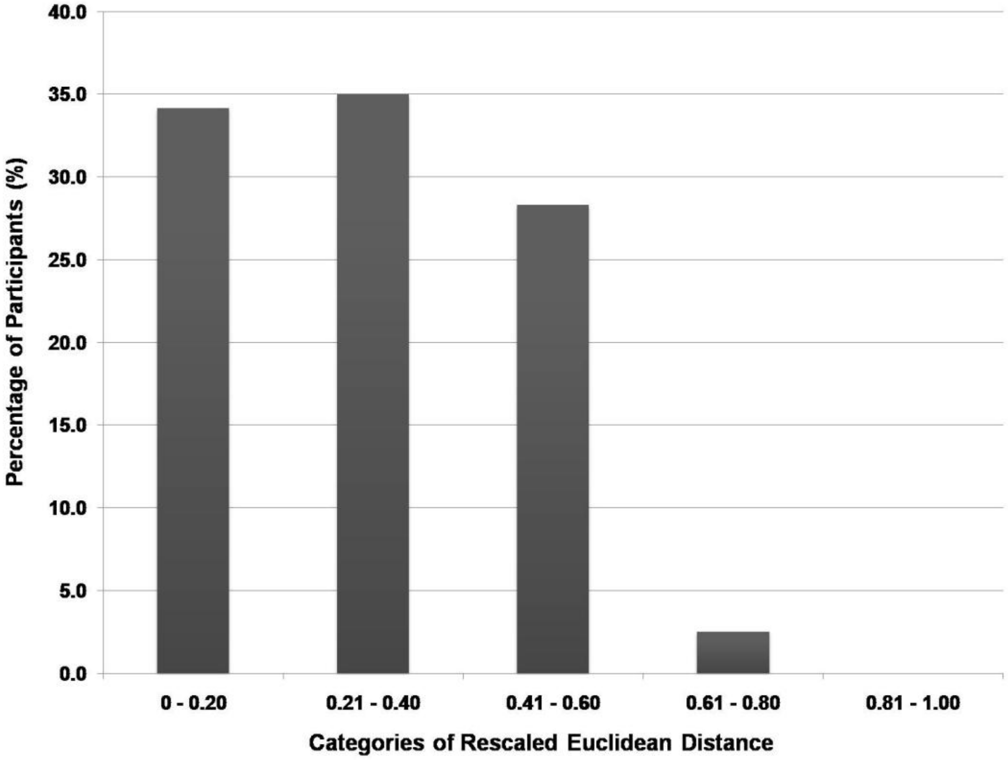

Figure 4.23 Percentage of participants across 12 different placement hitting conditions in each rescaled Euclidean distance category that was conducted on individual combined percentages of SPC and RSPC results versus group mean combined percentages of SPC and RSPC results.

Chapter 5: Discussion

Previous baseball and fast pitch softball research studies have provided a fundamental understanding on the mechanics of body motion and characteristics of bat swing (Gelinas, 1988; Hirano, 1987; Koike et al., 2003; LaBranche, 1994; McIntyre & Pfautsch, 1982; Messier & Owen, 1985; 1986; Race, 1961; Shapiro, 1974; 1979; Spragg & Noble, 1987; Welch et al., 1995). In baseball and fast pitch softball, the ball is pitched at a much higher velocity than slo-pitch, so the mechanics of hitting in baseball and fast pitch may be different from slo-pitch hitting. Due to the lack of empirical studies conducted on slo-pitch, the results of this study were compared to the previous studies on baseball and fast pitch in the hope of providing a more comprehensive understanding of the mechanics of slo-pitch hitting along with the similarities and differences between the three forms of hitting.

5.1 Slo-pitch Placement Hitting Performance

The research question of whether it was more advantageous for a slo-pitch batter to stride toward the ball than stride toward the pitcher or stride away from the ball was not supported in this research study. All slo-pitch players who participated in this study did not show a greater success rate in their batting performance by striding toward the ball. Also, the striding technique did not show any significant difference in the angular bat velocity. The striding technique only showed a significant difference in the linear bat velocity between the open and parallel stride techniques.

This indicated that the striding technique had a marginal influence on the linear motion of bat mechanics but not on the rotational motion of bat mechanics. When comparing the results of this study to the previous studies on fast pitch softball and baseball, the findings were similar. Messier (1982), Messier and Owen (1986) and LaBranche (1994) conducted research studies to examine three different striding techniques: open, closed and parallel. The authors found that there was no significant difference in the maximum linear bat velocity between the three stride techniques for fast pitch and baseball. Since the only significant finding from this study was found in the linear bat velocity variable between the open and parallel stride techniques, this study did not present overwhelming evidence to suggest that it was more advantageous for a slo-pitch batter to stride toward the ball than stride toward the pitcher or stride away from the ball.

Since all participants were right-handed batters, the participants did show a greater success rate (48.34 %) in hitting the ball to the same field (left field), and 49.42 % of the balls that were hit toward the same field successfully were ground balls. Moreover, the linear bat velocity was greater when the batter tried to place the ball to the same field. This is particularly more prominent when the batter used an open stride and hit inside pitched balls toward the same field instead of the opposite field. This may explain why many coaches believe that right handed batters are capable of hitting the ball farther and harder toward the same field (left field).

This study showed different findings from a previous baseball placement hitting study that was conducted by McIntyre and Pfautsch (1982). McIntyre and Pfautsch (1982) reported that the baseball players did not show any significant difference in the linear bat velocity between the same and opposite fields. The significant differences were found in bat swing time, angular bat velocity, and angular displacement of the bat between the same and opposite fields. The difference in findings between these two studies may be due to the difference in the nature of sport. This study examined the skill of slo-pitch placement hitting while the other study examined the skill of baseball placement hitting. In baseball the ball is pitched at a much higher velocity than in slo-pitch; the baseball batter does not have as much time to adjust their stride technique as in slo-pitch. Therefore, the striding technique may explain the observed difference between this study and McIntyre and Pfautsch (1982). In addition, McIntyre and Pfautsch (1982) conducted a 2D analysis with a single camera placed above the batter's head with the optical axis perpendicular to the ground. With this set-up the authors recorded the batter's bat motion under assumption the bat motion occurred mainly in a horizontal plane. This assumption might have influenced their findings since baseball hitting is not constrained to a horizontal plane but is three-dimensional in nature.

5.2 Mechanics of Slo-Pitch Placement Hitting

The mechanics analysis of slo-pitch placement hitting from this study showed similar findings to previous studies on fast pitch softball and baseball hitting. In this study the total bat swing time was found to be 0.57 ± 0.04 s, and this finding was the same as Welch, Banks, Cook, and Draovitch (1995)'s baseball bat swing time of 0.57 s and similar to Messier and Owen (1984)'s fast pitch softball bat swing time of 0.60 s. The maximum linear and angular bat velocities were reached 0.02 s prior to ball contact, and this finding was the same as that found by Spragg and Noble (1987)'s in their study on female fast pitch softball hitting and male baseball hitting. Messier and Own (1982) reported that the maximum linear bat velocity was reached at 0.026 s prior to ball contact and concluded that in a sporting skill in which a striking implement is used, the striking implement rarely reaches its maximum linear velocity at impact.

Kinematic results for the lower body, trunk and hip joint angles of this study showed slightly different results from the previous study. In this study at ball contact the mean lower body, trunk and upper body joint angles for the parallel stride were found to be at -1.04 ± 1.78 °, -0.39 ± 8.03 °, and 3.50 ± 5.94 °, respectively. The lower body (formed by left thigh and hips segments), trunk (formed by hips and shoulders segments) and upper body (formed by shoulders and arms segments) joints were closely aligned with each other in their respective segments when the batter was striking the ball. In Welch, Banks, Cook, and Draovitch

(1995)'s baseball swing study, their trunk and upper body joint angles for the parallel stride were -17.0 ° and 20.0 °, respectively. Their study indicated that the body segments of the trunk and upper body joints were not fully aligned with each other in their respective segments. The differences in the results between both studies may be explained by the differences in the task goal objectives and ball placement locations. In Welch, Banks, Cook, and Draovitch (1995)'s baseball swing study, participants hit balls with their maximum effort toward the neutral field (center field). However, in this study the participants hit balls with their maximum effort while in an attempt to place the ball either toward the same field (right field) or opposite field (left field). The task goal of this study was not simply on hitting power (maximum effort) alone but also on hitting accuracy (ball placement location, e.g. balls were hit toward either the same field or opposite field instead of neutral field). Hence, the differences in task goal objectives and ball placement locations between the two studies may have had an influence on the batting mechanics.

