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Examining Impulse-Variability Theory and the Speed-Accuracy Trade-Off in Children's Kicking Performance

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A B S T R A C T

Background: 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**: Forty-three children ages 9-11 were instructed to kick a ball at a target at 45%, 65%, 85%, and 100% of their maximum kicking speed. Results indicated a significant quadratic relationship in variable error across the target conditions (p=0.048), such that children demonstrated significantly lower variable error at 65% versus 100% max speed. Additionally, there was a significant inverse linear relationship was indicated for spatial error (p<.0001), with post-hoc analyses indicating that mean radial error at <59%, 60-69%, and 70-79% of maximum speed was higher than at >90% of maximum speed. **Results:** These data demonstrated that principles of impulse-variability theory (i.e., inverted-U function) and the speed-accuracy trade-off were not supported for the multi-joint ballistic skill of kicking in this sample of children. **Conclusion**: These results, along with other recent data, imply a need to reevaluate instructional emphases when promoting the learning of multi-joint ballistic skills such as kicking.

1. Introduction

Wulf and Shea (2002) called for investigators to use more complex skills in human movement research in order to gain insight into the motor skill learning process that will extend beyond knowledge from relatively simplistic lab-based studies. Fitts Law (Fitts, 1954) and impulse-variability (IV) theory (Schmidt, Zelaznik, Hawkins, Frank, & Quinn Jr, 1979; Sherwood & Schmidt, 1980) exemplify motor behavior principles/theories that were derived from research with laboratory tasks (e.g., simple discreet arm movements). Although it is tempting to generalize these and other motor behavior principles/theories, it is tempting to generalize to more complex skilled behavior, evidence supporting their generalizability to multi-joint ballistic skills is lacking. Vast differences across the lifespan in individual learners' physical, cognitive, and psychological development should be considered when broadly applying these principles and theories. Thus, it is important to understand the applicability of laboratory-based principles/ theories in complex skill performance of individuals at different levels of development.

The speed-accuracy trade-off is an important application of Fitts' Law (Fitts, 1954) that describes an inverse relationship between movement speed and movement accuracy. For over half of a century, the speed-accuracy trade-off has been broadly generalized to various target-directed human movements (Plamondon & Alimi, 1997). Yet, results of recent studies have failed to support a speed-accuracy trade-off when this theory is applied to multi-joint ballistic skills. Ballistic skills involve complex multi-segment coordination patterns and optimal energy transfers through multiple segments (e.g., throwing, kicking, and jumping), or joints, ultimately resulting in high distal segment velocities and/or high-power outputs (Langendorfer, Roberton, & Stodden, 2013). For example, Juras, Slomka, and Latash (2009) did not find significant differences in movement times when target distances and widths were adjusted for

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standing long jump performances. Also, when examining the speed-accuracy trade-off in overarm throwing performances with young adults across a continuum of speed performance (40-100%), no statistically significant differences were indicated (Urbin, Stodden, Boros, & Shannon, 2012). Similarly, in a child study, Molina and Stodden (2018) found no statistically significant differences in a variety of spatial error scores across a continuum of overarm throwing speed percentages. In contrast, young adults' kicking performances demonstrated increased accuracy across a kicking speed continuum, with 40-59% of maximum kicking speed associated with greater error than kicking speeds at 70-79% of maximum speed (Chappell, Molina, McKibben, & Stodden, 2016). Collectively, these data have failed to clearly support the speed-accuracy trade-off in multi-joint ballistic skill performance across a continuum of speeds in both children and adults.

