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Integration of Impulse-Variability Theory and the Speed-Accuracy Trade-Off in Children's Multijoint Ballistic Skill Performance

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INTEGRATION OF IMPULSE-VARIABILITY THEORY AND THE SPEED-ACCURACY TRADE-OFF IN CHILDREN'S MULTIJOINT BALLISTIC SKILL PERFORMANCE

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DEDICATION

To my parents, Al and Debbie: Thank you for your support and encouragement throughout this process. Your belief in me helped shape me into the person I am today. Thank you.

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ABSTRACT

A major purpose of the motor learning and motor control literature is to provide principles and theories (e.g., speed-accuracy trade-off) that can inform the instruction of young learners in motor skill competence. To be optimally effective, these principles and theories must be understood and applied in relation to authentic instructional contexts, complex motor patterns, and specific developmental levels of young learners. It is insufficient, for instance, to generalize research results with adults learning simple movements in controlled laboratory settings to an understanding of how children learn from fundamental movement skills in physical education classes. Based on this premise, the work presented herein focuses on several limitations to the knowledge base on impulse-variability theory and the speed-accuracy trade-off. Specifically although an established research literature with adult learners has develop to test fundamental principles within both perspectives, littles is known regarding the applicability of these principles to children learning multijoint ballistic skills, which are commonly taught in schools. Therefore, two studies conducted to examine impulse-variability theory and the speed-accuracy trade-off as they relate to children learning overarm throwing and kicking. In the first study 45 children ages 9 to 11 (mean age= 10.7 years; 21 girls) performed a total of 40 throwing trials at 45%, 65%, 85%, and 100% of their maximum speed at a target. Results indicated no statistical significance with either variable error or spatial error, failing to support either impulse-variability theory or the speed-accuracy trade-off.

In the second study, 43 children ages 9 to 11 (mean age= 10.7 years, 19 girls) kicked a ball at 45%, 65%, 85%, and 100% of their maximum speed at a wall target. Results indicated a U-shaped relationship with variable error, where the participants were less variable at the 65% target speed condition compared to maximum speed, failing to support impulse-variability theory and findings in adult kicking performances (Chappell et al., in press). A statistically significant inverse linear relationship was indicated with the spatial error were the mean radial error of the speed bandwidths of <59%, 60-69%, and 70-79% of maximum speed were greater than the >90% bandwidth of maximum speed. These results are inconsistent with the tenants of the speed-accuracy trade-off. Overall, findings suggest that variability and accuracy of multijoint ballistic skills performance in children fail to support general movement principles (i.e., speed-accuracy trade-off and impulse-variability theory). Therefore, current policy and practice of physical educators and coaches related to instructional emphases may need to be re-evaluated.

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LIST OF ABBREVIATIONS

BVE..Bivariate Variable Error

CE ....Centroid Error

IV ....Impulse-Variability

MRE..Mean Radial Error

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

The development of motor skill competence is suggested to be a prerequisite for physical activity and health-related physical fitness across the life span (Stodden et al., 2008). Unfortunately, motor skill levels, specifically fundamental motor skills (i.e., object control and locomotor) in youth have been noted as inadequate (Hardy, Reinten-Reynolds, Espinel, Zask, & Okely, 2012; Okely & Booth, 2004) specifically in overweight/obese children (Cliff et al., 2012). Promoting improved skill development is important not only for improved movement capabilities, but also may be important to promote healthy and active lifestyles. Variability, movement or projectile speed, and accuracy all are indicators of skill level in certain types of motor skills and are linked to developmental progressions (Stodden, Langendorfer, Fleisig, & Andrews, 2006a, 2006b; Urbin, Stodden, & Fleisig, 2013). Understanding how performance factors such as variability, speed and accuracy are integrated and linked to skill development will provide insight for promoting optimal developmental progression via developmentally appropriate practice.

Fitts' law (1954) and its application, the speed-accuracy trade-off, have long been noted as fundamental aspects of normal human movement (Urbin, Stodden, Fischman, & Weimer, 2011). The speed-accuracy trade-off refers to the fact that, across a variety of movement types and skills, increases in movement speed result in decreases in movement accuracy. However, recent research on a specific class of motor skills (i.e., multijoint ballistic skills) questions the applicability of the speed-accuracy trade-off and how it relates to developmental progressions (Chappell, Molina, McKibben, & Stodden, in press; Juras, Slomka, & Latash, 2009; Southard, 2014; Urbin, Stodden, Boros, & Shannon, 2012; van den Tillaar & Ettema, 2006).

Fitts' initial work also led to additional work to examine the cause of increased error with increasing speed of movements. This additional line of inquiry examined the variability in initial impulses that generated movements and led to the development of a theory of movement control. Impulse-variability (IV) theory (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979) provided a theoretical framework in which to understand the relationship between forces that produce movement and their variability across a continuum. The original theory, which was based on data from studies involving non-maximal force outputs, postulated a linear relationship between the initial impulse produced and its variability (Schmidt, Zelaznik, & Frank, 1978; Schmidt et al., 1979). Further work in this area with maximal force outputs led to a modification in the original tenants of impulse variability theory. Specifically, the relationship between force and force variability was found to follow an inverted-U shape. Force variability increased with greater force at low levels of force production, but above a certain percentage of maximal effort (i.e., 60-70%) force variability decreased with greater force (Sherwood & Schmidt, 1980; Schmidt and Sherwood, 1982).

Multijoint ballistic motor skills are a specialized group of skills, many of which we know as fundamental movement skills (FMS). Multijoint ballistic motor skills are defined as skills involving complex coordination and control involving a proximal to distal sequencing of multiple joints resulting in high distal segment velocities required for the projection of the body or an object, with or without an implement (e.g., throwing, striking, kicking, jumping, hopping, etc…; Stodden, 2006; Urbin et al., 2011). All skills within this specific group demonstrate proximal to distal sequencing of limbs when performed at moderate to high levels of effort. This contrasts with goal directed, non-ballistic movements where the force requirements of the movement are constrained by its purpose (i.e., tennis lob shot, shooting a free throw, dart throwing, etc…).

Urbin et al. (2011) suggest the tenets of IV theory (i.e., the inverted-U) may be generalized to all multijoint ballistic motor skills and one recent study that examined the skill of throwing supported this claim (Urbin et al., 2012). However, data from an additional study that examined kicking are inconsistent with this claim (Chappell et al., in press). Both studies that directly tested IV theory using multijoint ballistic skills demonstrated decreased variability of resultant projectile speed at near maximal and maximal levels of effort (Chappell et al, in press; Urbin et al., 2012). In addition, both studies also failed to support the speed-accuracy trade-off in that accuracy did not change with increasing projectile speeds. Thus, it is suggested that the decreased variability in projectile speed may be related to the lack of change in resultant accuracy as the system may be more consistently producing an output at near maximal or maximal levels of effort. One possibility is that the specific adaptations that lead to consistent performance at high levels of effort may actually lead to a violation of the speed-accuracy trade-off (Chappell et al., in press; Urbin et al., 2012). One problem with these two studies is that both Urbin et al. (2012) and Chappell et al. (in press) used adult samples (i.e., 18 years and older). Thus, the generalizability of their results, specifically with respect to performance in children is questionable.

As children progress through the stages of learning (Fitts & Posner, 1967) there is evidence that at least for multijoint ballistic skills individuals demonstrate decreased kinematics and performance variability with increasing levels of skill (Fleisig, Chu, Weber, & Andrews, 2009; Urbin, Stodden, & Fleisig, 2013). Children who demonstrate lower skill levels may inherently have increased variability in their movement patterns as compared to adults who may demonstrate more consistent coordination patterns. This begs the question: Will children's resultant performance and variability in performance in multijoint ballistic skills be similar to adult performances and support or refute the inverted-U phenomenon of IV theory and violate the speed-accuracy trade-off? The primary purpose of this study was to examine the applicability of IV theory and the speed-accuracy trade-off in children's throwing and kicking performance. Two research articles, one addressing each individual skill, were developed to fulfill the dissertation requirements.

The literature review describes the origins of Fitts' Law and how it led to the practical application of the law; the speed-accuracy trade-off. A brief overview of impulse variability theory is examined next. Research on applications of impulse-variability theory and the speed-accuracy trade-off in multijoint ballistic movements were then summarized. Finally, I examine weaknesses and limitations of previous research and a rationale is proposed as to how the two studies involved in this project help to advance our current understanding of the speed-accuracy trade-off and impulse-variability theory for teaching multijoint ballistic motor skills.

Review of Literature

Fitts Law/Speed-Accuracy Trade-Off

Woodworth (1899) produced one of the earliest studies testing the relationship between movement speed and accuracy. He examined repetitive movements over different rates per minute with participant's eyes open and closed. As the speed of the movement increased, the accuracy of the movements decreased. Woodworth theorized that two movement processes accounted for the movement trajectories he had observed. The first phase was referred to *initial impulse* and the second was called *current control* (i.e., modifying and making adjustments). The initial impulse of a movement was perceived to result in decreased accuracy as movement speed increased due to the inability to account for feedback. Alternatively, when current control was used in the process of controlling the movement it allowed for feedback. Over 50 years later, Paul Fitts (1954) conducted studies that produced similar results. He carried out a series of experiments in which participants performed reciprocal tapping or object transfer tasks under a variety of constraints. Altering the effective target width and distances between targets demonstrated that movement time (MT) was directly related to the amplitude (A) (i.e., distance) between targets and inversely related to the effective width (W) of the targets. Fitts' original work produced the equation, $MT = a + b[\text{Log}_2(2A / W)]$. In this equation a and b are both held as empirical constants. The practical application of this law is the speed-accuracy trade off where there is an inverse relationship between speed of a movement and the resultant accuracy of the movement outcome. In essence, as the speed of a movement increases, there will be a decrease in the accuracy of that movement. Fitts' Law has been supported in a variety of contexts such as human-computer interaction (Soukoreff & MacKenzie, 2004), motor imagery (Decety & Jeannerod, 1996), and others.

Connecting back to Woodworth (1899) and the suggestions about initial impulse affecting the resultant accuracy, increased variability also may lead to a decrease in accuracy as increased variability may lead to unnecessary and random initial impulse adjustments by the performer in subsequent trials that may not necessarily lead to improved accuracy. With low variability generally being considered as an important indicator of skilled performance (Newell & Corcos, 1993), any model or theory describing variability should be able to account for the variability of movement and the resultant output (Carlton & Newell, 1993).

Impulse-Variability Theory

Extensions from the variability concepts suggested by Woodworth (1899) were proposed by Schmidt, Zelaznik, Hawkins, Frank, & Quinn (1979). They initially proposed IV theory to explain the association between the speed-accuracy trade-off in rapid movements that did not require error corrections and feedback processing. IV theory postulates that pre-structured muscle commands (i.e., motor program) are responsible for the initial impulse in a movement, which would eliminate the necessity for feedback and its potential effect on the initial trajectory of the movement pattern. IV theory stipulates that before any response is initiated, the system specifies which muscles are to contract, in what order they fire, the relative and absolute forces with which they contract and the temporal relations among the contractions (Schmidt et al., 1979). The major implication for this study is that the original IV theory hypothesized within-subject force variability would be proportional to the force that is produced, with the emphasis on rapid force generation. Initial data with submaximal effort trials indicated that absolute force showed a linear relationship with force variability. However, one variable that wasn't comprehensively examined was the entire spectrum of force generating capacity.