5.3 Movement Coordination Pattern

Coordination is one of the key concepts in the study of motor learning and development. Nicolas Bernstein (1967), a Russian physiologist, defined coordination as "the organization of control of the motor apparatus" (p. 127) and proposed the development of coordination as "the process of mastering redundant degrees of freedom of the moving organ, in other words, its conversion to a controllable system" (p. 127).

Bernstein (1967) viewed the development of coordination as a result of a learner being able to utilize various methods “in order to reduce the number of degrees of freedom at the periphery to a minimum” (pp. 107-108), and the degrees of freedom was defined as the number of mechanical movements that the learner can use to achieve the task objective (Newell & Vaillancourt, 2001). Then the learner gradually releases all restrictions on the degrees of freedom of the movement control. This process is known as shifting from “freezing” to “freeing” in the number of degrees of freedom in movement control. Finally the learner utilizes and exploits this movement control to execute the task successfully (Newell & Vaillancourt, 2001). However, Broderick and Newell (1999) found that the concepts on coordination as proposed by Bernstein (1967) were not entirely true. Broderick and Newell (1999) conducted a study to examine the learning effect of beginner’s coordination in the skill of basketball bouncing. Participants showed an increase in the number of degrees of freedom which resulted in a change in their coordination pattern, and this change of coordination pattern was mainly due to influence of the task constraint factor.

This present study was guided by Hudson (1986)’s shared positive contribution (SPC) technique to assess coordination patterns by examining the temporal sequencing of the movement. The shared positive contribution is based on the rationale that the proximal segment or joint initiates its movement before the distal segment or joint. However, this principle does not apply to all striking and throwing sport skills (Alexander & Haddow, 1982; Marshall & Elliot, 2000; Milburn, 1982; Van Gheluwe et al., 1987). Hence, this study has included the reversed shared positive contribution (RSPC), in which the distal segment or joint initiates its movement before the proximal segment or joint. Both shared positive contribution and reversed shared positive contribution show the degree to which two segments or joints move either simultaneously or sequentially. A SPC or a RSPC of 0% indicates a sequential type of movement coordination pattern, and a SPC or a RSPC of 100% indicates a simultaneous type of movement coordination pattern. The two body segments that are used for the assessment of the movement coordination pattern must first be identified as either the proximal segment or joint or the distal segment or joint. Welch, Banks, Cook, and Draovitch (1995) examined baseball hitting mechanics and indicated that baseball hitting was a closed kinetic chain movement starting when the stride foot was planted on the ground. The sequence of segmental or joint movements to execute a hitting skill starts with the stride foot contact followed by the hip rotation then the shoulder rotation (trunk rotation) concluding with the arm rotation (Bennett & Yeager, 2000; Hay, 1978; Pardee, 1980; Shapiro, 1974; Welch et al., 1995). Since the hitting skill is a closed kinetic chain movement, the sequence of body movement is from the lower body joints to the upper body joints. Hence, in this study the proximal joint was defined as the joint that was closer to the fixed point (i.e. ground) of the kinetic link system, and the distal joint was defined as the joint that was furthest away from the fixed point of the kinetic link system. From the results of this study the participants demonstrated two types of body joint movement. Some participants showed a proximal to distal type of joint movement either with a sequential or a simultaneous coordination pattern while other participants showed a distal to proximal type of joint movement also either with a sequential or a simultaneous coordination pattern. Therefore, participants showed both types of joint movements and both types of movement coordination pattern across 12 different conditions. The results showed that participants may use multiple movement coordination patterns to achieve the task goal successfully. Since all participants were skilled players and they did not have any practice in each condition before the testing, the individual participant's change in coordination pattern across 12 different conditions was the result of their skill adaptation due to the influence of both task and environmental constraints. Therefore, this study supports Broderick and Newell (1999)'s rationale that the participant's change in coordination pattern is influenced by various constraints in action.

Further inspection of the results revealed that some participants showed different joint movements and different coordination patterns among the three trials in each condition. Therefore, in order to determine what type of joint movement and what type of coordination pattern best represent the individual participant movement in each condition, the participant's type of joint movement and type of coordination pattern were determined based on the following criteria in each condition. 1) If there was only one successful trial in the condition, the type of joint movement and coordination pattern of this trial was used to represent the participant's movement in this condition; 2) If there were two successful trials in a condition and if the type of joint movement and coordination patterns were different between these two trials, the trial that showed a higher linear bat velocity was used to represent the participant's movement; 3) If there were three successful trials, the type of joint movement and coordination patterns that occurred in two or more successful trials was used to represent the participant's movement in this condition; and 4) if there were no successful trials, the type of joint movement and coordination patterns that occurred in two or more unsuccessful trials was used to represent the participant's movement in this condition. The results revealed that a total of 73.3 % of participants showed either a SPC or a RSPC value of less than 50 %, a predominant sequential coordination pattern, between the lower body and trunk joints across all 12 conditions. There were 35.8 % of participants who showed a proximal to distal type of joint movement (SPC), and 37.5 % of participants who showed a distal to proximal type of joint movement (RSPC), Table 5.1. For the trunk and upper body coordination pattern, similar results were observed. A total of 68.4 % of participants showed either a SPC or a RSPC value of less than 50 %, also a predominant sequential coordination pattern. There were 34.2 % of participants who showed a proximal to distal type of joint movement (SPC), and also 34.2 % of participants who showed a distal to proximal type of joint movement (RSPC), Table 5.2.

Table 5.1 The breakdown of percentage of number of participants for lower body and trunk joints on both SPC and RSPC movement patterns across 12 placement hitting conditions

Conditions	**SPC**			**RSPC**		
	< 50 % (Seq.)	**≥ 50 % (Sim.)**	**Total**	**< 50 % (Seq.)**	**≥ 50 % (Sim.)**	**Total**
1	40.0	0.0	40.0	50.0	10.0	60.0
2	60.0	0.0	60.0	20.0	20.0	40.0
3	30.0	10.0	40.0	50.0	10.0	60.0
4	30.0	0.0	30.0	60.0	10.0	70.0
5	10.0	10.0	20.0	60.0	20.0	80.0
6	20.0	10.0	30.0	30.0	40.0	70.0
7	50.0	10.0	60.0	20.0	20.0	40.0
8	30.0	20.0	50.0	40.0	10.0	50.0
9	40.0	30.0	70.0	20.0	10.0	30.0
10	40.0	20.0	60.0	30.0	10.0	40.0
11	60.0	10.0	70.0	20.0	10.0	30.0
12	20.0	30.0	50.0	50.0	0.0	50.0
Mean	35.8	12.5	48.3	37.5	14.2	51.7

Table 5.2 The breakdown of percentage of number of participants for trunk and upper body joints on both SPC and RSPC movement patterns across 12 placement hitting conditions

Conditions	**SPC**			**RSPC**		
	< 50 % (Seq.)	**≥ 50 % (Sim.)**	**Total**	**< 50 % (Seq.)**	**≥ 50 % (Sim.)**	**Total**
1	60.0	10.0	70.0	30.0	0.0	30.0
2	20.0	20.0	40.0	50.0	10.0	60.0
3	60.0	0.0	60.0	20.0	20.0	40.0
4	40.0	10.0	50.0	50.0	0.0	50.0
5	20.0	20.0	40.0	30.0	30.0	60.0
6	30.0	20.0	50.0	40.0	10.0	50.0
7	20.0	10.0	30.0	40.0	30.0	70.0
8	30.0	10.0	40.0	30.0	30.0	60.0
9	10.0	20.0	30.0	50.0	20.0	70.0
10	50.0	10.0	60.0	20.0	20.0	40.0
11	40.0	10.0	50.0	10.0	40.0	50.0
12	30.0	20.0	50.0	40.0	10.0	50.0
Mean	34.2	13.3	47.5	34.2	18.3	52.5

This study suggests that the skill of slo-pitch placement hitting is a unique batting skill. In the mechanics of placement hitting, the bat speed is generated by the initiation of body movement from the rotation of lower body joint and then followed by the rotational movement of trunk and upper body joints. Since the bat speed is one of the critical factors in determining the success of placement hitting, a predominant sequential type of coordination pattern was observed. This corresponds to the coordination continuum that when a task objective is on speed, a sequential type of coordination pattern is observed (Hudson, 1986; Kreighbaum & Barthels, 1996). Another critical factor in determining the success of placement hitting is the accuracy of ball placement location. In this study a total of 26.7 %, for lower body and trunk, and 31.6 %, for trunk and upper body, of participants showed a simultaneous type of coordination pattern. This also corresponds to the coordination continuum when a task objective is on accuracy, a simultaneous type of coordination pattern is suggested (Hudson, 1986; Kreighbaum & Barthels, 1996). Even though the number of participants who showed a simultaneous type of coordination pattern is not as high as the number of participants who showed a sequential type of coordination, nevertheless, these participants were still able to accomplish the task goal successfully. This study suggests that since the skill of placement hitting has a concurrent task goal of both bat velocity and accuracy of ball placement location, participants were able to achieve the task goal either with a sequential or a simultaneous type of coordination pattern. Hence, the objective of the task goal has an influence on the human coordination pattern.