Impulse-variability (IV) theory was derived from the application of Fitts' Law. IV describes the relationship between force and force variability under the assumption that movements are preprogrammed (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 in this area included a broader range of force capabilities (Schmidt & Sherwood, 1982; Sherwood & Schmidt, 1980), temporal constraints on force production (K. M. Newell, Carlton, Carlton, & Halbert, 1980; K. M. Newell, Hoshizaki, Carlton, & Halbert, 1979), and accuracy of timing of forces produced (K. Newell, Carlton, & Hancock, 1984). Results from research that combined these factors (Sherwood, Schmidt, & Walter, 1988) demonstrated an inverted-U phenomenon, with force production most variable at approximately 60-70% of maximum force output (Schmidt & Sherwood, 1982; Sherwood & Schmidt, 1980). As forces produced continue to increase from 70% to maximum, output variability decreased. See Urbin, Stodden, Fischman, and Weimar (2011) for a review.

Urbin et al. (2011) suggested that the central findings from IV theory (i.e., the inverted-U) could be generalized to multi-joint ballistic skills; and this was later tested in overarm throwing performances with young adults ages 18-25 (Urbin et al., 2012). In this young adult test of IV theory generalizability, there was support for the inverted-U in that throwing speed (as a measure of systemic force) variability being most variable at 60% of maximum force (Urbin et al., 2012). In contrast, when variable error was examined in overarm throwing performances of children, there were no statistically significant differences in variable error across the target conditions (Molina & Stodden, 2018). As a follow-up to the Urbin et al. (2012) study, Chappell et al. (2016) applied the same methodology to kicking. While kicking and throwing are both multi-joint ballistic skills, kicking accuracy is arguably a more difficult skill than throwing accuracy, as kicking accuracy is required for both projecting the ball (i.e., appropriate contact with the foot) and hitting a target. In contrast to the Urbin et al. (2012) throwing results, Chappell et al. (2016) were unable to demonstrate support for 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), adding more uncertainty to the generalizability of IV theory to multi-joint ballistic skill performance. While we know what results look like with adult samples, we do not know what they would look like in a sample of children. During childhood, the development of kicking, along with other ballistic skill and fundamental movement skills, is suggested to be an integral part of comprehensive development of children and adolescents (Stodden et al., 2023). This study took the next logical research step and sought to examine the applicability of both the IV and speed-accuracy trade-off theories to children's kicking performance. By testing these motor control theories a greater understanding of human movement can potentially be developed and utilized to promote learning of ballistic motor skills. If the error of target accuracy isn't associated with the force output of ballistic skills, and we have evidence of children demonstrating more developmentally mature movement patterns at higher efforts (Mally, Battista, & Roberton, 2011; Sacko et al., 2021), then this information could be used inform physical education teachers and/or coaches during skill acquisition of these types of motor skills, which typically occurs during childhood.

2. Materials and Methods

2.1. Participants

An a-priori power analysis was conducted based on effect sizes demonstrated in Urbin et al. (2012), at a .8 level with a small to moderate effect size of .2 (Cohen, 2013). Those results indicated that to adequately power the study a minimum of 36 participants were needed (G-Power, version 3.1.9.2).We recruited a purposeful sample of 43 elementary school children (19 girls) ages nine to 11 years (M age = 10.7 years for girls and; 10.8 years for boys) capable of kicking at a maximum speed of at least 13.41 meters/second (30 mph). We used this required minimum maximal speed so that the participants would be able to successfully complete the task at our lower speed requirements (see task requirements in procedures below). We obtained the approval to conduct the study from the University's Human Subjects Review Board. Parent/guardians of all child participants gave their informed written consent for participant engagement in the study and we obtained verbal assent from all child participants prior to their involvement in the study.

2.2. Apparatus and Task

A 3 x 3 meter grid containing a 20 x 20 cm centroid target centered 1.0 meter above the ground along a wall served as a reference goal for the participants. For the kicking trials, the participants kicked a stationary playground ball (Sportime, 20.32 cm in diameter) to the target from a distance of 3.05 meters. This distance allowed participants to complete the task requirement of kicking and hitting the target at various percentages of their maximum speed while minimizing the potential impact of gravity on vertical trajectories. Participants were allowed an approach of their preference prior to kicking the ball (Chappell et al., 2016). Peak ball speed was measured using a Stalker Pro II radar gun (Stalker Inc., Plano, TX) and was interpreted as an index of overall systemic force output for each trial (Chappell et al., 2016; Molina & Stodden, 2018; Urbin et al., 2012). We measured spatial accuracy of the trials in both the X (horizontal) and Y (vertical) dimensions using a two-dimensional laser level by placing it over the center of the impact point of the ball and identifying the appropriate X and Y coordinates.