Sherwood and Schmidt (1980) proposed modifications to the original theory after examining forces above and below the mid-ranges that were used in their original studies. When implementing a broader range of force production capability, the data demonstrated that once force output reached approximately 65% of maximum the relationship between force and force variability was no longer linear. When force increased beyond 65%, force variability began to decrease which created an inverted-U effect (Sherwood & Schmidt, 1980). Further evidence for this new development in IV theory demonstrated that the variability in force and variability in duration of the force can influence the movement outcome. This observation was important because it demonstrated that effects of target accuracy were influenced by changes within movement variability (Schmidt & Sherwood, 1982).

Newell and Carlton (1985) questioned the inverted-U relationship, specifically in relation to peak force and the time to peak force that was reported in Sherwood and Schmidt (1980) and Schmidt and Sherwood (1982). They argued that the inverted-U could have resulted from participants using less time to attain peak force at lower force levels and demonstrating increased time to reach peak force as force levels increased (Newell & Carlton, 1985). Their results contradicted Schmidt and Sherwood's theory in that when the time to peak force was held constant, force variability continued to increase after approximately 65%, however there was a relative plateau effect after 65% of maximum force production (Newell & Carlton, 1985). In essence their data followed a negatively accelerating curvilinear relationship. In response to this finding, Sherwood, Schmidt, and Walter, (1988) conducted additional experiments that accounted for the time to peak force timing issue. While holding time to peak force as a constant, they examined the IV question using an isotonic elbow flexion task. The results provided a significant linear trend showing a proportional relationship between force and force variability along with a significant quadratic trend, which results in producing more of a parabolic curve; thus providing an indication of a curvilinear relationship (Sherwood et al., 1988). Unfortunately, there was a lack of support for the inverted-U function because the conducted study failed to reach significance within the three highest load conditions. Overall, there was limited support for Newell and Carlton's (1985) expectations of force variability producing a negatively accelerating curve when timing aspects were controlled. Sherwood et al. (1988) concluded that Newell and Carlton's ideas of force variability might be limited to isometric responses. Within a lab-controlled setting, isometric responses could be produced and measured, but the applicability of laboratory setting to real-world tasks needed to be addressed.

Highly controlled lab-based experiments do not necessarily demonstrate applicability in the real world. Moving beyond lab-based isometric and isotonic movements, Urbin et al. (2011) bridged the connection between impulse-variability theory and real-world applications of the theory by focusing on multijoint ballistic skills. These types of skills inherently involve three performance features that are relevant to IV theory (Urbin et al., 2011). The first was that forces are effectively and sequentially applied through the human kinetic link chain producing high distal segment velocities. Second, relative timing required of the sequential movements in the system is critical to produce maximum output. Lastly, the resultant velocity of the distal segment, implement, or projectile does not decelerate until after projectile release or striking of a projectile. In the only two studies that have addressed both IV theory and the speed-accuracy trade-off with ballistic skills in the same design, evidence suggests the performance of these skills may not follow the speed-accuracy trade-off as well as demonstrate decreased variability at maximal and near maximal systemic force levels (Chappell et al., in press; Urbin et al., 2012).

Summary of Studies

Surprisingly, limited research has been conducted to examine the practical application of the speed-accuracy trade-off and IV theory in promoting the acquisition of ballistic motor skills. One of the earliest studies implemented practice sessions with overarm throwing where feedback was provided to the experimental groups in the form of an emphasis on speed, accuracy, or both (Malina, 1969). Results demonstrated there was no significant difference in accuracy between any of the practice groups. However, there was significantly greater speed performed with the speed only and speed-accuracy feedback conditions when compared to the control group and accuracy emphasis group. Similar studies have been conducted with experimental groups that focus on either speed or accuracy with other ballistic motor skills including underhand softball pitching (Englehorn, 1997) and floor hockey shooting (Belkin & Eliot, 1997).

Englehorn (1997) examined underhand softball pitching using 10-11 year old girls. Using only two groups, one that emphasized speed and another that emphasized accuracy, the participants attended 12 practice sessions over a six week period. Results indicated that when the focus was on throwing for speed and proper mechanics instead of accuracy and proper mechanics, there was a significant increase in the speed of the fast-pitch softball pitch. Accuracy was not found to be significant between the groups.

Another study was conducted with floor hockey shooting as the task. Twelve children (ages 6-11) were separated into two groups and were given instruction and practice opportunities emphasizing either accuracy or speed (Belkin & Eliot, 1997). During the post-test the speed group significantly improved their speed from the pre-test while there was no difference in the group with the accuracy condition. The next recorded task was a combination of the speed and accuracy tasks and results showed that the speed group had a significantly higher speed than the accuracy group. There was no difference in spatial accuracy between the two groups in the combined post-test. Belkin and Eliot (1997) determined that there results disputed the speed-accuracy trade-off.

Using a slightly different accuracy methodology, Teixeira (1999) had five highly-skilled male adult participants kick different sized balls with either a speed or accuracy emphasis at either a defined target or without a defined target. Results demonstrated that speed was higher on the speed instructional emphasis where there was an undefined target compared to trials that used a target, again suggesting a speed-accuracy trade-off. Opposing findings were noted in tasks when the instructions were expanded to include only speed, only accuracy, or when one condition was emphasized over another (with two emphases) in overarm throwing (Van den Tillaar & Ettema, 2003a, 2003b, 2006), and striking (Southard, 1989). Additional studies designed with an instructional emphasis indicated that participants were significantly more accurate when the task emphasized accuracy compared to all other conditions (i.e., emphasis on performing as fast as possible and trying to hit the target, emphasis on hitting the target and performing as fast as possible) in overarm throwing with novices (Garcia, Sabido, Barbado, & Moreno, 2013) and kicking (Van den Tillaar & Ulvik, 2014).

Van den Tillaar and Ettema (2003a, 2003b) investigated the influence of instruction on speed and accuracy of overarm throwing with nine adult males that were experienced team handball players. After gathering data on individual's maximum throwing speed, each were given seven trials under different sets of instructions: a) throw the ball as fast as possible in the goal, b) throw the ball as fast as possible and try to hit the target, c) hit the target and throw as fast as possible, d) hit the target and try to throw as fast as possible, and e) hit the target. When accuracy was emphasized, speed was significantly slower as compared to the speed emphases. However, there was no effect on the accuracy between any of the conditions. This study was later extended to add a comparison with 13 inexperienced adult males (van den Tillaar and Ettema, 2006). When examining the speed-accuracy trade-off with experienced and inexperienced adult male handball players, results indicated that when accuracy was an emphasized condition speed of the ball decreased; however, throwing accuracy was not improved.

Southard (1989) observed the effects of speed and accuracy in 10 adult females striking a ball off of a tee. For five consecutive days participants performed 10 trials at each of three conditions: a) hitting with maximum speed, b) hitting with accuracy (to a target) as the focus, and c) hitting as fast and as accurate as possible. Even though there were significant differences between speeds of the groups, there were no significant differences in target accuracy between the conditions.

Garcia et al. (2013) investigated speed and accuracy of throwing with expert and novice handballers. After establishing maximum speed of the overarm throw, participants were asked to throw handballs; two sets of 10 trials at various targets were located seven meters away. The first 10 throws focused on accuracy and the second set emphasized speed. Results were similar to other studies that used instructions of speed and/or accuracy where both groups threw faster with a speed focus and there was no significant difference with accuracy in the expert group between the two sets of trials. One difference found in this study was in the novice group. Results indicated they were significantly more accurate in the accuracy condition when compared to their accuracy in the speed condition (Garcia et al., 2013).

Van den Tillaar & Ulvik, (2014) examined kicking speed and accuracy in 10 adults who practiced under four different instructional conditions. Participants kicked at a 1 x 1 cm centroid on a target located 1.25 meters off the ground at the distance of 11 meters. The instructions were for speed only, speed and hitting a target, hitting a target and going as fast as possible, and focusing on accuracy only. After taking eight trials at each condition results indicated there was significantly higher ball speed with the speed emphasis. The "accuracy only" emphasis produced significantly lower speeds when compared to all other conditions. Results also showed that participants were significantly more accurate in the accuracy only instructional condition when compared to the other conditions. Overall, results of this study provided evidence for a speed-accuracy trade-off.

Some of the methodological limitations in the previously noted studies include lack of ecological task validity by not including a target for all trials (Teixeira, 1999) or not recording accuracy in two-dimensions (Belkin & Eliot, 1997; Englehorn, 1997; Teixeira, 1999). It seems logical that both speed and accuracy data should be accounted for when examining this topic. Thus, results are equivocal in terms of providing a firm answer as to whether or not the speed-accuracy trade-off occurs in ballistic skill performance. Furthermore, examining accuracy through a variety of percentages of maximum capability, versus only one level of speed (i.e., maximum), would provide a more comprehensive and thorough examination of whether or not a trade-off occurred.

Other researchers have investigated the problem more thoroughly by having a constant target and varying percentages of an individual's maximum performance, which provides an estimate of within-subject accuracy performance over a continuum of effort (Cauraugh, Gabert, & White, 1990; Chappell et al., in press; Freeston, Ferdinands, & Rooney, 2007; Freeston & Rooney, 2014; Indermill & Husak, 1984; Juras et al., 2009; Southard, 2014; Urbin et al., 2012). Most studies used some combination of at least three different percentages of maximum projectile or implement speed (e.g., throwing, kicking & striking) ranging from 33% - 100% of maximum.

Indermill and Husak (1984) used three groups to study overarm throwing with 18 young adults performing at different percentages of their maximum speed (50, 75, and 100%). The target was a 23.5 cm diameter ring was placed 1.22 meters above the ground with 12.1 cm wide concentric rings progressing out. Participants were located 12.2 meters away from the target. The differences between the groups were the order of the percentage of maximum speed that they performed their test trials. Results showed that participants were more accurate at 75% of their maximum speed when compared to both 50% and 100%. Thus, results demonstrated a non-linear accuracy result in their study, which contradicts the inverse linear relationship that speed is supposed to have with accuracy.

Freeston et al. (2007) examined the overhead cricket throw in 110 cricket players that were separated into six different groups of males and females based on performance status. The target was a 71.1 cm vertical post that was 3.5 cm wide with zones marked every 14 cm out from the post and was placed at a distance of 20.14 meters away from the throwers. Participants performed a set of 10 trials at each of three percentages of their maximum speed (50, 75, and 100%) along with one set of trials at a self-selected speed. Results demonstrated that in the elite male group the self-selected speed (79.4%) was significantly more accurate than the 100% maximum speed trials with no other significant differences between sets of trials. Results also indicated that in two other groups self-selected velocities (elite under-19 males, 79.8%; sub-elite senior males, 81.7%) were significantly more accurate when compared to 50% of their maximum speed. The results from this study fail to describe an inverse linear relationship between speed and accuracy.

