Developmental sequences for observing and assessing forceful kicking

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Abstract

While football/soccer is the most influential sport in the world, it is surprising that developmental sequences of forceful kicking have not been adequately described and validated in the literature. The purpose of this study was to explore potential developmental sequences for forceful kicking using a prelongitudinal screening method. Data were derived from videotapes of 255 children (girls $n = 138$, boys: $n = 117$), ages 4–11 years. Seven potential component sequences in their respective developmental order were initially proposed based on biomechanical and motor developmental principles. Each participant was digitally videoed performing five kicks with maximal effort. Trained research staff coded the initial seven components for each kick and the mode of each participant's five kicks was used for data analysis. Component level probability curves for each component sequence across age were evaluated using the threshold based generalized partial credit model (Muraki, 1992) within the item response theory framework. As developmental theory would indicate, component levels generally increased with age for most components. Six component ordinal sequence progressions met model requirements (Rel $= 0.88$, item fit; $p > 0.05$). Ordinal levels for two components (*Knee action* and *Follow-through*) were altered based on initial empirical model structure fit and the *Ball contact* component was removed based on a lack of model fit. This

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study provides sufficient cross-sectional evidence for six component developmental sequences that adequately describe the development of kicking using cross-sectional data. Longitudinal data are required to provide further developmental validation for these sequences.

Keywords
Motor development, movement assessment, motor skills, prelongitudinal screening

Introduction

Instruction of motor skills by physical educators, sport coaches, and physical activity professionals includes the accurate identification of movement characteristics critical to the performance of an intended skill. The identification of different levels of a "critical feature" (e.g. hip rotation during kicking, throwing, and striking) requires both extensive experience in observation and knowledge about the intended movement (Barrett, 1984). These critical features are described, within the context of motor development sequences, as behaviors that are elicited by children throughout maturation as they progress through more advanced movements (Roberton et al., 2017). To facilitate the observation of varying levels of critical features within a particular motor skill, it is essential to determine the development of movement sequences (chronological ordering of qualitative changes that occur in the behavior of most individuals; Overton, 1998; Roberton, 1978) that represent our current understanding of the impact of growth, maturation, biomechanical principles, and experience (Gabbard, 2009; Wickstrom, 1975). Component developmental sequences are representative of age-related changes in movement based on growth, maturation, underlying neuromechanical principles, and experiences of children. Physical educators, sport coaches, and physical activity professionals can use these sequences to systematically evaluate movement patterns and appropriately align instructional strategies to enhance students' skill progression.

Based on the complex interactions between cognitive, social and physiological factors, children will develop skills at varying rates (Gallahue and Donnelly, 2007). Furthermore, the complex process of motor skill development may not be linear. That is, a child does not necessarily have to demonstrate an invariant order of progression in movement sequences across time (Garcia and Garcia, 2002), although most do. Many assessments of fundamental motor skills, however, dichotomize movement attributes as either "absent" or "present" during a movement. Ultimately, a beginner/novice performer and an advanced/expert performer are distinguishable due to the absence or presence of these dichotomized variables (e.g. The Developmental Sequence of Fundamental Motor Skills Inventory (Seefeldt and Haubenstricker, 1976); and Test of Gross Motor Development (Ulrich, 2013; Ulrich and Sanford, 1985)). In contrast, developmental sequences allow an observer/teacher to understand incremental improvements (i.e. more than two levels) in a body component or movement pattern that are appropriate for the developmental level of the learner (Cohen et al., 2012; Gesell, 1940).

Although longitudinal evidence is the preferred method to test and validate developmental change across time, Roberton (1978) pioneered the process of prelongitudinal screening developmental sequences as a means of overcoming the monumental task of tracking of children's movements longitudinally. Cross-sectional data collection from a wide range of relevant age ranges and representative skill levels provide initial insight on developmental movement progressions (Strohmeyer et al., 1991).

A valid developmental sequence depicts ordered advances in segmental movement levels of different body segments (e.g. shin, ankle, or knee) or components (e.g. stride) across time (Roberton et al., 2017). Thus, when employing a prelongitudinal screen, it is not expected that multiple levels appear in a significant proportion across all ages as the transition of levels should be in an orderly sequence from one adjacent level to the next. Should multiple levels appear in a significant proportion across a wide age range within a cross-sectional validation study, then the sequence is invalid (Roberton et al., 2017). The evaluation of developmental sequences has previously relied on descriptive statistics (Roberton, 1978) of increases and decreases in frequencies of sequence level appearance across age, with the assumption that the frequencies of each adjacent component level should first increase and then decrease across time (Roberton et al., 2017). Again, conclusions drawn from these descriptive interpretations are limited as development is age-related, but not age-dependent.