2.3. Procedures

Procedures for this study were similar to previous studies (Chappell et al., 2016; Molina & Stodden, 2018; Urbin et al., 2012). All participants were required to attend two testing sessions at least seven days apart to minimize potential for any soreness and fatigue between the first and the second sessions. At the beginning of each session, participants performed a general warm-up including upper and lower body exercises. Following the general warm up, participants were allowed up to 10 self- paced warm-up kicking trials to build up to maximum effort and gain familiarity with the task.

The purpose of the first session was to assess the participants' maximum kicking speeds and determine if they met the required minimum maximal speed of 13.41m/s. During the maximum speed testing session, children were provided 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. We used the fastest speed of five consecutive trials to determine the maximum speed for each participant. After the maximal speed testing, participants that met the study criteria were familiarized with the remaining study protocols. This protocol included calculating four percentages of maximum speed (45, 65, 85, and 100%) for each participant based on their maximum speed performance, which then served as target speed conditions for that participant for the study. To familiarize children with the target conditions, they performed kicking trials kicking to the wall target at each of the speed conditions until they were capable of producing two consecutive trials ± 0.89 m/s (± 2 mph) of each target condition. During the familiarization trials, we provided feedback to the child after each trial, limiting the feedback given to information about the speed of their performance and whether or not they needed to increase or decrease speed in order to reach the target speed for that trial condition. Data from the first session were not used in the analysis.

Following the general warm-up for session two, the children performed five consecutive blocks of trials. Each block contained two randomly generated trials at each of the four target conditions for a total of 40 trials per participant (10 trials at each target speed condition). Specific instructions provided to the participants in this testing session were to kick at the specified percentage of maximum speed and to hit the target. The only feedback about the trial offered to the participant was the exact kicking speed in miles-per-hour following each trial. Immediately following each trial, the contact point of the ball was visually identified and the X and Y coordinate distances from the target centroid were recorded. Children were allowed to rest at self-selected durations during this time to minimize potential fatigue.

Post hoc, the participants were placed into two groups (higher skilled n = 8; lower skilled n = 35) for analysis based on their maximum kicking speeds (Molina & Stodden, 2018; Urbin et al., 2012). The main reason for the post hoc group distinction was to determine if there were differences between groups of participants that were identified as higher skilled versus those that were identified as lower skilled based on their kicking speed. Due to a lack of specificity in prior literature regarding a criterion for kicking speeds, participants whose maximum kicking speeds were greater than or equal to one standard deviation above the mean (16.5 m/s or 37 mph) were placed in the skilled group for group comparisons.

2.4. Data analysis

Speed Variability. Variable speed error, $\sqrt{\sum(x_i - M)^2}$, on the 10 trials for each target speed condition was averaged and used for statistical analysis (Chappell et al., 2016; Molina & Stodden, 2018; Urbin et al., 2012). A repeated measures ANOVA (four levels) with built-in polynomial contrasts was used to analyze the data to determine within subject variability (Chappell et al., 2016; Molina & Stodden, 2018; Urbin et al., 2012). Bonferroni post-hoc tests were applied 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 skilled and unskilled groups. To determine if there was differences between the groups and each percentage of maximum, independent samples *t*-tests were conducted.