Freeston and Rooney (2014) examined throwing with 20 adult baseball players. Located 20 meters away from a target that was placed 70 cm above the ground, each participant performed 10 trials at 70, 80, 90, and 100% of their maximum effort. Results of this study found that error increased significantly from 70% to 100% of their maximum speed. It was concluded that accuracy was optimized at 70% for the overarm throw and the results supported a significant linear speed-accuracy trade-off within this continuum.

Cauraugh et al. (1990) examined speed and accuracy of the tennis serve in 15 highly skilled adult tennis players and analyzed their serve to the opponent court surface in sets of 10 trials at three percentages of maximum speed (70, 80, and 90%). Trials that were not within 5% of the speed condition were repeated. It was discovered that as the speed increased there was no resultant detriment to the target accuracy, failing to support a speed-accuracy trade-off. Juras et al (2009) tested the dependence of movement time and anticipatory postural adjustment time on distance and width of a target in a form of the standing long jump with 15 adult males. Participants performed eight sets of 15 jumps from two different distances representing 20% and 40% of their maximum to targets consisting of four varying widths (6, 10, 15, and 20 cm). The result of this study demonstrated a linear scaling of movement time with movement distance, but results did not demonstrate linear scale of movement time with target size, violating the speed-accuracy trade-off.

Southard (2014) examined 10 young adult men and 10 young adult women kicking a stationary ball at a vertical line performing five trials at each of three percentages of their maximal effort (33, 66, and 100%). Spatial accuracy was measured as absolute constant error from a vertical line representing the target. There were no significant main effects or interactions reported with either speed or accuracy, which failed to support the speed-accuracy trade-off.

Urbin et al. (2012) investigated IV theory and the speed-accuracy trade-off in overarm throwing performances using skilled and low-skilled adults. Eight women and 22 men performed 70 total throwing trials at seven percentages of their maximum speed (40, 50, 60, 70, 80, 90, and 100%). Participants threw at a general target from approximately 10 meters for all of the trials. Results demonstrated there was no significant linear relationship between percentage of maximum speed and spatial error ($F = 0.41$, $p = .5226$). Throwing speed variable error across the seven conditions reported a significant inverted-U ($p < .001$, $\eta 2 = .555$) curvilinear relationship. Both the skilled and low-skilled groups demonstrated similar inverted-U trajectories. The low-skilled demonstrated less variability overall while the skilled group demonstrated less variability at maximum effort. Results of this study support Sherwood and Schmidt's (1980) inverted-U theory as well as violating the speed-accuracy trade-off.

Chappell et al. (in press) also tested impulse-variability theory and the speed-accuracy trade-off by designing a study similar to Urbin et al. (2012), but used kicking. Kicking a stationary ball from the ground demands the performer overcome a double-accuracy constraint (i.e., accurate contact with the ball and target accuracy), which arguably makes it a more difficult task to test than throwing. Five women and 23 men performed 60 total kicking trials (10 per condition) toward a target at six percentages of their maximum speed (50, 60, 70, 80, 90, and 100%). Spatial accuracy results indicated a significant quadratic function ($p < .0001$, $\eta 2 = .474$) providing no support for the speed-accuracy trade-off. There also was a significant inverse linear function ($p < 0.001$, $\eta 2 = .345$) for kicking speed variability across the target speed percentages indicating that, as force increased, the consistency kicking speed improved. While failing to support the inverted-U hypothesis, the results directly opposed the initial tenants of IV theory.

Results of all but one study in the last aforementioned group of studies did not demonstrate evidence of a speed-accuracy trade-off across the various percentages of maximum effort. Two of the studies also reported the variability (i.e., consistency) of performance and discovered partial support for the inverted-U hypothesis and both noted decreased variability when performing at maximum speed in throwing (skilled and low-skilled; Urbin et al., 2012) and kicking (Chappell et al., in press). In fact, variability in resultant projectile speed, which is an important predictor of learning and performance in these types of skills, was lowest at maximal performance speeds. Urbin et al. (2012) and Chappell et al. (in press) have been the only two studies that have tested the application of both impulse-variability theory and the speed-accuracy trade-off in ballistic skills in the same study. While results of speed variability data were not quite similar in kicking and throwing data, both studies (as have many other studies) violated the speed-accuracy trade-off.

Limitations of previous studies

Based on the compilation of data presented in this review, previous studies have not clearly established a consistent relationship between speed and accuracy performance that exists while performing ballistic skills. Attempts have been made to situate results that align with the speed-accuracy trade-off assumption without showing trials over a range of conditions that could produce a linear description. Many studies also have been limited by only comparing two points of reference (i.e., accuracy emphasis and speed emphasis) instead of manipulating the trials over a wide range of velocities including maximum speed. There also have been differences in tasks with the manipulation of different constraints such as target or implement modification. And, some aspect of performance variability has only been examined in a few studies. This has been controlled by only allowing trials that are performed within a certain percentage of the required instructions for that trial. Other studies have varied their calculations of spatial accuracy providing scores based on inappropriate one-dimensional accuracy measures (e.g., hit the target or absolute error) instead of direct measurement by using two-dimensional coordinates produced at the point-of-contact. Sample size of many studies also is a noted limitation, with some samples having only 12 or less total participants. Lastly, a limitation that was seen in previous studies based on the use of adults in most studies, or that the use of only one skill level (i.e., mostly skilled performers). One of the primary gaps in the literature for testing IV theory is the lack of testing this theory with children as the sample group. In addition, potential sex and skill level differences have rarely been addressed. .

Statement of Purpose

In ballistic multijoint movements, such as throwing and kicking, variability could be a limiting factor on performance. In addition, consistency is an important factor that provides a measure of skillfulness. Impulse variability theory and the speed-accuracy trade-off have not been examined within the same study using children, which is an important limitation as understanding their applicability for instruction is important. Therefore, the study has two purposes. The first purpose of the current study is to examine IV theory as it applies to throwing and kicking in a sample of children of various skill levels and gender. The second purpose is to examine the speed-accuracy trade-off as it applies to throwing and kicking in a sample of children of various skill levels and gender. Each purpose is addressed in a separate research article

In the first article, two hypotheses are tested. The first hypothesis is that variability in throwing speed will replicate an inverted-U that has been associated with impulse variability theory and also demonstrated in a sample of young adults (Sherwood

& Schmidt, 1980; Urbin et al., 2012). The second hypothesis is that variable error in kicking performances will demonstrate an inverse linear function what was demonstrated in a sample of young adults (Chappell et al., in press). In the second article, the hypothesis tested is that the relationship between throwing and kicking speed and spatial error will not support the speed-accuracy trade-off (Chappell et al., in press; Urbin et al., 2012).

CHAPTER 2

EXAMINING IMPULSE-VARIABILITY THEORY AND THE SPEED-ACCURACY TRADE-OFF IN CHILDREN'S OVERARM THROWING PERFORMANCE[1]

[1] Molina, S.L. and Stodden, D. F. To be submitted to Research Quarterly for Exercise and Sport

The development of motor competence is important for promoting physical activity and health related fitness across the lifespan (Cattuzzo et al. 2014; Holfelder & Schott, 2014; Lubans, Morgan, Cliff, Barnett, & Okely, 2010; Stodden et al., 2008). As the acquisition of motor skill competency (e.g., fundamental motor skills) does not occur naturally, it must be taught and practiced in order to consistently improve (Logan, Robinson, Wilson, & Lucas, 2012). Evidence-based principles and theories from the motor learning and motor control literature can play an important role in the pedagogical practices of practitioners (e.g., physical educators, coaches, and other movement educators).

Fitts' law (1954) and its application, the speed-accuracy trade-off, are well-known principles that can be applied to many fundamental movements and performance (Urbin, Stodden, Fischman, & Weimer, 2011). Specifically, the speed-accuracy trade-off describes an inverse linear relationship between the speed of a movement and the accuracy of that movement. However, when examining the speed-accuracy trade-off in multijoint ballistic skills (e.g., throwing, kicking, jumping), recent research does not support the inverse linear relationship between speed and accuracy (Chappell, Molina, McKibben, & Stodden, in press; Juras, Slomka, & Latash, 2009; Southard, 2014; Urbin, Stodden, Boros, & Shannon, 2012; van den Tillaar & Ettema, 2006). For example, Urbin et al. (2012) indicated there was no statistically significant relationship between speed and the resultant spatial error across a range of speed percentages (40-100%) in overarm throwing. Chappell et al. (in press) also showed that 40-59% of maximum kicking speed actually resulted in greater spatial error than speeds approximately 70-79% of maximum. These results were surprising given the consistency of prior research regarding the generalizability of the speed-accuracy trade-off in experimental as well as applied settings. For instance, the speed-accuracy trade-off is incorporated in national standards and grade level outcomes for physical education (S2.H2.L2, p. 34; SHAPE America, 2013).

Inquiry from Fitts' initial work also led to the development of impulse-variability (IV) theory (Schmidt et al., 1979), which provides a theoretical framework to describe the relationship between force and force variability (see Urbin et al. 2011 for a review of IV theory). Original tenets of IV theory suggested there would be a direct linear relationship between force output and force variability, but this hypothesis was based on a limited range of force production capability (i.e., up to 65%; Schmidt et al, 1979; Sherwood & Schmidt, 1980). Further research in this area examined a more extensive range of force production (i.e., up to maximum output) and the resulting variability profile resembled an inverted-U, where variability of force was greatest at approximately 60-70% of maximum force. As force continued to increase to maximum, force variability decreased (Schmidt & Sherwood, 1982; Sherwood & Schmidt, 1980). Urbin et al. (2011) suggested that IV theory, which was based on single-joint movements or static force production, could be generalized to more complex multijoint ballistic skills, allowing for an examination of movement force variability using resultant speed of a projected object (e.g., ball) or mass (i.e., total body mass), or an implement as a measure of systemic force output. This suggestion led to investigations of IV theory in overarm throwing and kicking (Chappell et al., in press; Urbin et al., 2012).

Urbin and colleagues (2012) examined the application of IV theory in overarm throwing across a wide spectrum of throwing speed percentages (40-100%) with young adults (i.e., 18-25 years old). Force variability results clearly demonstrated the inverted-U identified by Schmidt and Sherwood (1982) and the participants actually demonstrated the highest throwing speed consistency at maximum throwing speed (i.e., hypothetical maximum systemic force output). In addition, the lower-skilled throwers in this sample actually were more consistent than the higher-skilled performers except at 90-100% maximum speed. As previously mentioned, there were no differences in accuracy across the entire spectrum of throwing speed percentages.