As for the type of joint movement between the lower body and trunk, approximately 48.3 % of participants showed a proximal to distal type of joint movement, and approximately 51.7 % of participants showed a distal to proximal type joint movement. Similar findings were observed between the trunk and upper body. Approximately 47.5 % of participants showed a proximal to distal type of joint movement, and approximately 52.5 % of participants showed a distal to proximal type joint movement. This indicated that participants were able to use either type of joint movement to perform the skill of placement hitting successfully. The results from this study suggest that participants can use multiple movement solutions to achieve the same task goal. Participants can use either a sequential or a simultaneous type of coordination pattern, and these types of coordination pattern can be performed with a proximal to distal type of joint sequencing or a distal to proximal type of joint sequencing.

5.4 Ecological Task Analysis

Newell (1986) proposed three categories of constraints (organismic, environmental and task) that interact closely with each other and have an influence on the development of coordination and control. Davis and Burton (1991) developed ecological task analysis based on the approach taken by Newell (1986). Ecological task analysis (ETA) examines a movement skill performance outcome by evaluating the influence of task, performer and environment constraints collectively (David & Broadhead, 2007; Davis & Burton, 1991). In this study the performer constraint was the participant's skill level, and this constraint was not evaluated in the study. Task constraints were the designated field location of ball placement and stride technique, and the environmental constraint was the pitched ball location. These constraints were evaluated to examine their influence on the skill of placement hitting. Participants were asked to use a specific stride and placed the ball to a designated field location. The kinematics findings from this study showed that the lower body, trunk and upper body angles were significantly different between the open and closed stride technique. Hence, the body mechanics of using an open stride technique was quite different from using a closed stride technique, and these two techniques could be recognized as the two extremes of batting stride techniques. However, the results of the study showed that there was no significant difference on the success rate of placement hitting and coordination pattern between different stride techniques. In addition, pairwise comparisons conducted on linear and angular bat velocities showed no significant difference between striding toward the ball and striding toward the pitcher or striding away from the ball. Therefore, the results of this study support the principle of ecological task analysis that there may be multiple movement solutions to achieve a task goal. Participants are equally successful in using all three different stride techniques in the skill of placement hitting. They may accomplish their task goal using either a proximal to distal or a distal to proximal type of body joint movement pattern and either with a sequential or a simultaneous type of coordination pattern. This finding may be due to the confluence of task and environmental constraints which allow the participants to explore whichever type of joint movement and type of coordination pattern that is best suited for them to achieve the task objective successfully. The differences in participants' joint movement and coordination pattern should not simply be explained by the learning effect or skill level. Hence, the traditional task analysis that only one best movement solution should be used to instruct all participants the same way is not supported by the results of this study. This study encourages participants to explore their own movement solutions to achieve their task goal.

5.5 Generalizability of the Study

Bouffard (1993) discussed the perils of averaging data and argued that patterns or results found by aggregating data might not necessarily apply to all individuals in a group. Individuals in a group must react similarly to the same treatment (homogeneity of the group) so that inferences from aggregate data to universal type propositions can be made. In this study a Euclidean distance analysis was conducted on participants' outcome variables (performance, kinematics and movement coordination) to exam whether participants had reacted similarly to the same treatment. The results of the study showed that participants generally reacted similarly to the same treatment. The degree of dissimilarity between the individual result and group mean result was low. Approximately 70 % of participants showed a degree of dissimilarity less than or equal to 0.40 in both performance outcomes and movement coordination patterns. This was slightly more prominent in the kinematic variables which approximately 75 % of participants showed a degree of dissimilarity less than or equal to 0.40. The results indicated that the individual participant's results were quite similar to the group mean results. In another word, participants showed similar results between each other; hence, the participants were quite homogeneous in this study. Therefore, based on the knowledge about the degree of generalizability coaches and researchers may apply the findings from this study to other similar players accordingly.

5.6 Considerations of the Study

This study is guided by Hudson (1986)'s percentage of shared positive contribution (% SPC) in assessing coordination pattern. Hudson (1986) only discussed % SPC but not percentage reversed shared positive contribution (% RSPC) in her vertical jump study. Bird, Hills and Hudson (1991) conducted a badminton deep serve study between four novice and one advanced players. The authors found that the advanced player used a proximal to distal type of joint movement with a sequential type of coordination pattern, and the novice players showed both proximal to distal and distal to proximal joint movements with both sequential and simultaneous coordination patterns. Therefore, the authors concluded that the choice of joint movement and coordination pattern may dependent on player's talents. However, it may be difficult to generalize their findings to other players from such a small sample size. In this study a Euclidean distance was conducted on participants' outcome variables to exam whether participants had reacted similarly to the same treatment. The results indicated that the participants were quite homogeneous, so the influence of different individual skill levels was minimal in this study.

From the evidence provided by this study, the body segmental or joint movement is not necessary confined to always being initiated by the proximal segment movement and followed by the distal segment movement. There are other striking and throwing sport skills in which players show a distal segment initiation followed by a proximal segment movement. For example, Milburn (1982) showed that the wrist angle starts to increase well before the leading arm reaches its maximum angular velocity during the downswing of a golf drive. Alexander and Haddow (1982) showed a proximal to distal type of joint movement with a sequential coordination pattern between the upper arm and lower arm segments but not the lower arm and hand segments in windmill pitching. Van Gheluwe et al. (1987) found that the shoulder internal rotation increases sharply when the forearm pronation decreases in a tennis serve. Marshall and Elliot (2000) provided further evidence to show that in the longitudinal axis of the arm in a tennis serve, the pronation of the forearm occurs before or simultaneous with the internal rotation of the shoulder. It is evident that the traditional concept of a proximal to distal type of joint movement with a sequential coordination pattern as proposed by Bunn (1972) and Kreighbaum and Barthels (1996) cannot simply be used to generalize to all striking and throwing actions without considering the confluence of task and environmental constraints.

During the data analysis an unexpected limitation related to % SPC and % RSPC was found. This was due to the mathematical representation of movement coordination patterns provided by equations (21) and (22). There can be instances when % SPC or % RSPC can be a negative value that is less than 0 % or a positive value that is greater than 100 %. Also, it is possible that % SPC or % RSPC is undefined when the denominator equals zero. In this study data were collected at 240 Hz and multiple trials were collected for each participant under each condition. There were only a few trials that % SPC or % RSPC was undefined when the denominator was zero; therefore, the impact to the results of this study was minimal. The findings from using % SPC and % RSPC measurement technique to assess coordination in this study warrants further investigation on coordination pattern under different constraints in varies sports skills are required in order to better understand the mechanics of human movement coordination.

Chapter 6: Conclusion

This study used 10 elite slo-pitch batters to examine the influence of task and environmental constraints on performance outcomes, kinematics and movement coordination patterns. The results showed that participants were more successful in placing the ball to the same field instead of placing the ball to the opposite field. The pitched ball location and stride techniques did not have an influence on the performance outcomes. Therefore, the research question if striding toward the ball in placement hitting was more advantageous is not supported by the results of this study. The results of this study recommend players explore different stride techniques. The selected stride technique may simply be based on what they are most familiar with to hit the ball. Since the movement coordination pattern did not show any significant difference across 12 conditions, players may use different coordination patterns to place the ball to the desired field location as long as they are able to keep their lower body (formed by left thigh and hips segments), trunk (formed by hips and shoulders segments) and upper body (formed by shoulders and elbows segments) joints closely align with each other in their respective segments at ball contact.

In terms of generalizability of the study, the majority of participants showed a degree of dissimilarity that is less than or equal to 0.40 when comparing their individual result to the group mean result. This study indicated that the participants from this study were quite similar to each other and homogeneous as a group. Therefore, participants generally showed a strong similar response to the treatment and as such, base on the knowledge about the degree of generalizability coaches and researchers may utilize the findings from this study to other players.