Surprisingly, developmental sequences for kicking, which is perhaps the most demonstrated ballistic movement skill around the world, have not been extensively developed and validated longitudinally. Examples of previously noted kicking sequences include: (a) Gesell et al. (1940) who reported that 18-month-olds kick a ball only by stepping forward and making contact while 2-year olds can actually "kick" or forcefully connect with the ball by swinging their leg; (b) Roberts and Metcalfe (1969) claimed that kicking is an extension of running, thus suggesting that if a child can run, a child can kick; and (c) Wickstrom (1975) (relying heavily on research performed by Deach, 1950), described the mechanics of kicking in children as they relate to gross biomechanical movements and focused more heavily on punting. However, developmental sequences were not offered. Interestingly, in a study of United States children (age range of 7.5–9.0 years-old) Seefeldt and Haubenstricker (1976) found that only 10% of the children exhibited "advanced" kicking form. The Developmental Sequence of Fundamental Motor Skills Inventory (Seefeldt and Haubenstricker, 1976), the Australian resource "Get Skilled, Get Active" (Ryde, 2000), and the Test of Gross Motor Development (Ulrich, 2013; Ulrich and Sanford, 1985) all offer valuable insight into potential developmental levels of kicking; however, these tools evaluate kicking performance by dichotomously categorizing independent movement components as only "absent" or "present" during kicking performance. The dichotomous categorization of a movement component can lead to ceiling or floor effects within skill performance testing; thus, creating a potential measurement sensitivity issue when evaluating the predictive utility of skill levels on different outcome variables (Logan et al., 2017; Ré et al., 2017). At this time, no assessment tool exists for the skill of forceful kicking that offers more than two levels of movement pattern sequencing. Without a viable assessment tool, physical educators, sport coaches, and physical activity professionals lack the resource needed to swiftly and accurately identify movement characteristics that are critical to the optimal performance of a forceful kicking action. Therefore, the purpose of this study was to address this knowledge gap by initially conducting a prelongitudinal screen to assess the validity of hypothesized component sequences of kicking.

Methods

Hypothesized developmental levels

Seven hypothesized component developmental sequences for forceful kicking were created based on the existing biomechanical and motor development literature (Deach, 1950; Gesell et al., 1940; Haywood and Getchell, 2019; Lees et al., 2010; Roberts and Metcalfe, 1969; Seefeldt and Haubenstricker, 1976; Wickstrom, 1975) and expert ratings (depicted in Table 1). The seven separate

Table 1. Hypothesized developmental sequences for forceful kicking as initially hypothesized.

Skill	Level 1	Level 2	Level 3	Level 4	Level 5
Approach	*No approach*: Both feet positioned directly behind the ball and no steps are taken	*Linear approach*: Positioned at a distance directly behind the ball in such a manner that allows for forward movement toward the ball before kicking	*Angular approach*: Positioned at an angle behind and to the side of the ball in such a manner that allows for accelerated movement toward the ball before kicking		
Support (plant) foot location	*Stationary*: Support foot behind ball (as a result of no stepping action). At the initiation of the kicking motion the support foot remains at rest behind the ball	*Reaching*: Supporting foot, as a result of an approaching step, is placed one-foot length (performer's foot) beyond or before the mid-point of the ball. (i.e. before or after the ball)	*Aligned*: Supporting foot, after an approaching step, is placed within one-foot length (performer's foot) of the mid-point of the ball (i.e. either before or after the ball)		
Knee action	*Fixed*: Throughout the kicking motion the knee of the kicking leg is fixed while only the hip is flexed to create contact with the ball. This occurs without a preparatory backswing	*Flexed*: Prior to contact with the ball the knee of the kicking leg is flexed to raise the ankle to a position above the ground in preparation for the kick. This motion is observed in the absence of an approach prior to kicking	*Passive height*: As a result of a preparatory step the ankle maintains a position no higher than the knee in preparation for the kick. No independent raising of ankle observed	*Knee height*: During a stepping or running approach the ankle is actively raised to a height above the knee and below the hip independent from the height gained from the approach	*Hip height*: During a stepping or running approach the ankle is actively raised to a height above the hip independent from the height gained from the approach
Trunk action	*No rotation*: No preparatory extension or rotation of the pelvis or trunk	*Total trunk ("block") rotation*: The pelvis and/or truck externally rotate away from the intended flight of the ball and then simultaneously begin forward rotation toward the intended flight path of the ball as a single unit	*Differentiated rotation*: the kicker twists the pelvis away from the intended flight path of the ball. The pelvis then begins forward rotation prior to the movement of the torso		

(continued)

Table 1. (continued)

Skill	Level 1	Level 2	Level 3	Level 4	Level 5
Ball contact	*Toe*: The toes are the first surface of the foot to come in contact with the ball during kicking. The ankle is typically in a fixed dorsiflexed position	*Instep*: The instep, laces or inside surface of the foot is the first to come in contact with the ball during kicking. The ankle is typically in a fixed plantar-flexed and everted position			
Arm action	*Bilateral inactive*: No arm movement during kicking. (i.e. arms held by side)	*Bilateral reactive*: Arm movement unsynchronized and reactive and is utilized only to maintain balance	*Bilateral active*: Arm movement of contralateral arm assists in the differentiation of the trunk while the ipsilateral arm maintains are outstretched. The arm motion is actively used for force generation by aiding in the rotation and differentiation of the trunk		
Follow-through	*Planted*: The support foot and heel do not leave contact with the ground. The kicking leg will come to rest in its original position next to the support foot or within the length of half of the height of the kicker	*Heel raise*: The heel of the support foot leaves the ground while the toe remains in contact. The force generated by the kicking leg brings the performer into a plantar flexed position while the toe remains in contact with the ground	*Hop*: The support foot, as a result of the momentum generated during the kicking motion, leaves contact with the ground and becomes the first foot to regain contact with the ground upon landing	*Leap*: The support foot leaves contact with the ground, as a result of momentum generated during the kicking motion. The kicking foot becomes the first foot to regain contact with the ground upon landing	

"components" were titled as follows: *Approach*; *Support (plant) foot location*; *Knee action*; *Trunk action*; *Ball contact*; *Arm action*; and *Follow-through*.