Chappell and colleagues (in press) followed a similar methodology to Urbin et al. (2012) when examining IV theory and the speed-accuracy trade-off in kicking across a continuum of individual kicking speeds (50-100%) in young adults. Variable error findings were similar to Urbin et al. (2012) with kickers performing most consistently at 90-100% maximum speed. However, unlike Urbin et al., overall variable error results demonstrated an inverse linear relationship across the entire spectrum of kicking speeds. Thus, these data not only failed to support an inverted-U identified with IV theory (Schmidt & Sherwood, 1982), but the data also were in direct contradiction of the original hypotheses of IV theory.

While these recent data examining IV theory and the speed-accuracy trade-off in ballistic skills are intriguing, of perhaps greater importance for practitioners and coaches is to understand whether these outcomes would be demonstrated in children's performance. Ballistic skill performance in early learners (e.g., children) has been associated with increased variability and lower levels of performance (i.e., accuracy) based on the learner's overall lack of experience with these types of skills and based on their continued exploration of a variety of movement skills across childhood in an attempt establish and/or develop a more advanced movement pattern (Gentile, 1972; Fitts & Posner, 1967). Specifically, performance in overarm throwing in children and adolescents is more variable than in adult performers (Fleisig, Chu, Weber, & Andrews, 2009; Urbin, Stodden, & Fleisig, 2013). However, Urbin et al. (2012) indicated that lower skilled young adult throwers were actually more consistent at lower levels of performance (i.e., 40-80% maximum speed), as compared to higher skilled throwers. In addition, there were no differences in accuracy measures between higher and lower skilled throwers. Chappell et al. (in press) also indicated that there was no difference in variability between high and low skilled kickers. Based on the aforementioned studies, the appropriateness of generalizing findings demonstrated in adults and applying them to developing children is questionable. Unfortunately, information regarding ballistic movement skill performance, specifically relating to IV theory or the speed-accuracy trade-off in children is limited mostly to a dichotomous instructional or task-specific goal emphasis (i.e., speed only, accuracy only, or both; Belkin & Eliot, 1997; Engelhorn, 1997). A more comprehensive approach to the question would be to elicit performance across a continuum of effort levels. Thus, the purpose of this study was to examine the applicability of IV theory and the speed-accuracy trade-off in in children's overarm throwing performance.

Methods

Participants

Based on effect sizes demonstrated in Urbin et al. (2012), an a-priori power analysis at a .8 level with a small to moderate effect size of .2 (Cohen, 1988) indicated a minimum of 36 participants were needed to adequately power the study (G-Power, version 3.1.9.2). A purposeful sample of 45 elementary children (21 girls) between the ages of nine and 11 years (mean age = 10.6 years for girls; 10.7 years for boys) capable of throwing at a maximum speed of at least 13.41 m/s (30 mph) were recruited to participate in the study. Permission to conduct the study was obtained from the participating school district and the University's Human Subjects Review Board. All participants provided verbal assent and had Parental/guardian informed consent prior to participation in the study.

Instruments

A grid containing a target with a 20 x20 cm centroid was placed 1.5 meters above the ground on a gymnasium wall to serve as a reference goal for the participants. Participants used a developmentally appropriate hand-sized ball (Volley, 6.7 cm in diameter, 12 g) for throwing. They were allowed an approach of their preference prior to throwing the ball (Urbin et al., 2012), but were prompted to stay behind a marking on the floor that was 3.05 meters (i.e., 10 feet) from the target. Ball speed was measured using a Stalker Pro II radar gun (Stalker Inc., Plano, TX) and interpreted as an index of systemic force output (Chappell et al., in press; Urbin et al., 2012). Peak speed was recorded for each throwing trial. Researchers measured the two-dimensional location of each throw using a two dimensional laser level and placing it over the approximate center of the strike point of the ball. X- and Y-coordinate measurements were recorded after each trial.

Procedures

Procedures for this study were similar to Chappell et al. (in press) and Urbin et al. (2012). Participants were required to attend two testing sessions during their regular physical education class with at least one week between sessions to minimize any potential soreness and fatigue between testing days. Upon arrival for each testing session, participants completed a general five-minute warm-up protocol. The warm-up involved dynamic movements manipulating the upper and lower body limbs through a full range of motion. After the initial warm-up, children were allowed up to ten self-paced warm-up trials of overarm throwing in order to build up to maximum effort testing .

The purpose of the first session was to identify each individual's maximum throwing speed and to familiarize participants with the study protocols. Following the warm-up activities on the first testing session, participants were allowed five overarm throwing trials and were instructed to "throw the ball as hard as you can." There was no target specified for trials in the first session. The highest speed of five maximum-effort trials was used to determine the maximum speed and calculate percentages of maximum speed for each participant. Immediately following maximum speed testing, four percentages of maximum speed (45, 65, 85, and 100%) were calculated for each individual and served as target speed conditions for the second testing session. To familiarize participants with the target conditions, they performed overarm throws at each of the speed conditions toward the target until they were capable of producing two consecutive trials ± 0.89 m/s (± 2 mph) of each target condition. Throwing speed feedback in miles per hour was provided to the participant after each trial, but the information was limited to details on the speed of their performance and whether they needed to increase or decrease speed in order to reach their target speed for that trial condition. Data from the first session were not used in the analysis.

After completing the warm-up protocol for the second testing session, participants performed, in succession, five blocks of eight trials (40 total trials). Within each block there were two trials at each of the four target speed conditions. The target speed trial order within each block was structured by way of a random number generator. Specific instructions given prior to each trial were for the participants to throw at the specified percentage of maximum speed and to hit the target. Following each trial, researchers provided exact throwing speed feedback in miles per hour. No other information or feedback about each trial was provided. The contact point of the ball on the wall identified the X and Y distance from the centroid (measured in cm) on the two-dimensional target and was recorded immediately after each trial. Participants were allowed to rest at self-selected durations during this time to minimize fatigue, with a minimum of one minute between testing blocks.

Statistical Analysis

Speed Variability. Variable speed error ($\sqrt{\sum(\mathrm{x}_i - \mathrm{M})^2}$) on the 10 trials for each specific prescribed speed percentage were averaged and used for statistical analysis (Chappell et al., in press; Urbin et al., 2012). These data were analyzed using a repeated measures ANOVA (four levels) with built-in polynomial contrasts to determine within subject variability (Chappell et al., in press; Urbin et al., 2012). Bonferroni corrected post-hoc tests were implemented to examine differences in speed variability between percentages of maximum conditions. A 2 (performance level) x 4 (condition) mixed model repeated measures ANOVA was used to examine speed variability between high and low performer groups. Independent samples *t* tests were conducted to detect differences between the performance level groups at each percentage of maximum. Significance for each of the sets of analysis was set at the .05 level.

Spatial Accuracy. To analyze spatial error associated with individual participants' throwing speed percentage, each throw was normalized to a percentage of their maximum speed and grouped into five bandwidths (≤59%, 60-69%, 70-79%, 80-89%, and ≥ 90%; Chappell et al., in press). A repeated measures ANOVA (5 levels) with polynomial contrast was utilized to calculate mean radial error (MRE). To provide a more sensitive measure of accuracy, subject-centroid radial error (CE) and bivariate variable error (BVE) also were analyzed using a repeated measures ANOVA (five levels) with built-in polynomial contrasts. The combination of MRE, CE, and BVE is suggested to provide a more comprehensive understanding of spatial error in two-dimensions (Hancock, Butler, & Fischman, 1995). Bonferroni post-hoc tests were implemented to examine the differences in spatial accuracy error scores (MRE, CE, and BVE) across the represented bandwidth percentages of maximum speed. A 2 (performance level) x 5 (condition) mixed model repeated measures ANOVA was used to examine spatial accuracy via MRE, CE, and BVE between high and low performer groups. Due to a lack of kinematic analysis in this study, higher and lower performing groups were identified using criterion data from Stodden, Langendorfer, Fleisig, and Andrews (2006) where ball speeds of a trunk level 2 were averaged to be 14.20 m/s with a standard deviation of 4.58 m/s. Using this criterion, the higher performing group was identified being able to produce maximum speeds of at least one standard deviation above the criterion mean.

Therefore, 18.78 m/s (i.e., 42 mph) was used as the cutoff between the two groups. Independent samples *t* tests were implemented to detect differences between the performance level groups at each bandwidth of maximum. Significance for each of the sets of analysis was set at the .05 level.

Results

Speed Variability

Mean variable error for throwing speed (m/s) as a function of percentages of maximum speed across all participants is displayed in Figure 1. Results indicated that there was no statistically significant difference across the target conditions, F (3, 176) = 0.45, $p = 0.72$. Due to a lack of statistical significance, no follow-up tests were conducted. Between group differences with higher/lower performers were statistically significant, F (1, 172) = 37.90, $p < .001$, $\eta 2 = .465$, with lower skilled demonstrating less variability across the target speed conditions. T-tests revealed statistically significant differences at 45%, 65%, and 100% of maximum (see Table 1, Figure 2).

Spatial Accuracy

Results for spatial accuracy indicated that there were no statistically significant differences in mean radial error, F (4, 207) = 1.59, $p = 0.18$, $\eta 2 = .20$, subject-centroid radial error, F (4, 207) = 1.82, $p = 0.13$, $\eta 2 = .20$, and bivariate variable error, F (4, 202) = 2.15, $p = 0.08$, $\eta 2 = .20$ (see Figure 3, 4, and 5, respectively). Due to lack of statistical significance, no follow-up tests were conducted. Even though the BVE results were trending toward significance, the study was powered to detect moderate main effects that have been demonstrated in prior literature (Chappell et al., in press; Urbin et al., 2012).

Therefore, with lack of statistical significance at a small effect size, a larger sample would be needed to detect significant differences with minimal to small effect sizes (Cohen, 1988). Group differences between the higher and lower performance groups with mean radial error, F (1, 202) = 2.99, p = 0.09, and CE, F (1, 202) = 0.61, p = 0.43, were not statistically significant; thus, no follow up tests were conducted. Bivariate variable error was found to be statistically significant between groups, F (1, 197) = 5.27, p = .02. Follow-up t-tests indicated that 80-89% of speed bandwidth was statistically significant, t(41) = 2.22, p = .03, with the higher performing group (M = 0.31 m, SD = .12) demonstrating greater precision than the lower performing group (M = .41, SD = .14).

Discussion

This study examined the applicability of IV theory and the speed-accuracy trade-off in in children's overarm throwing performance. Variable error results failed to support the inverted-U that has been theorized by IV theory (Sherwood & Schmidt, 1980) and was demonstrated in overarm throwing with adults (Urbin et al., 2012). Data from this sample of children indicated that there was no significant increase or decrease in speed variability across a range of throwing speed percentages of maximum. When compared to adults (Urbin et al., 2012), the variable error failed to decrease, especially at the lower and upper ends of the continuum of performance. This indicates that systemic force output regulation in performances of overarm throws in developing children may be different from that of adults. Differences in force regulation may be a function of the relative stability of intersegmental coordination among the many degrees of freedom in the throwing patterns of children. Overall, when children are compared to adults, there is greater stability in the adult movement patterns, regardless of skill level (Fleisig et al., 2009).