This study supports the ecological task analysis that the players should explore different movement solutions to achieve their goal. The traditional task analysis of only one best possible movement solutions is not observed in this study. This study is another example in the area of sports biomechanics that is able to provide evidence to support the principle of ecological task analysis. These elite slo-pitch participants were able to adapt their movement coordination under different constraint conditions within a relatively short period of time. In some constraint conditions, participants had minimal previous experience but still managed to perform at a level comparable to their performance in the other more familiar constraint conditions. This study indicated that these elite slo-pitch participants had a strong adaptability to different task and environmental constraints. Studying the influence of task and environmental constraints to evaluate a sport skill in the area of sport biomechanics is practical and critical. It allows the researchers to improve the validity of the study and also to be able to obtain a more comprehensive understanding on the mechanics of human movements. This study used an interdisciplinary approach that utilizes the principles from motor learning and biomechanics to study the mechanics of human motion. It is anticipated that this unique interdisciplinary approach will have a profound application to future research studies.

From the findings of this study, several important research questions have been developed that need to be addressed in future studies. This study has clearly demonstrated there are two types of joint movement (proximal to distal vs distal to proximal) and two types of movement coordination pattern (sequential vs simultaneous). In order to evaluate the type of joint movement and type of movement coordination pattern specifically in a future study, both the number of trials per condition (i.e. 5 trials/condition) and the number of participants (i.e. 20 participants) need to be increased from the current study. Also, the current study focused on the mechanics of lower body and trunk and the trunk and upper body only. The bat segment (wrist and bat) movement was not evaluated in the study. However, in slo-pitch hitting the bat segment is the last segment of the whole kinetic chain and produces the end point velocity of the system. Therefore, in a future study the bat segment may be included in the examining of the movement coordination sequence. Current and previous research studies have evaluated movement coordination by paring up two intra- or inter- segments or joints together. However, the kinetic chain of the system usually involves two or more body segments or joints in performing a striking or throwing skill (i.e. lower body, trunk, upper body and wrist joints), therefore future research related to ETA in conjunction with movement coordination analysis needs to extend the current research to include all participating segments collectively in their evaluation.

Additionally, it will also be important to evaluate whether similar results can be seen in the beginner slo-pitch player or in different sporting skills under principles of ecological task analysis. Furthermore, since the participants from this study have had a chance to experience different placement hitting conditions, a follow up research study can be conducted to examine the learning effect of their slo-pitch performance in using placement hitting technique modification.

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Appendix A: Participant Data Sheet

PARTICIPANT DATA SHEET
Sports Biomechanics Laboratory
Faculty of Physical Education and Recreation
University of Alberta

Title: Slo-pitch Placement Hitting Movement Analysis

Name: Date:

Age: Team:

Level: Years of
Experience:

Height: Weight:

Trial Conditions	Successful	Unsuccessful	Fly Ball	Ground Ball	Pop Fly	Max. Contact	Field (S,N, O)
F1P1S1T1							
F1P1S1T2							
F1P1S1T3							
F1P1S2T1							
F1P1S2T2							
F1P1S2T3							
F1P1S3T1							
F1P1S3T2							
F1P1S3T3							
F1P2S1T1							
F1P2S1T2							
F1P2S1T3							
F1P2S2T1							
F1P2S2T2							
F1P2S2T3							
F1P2S3T1							
F1P2S3T2							
F1P2S3T3							
F2P1S1T1							
F2P1S1T2							
F2P1S1T3							
F2P1S2T1							
F2P1S2T2							
F2P1S2T3							
F2P1S3T1							
F2P1S3T2							
F2P1S3T3							
F2P2S1T1							
F2P2S1T2							

F2P2S1T3							
F2P2S2T1							
F2P2S2T2							
F2P2S2T3							
F2P2S3T1							
F2P2S3T2							
F2P2S3T3							
Total							

F1 = Same field (Left field), F2 = Opposite field (Same field)
P1 = Inside pitch, P2 = Outside pitch
S1 = Open stride, S2 = Parallel stride, S3 = Closed stride
T1 = Trial #1, T2 = Trial #2, T3 = Trial #3

*Fly Ball: A batted ball that lands beyond the bases.
*Ground Ball: A batted ball that is lower than the participant's height and lands
before the bases.
*Pop Fly: A batted ball that is higher than the participant's height and lands
before the bases.

*Field (S = Same, N = Neutral, O = Opposite)

Appendix B: Statistical Analysis on Performance Outcomes

% Success Rate

Participants' performance on success rate in each placement hitting condition

Conditions	Mean (%)	SD (%)	Conditions	Mean (%)	SD (%)
1	29.99	39.90	**7**	16.65	17.55
2	53.33	32.22	**8**	16.67	28.34
3	60.01	30.64	**9**	29.99	24.60
4	43.34	35.32	**10**	19.99	23.31
5	56.67	22.52	**11**	40.00	34.44
6	46.67	23.33	**12**	13.33	23.31

Tests of within-subjects effects on success rate

Effects (Huynh-Feldt)	Mean Square	df	F	*p*	Eta Squared	Observed Power
Field	19604.52	1.00	49.60	0.00*	0.85	1.00
Error	395.26	9.00				
Pitch	148.74	1.00	0.20	0.66	0.02	0.07
Error	745.86	9.00				
Stride	2122.99	2.00	2.10	0.15	0.19	0.37
Error	1009.87	18.00				
Field x Pitch	36.96	1.00	0.03	0.87	0.00	0.05
Error	1251.74	9.00				
Field x Stride	453.66	2.00	0.55	0.59	0.06	0.13
Error	824.553	18.00				
Pitch x Stride	2287.94	2.00	2.91	0.08	0.25	0.50
Error	785.02	18.00				
Field x Pitch x Stride	620.05	2.00	1.03	0.38	0.38	0.20
Error	600.03	18.00				

*Statistical significant at $p < 0.05$

% Fly Ball

Participants' performance on fly ball in each placement hitting condition

Conditions	Mean (%)	SD (%)	Conditions	Mean (%)	SD (%)
1	13.33	23.31	**7**	16.67	17.57
2	33.33	31.43	**8**	10.00	22.50
3	23.33	31.62	**9**	26.67	21.09
4	13.33	23.31	**10**	16.67	17.57
5	26.67	30.63	**11**	33.33	31.43
6	20.00	23.31	**12**	13.33	23.31

Tests of within-subjects effects on fly ball

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	148.16	1.00	0.22	0.65	0.02	0.07
Error	662.53	9.00				
Pitch	0.00	1.00	0.00	1.00	0.00	0.05
Error	267.52	9.00				
Stride	1176.12	2.00	1.30	0.30	0.13	0.24
Error	908.44	18.00				
Field x Pitch	333.47	1.00	0.52	0.49	0.06	0.10
Error	642.02	9.00				
Field x Stride	431.93	1.59	0.47	0.59	0.05	0.11
Error	925.17	14.27				
Pitch x Stride	694.31	2.00	1.17	0.33	0.12	0.23
Error	591.57	18.00				
Field x Pitch x Stride	1083.47	2.00	2.06	0.16	0.19	0.37
Error	527.78	18.00				

*Statistical significant at $p < 0.05$

% Ground Ball

Participants' performance on ground ball in each placement hitting condition

Conditions	**Mean (%)**	**SD (%)**	**Conditions**	**Mean (%)**	**SD (%)**
1	16.67	23.57	**7**	0.00	0.00
2	20.00	17.21	**8**	3.33	10.54
3	33.33	27.22	**9**	0.00	0.00
4	30.00	24.60	**10**	3.33	10.54
5	20.00	17.21	**11**	6.67	14.05
6	23.33	27.44	**12**	0.00	0.00

Tests of within-subjects effects on ground ball

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	14082.25	1.00	37.09	0.00*	0.81	1.00
Error	379.65	9.00				
Pitch	83.32	1.00	0.67	0.43	0.07	0.11
Error	124.49	9.00				
Stride	37.07	2.00	0.11	0.90	0.01	0.06
Error	345.68	18.00				
Field x Pitch	9.26	1.00	0.05	0.82	0.01	0.06
Error	173.85	9.00				
Field x Stride	444.52	2.00	1.72	0.21	0.16	0.31
Error	259.27	18.00				
Pitch x Stride	444.42	2.00	1.86	0.18	0.17	0.34
Error	238.67	18.00				
Field x Pitch x Stride	261.10	1.99	0.86	0.44	0.09	0.17
Error	302.53	17.87				

*Statistical significant at $p < 0.05$

% Pop Fly

Participants’ performance on pop fly in each placement hitting condition

Conditions	**Mean (%)**	**SD (%)**	**Conditions**	**Mean (%)**	**SD (%)**
1	0.00	0.00	**7**	0.00	0.00
2	0.00	0.00	**8**	3.33	10.53
3	3.33	10.53	**9**	3.33	10.53
4	0.00	0.00	**10**	0.00	0.00
5	10.00	22.50	**11**	0.00	0.00
6	3.33	10.53	**12**	0.00	0.00