Approach: No approach (Level 1). Performers position themselves directly behind the ball prior to kicking. No observation of forward momentum in an approach occurs. An approach of one or a few short steps may be taken as a performer adjusts their position behind the ball; however, a pause prior to a wind up of the leg is taken resulting in the removal of any force generating momentum. Novice approach steps lack refinement in the ability to coordinate and control movements in a smooth forceful pattern when attempting to kick a ball. As a result, a performer's range of motion is impeded as degrees of freedom are reduced and potential approach speed is minimized, a concept that aligns with principles of the speed–accuracy trade-off (Molina et al., 2019; Newell, 1986). A *Linear approach (Level 2)* is taken by those who have developed the ability to coordinate a transition from a walking or running motion to a kicking motion. The approach is linear in nature, adequately enhances linear momentum, and is most often performed over the distance of a few steps but may be more. An *Angular approach (Level 3)* occurs when a performer begins their approach from a position offset from a position directly behind a ball (i.e. 0°). The path of the *Angular approach* may be performed as in a straight line or, more often, as a curved approach (Marqués-Bruna et al., 2008).

Support (plant) foot location. The non-kicking foot, referred to as the "support" or "plant foot", is responsible for balance and remains in contact with the ground during the kicking motion. The ability of a performer to place their support foot in an optimal position reflects their level of skill as success or failure to make optimal contact with the ball is largely relegated by foot placement position.

Stationary (Level 1). An initial level of development is reflective of the lack of approach taken by a performer. Once a performer has situated themselves in a position close to the ball to initiate a kicking motion the non-kicking foot remains stationary.

Reaching (Level 2). When a performer places their foot at a distance of at least one-foot length prior to the mid-point of the ball or one-foot length past the ball, they are considered to be in a reaching position. If a performer plants their foot at a distance too far behind the ball the result of the kicking motion will cause the performer to contact the ball at a position higher than desired or not at all. In contrast, a support foot placement well beyond a stationary ball will result in contact of the ball that causes the ball to be driven down into the ground.

Aligned (Level 3). As performers become more skilled in their approach, they optimize performance by appropriately placing the support foot next to the ball. An aligned position of support foot placement is achieved when the performer's non-kicking foot is placed within the length of one foot (i.e. relative to each performer) of the mid-point of the ball.

Knee action. The relationship between foot swing velocity and ball velocity is well understood (Barfield et al., 2002; Nunome et al., 2006a, 2006b). Higher acceleration rates of the kicking foot result in greater forces being applied to the ball at contact and thus, a greater velocity of ball flight. To attain the greatest acceleration of the kicking foot a performer must raise the foot to an optimal position during the approach to the ball.

Fixed (Level 1). The lowest level of development reflects the lack of a backswing prior to contact, which will result in a weak force application to the ball. The initial lifting and pushing motion were noted by Wickstrom (1975) and Seefeldt and Haubenstricker (1976).

Flexed (Level 2). While a performer remains in a stationary position prior to contact with the ball, the knee is flexed, which allows for a brief wind-up of the kicking leg and increased rate of acceleration of the kicking foot prior to contact, ultimately resulting in higher forces applied to the ball than what is produced by the pushing motion of *Level 1*.

Passive height (Level 3). When a performer has gained the ability to approach a ball from a step, leap or hop, he/she elicits passive flexion of the knee.

Knee height (Level 4). A greater range of motion through the swinging phase of kicking is achieved when an individual is able to actively flex the knee during the backswing of a step, leap, or hop to a height equal to or above the knee joint of the kicking leg.

Hip height (Level 5). Finally, some performers are able to generate the greatest range of motion by actively raising the foot to a height above the axis of the hip joint (i.e. acetabulum), allowing the greatest distance for acceleration of the kicking foot prior to contact with the ball.

Trunk action: No rotation (Level 1). This lowest level kicking motion is observed with a lack of preparatory extension or rotation of the pelvis or trunk. This stage involves no angular displacement of the pelvis or trunk.

Total trunk ("block") rotation (Level 2). As a performer's skill increases, typically paralleled by higher approach levels (i.e. linear or angular), they increase hip and trunk linear velocity and pelvis linear velocity. Rotation of the hip and trunk must occur prior to contact with the ball. At the beginning of a performer's step, leap, or hop the hip and trunk are rotated away from the intended flight path of the ball. Just prior to contact with the ball the performer's pelvis and trunk rotate simultaneously to face the intended flight path of the ball.