This idea is possibly demonstrated in both these data and the recent adult data as the difference in variable error between the higher and lower performing groups of children were similar to the adult data from approximately 40% to 80% of maximum force output. The unskilled adult participants had lower variable error and followed along a similar trajectory with the skilled participants up until 90% and 100% of maximum force output (Urbin, 2012). As suggested by Urbin and colleagues (2012) it is likely that the higher skilled performers, via having more experiences throwing, have the capability of exploring more strategies for producing various speeds (i.e., preparatory positions and manipulating timing of segmental interactions) in an attempt to achieve the respective speed goals. Lower performing persons may have demonstrated a more consistent movement pattern strategy at all force levels (i.e., attractor state; Langendorfer & Roberton, 2002) that would function to constrain degrees of freedom within the system (Bernstein, 1967; Whiting, 1984), which could account for the overall lower speed variability levels. In contrast, other data have demonstrated higher kinematic variability with overarm throwing in lower skilled compared to higher skilled individuals at maximum speed (Southard, 2002; 2009; Urbin et al., 2013), yet the consistency in throwing speed was not addressed. Children’s force regulation may not be as consistent as adults based on the decreased general amount of experience, not only in this specific task, but all other forms of multi-segment movements where energy transfer among segmental movements is important. Further testing of biomechanical parameters (e.g., kinetics and relative temporal variables) would be needed to understand the association of variability of kinematics and the variability of performance in both skilled and unskilled individuals within performances across a continuum of speeds.

The observed spatial error data also failed to support a speed-accuracy trade-off. With the small sample size, this study was powered to detect small to moderate main effect sizes and not necessarily to detect small differences between groups. Thus, although there was a trend for increasing error with increased speed, the effective change is quite small. This non-support of the application of Fitts' Law in a sample of children provides further support against a speed-accuracy trade-off in ballistic skills (Chappell et al., in press; Juras et al., 2009; Southard, 2014; Urbin et al., 2012; van den Tillaar & Ettema, 2006).

Limitations

Several limitations of this study should be identified. First, in other studies examining IV theory in multijoint ballistic skills a bandwidth of ±10% was used to compare force variability (Chappell et al., in press; Urbin et al., 2012). In this study it was determined that the selected bandwidths would be more developmentally appropriate based on the children's cognition levels. Therefore, only four target conditions across the continuum of maximum speeds were utilized compared to six or seven target conditions that were used in adult performances. Second, specific biomechanical parameters of throwing were not examined in this study. Understanding movement pattern differences based on kinematic or kinetic analyses may provide more insight on changes in coordination patterns as well as performance across conditions.

Implications for Practitioners

Results from this study have implications practitioners (e.g., physical educators, coaches, and other movement educators). In practice, Roberton (1996) was an early advocate of emphasizing the removal of accuracy constraints during initial learning of ballistic motor skills. Removing accuracy constraints and promoting an emphasis on movement/outcome speed promotes the development of advanced movement coordination patterns and outcomes (i.e., maximum speed; Chappell et al., in press; Urbin et al., 2012) without sacrificing accuracy (i.e., success in accomplishing the target goal). This application of practice can be reflected in texts that provide instructional strategies to physical education teachers (Graham, Holt/Hale, & Parker, 2012; Pangrazi & Beighle, 2012; Rink, 2013; Rovegno & Bandhauer, 2013). In essence, focusing on effortful practice without an accuracy constraint would reduce the cognitive processing load for children, which is supported by motor learning principles regarding the amount of instruction (i.e., modeling and verbal) and augmented feedback information (Magill & Anderson, 2013). Designing task progression and promoting developmentally appropriate environments in ways that elicit the most advanced movement pattern should be promoted to expedite a child's progresses toward an autonomous stage (Fitts & Posner, 1967) of learning.

What Does This Article Add?

The results of this study provide evidence that the systemic force output in children's overarm throwing performance failed to support the inverted-U of impulse-variability theory. These variable error results also contrast the findings from adults.

Results indicated the speed-accuracy trade-off, which has been generalized to all human movement for decades, is not supported in children's performance in ballistic motor skills such as overarm throwing. Based on the results of this study and other mounting evidence in adults (Chappell et al., in press; Juras et al., 2009; Southard, 2014; Urbin et al., 2012; van den Tillaar & Ettema, 2006), the promoting of learning of ballistic motor skills should be revisited.

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Table 2.1.

Follow-up analysis for between group differences of variable error.

Target Speed Condition	Lower Performing		Higher Performing			
	M	SD	M	SD	*t* (43) =	*p*
45%	1.14	.52	1.59	.53	2.655	=.01
65%	1.13	.34	1.82	.57	5.090	<.01
85%	1.21	.43	1.48	.48	0.070	=.07
100%	1.26	.44	1.70	.52	2.944	<.01

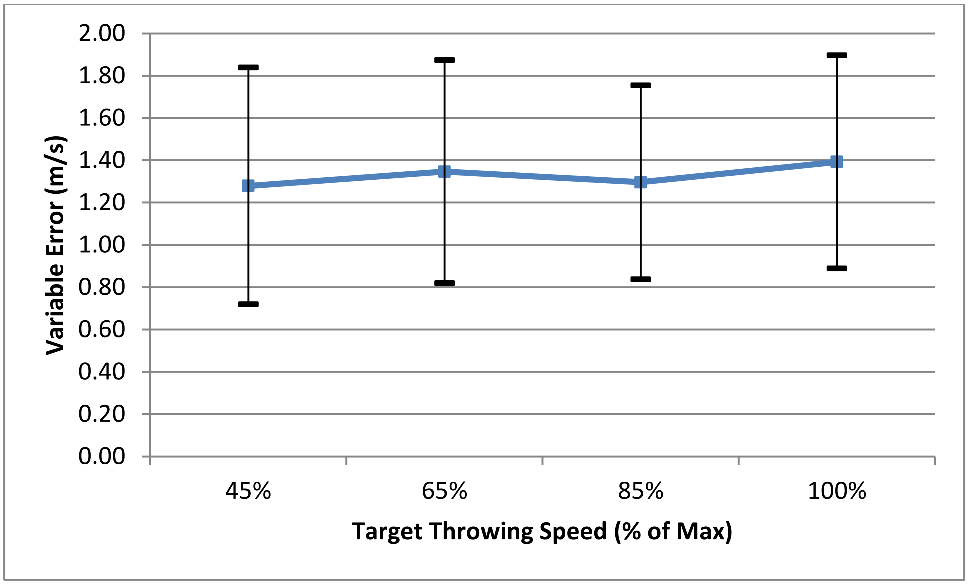

Figure 2.1. Means and standard deviations of variable error of throwing speed as a function of percentage of maximum effort across all participants.

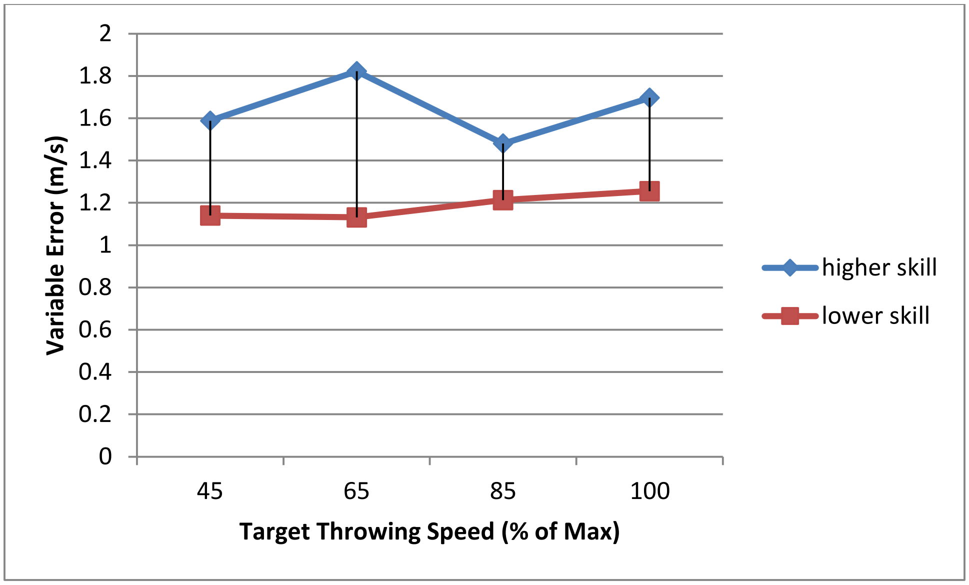

Figure 2.2. Mean variable error of throwing speed as a function of percentage of maximum effort across lower skilled and higher skilled participants

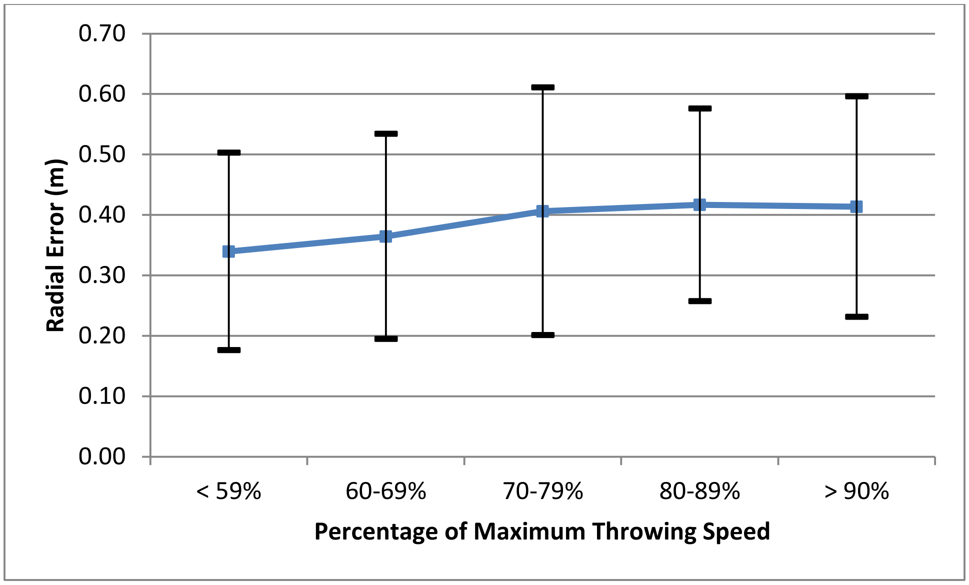

Figure 2.3. Means and standard deviations of mean radial error (m) at different observed throwing speed ranges.