Spatial Accuracy. To analyze spatial error, each kicking trial was normalized to a percentage of the participant's maximum kicking speed and grouped into five bandwidths of speed percentage (≤ 59.9%, 60-69.9%, 70-79.9%, 80-89.9%, and ≥ 90%) (Chappell et al., 2016; Molina & Stodden, 2018). This data was analyzed using a repeated measures ANOVA (five levels) with polynomial contrasts to calculate mean radial error (MRE). Participant-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 been 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 skilled and unskilled groups. Independent samples *t*-tests were performed to detect differences between groups at each bandwidth of speed. Significance for each of the sets of analysis was set at the .05 level.

3. Results

3.1. Speed Variability

Results for mean variable error for kicking speed (m/s) indicated that there was a statistically significant quadratic relationship across the target speed conditions ($p = 0.048$, $\eta 2 = .288$; Figure 1). Follow-up tests revealed that 100% maximum speed had significantly higher variability than the 65% condition (p =0 002, $d = .674$). Variable error between skilled and unskilled groups were not statistically different.

3.2. 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 2, 3, and 4) and there was decreased error (i.e., increased accuracy) with increased percentages/bandwidths of speed. Follow-up tests displaying statistically significant differences between bandwidths of speed are displayed in Table 1. Group differences between the skilled and unskilled groups were not statistically significant for MRE, CE, or BVE.

Table 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. *p < .05; MRE = mean radial error; CE = subject-centroid radial error; BVE = bivariate variable error. Bold indicates greater error

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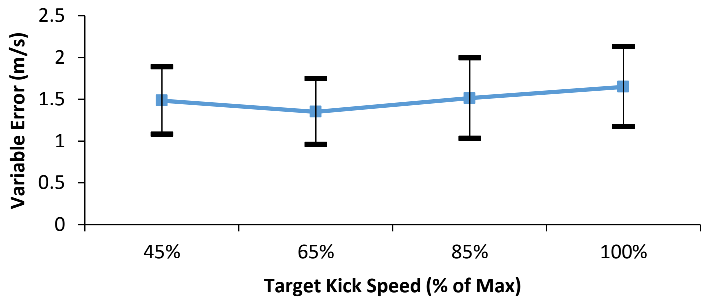

Figure 1. Means and standard deviations of variable error of kicking speed as a function of percentage of maximum effort across all subjects.

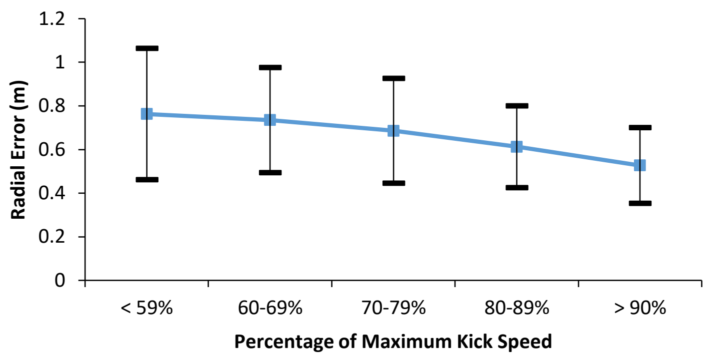

Figure 2. Means and standard deviations of mean radial error (m) at observed kick speed ranges.

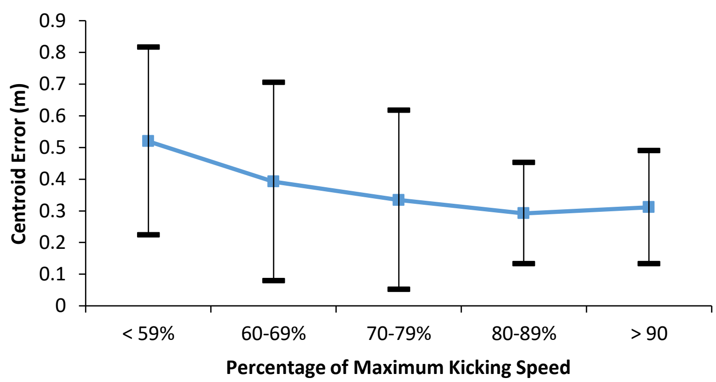

Figure 3. Means and standard deviations of centroid error (m) at observed kick speed ranges.