Differentiated rotation (Level 3). Differentiated rotation (Level 3) of the pelvis occurs when the trunk of the performer and the pelvis move temporarily, in opposition to each other. Rotation occurs in the pelvis that elicits a stretch-shortening reflex to occur in the hip garnering increased rotation speed of the lower leg. During a kicking motion, the pelvis moves through a significant range of motion to impact a ball (Lees et al., 2010). Highly skilled ranges of motion between 30° and 36° have been reported for pelvic retraction to protraction at ball contact (Lees et al., 2010). At a highly skilled level of kicking, pelvis rotation precedes upper torso rotation pelvis allowing the stretch-shorting reflex of the external oblique to increase the speed of rotation, resulting in higher acceleration speeds for the kicking leg.

Ball contact. The foot consists of many surfaces that are known by varying names throughout sports from around the world (e.g. toe, instep, and laces). Though many strategies for ball contact have been used by highly skilled individuals to elicit spin on a ball or are preferable for increased accuracy, this study focuses on the surface selection during forceful contact of the ball for the achievement of maximal velocity.

Toe (Level 1). Initial contact with the ball by the toe has been noted as an initial developmental level of kicking (Gesell et al., 1940; Wickstrom, 1975). Initial contact of the ball with the toe allows for the least amount of diversion from a running/walking motion. A dorsiflexed position of the ankle may also be observed in complex kicking motions (e.g. attempting to spin the ball for angled flight); however, the toe is not used to make initial contact. Thus, it is noted that this lowest kicking level is defined when the toe is the first surface of the foot to come in contact with the ball.

Instep (Level 2). The speed of a kicked ball is maximized when the area of impact by a foot is nearest to the center of gravity of the foot (Ishii and Maruyama, 2007). This is achieved when the foot is plantar flexed and slightly abducted. The kicking leg may be externally rotated allowing for first contact by the medial portion of the arch of the foot.

Arm action

Bilateral inactive (Level 1). Low skilled performers are noted as having arms in a stationary position. During early stages of development, degrees of freedom are reduced (Bernstein, 1967). The process of approaching a stationary ball or swinging a leg forcibly in a kicking motion will, in turn, disrupt the axis of rotation of the performer. A lack of disruption of the performer's axis of rotation allows the arms to remain stationary as they are not needed to maintain stability.

Bilateral reactive (Level 2). A performer uses their arms as a means of stability and control of their axis of rotation. However, during this level of skill development, the action produced by the arms does not actively aid in the generation of force, rather it is responsible for maintaining balance during kicking movements.

Bilateral active (Level 3). Individuals who demonstrate kicking skill of the highest level utilize their arms to generate rotational torque. During this level, both arms are actively involved in the generation of momentum. The arm opposite the kicking leg is abducted and horizontally extended before the support foot makes contact with the ball and then adducts and horizontally flexes (Lees, 2013).

Follow-through. The follow-through is representative of deceleration of the kicking leg and momentum generated about the axis of rotation during the kicking motion. As a result, kicking motions that elicit the least amount of momentum generation will result in little to no follow-through, while in contrast, those that elicit the largest generation in momentum will result in the largest follow-through to decelerate the kicking leg and axis of rotation and to maintain upright posture.

Planted (Level 1). The support foot stays in complete contact with the ground. The lack of linear momentum allows the performer to return their foot to a position at rest next to or near the support foot.

Heel raise (Level 2). When linear momentum is increased via a forward approach, the center of mass of the performer will continue to move forward after ball contact. This forward movement will draw the support foot of the performer into a plantar flexed position where the heel is raised and only the toes and forefoot remain in contact with the ground. A stepping motion at lower speeds will elicit a similar response.

Hop (Level 3). As the performer continues to increase the amount of momentum gained through an approach and forward swinging motion of the kicking leg the performer's movements result in their body being carried forward. A momentary flight phase of the support leg is observed when the performer hops forward to keep a base of support directly under the axis of rotation that is continuing to translate anteriorly. The support foot in this level is defined as the last part of the body to leave contact with the ground and is also the first to regain contact upon landing.

Leap (Level 4). Finally, it was hypothesized that in the highest level of follow-though the momentum gained by the kicking leg would carry the performer forward with enough velocity to force the foot of the kicking leg to regain contact with the ground first as the performer continues in a walking/running motion toward the intended flight path of the ball.

Participants and procedures

This study compiled de-identified data collected from three different projects that used identical methodologies and protocols. The total sample of cross-sectional data were derived from video-tapes of 255 children (boys: $n = 117$, girls: $n = 138$). Age ranges yielded the following sample sizes; 16 4-year-olds; 27 5-year-olds; 14 6-year-olds; 43 7-year-olds; 75 8-year-olds; 37 9-year-olds; 30 10-year-olds; and 13 11-year-olds. The children whose videos were studied attended Title 1 schools that represented the Midwest, Southwest, and Southeast regions of the United States from 2012–2016. Race/ethnicity of participants were self-reported as follows: 154 Non-Hispanic White; 51 Hispanic; 43 African American; and seven were classified as "other." Parental/caregiver consent and child assent was secured along with school district approval for the research. Institutional Review Boards at all participating institutions approved the study.