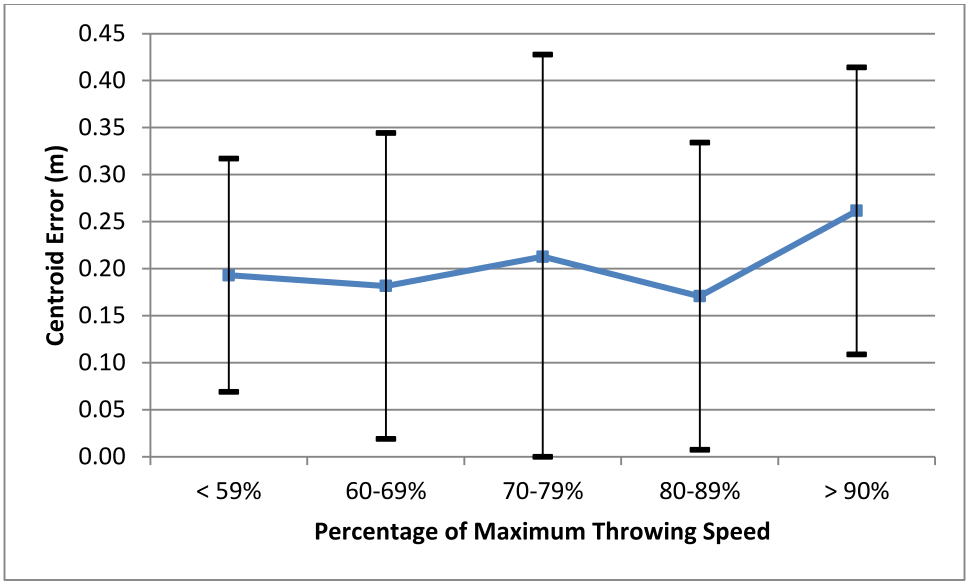

Figure 2.4. Means and standard deviations of centroid error (m) at different observed throwing speed ranges.

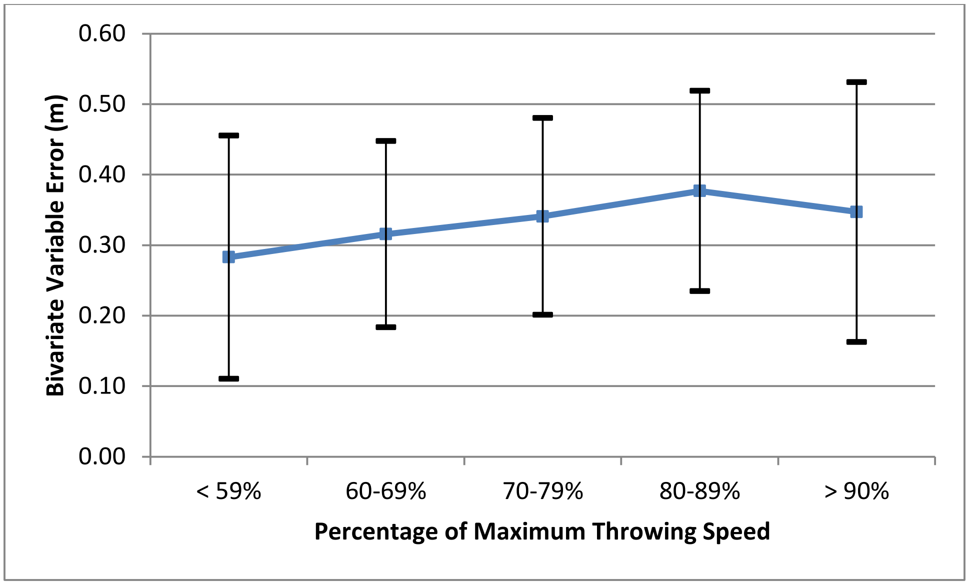

Figure 2.5. Means and standard deviations of bivariate variable error (m) at different observed throwing speed ranges.

CHAPTER 3

EXAMINING IMPULSE-VARIABILITY THEORY AND THE SPEED-ACCURACY TRADE-OFF IN CHILDREN'S KICKING PERFORMANCE[2]

[2] Molina, S. L. and Stodden, D. F. To be submitted to Motor Control.

Wulf and Shea (2002) called for a need to use more complex skills in human movement research in order to gain insight into the learning process that extends beyond results demonstrated with relatively simplistic lab-based studies. Fitts' Law (1954) and impulse-variability (IV) theory (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Sherwood & Schmidt, 1980) are both examples of motor behavior principles/theories that were derived using simple laboratory tasks. Although with these and other motor behavior principles/theories, it is tempting to generalize these laws to more complex skilled behavior (i.e., multijoint ballistic skills), evidence supporting this is lacking. As there are physical, cognitive, and psychological differences in learners across the lifespan, developmental differences across age should be considered when testing principles and theories for the purpose of generalization. Specifically, as children transition into adolescence and adulthood, they are engaged in processes associated with of growth, maturation, as well as cognitive and psychological development with a wide range of variation in these processes during the growing years (Malina, Bouchard, Bar-Or, 2004). Thus, it is important to understand the applicability of these principles/theories in complex skill performance across development.

The speed-accuracy trade-off is an important application of Fitts' Law (1954) that describes an inverse relationship between movement speed and accuracy of the movement. For over half of a century, the speed-accuracy trade-off has been generalized to human movements and indicated in various target-directed movements (Plamondon & Alimi, 1997). Although the speed-accuracy trade-off has been generalized to different aspects of movement, results of recent studies have failed to support a speed-accuracy trade-off when applied to multijoint ballistic skills (e.g., throwing, kicking, and jumping).

For example, Juras, Slomka, and Latash (2009) did not find significant differences in movement times when target distances and widths were adjusted for standing long jump performances. When examining the speed-accuracy trade-off in overarm throwing performances across a continuum of speed performance (40-100%), no statistically significant differences were indicated (Urbin, Stodden, Boros, & Shannon, 2012). In contrast, kicking performances with young adults demonstrated increased accuracy across a continuum of kicking speed with 40-59% of maximum kicking speed resulting in greater error than speeds 70-79% of maximum speed (Chappell et al., in press). Overall, emerging evidence has demonstrated a lack of support for the speed-accuracy trade-off in multijoint ballistic skill performance across a continuum of speeds.

Impulse-variability theory was derived from the application of Fitts' Law and describes the relationship between force and force variability under the assumption that movements are preprogramed (Schmidt et al., 1979). Resultant limb trajectories are therefore dependent on the variability of multiple force impulses produced and their duration during movement (Schmidt et al., 1979). Original tenants of IV theory proposed a direct linear relationship between force and force variability (Schmidt et al., 1979); however, continued research on the topic that included a broader range of force capabilities (Schmidt & Sherwood, 1982; Sherwood & Schmidt, 1980), temporal constraints on force production (Newell, Carlton, Carlton, & Hancock, 1980; Newell, Hoshizaki, Carlton, & Halbert, 1979), accuracy of timing of forces produced (Newell, Carlton, & Hancock, 1984) and combinations of these factors (Sherwood, Schmidt, & Walter, 1988) resulted in the demonstration of an inverted-U phenomenon, with force being most variable at approximately 60-70% of maximum (Schmidt & Sherwood, 1982;

Sherwood & Schmidt, 1980). As forces produced continue to increase from 70% to maximum, output variability decreased. See Urbin, Stodden, Fischman, & Weimer, 2011 for a comprehensive review of IV theory.

Urbin et al. (2011) suggested that the tenants of IV theory (i.e., the inverted-U) could be generalized to multijoint ballistic skills and tested this assumption in overarm throwing with young adults (ages 18-25). Their results supported the inverted-U of IV theory with throwing speed (as a measure of systemic force) variability being most variable at 60% of maximum (Urbin et al., 2012). As a follow-up to this study, Chappell et al. (in press) applied the same methodology to kicking. While kicking and throwing are both multijoint ballistic skills, kicking is arguably a more difficult skill than throwing as accuracy is required for both projecting the ball (i.e., appropriate contact with the foot) and hitting a target. In contrast to the throwing results demonstrated by Urbin et al. (2012), their results failed to support the inverted-U and actually demonstrated an inverse linear relationship across a continuum of kicking speeds. Chappell et al.'s results directly opposed the original tenets of IV theory (Schmidt et al., 1979), thus adding more uncertainty to the applicability of IV theory in multijoint ballistic skill performance.

Unfortunately, both of the studies that examined IV theory and the speed-accuracy trade-off in multijoint ballistic skills have been conducted with adult samples (i.e., 18 years and older). A next logical step would be to examine whether performance of developing children, who tend to be more variable in their performance (Fleisig, Chu, Weber, & Andrews, 2009; Urbin, Stodden, & Fleisig, 2013), would support or refute IV theory principles and the speed-accuracy trade-off. Therefore, the purpose of this study was to examine the applicability of impulse-variability theory and the speed-accuracy trade-off in children's kicking performance.

Methods

Participants

A purposeful sample of 43 elementary children, (19 girls; mean age = 10.7 years for girls; 10.8 years for boys) capable of kicking at a maximum speed of at least 13.41 m/s (30 mph) were recruited to participate in the study. Permission to conduct the study was obtained from the University's Human Subjects Review Board. All participants provided verbal assent and had Parental/guardian informed consent prior to participation in the study.

Instruments

A 3 x 3 m grid containing a 20 x 20 cm centroid target placed 1.0 meter above the ground along a gymnasium wall served as a reference goal for the participants. For the kicking trials, the participants kicked a playground ball (Sportime, 20.32 cm in diameter) to the target from a distance of 3.05 meters and were allowed an approach of their preference prior to kicking the ball (Chappell et al., in press). Ball speed was measured using a Stalker Pro II radar gun (Stalker Inc., Plano, TX) and interpreted as an index of overall systemic force output (Chappell et al., in press; Urbin et al., 2012). Peak speed was recorded for each trial. Researchers measured spatial accuracy of the trials in both the X and Y dimensions using a two-dimensional laser level and placing it over the center of the impact point of the ball.

Procedures

Procedures for this study were similar to Chappell et al. (in press) and Urbin et al. (2012). All children were required to attend two testing sessions with at least seven days between testing days to minimize the potential for any soreness and fatigue between sessions. The purpose of the first session was to identify the individuals' maximum kicking speeds and to familiarize the children with the study protocols. Each child was led through a general warm-up that included upper and lower body flexibility exercises through a full range of motion. Following the warm up, children were allowed up to 10 self-paced warm-up kicking trials to build up to maximum effort.

Following the warm-up activities on the first testing session, children were provided with five kicking trials and were given the instruction of, "kick the ball as hard as you can". There was no target specified for these trials. The highest speed of five consecutive maximum effort trials was used to determine the maximum speed and to calculate percentages of maximum speed for each participant. Four percentages of maximum speed (45, 65, 85, and 100%) were calculated for each participant serving as target speed conditions for the study. Participants were required to demonstrate maximum kicking speed of at least 13.41 m/s (30 mph) to be allowed in the study. To familiarize children with the target conditions, they performed kicking trials at each of the speed conditions to the target until they were capable of producing two consecutive trials ± 0.89 m/s (± 2 mph) of each target condition. During the familiarization feedback was provided from the researcher to the child after each trial, but the information was limited to information on the speed of their performance and whether or not they will need to increase or decrease speed in order to reach their target speed for that trial condition. Data from the first session were not used in the analysis.