Tests of within-subjects effects on pop fly

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	83.33	1.00	1.33	0.28	0.13	0.18
Error	62.74	9.00				
Pitch	9.30	1.00	0.13	0.73	0.01	0.06
Error	70.97	9.00				
Stride	158.44	1.52	1.21	0.32	0.12	0.20
Error	131.34	13.67				
Field x Pitch	231.30	1.00	2.65	0.14	0.23	0.31
Error	87.37	9.00				
Field x Stride	43.36	1.23	0.41	0.59	0.04	0.09
Error	107.46	11.54				
Pitch x Stride	97.53	1.33	1.00	0.36	0.10	0.16
Error	97.48	11.96				
Field x Pitch x Stride	136.62	1.76	1.21	0.32	0.12	0.22
Error	113.20	15.85				

*Statistical significant at $p < 0.05$

Appendix C: Statistical Analysis of Individual VS Group on Performance Outcomes

The rescaled Euclidean distance (0 to 1) on the percentages of success rate, fly ball, ground ball and pop fly in each condition (#1- #6) between individual participant results versus group mean results

Participant\Condition	1	2	3	4	5	6
1	0.21	0.39	0.37	0.16	0.36	0.52
2	0.26	0.46	0.37	0.42	0.28	0.31
3	0.71	0.46	0.43	0.38	0.28	0.56
4	0.29	0.39	0.24	0.16	0.43	0.52
5	0.21	0.37	0.53	0.63	0.67	0.27
6	0.73	0.39	0.10	0.38	0.36	0.31
7	0.29	0.46	0.10	0.23	0.69	0.27
8	0.29	0.46	0.61	0.42	0.28	0.27
9	0.29	0.55	0.65	0.23	0.39	0.56
10	0.29	0.24	0.38	0.59	0.43	0.69
Mean	0.36	0.42	0.38	0.36	0.42	0.43
SD	0.19	0.08	0.19	0.17	0.15	0.16

The rescaled Euclidean distance (0 to 1) on the percentages of success rate, fly ball, ground ball and pop fly in each condition (#7- #12) between individual participant results versus group mean results

Participant\Condition	7	8	9	10	11	12
1	0.15	0.66	0.10	0.32	0.55	0.20
2	0.35	0.86	0.55	0.34	0.12	0.30
3	0.35	0.26	0.41	0.72	0.35	0.20
4	0.15	0.19	0.41	0.32	0.39	0.20
5	0.35	0.19	0.10	0.34	0.35	0.20
6	0.15	0.19	0.10	0.32	0.65	0.20
7	0.15	0.19	0.10	0.34	0.35	0.80
8	0.15	0.19	0.41	0.34	0.39	0.30
9	0.35	0.19	0.10	0.32	0.12	0.20
10	0.65	0.19	0.71	0.34	0.39	0.20
Mean	0.28	0.31	0.30	0.37	0.37	0.28
SD	0.16	0.24	0.23	0.12	0.16	0.19

Appendix D: Statistical Analysis on Kinematic Variables

Linear Bat Velocity

Participants' performance on linear bat velocity in each placement hitting condition

Conditions	Mean (m/s)	SD (m/s)	Conditions	Mean (m/s)	SD (m/s)
1	31.67	2.40	**7**	28.04	1.56
2	31.71	2.37	**8**	30.70	2.33
3	31.10	2.44	**9**	30.46	2.56
4	30.53	2.92	**10**	28.93	1.63
5	32.21	1.32	**11**	29.95	1.47
6	31.58	3.09	**12**	29.62	2.84

Three-way overall (2 x 2 x 3) tests of within-subjects effects on linear bat velocity

Effects (Huynh-Feldt)	Mean Square	df	F	*p*	Eta Squared	Observed Power
Field	102.97	1.00	17.24	0.00*	0.66	0.96
Error	5.98	9.00				
Pitch	0.65	1.00	0.30	0.60	0.03	0.08
Error	2.16	9.00				
Stride	20.95	1.78	4.26	0.04*	0.32	0.63
Error	4.92	16.01				
Field x Pitch	0.24	1.00	0.12	0.74	0.01	0.06
Error	1.98	9.00				
Field x Stride	6.57	1.47	1.64	0.23	0.15	0.25
Error	4.00	13.19				
Pitch x Stride	0.06	2.00	0.00	1.00	0.00	0.05
Error	2.13	18.00				
Field x Pitch x Stride	9.32	2.00	11.86	0.00*	0.57	0.99
Error	0.79	18.00				

*Statistical significant at $p < 0.05$

Pairwise comparisons of different strides on linear bat velocity

Strides	Mean (SD) (m/s)	*p*
Open vs	29.80 (0.51)	0.01*
Parallel	31.14 (0.50)	
Open vs	29.80 (0.51)	0.38
Closed	30.69 (0.75)	
Parallel vs	31.14 (0.50)	1.00
Closed	30.69 (0.75)	

*Statistical significant at $p < 0.02$

Three-way limited (2 x 2 x 2) tests of within-subjects effects on linear bat velocity between open and parallel strides

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	90.93	1.00	23.52	0.00*	0.72	0.99
Error	3.87	9.00				
Pitch	0.36	1.00	0.22	0.65	0.02	0.07
Error	1.62	9.00				
Stride	35.98	1.00	18.48	0.00*	0.67	0.97
Error	1.95	9.00				
Field x Pitch	0.79	1.00	0.44	0.52	0.05	0.09
Error	1.78	9.00				
Field x Stride	4.94	1.00	1.43	0.26	0.14	0.19
Error	3.46	9.00				
Pitch x Stride	0.00	1.00	0.00	0.99	0.00	0.05
Error	2.54	9.00				
Field x Pitch x Stride	13.65	1.00	19.18	0.00*	0.00	0.97
Error	0.71	9.00				

*Statistical significant at $p < 0.05$

Three-way limited (2 x 2 x 2) tests of within-subjects effects on linear bat velocity between open and closed strides

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	76.93	1.00	12.95	0.01*	0.59	0.89
Error	5.94	9.00				
Pitch	0.49	1.00	0.19	0.67	0.02	0.07
Error	2.54	9.00				
Stride	15.83	1.00	2.85	0.13	0.24	0.33
Error	5.55	9.00				
Field x Pitch	0.64	1.00	0.36	0.57	0.04	0.08
Error	1.80	9.00				
Field x Stride	8.92	1.00	2.02	0.19	0.18	0.25
Error	4.42	9.00				
Pitch x Stride	0.01	1.00	0.00	0.95	0.00	0.05
Error	1.41	9.00				
Field x Pitch x Stride	14.31	1.00	17.97	0.00*	0.67	0.96
Error	0.80	9.00				

*Statistical significant at $p < 0.05$

Three-way limited (2 x 2 x 2) tests of within-subjects effects on linear bat velocity between parallel and closed strides

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	42.90	1.00	8.46	0.02*	0.49	0.74
Error	5.07	9.00				
Pitch	0.46	1.00	0.20	0.67	0.02	0.07
Error	2.29	9.00				
Stride	4.08	1.00	0.73	0.42	0.08	0.12
Error	5.63	9.00				
Field x Pitch	8.37	1.00	7.27	0.03*	0.45	0.67
Error	1.15	9.00				
Field x Stride	0.59	1.00	0.64	0.44	0.07	0.11
Error	0.91	9.00				
Pitch x Stride	0.01	1.00	0.00	0.95	0.00	0.05
Error	0.25	9.00				
Field x Pitch x Stride	0.01	1.00	0.01	0.93	0.00	0.05
Error	0.85	9.00				

*Statistical significant at $p < 0.05$

Two-way tests (2 x 2) of within-subjects effects on linear bat velocity for the open stride technique

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	69.12	1.00	11.81	0.01*	0.57	0.86
Error	5.85	9.00				
Pitch	0.19	1.00	0.12	0.74	0.01	0.06
Error	1.68	9.00				
Field x Pitch	10.51	1.00	6.80	0.03*	0.43	0.64
Error	1.54	9.00				

*Statistical significant at $p < 0.05$

Two-way tests (2 x 2) of within-subjects effects on linear bat velocity for the parallel stride technique

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	26.75	1.00	18.15	0.00*	0.67	0.97
Error	1.47	9.00				
Pitch	0.17	1.00	0.07	0.80	0.01	0.06
Error	2.48	9.00				
Field x Pitch	3.94	1.00	4.15	0.07	0.32	0.44
Error	0.95	9.00				