Prior to testing sessions, children completed a general warm-up routine and 3–5 practice kicking trials. All testing sessions were performed in a school gymnasium against an unmarked wall from a distance of approximately nine meters. Each participant was videoed performing five kicks of playground balls (circumference 67.8 cm, mass 362.0 g) with maximal effort. Each performer was asked to "kick the ball as hard as possible" with no demonstration given prior to beginning the task. Children received speed/distance feedback on each trial and were prompted to see if they could do better on subsequent trials (Stodden et al., 2014). Video data were collected using digital video cameras with a frame rate of 60 Hz that were placed perpendicular to the participants' intended direction of kicking. Video data were analyzed using DartFish® (Fribourg, Switzerland) software that allows for frame-by-frame evaluation of video data.

Observer objectivity

Prior to data reduction of the videos, five members of the research team categorized 50 randomly-selected trials of the children attempting to forcefully kick a ball to establish inter-rater reliability. Inter-rater reliability was established using a Kappa statistic (Safrit and Wook, 1995) to determine the strength of agreement between members of the research team which ranged from $k = 0.860$–0.990. Fourteen days after initial coding, each of the five research team members coded the same randomly-selected trials to establish intra-rater reliability. Intra-rater ranged from $k = 0.890$–0.988.

Data analysis

Data were analyzed blinded to all preceding sequence explanations. The mode of each participant's five kicks was used for data analysis. Each sequence was given a number to maintain objectivity during analysis. After the statistical analysis was completed, the numerical sequences were matched to sequence names. Data analysis was conducted in R (R Core Team, 2017) with the mirt package (Chalmers, 2012).

Table 2. Descriptive statistics for the individual components and levels.

			Component level number				
Sequence	Range	Mean	1	2	3	4	5
Approach	1–3	2	37	161	56		
Support (plant) foot location	1–3	2	30	172	52		
Knee action	1–5	3	11	40	120	60	23
Trunk action	1–3	1	150	84	20		
Ball contact	1–2	1	186	86			
Arm action	1–3	2	38	174	42		
Follow-through	1–4	2	66	131	29	28	

In the current study, the generalized pulse-code modulation (gPCM) was used, which is capable of modeling several scales with a variable number of levels between test items simultaneously (Muraki, 1992). Within the gPCM, the overall capability level (Θ as a value for forceful kicking) of each participant is modeled on a so-called logit scale. The modeling of the capability incorporates weighted information from all components. The logit scale mean is zero and can be compared to z values. Each of the body segment components consists of several levels that are ordinal-scaled (see Table 2). This intuitively intended order was examined using a data-driven approach under the assumption that each participant is regarded to have an individual manifestation on the latent trait (or skill), which can be modeled on a continuous basis.

Evaluating the statistical model fit of the gPCM is two-fold. First, item fit for each component (item) is indicated by the Chi-square (χ^2) statistics for $p > 0.05$. Further, the gPCM models the difficulty of each component, but also the difficulty and probability $P(\Theta)$ of each individual component level given a certain capability separately on the same logit scale as the participants' capability Θ. Based on these probabilities, all thresholds b_i between each consecutive level for each component are modeled also on the logit scale. Figure 1 illustrates a component with three ordered levels (for an illustration of unordered levels see Figure 2).

The item response curves p(Level 0), p(Level 1), and p(Level 2) show the probability of that response given a certain capability Θ. All three curves show a maximum somewhere on the x-axis (ability scale). It would be most probable for a participant to show Level 1 with a capability below -1.25 while participants with a capability from -1.25 to 1.15 would reach Level 2 and participants above 1.15 would reach Level 3. Thus, for a component consisting of three levels, two thresholds b_1 and b_2 were estimated. A developmentally valid sequence is assumed in case of fitting χ^2 statistics and accurate statistical order of the levels within each component, $b_i < b_{i+1}$. An invalid order would also be shown graphically if the probability curve of a component level does not show a maximum somewhere on the continuum of the skill (see Figure 1).

An invalid order for hypothetical Level 2 and Level 3 means (e.g. $p < 0.05$), for instance, that it would be arbitrary for a participant to progress from Level 1 into Level 2 or immediately into Level 3 and, thus, these unordered sequences could not be regarded as being developmental. In cases where levels show invalid statistical order, relevant levels are merged and the resulting new threshold order is analyzed again. Items with only two levels do not provide information regarding their statistical order. Here, the χ^2 statistics fully indicate model fit. Within the modeling process,

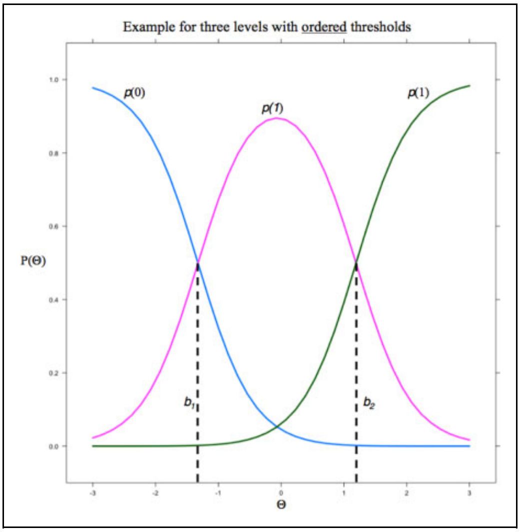

Figure 1. Example for item response curves for a component with three ordered levels. The probability curves—*p*(0) for level 0, *p*(1) for level 1, and *p*(2) for level 2—show the probability for a certain level given a certain ability Θ. A threshold b_i is estimated between each consecutive pair of curves. Thus, two thresholds are estimated for a component consisting of three levels.