For session two, after completing a warm-up, children performed five blocks of eight trials (40 total trials) in succession. There were two trials at each of the four target conditions within each block of trials. Trials within each block were structured by way of random number generator. The specific instructions given prior to each trial were for the participants to kick at the specified percentage of maximum speed and to hit the target. Following each trial, the researchers provided exact kicking speed feedback in miles-per-hour. No other information or feedback about the trial was provided, although generic positive encouragement was randomly provided. Research staff identified the contact point of the ball on the wall for each kick and measured the X and Y distance from the centroid (measured in cm) on the two-dimensional target. The coordinates were recorded after each trial. Children were allowed to rest at self-selected durations during this time to minimize fatigue, with a minimum of one minute between testing blocks.

Statistical Analysis

Speed Variability. Variable speed error ($\sqrt{\sum(\mathrm{x}_i - \mathrm{M})^2}$) on the ten trials for each specific prescribed speed percentage were averaged and used for statistical analysis. These data were analyzed using a repeated measures ANOVA (four levels) with built-in polynomial contrasts to determine within subject variability (Chappell et al., in press; Urbin et al., 2012). Bonferroni post-hoc tests were implemented to examine differences in speed variability across percentages of maximum. A 2 (skill level) x 4 (condition) mixed model repeated measures ANOVA was used to examine speed variability between higher and lower performing groups. Independent samples *t*-tests were conducted to detect differences between the groups at each percentage of maximum. Significance for each of the sets of analysis was set at the .05 level.

Spatial Accuracy. To analyze spatial error associated with individual participants' kicking speed, each kick was normalized to a percentage of their maximum and grouped into five bandwidths of speed percentage (≤ 59.9%, 60-69.9%, 70-79.9%, 80-89.9%, and ≥ 90%). A repeated measures ANOVA (five levels) with polynomial contrasts was utilized to calculate mean radial error (MRE). Subject-centroid radial error (CE) and bivariate variable error (BVE) were also calculated with the same procedure to provide a more sensitive measure of spatial accuracy. The combinations of MRE, CE, and BVE have are suggested to provide a more complete vision of spatial error of kicking at a two-dimensional target centroid (Hancock, Butler, & Fischman, 1995). Bonferroni post-hoc tests were implemented to examine the differences in spatial accuracy error scores across the represented bandwidths of maximum speed. Significance for each of the sets of analysis was set at the .05 level. A 2 (performance level) x 5 (condition) mixed model repeated measures ANOVA also was used to examine MRE, CE, and BVE between higher and lower performing groups. Due to lack of literature providing a criterion for kicking speeds suggesting higher levels in children, children whose maximum kick speeds were greater than or equal to one standard deviation above the mean were noted as highly skilled. . Independent samples *t*-tests were performed to detect differences between higher and lower performing groups at each bandwidth of speed.

Results

Speed Variability

Mean variable error for kicking speed (m/s) as a function of maximum speed across all participants is displayed in Figure 1. Results indicated that there was statistically significant quadratic relationship across the target conditions (p = 0.048, $\eta 2$ = .288). Follow-up tests revealed that 100% maximum speed had significantly higher variability than the 65% condition (p =0 002, d = .674). Variable error between higher and lower performing groups were not statistically different, F (1, 164) = 2.26, p = .14, eliminating the necessity for any follow-up tests (figure 2).

Spatial Accuracy

Results for spatial accuracy indicated that there were statistically significant linear relationships with MRE, CE, and BVE (p < .001, $\eta 2$ = .485, p < .001, $\eta 2$ = .450, and p < .001, $\eta 2$ = .389, respectively; see Figure 3, 4, and 5). Follow-up tests displaying statistically significant differences between bandwidths of speed are displayed in Table 1. Group differences in MRE between the higher and lower performance groups, F (1, 199) = .06, p = .81, CE, F (1, 199) = 0.10, p = .75, and BVE, F (1, 190) = 0.76, p = .38, were not statistically significant. Due to lack of statistical significance, no follow-up tests were conducted.

Discussion

The purpose of this study was to examine of the applicability of impulse-variability theory and the speed-accuracy trade-off in children's kicking performance.

Children’s variable error data failed to support the inverted-U that has been theorized by impulse variability theory (Sherwood & Schmidt, 1980) and the inverse linear relationship demonstrated in kicking performances with young adults (Chappell et al., in press). In contrast, a statistically significant quadratic function demonstrating a U-shaped pattern with the target speed condition of 65% being less variable than the 100% target speed condition directly opposes the inverted-U associated with IV theory. With variability being the greatest at 100%, these data directly opposes the kicking variable error data from a young adult sample, which indicated the least amount of variability at 100% (Chappell et al., in press). These data suggest that force output regulation in a multijoint ballistic skill in children may be different from that of adults who generally demonstrate more of a consistent coordination pattern, regardless of their skill level (Chappell et al., in press). Additional evidence to support this contention is needed as there were no statistically significant differences in ability to regulate force output when comparing kicking performances between higher and lower performing children.

The lack of differences in speed variability between higher and lower performing children does not support data from Urbin et al.(2013) who demonstrated lower skilled children were more variable in throwing kinematic parameters than more highly skilled children. Overall, when examining the force/force variability relationship in multijoint ballistic skills the findings have failed to produce consistent results. This could imply that children and adults vary in their ability to regulate force output in the multijoint ballistic skill of kicking. Therefore, more work in the area is needed to provide a more definitive understanding of the relationship between force and force variability in multijoint ballistic skills at different developmental levels.

Spatial Error

The observed spatial error data failed to support a speed-accuracy trade-off and, in fact, demonstrated an inverse relationship between kicking speed and accuracy. This violation of the application of Fitts' Law with children provides further support against the speed-accuracy trade-off in ballistic motor skills (Chappell et al., in press; Juras et al., 2009; Urbin et al., 2012). In this study, individuals were able to perform kicking trials across a spectrum of speeds with improved accuracy as speed increased. Results also showed that there were no statistically significant differences between higher and lower performers. Thus, the spatial accuracy of kicking performance was not a function of performance capability of the children.

The results of the three spatial error measures (inverse linear relationship) did not follow the same patterns as the variable error data resulting in an explanation that is not straightforward. In essence, spatial error decreased while variability increased across increased speed percentages. When examining the integration of force output variability and spatial error in kicking performances with young adults (Chappell et al., in press), they could successfully adapt to higher systemic force demands while being able to maintain or even improve spatial accuracy. While speed variability tended to increase as force output (i.e., speed) increased toward maximum, the spatial measures of accuracy, magnitude, and bias of the spatial error improved. So even though the children were less consistent in their ability to produce maximum speeds during kicking performances compared to lower speeds, when higher speeds were achieved, they were more accurate. The combination of increased force output variability and increased spatial accuracy at maximum speed, according to the tenants of IV theory, is difficult to explain. However, as demonstrated by other researchers, speed or trajectory of movements and final position or accuracy of movements may be differentially controlled (Murtha & Sainburg, 2007).

Dynamic balance has been suggested to be a rate-limiter with kicking performance in children as a result of having to control their balance on one leg while swinging their other leg (Langendorfer, Roberton, & Stodden, 2012). Mally, Battista, and Roberton (2011) indicated that increases in force production of kicking performances with children produced movement changes in aspects of their approach, forward leg swing, and follow through. It would be feasible that movement changes across a continuum of force output production with children lead to greater force variability due to a lack of dynamic stability in the movement patterns that adults demonstrate (Fleisig et al., 2009). Overall, force regulation data with multijoint ballistic motor skills in children are very limited and need to be examined in greater detail.

Limitations

There are several limitations that should be mentioned. There was a lack of consistency in the variability in how the ball was kicked (i.e., toe, instep, or side of foot), the approach that was used for each kick, and the variability or error at the point of contact on the ball. A lack of consistency in these factors may have influenced both the ball speed as well as the resultant accuracy. However, kicking across a wide range of an individual's performance capability would inherently demand changes in coordination patterns, specifically in developing children. Thus, performance of a ballistic motor skill does not lend itself to a high degree of consistency in performance. In addition, not controlling for these factors would seemingly promote both increased speed variability and spatial accuracy, which was not the case; thus providing a stronger argument that that the speed-accuracy trade-off does not apply in ballistic motor skill performance. Resultant spatial accuracy did not take into account the trajectories that were demanded from the performances at the various speeds; however, the target distance was not excessive so even at lower speeds the projectiles were capable of reaching the target without dramatic changes in ball trajectories. Kinematic and kinetic aspects of the movements were not assessed, which could provide a more detailed analysis of performance measures and possibly help to explain the unexpected results. Finally, adult studies examining IV theory in multijoint ballistic skills used bandwidths of ±10% to compare force variability (Chappell et al., in press; Urbin et al., 2012). For this study only four target conditions across maximum speeds were used due to it being determined that the limited number of bandwidths was more developmentally appropriate based on the children's cognition and experience levels with kicking at various percentages of their maximum performance..

Conclusions and Applications

The findings of this study support the conclusions drawn from previous research (Cauraugh, et al., 1990; Chappell et al., in press; Engelhorn, 1997; Roberton, 1996; Urbin et al., 2012; van den Tillaar & Ettema, 2006) suggesting that sacrificing speed in ballistic motor skill acquisition would hinder optimal developmental progression of learning the skill and not provide an advantage in accuracy. Therefore, promoting a learning environment that emphasizes speed over form or accuracy would promote an advanced movement pattern and facilitate learning of multijoint ballistic skills in children. Overall, as motor behavior principles/theories are tested and applied using complex real-world skills, it is clear that more work needs to be conducted in these areas. There is a need to continue examining principles/theories beyond simple movement tasks and to test their applicability across different developmental levels.

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Table 3.1.

Post-hoc statistically significant differences between bandwidths in spatial error measures

Error Measure	Bandwidths	*p*	Effect Size (*d*)
MRE	**≤59%** - 80-89%	.004	0.65
	≤59% - ≥90%	<.001	1.02
	60-69% - ≥90%	<.001	0.90
	70-79% - ≥90%	.002	0.69
CE	**≤59%** - ≥90%	<.001	0.82
	≤59% - 80-89%	<.001	0.90
	≤59% - 70-79%	.001	0.73
BVE	**≤59%** - ≥90%	.001	0.73
	60-69% - ≥90%	<.001	0.85
	70-79% - ≥90%	<.001	0.78

Note. MRE = mean radial error; CE = subject-centroid radial error; BVE = bivariate variable error. Bold indicates greater error

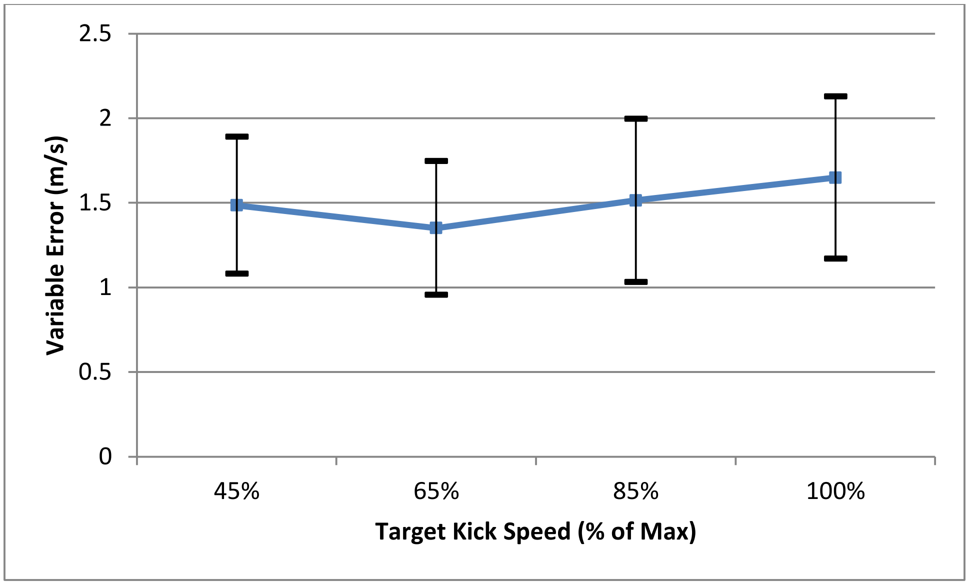

Figure 3.1. Means and standard deviations of variable error of kicking speed as a function of percentage of maximum effort across all subjects.