*Statistical significant at $p < 0.05$

Two-way tests (2 x 2) of within-subjects effects on linear bat velocity for the closed stride technique

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	16.73	1.00	3.71	0.09	0.29	0.41
Error	4.51	9.00				
Pitch	0.31	1.00	0.13	0.72	0.02	0.06
Error	2.27	9.00				
Field x Pitch	4.44	1.00	4.21	0.07	0.32	0.45
Error	1.05	9.00				

*Statistical significant at $p < 0.05$

Summary of two-way interaction tests of within-subjects effects with adjusted F-values on linear bat velocity

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***
Field x Pitch (open stride)	10.51	1.00	13.30	$p < 0.05$*
Field x Pitch (parallel stride)	3.94	1.00	5.00	$p < 0.05$*
Field x Pitch (closed stride)	4.44	1.00	5.62	$p < 0.05$*
Error (three-way overall)	0.79	18.00		

Critical F-value F(1,18) = 4.41 at $\alpha = 0.05$

*Statistical significant at $p < 0.05$

Follow-up pairwise comparisons of two-way interaction effects on linear bat velocity for open stride

Two-way (2 fields x 2 pitches)	**Mean (SD) (m/s)**	***p***
Same, Inside vs	31.70 (2.40)	0.003*
Opposite, Inside	28.04 (1.56)	
Same, Outside vs	30.53 (2.92)	0.074
Opposite, Outside	28.93 (1.63)	

*Statistical significant at $p < 0.025$

Follow-up pairwise comparisons of two-way interaction effects on linear bat velocity for parallel stride

Two-way (2 fields x 2 pitches)	**Mean (SD) (m/s)**	***p***
Same, Inside vs	31.71 (2.37)	0.090
Opposite, Inside	30.70 (2.33)	
Same, Outside vs	32.21 (1.32)	0.001*
Opposite, Outside	29.95 (1.47)	

*Statistical significant at $p < 0.025$

Follow-up pairwise comparisons of two-way interaction effects on linear bat velocity for closed stride

Two-way (2 fields x 2 pitches)	**Mean (SD) (m/s)**	***p***
Same, Inside vs	31.09 (2.44)	0.369
Opposite, Inside	30.46 (2.56)	
Same, Outside vs	31.58 (3.09)	0.041
Opposite, Outside	29.62 (2.84)	

*Statistical significant at *p < 0.025*

Pairwise comparisons of different field x pitch x stride conditions on linear bat velocity

Conditions	**Mean (SD) (m/s)**	***p***
1 vs	31.70 (2.40)	0.981
2	31.71 (2.37)	
1 vs	31.70 (2.40)	0.437
3	31.01 (2.44)	
2 vs	31.71 (2.37)	0.218
3	31.09 (2.44)	
4 vs	30.53 (2.92)	0.076
5	32.21 (1.32)	
4 vs	30.53 (2.92)	0.323
6	31.58 (3.09)	
5 vs	32.21 (1.32)	0.447
6	31.58 (3.09)	
7 vs	28.04 (1.56)	0.005
8	30.70 (2.33)	
7 vs	28.04 (1.56)	0.015
9	30.46 (2.56)	
8 vs	30.70 (2.33)	0.704
9	30.46 (2.56)	
10 vs	28.93 (1.63)	0.085
11	29.95 (1.46)	
10 vs	28.93 (1.63)	0.179
12	29.62 (2.84)	
11 vs	29.95 (1.46)	0.721
12	29.62 (2.84)	

*Statistical significant at *p < 0.004*

Angular Bat Velocity

Participants' performance on angular bat velocity in each placement hitting condition

Conditions	**Mean** (°/s)	**SD** (°/s)	**Conditions**	**Mean** (°/s)	**SD** (°/s)
1	2045.62	156.90	**7**	1883.96	126.77
2	2056.77	240.60	**8**	2074.26	231.08
3	2052.63	226.02	**9**	2076.43	214.05
4	1923.21	179.75	**10**	1927.67	152.98
5	2029.47	199.38	**11**	2026.32	118.54
6	2067.93	283.35	**12**	1960.99	228.48

Three-way overall (2 x 2 x 3) tests of within-subjects effects on angular bat velocity

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	42564.46	1.00	1.37	0.27	0.13	0.18
Error	30979.36	9.00				
Pitch	53800.17	1.00	1.62	0.24	0.15	0.21
Error	33213.19	9.00				
Stride	181287.36	1.42	2.73	0.12	0.23	0.38
Error	66482.31	12.76				
Field x Pitch	180.93	1.00	0.01	0.91	0.00	0.05
Error	13122.34	9.00				
Field x Stride	18503.60	2.00	1.22	0.32	0.12	0.23
Error	15217.99	18.00				
Pitch x Stride	511.12	1.78	0.01	0.98	0.00	0.05
Error	36553.61	16.04				
Field x Pitch x Stride	59786.91	1.88	4.45	0.03*	0.33	0.67
Error	13424.33	16.95				

*Statistical significant at $p < 0.05$

Three-way limited (2 x 2 x 2) tests of within-subjects effects on angular bat velocity between open and parallel strides

Effects (Huynh-Feldt)	Mean Square	df	F	*p*	Eta Squared	Observed Power
Field	25511.53	1.00	1.49	0.25	0.14	0.19
Error	17167.75	9.00				
Pitch	29619.21	1.00	0.65	0.44	0.07	0.11
Error	45871.71	9.00				
Stride	206415.64	1.00	10.31	0.01*	0.53	0.82
Error	20026.17	9.00				
Field x Pitch	26454.45	1.00	1.35	0.28	0.13	0.18
Error	19566.32	9.00				
Field x Stride	36778.61	1.00	2.02	0.19	0.18	0.25
Error	18183.36	9.00				
Pitch x Stride	14.92	1.00	0.00	0.98	0.00	0.05
Error	33149.15	9.00				
Field x Pitch x Stride	43606.13	1.00	4.05	0.08	0.31	0.44
Error	10774.33	9.00				

*Statistical significant at $p < 0.05$

Three-way limited (2 x 2 x 2) tests of within-subjects effects on angular bat velocity between open and closed strides

Effects (Huynh-Feldt)	Mean Square	df	F	*p*	Eta Squared	Observed Power
Field	72202.94	1.00	2.39	0.16	0.21	0.28
Error	30236.12	9.00				
Pitch	39983.26	1.00	2.07	0.18	0.19	0.25
Error	19302.40	9.00				
Stride	178157.35	1.00	4.27	0.07	0.32	0.46
Error	41716.65	9.00				
Field x Pitch	1565.03	1.00	0.14	0.72	0.02	0.06
Error	11275.21	9.00				
Field x Stride	6854.99	1.00	0.41	0.54	0.04	0.09
Error	16851.19	9.00				
Pitch x Stride	575.66	1.00	0.03	0.86	0.00	0.05
Error	16688.67	9.00				
Field x Pitch x Stride	110163.26	1.00	13.27	0.01*	0.60	0.90
Error	8300.98	9.00				

*Statistical significant at $p < 0.05$

Three-way limited (2 x 2 x 2) tests of within-subjects effects on angular bat velocity between parallel and closed strides

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	5918.00	1.00	0.20	0.67	0.02	0.07
Error	29772.84	9.00				
Pitch	38453.38	1.00	1.14	0.31	0.11	0.16
Error	33828.95	9.00				
Stride	1039.61	1.00	0.01	0.91	0.00	0.05
Error	79670.34	9.00				
Field x Pitch	28649.04	1.00	3.56	0.09	0.28	0.39
Error	8046.04	9.00				
Field x Stride	11877.21	1.00	1.12	0.32	0.11	0.16
Error	10619.43	9.00				
Pitch x Stride	775.95	1.00	0.02	0.90	0.00	0.05
Error	47892.22	9.00				
Field x Pitch x Stride	15150.59	1.00	0.80	0.39	0.08	0.13
Error	18853.38	9.00				

*Statistical significant at $p < 0.05$

Two-way tests (2 x 2) of within-subjects effects on angular bat velocity for the open stride technique

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	61776.46	1.00	2.94	0.12	0.25	0.33
Error	21023.07	9.00				
Pitch	15481.86	1.00	0.93	0.36	0.09	0.14
Error	16645.38	9.00				
Field x Pitch	68994.62	1.00	6.00	0.04*	0.40	0.59
Error	11508.70	9.00				

*Statistical significant at $p < 0.05$

Two-way tests (2 x 2) of within-subjects effects on angular bat velocity for the parallel stride technique