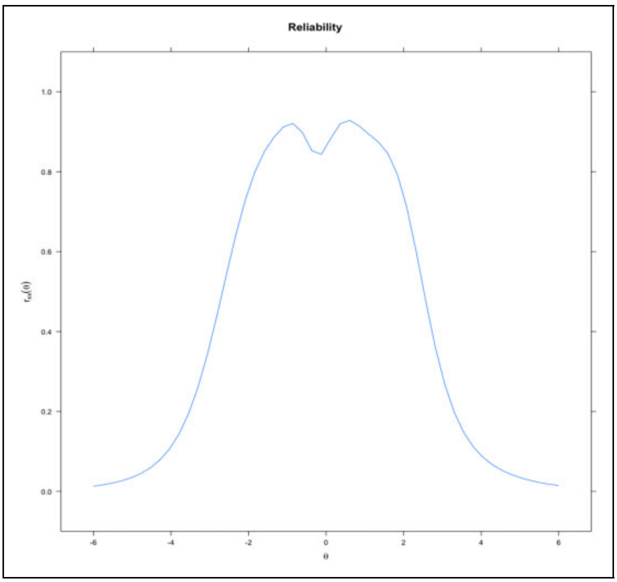

Figure 2. Reliability function for the seven-sequence scale "developmental sequences for forceful kicking".

misfitting components were excluded from the model one at a time, and the modeling process was repeated and reliability information for the scales were provided.

Table 3. Threshold parameters and item fit indices from the generalized partial credit model for the original seven sequences.

Sequence	Discrimination index	Thresholds				Item fit		
		b_1	b_2	b_3	b_4	χ^2	*df*	*p*
Approach	2.77	-1.30	0.93			10.17	11	0.52
Support (plant) foot location	1.58	-1.76	1.20			17.07	12	0.147
Knee action	3.13	-2.08	-0.96	0.61	1.35	27.15	12	0.007
Trunk action	3.20	0.36	1.46			8.07	8	0.42
Ball contact	0.48	1.48				19.92	10	0.03
Arm action	2.47	-1.31	1.17			25.25	12	0.014
Follow-through	0.50	-1.61	3.25*	0.622*		33.80	22	0.051

Note: * shows unordered thresholds.

Results

The frequencies of each level within each of the seven components are shown in Table 2. For the validation, the gPCM was computed for all seven components. Threshold parameters b_i show several model violations for the *Follow-through* sequence (see Table 3 and Figure 2). For *Follow-through*, threshold b_3 (0.622) was smaller than threshold b_2 (3.25) indicating that the ordinal scale of the levels was violated. Thus, it was random whether children whose skill increased (i.e. reached component Level 3 or skipped Level 3) progressed directly into Level 4. Further model evaluation shows that several items showed no initial item fit, because χ^2 tests indicate fit violations (i.e. *Knee action*, *Arm action*, and *Ball contact*; *p*s < 0.05, Table 2). The modeling process revealed that for some components some levels had to be merged to reflect the lack of difference between identified levels (i.e. *Follow-through*) or the lack of item fit (i.e. *Knee action*). After merging *Knee action* Level 1 and Level 2 as well as Level 4 and Level 5, *Follow-through* Level 3 and Level 4, six sequence progressions (*Approach*, *Support (plant) foot location*, *Knee action*, *Trunk action*, *Arm action*, and *Follow-through*) met model requirements (item fit χ^2 all *p*s > 0.05). One item had to be removed (i.e. *Ball contact*, item fit $p < 0.05$). Final model results show ordinally scaled levels for all components and are presented in Table 3. The reliability point estimate for the six-sequence scale is Rel = 0.88. The gPCM provides information regarding the reliability given a certain capability showing that the reliability was highest for children slightly below or above average (see Figure 2).

In summary, data analysis provided for a reduction from seven hypothesized sequences to six (removing *Ball contact* due to a lack of item fit; Table 4). Data analysis also provided for the consolidation of *Knee action* (five levels to three) and *Follow-through* (four levels to three). The sequences for Level 1 and Level 2 of *Knee action* were combined as neither hypothesized levels required an approach; however, no participants were found to elicit the action that would coincide with a Level 1 (i.e. pushing motion with no backswing). Level 4 and Level 5 of *Knee action* were also combined to reflect any motion in which the ankle was actively raised above the height of the knee gained with an approach. Lastly, Level 3 and Level 4 of the *Follow-through* were combined to reflect any generation of force that would propel a kicker into the air using either a hop or leap. All amended hypothesized sequences met model requirements (item fit all *ps* > 0.05; see Table 4). The complete description of each sequence analyzed and the subsequent adjustments can be found in Table 1 and Table 5.

Table 4. Threshold parameters and item fit indices for the remaining six sequences.