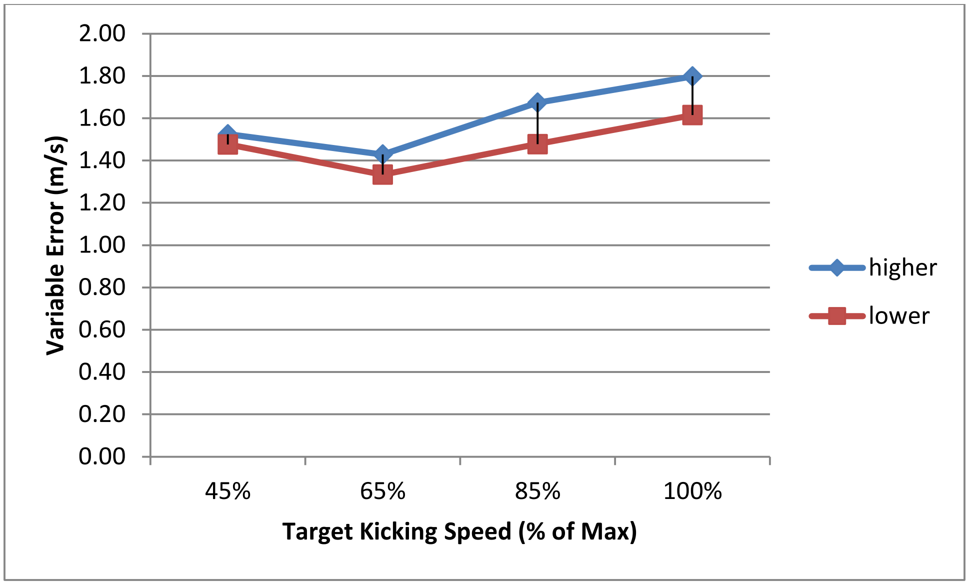

Figure 3.2. Mean variable error of kicking speed as a function of percentage of maximum effort across performance levels of participants.

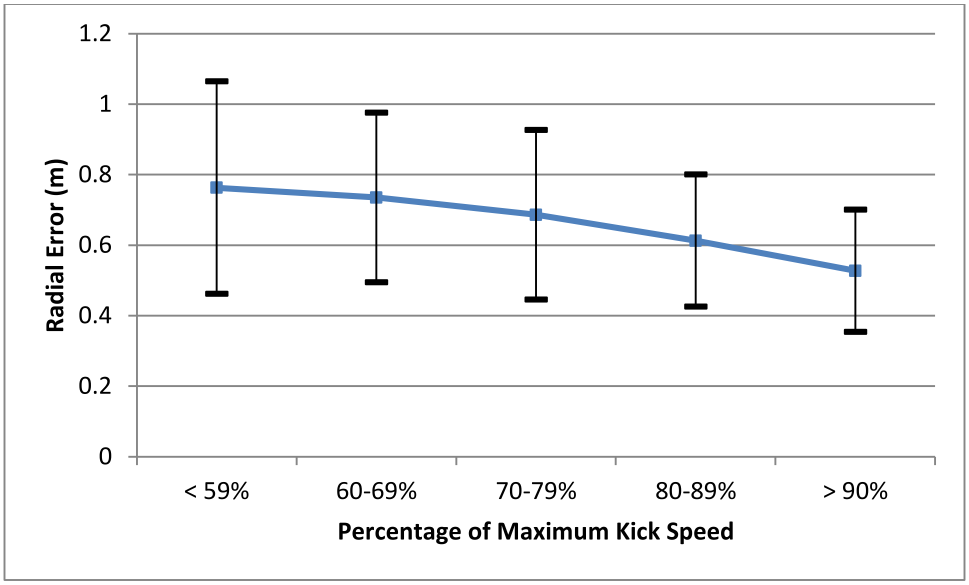

Figure 3.3. Means and standard deviations of mean radial error (m) at observed kick speed ranges.

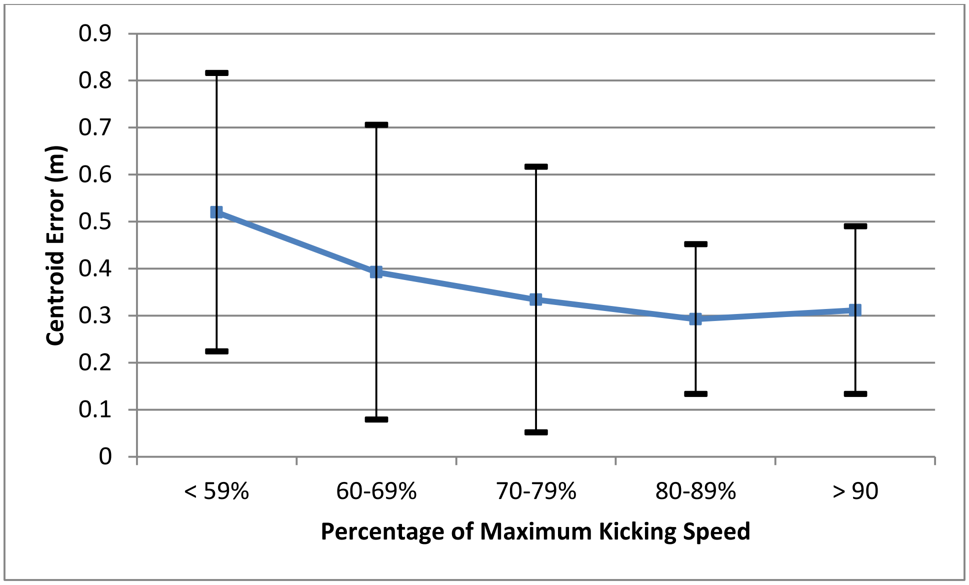

Figure 3.4. Means and standard deviations of centroid error (m) at observed kick speed ranges.

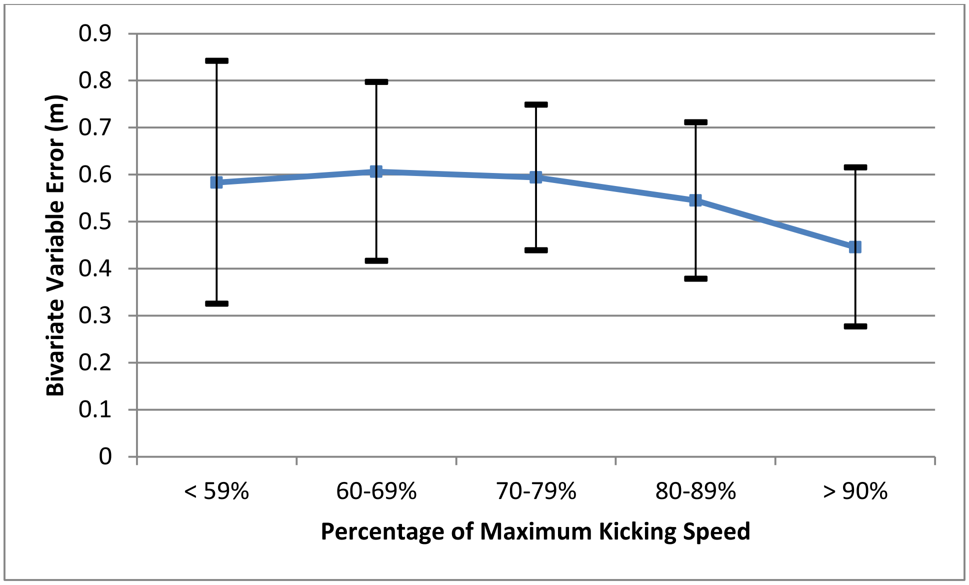

Figure 3.5. Means and standard deviations of bivariate variable error (m) at observed kick speed ranges.

CHAPTER 4

DISCUSSION

The purpose of this research project was to examine the applicability of two motor behavior perspectives - impulse-variability theory and the speed-accuracy trade-off - in the multijoint ballistic skills of overarm throwing and kicking performances with children. Two separate studies were conducted. The first study (see Chapter 2) examined both perspectives in overarm throwing performances with children (9 to 11 year olds). Based on the tenants of IV theory and previous literature that examined IV theory in overarm throwing performances with adults, it was hypothesized that variable error would demonstrate an inverted-U with approximately 60-70% of maximum force producing the greatest amount of variability. For the speed-accuracy trade-off, based on previous literature where it was examined in multijoint ballistic skills, the hypothesis was that the results would fail to support the speed-accuracy trade-off. Overall results did not indicate any significant difference between group means for variable error, failing to support the inverted-U of IV theory. For spatial error, there were no significant differences across a continuum of speeds, suggesting that a speed-accuracy trade-off was not observed in throwing performances.

The second study (see Chapter 3) examined IV theory and the speed-accuracy trade-off in kicking performances with children (9 to 11 year olds). Based on previous literature where IV theory was examined in kicking with adults, it was hypothesized that the results would indicate an inverse linear relationship in variable error with the leastamount of variability being at maximum speed. For the speed-accuracy trade-off, based on previous literature where it was examined in kicking performances and other multijoint ballistic skills, the hypothesis was that the results would fail to support a speed-accuracy trade-off. Overall results for variable error indicated a U-shaped pattern between speed and variability, where variability was greatest at maximum speed. This failed to support the predicted inverse linear relationship for variable error. For spatial error, there was a significant inverse linear relationship where spatial error decreased across the continuum of speed bandwidths with spatial error being the least at the fastest speed bandwidth, failing to support a speed-accuracy trade-off.

Future research should continue to examine the applicability of impulse-variability theory and the speed-accuracy trade-off within multijoint ballistic skills across adolescents. Developing an understanding of how force regulation occurs across the growing years into adulthood could provide insight to how learning occurs. It would also be important to examine movement kinematics and kinetics in multijoint ballistic skills in children and adolescents across a continuum of maximum speeds to provide a base of knowledge that could inform instructional strategies and practice for practitioners to produce optimal learning.

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