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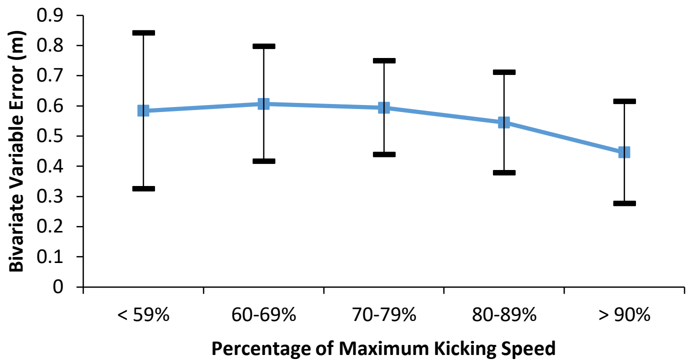

Figure 4. Means and standard deviations of bivariate variable error (m) at observed kick speed ranges.

4. Discussion and conclusion

The purpose of this study was to examine of the applicability of IV theory and the speed-accuracy trade-off in children's kicking performance. Children's variable error data failed to support either the inverted-U performance expectation that has been theorized by IV theory (Sherwood & Schmidt, 1980) or the inverse linear relationship demonstrated in kicking performances with young adults (Chappell et al., 2016). In contrast, these analyses revealed a statistically significant quadratic function demonstrating a U-shaped pattern with the target speed condition of 65% less variable than the 100% target speed condition. This finding directly opposes the inverted-U associated with IV theory. With variability being greatest at 100%, these data also directly oppose the kicking variable error data from a prior young adult sample in which the least amount of variability was at 100% (Chappell et al., 2016). These data suggest that force output regulation in a multi-joint ballistic skill in children may be different from that of adults who generally demonstrate a more consistent coordination pattern, regardless of their skill level, relative to their peers (Chappell et al., 2016). Additional evidence to support this developmental difference is needed, as findings indicated there were no statistically significant differences in ability to regulate force output when comparing kicking performances between skilled and unskilled children.

A lack of significant differences in speed variability of skilled and unskilled children also fails to support data from Urbin, Stodden, and Fleisig (2013) who demonstrated that lower skilled children were more variable in maximum speed throwing kinematic parameters than were more highly skilled children. Overall, when examining the force/force variability relationship in multi-joint ballistic skills, findings across various studies have failed to produce consistent results. This inconsistency may imply that children and adults vary in their ability to regulate force output in the multi-joint ballistic skill of kicking. Therefore, more work in this area is needed to provide a more definitive understanding of the relationship between force and force variability in multi-joint ballistic skills of participants at different developmental levels.

The observed spatial error data in this study failed to support a speed-accuracy trade-off and demonstrated an inverse relationship between kicking speed and accuracy. This violation of the application of Fitts' Law when it is applied to children in this study provides a further challenge to the presumed speed-accuracy trade-off in the performance of ballistic motor skills (Chappell et al., 2016; Juras, Slomka, & Latash, 2009; Molina & Stodden, 2018; 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. Our results also showed that there were no statistically significant differences between skilled and unskilled performers. Thus, the spatial accuracy of the children's kicking performance was not a function of their performance capability.

In this study, the results of the three spatial error measures (inverse linear relationship) did not follow the same patterns as the variable error data, leading to 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 in a past study with young adults (Chappell et al., 2016), the young adult participants were able to successfully adapt to higher systemic force demands while maintaining or even improving spatial accuracy. In the present study, while speed variability increased as force output (i.e., speed) increased toward maximum, each of the measures of spatial error improved. So even though the children in this study 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 (Mutha & Sainburg, 2007).