		Thresholds		Item fit		
Sequence	Discrimination index	b_1	b_2	χ^2	*df*	*p*
Approach	3.08	-1.25	0.88	3.90	6	0.69
Support (plant) foot location	1.75	-1.68	1.13	11.67	7	0.11
Knee action	5.10	-0.85	0.53	9.88	5	0.08
Trunk action	3.15	0.35	1.45	9.61	5	0.09
Arm action	2.26	-1.32	1.20	12.76	7	0.08
Follow-through	0.83	-1.10	1.34	16.00	11	0.14

Discussion

The purpose of this study was to conduct a prelongitudinal screen to assess the validity of hypothesized component sequences of kicking. Our results suggest that several differences can be noted across low to more advanced skilled kickers in relation to the six identified component developmental sequences. The depictions of low skilled and skilled kickers for each developmental sequence are discussed individually.

Approach

The initial stage of an approach (Level 1) to forceful kicking, that had been previously described in the early motor developmental literature (Gesell et al., 1940; Seefeldt and Haubenstricker 1976; Wickstrom, 1975) as a push of a ball from a standing position (Gesell et al., 1940), was not observed even with the youngest of our participants (4 years old). The results of the present study show that highly skilled kickers perform an approach that consists of step, hop, or leap (i.e. resultant from a walking or running stride) just prior to contacting the ball as suggested by Haywood and Getchell (2019). The momentum gained from the approach contributes to the momentum generated prior to ball contact of the kick. When an approach is coupled with an *Angular approach* the range of motion increases and the maximal possible radius of the swinging leg increases potentially resulting in increases in acceleration and force production (Kellis and Katis, 2007).

Support (plant) foot location

Lower skilled kickers will stand directly behind a ball prior to swinging the kicking leg. As a result, there is no selection of support foot location. As performers increase their skill level by adopting a linear or angled-approach they will optimize their performance by planting their foot for support close to the ball. The highest skilled kickers will place their foot parallel to the middle of the ball they intend to kick (*aligned*). Placing their foot before or after the middle of the ball is a result of a lack of coordination and control of their center of mass that will directly result in changes to the kinetic chain throughout the kicking motion that may decrease the likelihood that the foot will reach an optimal contact position with the ball (Lees et al., 2010).

Knee action

From a stationary position, low skilled kickers will flex the knee prior to kicking without the aid of an approach. During a linear or angular approach, skilled kickers will actively flex their knee, raising their foot and ankle to a height equal to or above the height of the midline of the knee of the kicking leg. This active preparatory backswing increases the kicker's range of motion allowing for concentric contraction of the quadriceps and increased acceleration prior to contact with the ball (Kellis and Katis, 2007). Thus, an increased force is applied to the ball at contact over that of low skilled kickers.

Trunk action

Low skilled kickers lack trunk and pelvis rotation. This finding confirms the suggestion by Haywood and Getchell (2019) who report that the trunk and arms minimally rotate and may even remain stationary during the kicking motion of low skilled performers. Skilled kickers will initiate a differentiated rotation of the pelvis and trunk by initially turning their pelvis and torso away from the intended flight path of the ball (Dorge et al., 2002). *Trunk action* may be maximized with an angular approach when the performer moves their pelvis toward the intended flight path of the ball immediately prior to movement of the torso and the upper thigh and shank (shin, ankle, and knee). This increased eccentric loading of the hip flexors and knee extensors may facilitate increased storage and recovery of the elastic energy component of the stretch–shortening cycle leading to increased power production during the kicking motion (Barfield et al., 2002; Kellis and Katis, 2007; Lees et al., 2010).

Arm action

Low skilled kickers lack arm movement, using their hands only for balance. There is a noted use of both arms in skilled kickers to assist in force generation. A large variance in the use of arms exists and warrants further study to determine if an optimal strategy exists for maximal force generation. It was hypothesized by the authors of this study that to generate trunk rotational forces and leg swing momentum requires the use of the arms to maintain balance and stability throughout the kicking motion and upon landing. However, these results cannot confirm this suggestion (Haywood and Getchell, 2019; Wickstrom, 1975). The results of this study concluded that arm movement of the contralateral arm assists in the differentiation of the trunk while the ipsilateral arm remains outstretched. It appears that the arm motion may be actively used for force generation by aiding in rotation and differentiation of the trunk.

Follow-through

Low skilled kickers lack an approach and momentum generation. As a result, there is no follow-through, thus, they will place the foot of their kicking limb back in a position similar to the position used prior to initializing the kicking motion. The momentum generated by the approach, center of mass translation, and leg swing of a skilled kicker will result in a stepping, hopping (landing on non-kicking leg) or leaping (landing on kicking leg) motion. The variance of these movements is most likely dependent on the intended flight trajectory of the ball. For example, if the intended trajectory is high (i.e. kicking a field goal in American Football) the resultant follow-through is a hopping motion while a lower trajectory (i.e. shooting a ball at a goal in soccer/football) will result in a leaping motion.