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	513.73	1.00	0.04	0.85	0.00	0.05
Error	14328.03	9.00				
Pitch	14152.27	1.00	0.23	0.65	0.03	0.07
Error	62375.48	9.00				
Field x Pitch	1065.95	1.00	0.06	0.82	0.01	0.06
Error	18831.94	9.00				

*Statistical significant at $p < 0.05$

Two-way tests (2 x 2) of within-subjects effects on angular bat velocity for the closed stride technique

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	17281.48	1.00	0.66	0.44	0.07	0.11
Error	26064.24	9.00				
Pitch	25077.06	1.00	1.30	0.28	0.13	0.18
Error	19345.69	9.00				
Field x Pitch	42733.68	1.00	5.30	0.05	0.37	0.54
Error	8067.48	9.00				

*Statistical significant at $p < 0.05$

Summary of two-way interaction tests of within-subjects effects with adjusted F-values on angular bat velocity

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***
Field x Pitch (open stride)	68994.62	1.00	5.14	$p < 0.05$*
Field x Pitch (parallel stride)	1065.95	1.00	0.08	$p > 0.05$
Field x Pitch (closed stride)	42733.68	1.00	3.18	$p > 0.05$
Error (three-way overall)	13424.33	16.95		

Critical F-value F(1,17) = 4.45 at $\alpha = 0.05$

*Statistical significant at $p < 0.05$

Follow-up pairwise comparisons of two-way interaction effects on angular bat velocity for open stride

Two-way (2 fields x 2 pitches)	**Mean (SD) (m/s)**	***p***
Same, Inside vs	2045.62 (156.90)	0.006*
Opposite, Inside	1883.96 (126.77)	
Same, Outside vs	1923.21 (179.75)	0.948
Opposite, Outside	1927.67 (152.98)	

*Statistical significant at $p < 0.025$

Pairwise comparisons of different field x pitch x stride conditions on angular bat velocity

Conditions	**Mean (SD)** (°/s)	***p***
1 vs	2045.62 (156.90)	0.853
2	2056.77 (240.60)	
1 vs	2045.62 (156.98)	0.925
3	2052.63 (226.02)	
2 vs	2056.77 (240.60)	0.959
3	2052.63 (226.02)	
4 vs	1923.21 (179.75)	0.200
5	2029.47 (199.38)	
4 vs	1923.21 (179.75)	0.084
6	2067.93 (283.35)	
5 vs	2029.47 (199.38)	0.762
6	2067.93 (283.35)	
7 vs	1883.96 (126.77)	0.020
8	2074.26 (231.08)	
7 vs	1883.96 (126.77)	0.010
9	2076.43 (214.05)	
8 vs	2074.26 (231.08)	0.978
9	2076.43 (214.05)	
10 vs	1927.67 (152.98)	0.086
11	2026.32 (118.54)	
10 vs	1927.67 (152.98)	0.511
12	1960.99 (228.48)	
11 vs	2026.32 (118.54)	0.345
12	1960.99 (228.48)	

*Statistical significant at $p < 0.004$

Bat Swing Time

Participants' performance on bat swing time in each placement hitting condition

Conditions	**Mean (s)**	**SD (s)**	**Conditions**	**Mean (s)**	**SD (s)**
1	0.56	0.11	**7**	0.63	0.13
2	0.60	0.15	**8**	0.56	0.25
3	0.63	0.18	**9**	0.59	0.21
4	0.57	0.18	**10**	0.64	0.19
5	0.58	0.11	**11**	0.55	0.16
6	0.57	0.15	**12**	0.57	0.16

Tests of within-subjects effects on bat swing time

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	0.00	1.00	0.03	0.87	0.00	0.05
Error	0.02	9.00				
Pitch	0.01	1.00	1.74	0.22	0.16	0.22
Error	0.00	9.00				
Stride	0.01	2.00	0.64	0.54	0.07	0.14
Error	0.01	18.00				
Field x Pitch	0.00	1.00	0.08	0.78	0.01	0.06
Error	0.01	9.00				
Field x Stride	0.03	2.00	2.63	0.10	0.23	0.46
Error	0.01	18.00				
Pitch x Stride	0.01	1.56	0.29	0.67	0.03	0.84
Error	0.03	13.91				
Field x Pitch x Stride	0.00	1.77	0.15	0.84	0.02	0.07
Error	0.01	15.90				

*Statistical significant at $p < 0.05$

Lower Body Angle

Participants' performance on lower body angle in placement hitting each condition

Conditions	Mean (°)	SD (°)	Conditions	Mean (°)	SD (°)
1	-2.54	9.55	**7**	0.44	13.30
2	-1.07	12.22	**8**	1.48	11.38
3	-7.25	12.87	**9**	-7.60	16.91
4	10.67	18.32	**10**	2.84	5.96
5	-2.22	20.00	**11**	-2.34	10.76
6	-4.67	12.06	**12**	-6.07	14.41

Tests of within-subjects effects on lower body angle

Effects (Huynh-Feldt)	Mean Square	df	F	*p*	Eta Squared	Observed Power
Field	14.58	1.00	0.11	0.75	0.01	0.06
Error	131.41	9.00				
Pitch	181.11	1.00	0.66	0.44	0.07	0.11
Error	274.78	9.00				
Stride	862.36	2.00	7.33	0.01*	0.45	0.89
Error	117.60	18.00				
Field x Pitch	176.23	1.00	2.10	0.18	0.19	0.25
Error	83.96	9.00				
Field x Stride	33.52	2.00	0.22	0.80	0.02	0.80
Error	150.13	18.00				
Pitch x Stride	266.62	2.00	2.67	0.10	0.23	0.46
Error	99.74	18.00				
Field x Pitch x Stride	92.58	1.48	1.56	0.24	0.15	0.24
Error	59.34	13.33				

*Statistical significant at $p < 0.05$

Pairwise comparisons of different strides on lower body angle

Strides	Mean (SD) (°)	*p*
Open vs Parallel	2.85 (1.91) -1.04 (3.37)	0.33
Open vs Closed	2.85 (1.91) -6.40 (3.74)	0.01*
Parallel vs Closed	-1.04 (3.37) -6.40 (3.74)	0.22

*Statistical significant at $p < 0.02$

Trunk Angle

Participants' performance on trunk angle in each placement hitting condition

Conditions	**Mean** (°)	**SD** (°)	**Conditions**	**Mean** (°)	**SD** (°)
1	-0.34	11.37	**7**	-1.80	25.03
2	-5.15	10.31	**8**	-4.42	20.13
3	-12.42	10.35	**9**	-1.81	20.04
4	5.47	20.32	**10**	4.79	19.97
5	-3.61	19.56	**11**	11.62	20.75
6	-13.30	19.21	**12**	-4.71	15.96

Tests of within-subjects effects on trunk angle

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	908.16	1.00	2.53	0.15	0.22	0.30
Error	358.43	9.00				
Pitch	572.21	1.00	2.70	0.14	0.23	0.31
Error	211.91	9.00				
Stride	1110.03	2.00	7.59	0.00*	0.46	0.90
Error	146.18	18.00				
Field x Pitch	146.52	1.00	0.63	0.45	0.07	0.10
Error	234.53	9.00				
Field x Stride	361.25	1.83	2.24	0.14	0.20	0.38
Error	161.57	16.47				
Pitch x Stride	427.10	1.45	2.25	0.15	0.20	0.33
Error	190.06	13.01				
Field x Pitch x Stride	237.65	1.64	3.29	0.07	0.27	0.49
Error	72.16	14.79				

*Statistical significant at $p < 0.05$

Pairwise comparisons on different strides on trunk angle

Strides	**Mean (SD)** (°)	***p***
Open vs Parallel	2.03 (5.23) -0.39 (4.55)	1.00
Open vs Closed	2.03 (5.23) -8.06 (3.89)	0.01*
Parallel vs Closed	-0.39 (4.55) -8.06 (3.89)	0.03

*Statistical significant at $p < 0.02$

Upper Body Angle

Participants' performance on upper body angle in each placement hitting condition

Conditions	**Mean** (°)	**SD** (°)	**Conditions**	**Mean** (°)	**SD** (°)
1	-11.35	10.15	**7**	-13.70	16.70
2	-3.69	12.30	**8**	9.27	18.11
3	4.98	12.68	**9**	7.81	15.14
4	-5.63	10.05	**10**	-6.44	11.94
5	1.06	14.06	**11**	7.37	18.47
6	9.86	11.87	**12**	4.02	20.95