Dynamic balance has been suggested to be a rate-limiter for kicking performance in children due to the need to control balance on one leg while swinging the other (Langendorfer, Roberton, & Stodden, 2013). Mally, Battista, and Roberton (2011) and Sacko et al. (2021) indicated that increases in force production of children's kicking performances produced movement changes in aspects of their approach, forward leg swing, and follow through. Possibly, children's movement changes across a continuum of force output production lead to greater force variability due to a lack of dynamic stability in the movement patterns that adults demonstrate more easily (Fleisig, Chu, Weber, & Andrews, 2009). Overall, force regulation data with multi-joint ballistic motor skills in children are very limited and need to be examined in greater detail.

There are several limitations that should be mentioned. First, there was no function in place to control for the amount of experience that the participants had prior to the study. There was a lack of consistency in how participants in this study kicked the ball (i.e., toe, instep, or side of foot), the approach they used for each kick, and the variability or error they demonstrated at the point of contact on the ball. These inconsistencies may have significantly influenced systemic kinematics and their potential impact on ball speed and the resultant accuracy. However, kicking across a wide range of an individual's performance capability would inherently suggest

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changes in coordination patterns, specifically in developing children. Thus, performance of a ballistic motor skill across a spectrum of performance effort does not lend itself to a high degree of performance consistency. In addition, not controlling for these factors would seemingly promote both increased speed variability and spatial accuracy, which was not observed. These data provide additional support for the argument that the speed-accuracy trade-off does not necessarily apply in ballistic motor skill performance for either children or adults. However, an additional limitation of this study is that resultant spatial accuracy did not take into account the ball trajectories that were demanded from the performances at the various speeds. Therefore, the distance chosen limited dramatic changes in ball trajectories that would influence individual's perceptions of where they would aim.

Additionally, kinematic and kinetic aspects of the movements were not assessed. This data might provide a more detailed analysis of performance and help to better explain these contrasting speed variability and accuracy results. Additional research should be conducted in order to better understand differences in movement kinematics across the speed continuum. Finally, adult studies examining IV theory in multi-joint ballistic skills used bandwidths of ±10% to compare force variability (Chappell et al., 2016; Urbin et al., 2012). This study included only four target conditions across maximum speeds due to judgement that a limited number of bandwidths was more developmentally suited to children's cognition and kicking experience levels at various percentages of their maximum performance.

The findings of this study support other researchers' impressions (Cauraugh, Gabert, & White, 1990; Chappell et al., 2016; Engelhorn, 1997; Molina & Stodden, 2018; Roberton, 1996; Urbin et al., 2012; van den Tillaar & Ettema, 2006) that sacrificing speed in order to focus on accuracy in the acquisition of ballistic motor skills would hinder optimal developmental progressions in learning the skill as it does not demonstrate improved accuracy (Molina, Bott, & Stodden, 2019; Roberton, 1996). Practically, this implies that emphasizing speed over accuracy in children's motor learning might promote greater development of multi-joint ballistic skills (Langendorfer, Roberton, & Stodden, 2013; Molina, Bott, & Stodden, 2019) that are, important in turn, for promoting children's long term physical activity (Logan, Robinson, Getchell, Webster, Liang, & Golden, 2014) and physical fitness levels (Cattuzzo et al., 2016). Overall, we agree with Wulf and Shea (2002) that more work is needed in testing motor behavior principles/theories with complex real-world skills for participants across the lifespan. Specifically, during the development and performance of multi-joint ballistic skills, the central nervous system may be able to adapt in unique ways, as compared to single joint (i.e., 1 degree of freedom) movements and/or more constrained task methodologies (Urbin, 2012, 2013; Wagner, Pfusterschmied, Klous, von Duvillard, & Müller, 2012).

Authors' contributions

Conception and design of the study: S.L.M, D.F.S; Data collection: S.L.M; Data analysis and/or interpretation: S.L.M, D.F.S; Drafting of manuscript and/or critical revision: S.L.M, D.F.S; Approval of final version of manuscript: S.L.M.

Conflict of interests

The authors declare that there is no conflict of interest.

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