Practical implications

Children without disabilities (in the present study) were expected to reach the highest developmental levels of kicking by age 14; however, many of those represented by this sample did not. This observation implies that children may lack adequate instruction and practice time related to the skill of kicking. Therefore, these sequences may aid in the identification of those lacking appropriate kicking development. Mally et al. (2011) indicated that kicking for distance is a control parameter for performance, thus, kicking with high levels of effort can help promote increased skill development. An increased approach distance and more complete action of the kicking leg on the windup and follow-through, as well as the coordinated action of the trunk and arms is necessary for promoting kicking speed. The final hypothesized development sequences for forceful kicking noted in Table 5 provide a useful assessment tool for physical educators, sport coaches, and physical activity professionals. Future development of learning activities and instructional materials are warranted to facilitate the successful dissemination of these hypothesized sequences to teachers and coaches. Teaching methods should emphasize instruction that encourages, rather than constrains, large rapid movements in kicking and avoid the use of specific targets (Molina et al., 2019; Roberton, 1996).

As previously noted, cross-sectional screening methods, such as those used for this study, are used as a first step in the validation of developmental sequences. Therefore, the developmental validity of the order of each sequence should be confirmed with longitudinal data. While this study sample is representative of children from Midwest, Southwest, and Southeast regions of the United States, results may not be representative of children from other cultures. Luz et al. (2019) in a comparison of United States and Portuguese children's motor competence highlighted cultural differences as a cause of sex differences in kicking performances, noting specifically that the popularity of girls' inclusion in soccer in the United States may have significantly impacted their kicking performance over that of their Portuguese peers. Further research is warranted to examine any potential differences in component sequence order across international populations.

The initial (i.e. Level 1) developmental approach suggested by Gesell et al. (1940) was not found within the population of this study. Previous motor developmentalists predicted that the ability to kick a ball correlated with the onset of running, which first appears around the age of 18 months (Gessel et al., 1940; Roberts and Metcalfe, 1969). Thus, the lack of support for the hypothesized level 1 approach may be due to the lack of inclusion of younger children (ages 1–3 years) in this sample.

Conclusion

The purpose of this study was to provide validated cross-sectional, developmental sequences for use by physical education teachers, sport coaches, and physical activity professionals. Due to a lack of empirical evidence from modeling, two component sequences (*Knee action* and *Follow-through*) contained levels that were merged to reflect the lack of difference between identified levels. One component of the initial seven hypothesized sequences (*Ball contact*) was removed entirely. Overall, our results provide sufficient cross-sectional evidence for six component developmental sequences progressions (*Approach*, *Support (plant) foot location*, *Knee action*, *Trunk action*, *Arm action*, and *Follow-through*) that adequately describe the development of kicking across childhood that can be used for the instruction of forceful kicking.

Table 5. Final hypothesized developmental sequences for forceful kicking.

Skill	Level 1	Level 2	Level 3
Approach	*No approach*: Both feet positioned directly behind the ball and no steps are taken	*Linear approach*: Positioned at a distance directly behind the ball in such a manner that allows for forward movement toward the ball before kicking	*Angular approach*: Positioned at an angle behind and to the side of the ball in such a manner that allows for accelerated movement toward the ball before kicking
Support (plant) foot location	*Stationary*: Supporting foot behind ball (as a result of no stepping action). At the initiation of the kicking motion the support foot remains at rest behind the ball	*Reaching*: Supporting foot, as a result of an approaching step, is placed one-foot length (performer's foot) beyond or before the mid-point of the ball. (i.e. before or after the ball)	*Aligned*: Supporting foot, after an approaching step, is placed within one-foot length (performer's foot) of the mid-point of the ball (i.e. either before or after the ball)
Knee action	*Flexed*: Prior to contact with the ball the knee of the kicking leg is flexed to raise the ankle to a position above the ground in preparation for the kick. This motion is observed in the absence of an approach prior to kicking. This motion may also occur without the presence of a preparatory backswing	*Passive height*: As a result of a preparatory step the ankle maintains a position no higher than the knee of the kicking leg in preparation for the kick. No independent raising of ankle observed	*Knee height*: During a stepping or running approach the knee is flexed to raise the ankle to a height above the knee independent from the height gained from an approach
Trunk action	*No rotation*: No preparatory extension or rotation of the pelvis or trunk.	*Total trunk ("block") rotation*: The pelvis and/or trunk externally rotate away from the intended flight of the ball and then simultaneously begin forward rotation towards the flight path of the ball as a single unit	*Differentiated rotation*: The kicker externally rotates the pelvis away from the intended flight path of the ball. The pelvis then begins forward rotation prior to the movement of the trunk.
Arm action	*Bilateral inactive*: No arm movement during kicking (i.e. arms held by side)	*Bilateral reactive*: Arm movement unsynchronized and reactive and is utilized only to maintain balance	*Bilateral active*: Arm movement of contralateral arm assists in the differentiation of the trunk while the ipsilateral arm maintains an outstretched. The arm motion is actively used for force generation by aiding in differentiation rotation

(continued)

Table 5 (continued)

Skill	Level 1	Level 2	Level 3
Follow-through	*Planted*: The support foot and heel do not leave contact with the ground. The kicking leg will come to rest in its original position next to the support foot or within the length of half of the height of the kicker	*Heel raise*: The heel of the support foot leaves the ground while the toe remains in contact. The force generated by the kicking leg brings the performer into a plantar flexed position while the toe remains in contact with the ground	*Hop*: The support foot, as a result of the momentum generated during the kicking motion, leaves contact with the ground and becomes the first foot to regain contact with the ground upon landing

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