Tests of within-subjects effects on upper body angle

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	143.31	1.00	0.47	0.51	0.05	0.09
Error	308.23	9.00				
Pitch	238.07	1.00	2.44	0.15	0.21	0.29
Error	97.72	9.00				
Stride	2850.31	2.00	17.60	0.00*	0.66	1.00
Error	161.92	18.00				
Field x Pitch	158.29	1.00	0.90	0.37	0.09	0.14
Error	176.78	9.00				
Field x Stride	566.61	1.47	2.56	0.13	0.22	0.37
Error	221.05	13.23				
Pitch x Stride	102.86	2.00	0.68	0.52	0.07	0.15
Error	152.41	18.00				
Field x Pitch x Stride	72.91	2.00	0.39	0.68	0.04	0.10
Error	186.98	18.00				

*Statistical significant at $p < 0.05$

Pairwise comparisons of different strides on upper body angle

Strides	**Mean (SD)**	***p***
Open vs	-9.28 (2.35)	0.01*
Parallel	3.50 (3.60)	
Open vs	-9.28 (2.35)	0.00*
Closed	6.67 (2.68)	
Parallel vs	3.50 (3.60)	1.00
Closed	6.67 (2.68)	

*Statistical significant at $p < 0.02$

Appendix E: Statistical Analysis of Individual VS Group on Kinematic Variables

The rescaled Euclidean distance (0 to 1) in the resultant linear bat velocity, resultant angular bat velocity, bat swing time, lower body rotational angle, trunk rotational angle and upper body rotational angle in each condition (#1- #6) between individual participant results versus group mean results

Participant\Condition	1	2	3	4	5	6
1	0.18	0.13	0.31	0.50	0.58	0.49
2	0.41	0.22	0.00	0.18	0.10	0.11
3	0.18	0.58	0.19	0.27	0.11	0.31
4	0.00	0.06	0.22	0.24	0.00	0.48
5	0.49	0.22	0.44	0.10	0.33	0.20
6	0.24	0.30	0.19	0.43	0.06	0.07
7	0.47	0.03	0.09	0.58	0.14	0.42
8	0.53	0.32	0.51	0.00	0.02	0.29
9	0.12	0.16	0.24	0.29	0.19	0.23
10	0.45	0.07	0.21	0.30	0.35	0.11
Mean	0.31	0.21	0.24	0.29	0.19	0.27
SD	0.18	0.16	0.15	0.18	0.18	0.15

The rescaled Euclidean distance (0 to 1) in the resultant linear bat velocity, resultant angular bat velocity, bat swing time, lower body rotational angle, trunk rotational angle and upper body rotational angle in each condition (#7- #12) between individual participant results versus group mean results

Participant\Condition	7	8	9	10	11	12
1	0.31	0.44	0.25	0.32	0.57	0.46
2	0.65	0.09	0.08	0.32	0.21	0.52
3	0.27	0.00	0.59	0.54	0.45	0.41
4	0.25	0.61	0.32	0.18	0.28	0.06
5	0.24	0.32	0.06	0.55	0.35	0.28
6	0.09	0.32	0.13	0.16	0.16	0.23
7	0.04	0.30	0.00	0.53	0.35	0.37
8	0.14	0.39	0.01	0.00	0.32	0.31
9	0.01	0.29	0.10	0.21	0.29	0.13
10	0.18	0.10	0.04	0.25	0.39	0.00
Mean	0.22	0.29	0.16	0.31	0.34	0.28
SD	0.18	0.18	0.18	0.19	0.12	0.17

Appendix F: Statistical Analysis on Movement Coordination Patterns

Lower Body and Trunk

Participants' performance on combined % SPC and % RSPC of lower body and trunk movement coordination pattern in each placement hitting condition

Conditions	**Mean (%)**	**SD (%)**	**Conditions**	**Mean (%)**	**SD (%)**
1	14.47	61.50	**7**	32.91	34.85
2	10.39	31.11	**8**	31.00	43.43
3	23.59	44.12	**9**	46.10	74.68
4	28.49	55.91	**10**	14.67	49.43
5	20.02	32.64	**11**	23.18	22.18
6	44.84	59.00	**12**	41.76	43.40

Tests of within-subjects effects on combined % SPC and % RSPC of lower body and trunk movement coordination pattern

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	1904.98	1.00	0.57	0.47	0.06	0.10
Error	3351.58	9.00				
Pitch	175.53	1.00	0.04	0.85	0.00	0.05
Error	4736.45	9.00				
Stride	3958.22	2.00	1.46	0.26	0.14	0.27
Error	2705.01	18.00				
Field x Pitch	4725.79	1.00	4.29	0.07	0.32	0.46
Error	1101.95	9.00				
Field x Stride	251.90	2.00	0.13	0.88	0.01	0.07
Error	2015.31	18.00				
Pitch x Stride	296.12	2.00	0.16	0.85	0.02	0.07
Error	1807.46	18.00				
Field x Pitch x Stride	137.44	2.00	0.13	0.89	0.01	0.07
Error	1051.79	18.00				

*Statistical significant at $p < 0.05$

Trunk and Upper Body

Participants' performance on combined % SPC and % RSPC of trunk and upper body movement coordination pattern in each placement hitting condition

Conditions	**Mean (%)**	**SD (%)**	**Conditions**	**Mean (%)**	**SD (%)**
1	-4.19	36.91	**7**	43.59	37.29
2	34.30	30.14	**8**	52.99	43.41
3	27.27	37.25	**9**	39.33	51.01
4	13.11	15.76	**10**	40.87	37.08
5	43.51	46.19	**11**	49.00	35.37
6	32.93	24.28	**12**	20.67	44.10

Tests of within-subjects effects on combined % SPC and % RSPC of trunk and upper body movement coordination pattern

Effects (Huynh-Feldt)	**Mean Square**	**df**	**F**	***p***	**Eta Squared**	**Observed Power**
Field	8253.90	1.00	3.82	0.08	0.30	0.42
Error	2158.19	9.00				
Pitch	38.35	1.00	0.04	0.85	0.00	0.05
Error	975.40	9.00				
Stride	4889.91	2.00	2.22	0.14	0.20	0.39
Error	2206.17	18.00				
Field x Pitch	2757.75	1.00	4.07	0.07	0.31	0.44
Error	677.09	9.00				
Field x Stride	3737.17	2.00	2.70	0.09	0.23	0.47
Error	1384.82	18.00				
Pitch x Stride	496.84	1.99	0.36	0.70	0.04	0.10
Error	1378.08	17.80				
Field x Pitch x Stride	81.58	1.93	0.10	0.90	0.01	0.06
Error	807.25	17.34				

*Statistical significant at $p < 0.05$

Appendix G: Statistical Analysis of Individual VS Group on Movement Coordination Patterns

The rescaled Euclidean distance (0 to 1) on combined percentages of SPC and RSPC of both lower body and trunk, and trunk and upper body joints in each condition (#1- #6) between individual participant results versus group mean results

Participant\Condition	1	2	3	4	5	6
1	0.09	0.07	0.46	0.15	0.11	0.57
2	0.24	0.41	0.12	0.30	0.42	0.01
3	0.38	0.23	0.47	0.03	0.46	0.00
4	0.48	0.28	0.46	0.46	0.02	0.44
5	0.44	0.18	0.51	0.00	0.42	0.41
6	0.60	0.40	0.50	0.34	0.12	0.28
7	0.39	0.54	0.36	0.70	0.47	0.15
8	0.35	0.41	0.03	0.00	0.19	0.15
9	0.42	0.19	0.36	0.23	0.19	0.23
10	0.26	0.25	0.08	0.22	0.52	0.37
Mean	0.37	0.30	0.34	0.24	0.29	0.26
SD	0.14	0.14	0.19	0.22	0.18	0.19

The rescaled Euclidean distance (0 to 1) on combined percentages of SPC and RSPC of both lower body and trunk, and trunk and upper body joints in each condition (#7- #12) between individual participant results versus group mean results

Participant\Condition	7	8	9	10	11	12
1	0.54	0.08	0.58	0.26	0.46	0.08
2	0.00	0.14	0.01	0.39	0.00	0.15
3	0.51	0.29	0.53	0.36	0.30	0.31
4	0.07	0.02	0.42	0.26	0.44	0.66
5	0.54	0.01	0.07	0.47	0.21	0.14
6	0.46	0.65	0.34	0.25	0.37	0.33
7	0.32	0.20	0.24	0.58	0.35	0.40
8	0.22	0.23	0.11	0.00	0.15	0.12
9	0.05	0.13	0.07	0.42	0.36	0.15
10	0.26	0.24	0.37	0.12	0.59	0.24
Mean	0.30	0.20	0.27	0.31	0.32	0.26
SD	0.21	0.18	0.20	0.17	0.17	0.18