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Evaluation of the Throw-Catch Assessment

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DEDICATION

To Mom and Dad,

I leaned on your unrelenting love, support, and confidence in me throughout this process more than you can ever know.

Thank you for making me the person I am today.

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ABSTRACT

Motor competence assessment has been characterized by the evaluation of motor skill performance in closed performance contexts that lack task and environmental constraints reflective of real-world contexts. In contrast, the throw-catch (TC) assessment employs a dynamic task environment that allows performers to adapt over multiple trials to evaluate the degree of skilled performance via demonstration of a flexible and adaptable repertoire of both throwing and catching actions. The purpose of this dissertation was to investigate the developmental validity of the TC, as well as the content validity of the TC in terms of assessing throwing skillfulness.

Performance of the TC task demonstrated a strong positive relationship with age (r = .743) in participants 8-22 years old and demonstrated similar trends in both males (r = .746) and females (r = .698). Further, TC scores demonstrated strong relationships with process- (component developmental sequences; r = .588) and product-oriented (maximum throwing speed; r = .640) assessments of throwing skill in young adults.

These data provide preliminary support for the TC as a developmentally valid and practical assessment of throwing. In addition, this novel assessment enhances the ecological validity of MC assessment via the integration of two foundational motor skills that are concurrently performed in many real-world performance contexts, demonstrating the complementary interplay between the two skills. Future research on the TC

assessment should verify its validity via longitudinal designs and with larger culturally diverse samples.

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CHAPTER 1

INTRODUCTION

1.1 Motor Competence Assessment

The assessment of motor competence (MC) is critical for examining motor skill development and its role in promoting various health-related outcomes (Stodden et al., 2008; Robinson et al., 2015) and other developmental domains (e.g., cognition, self-efficacy; Haapala, 2013; Leondard & Hill, 2014; Pesce, Vazou et al., 2021). Assessments of motor skill competence are designed to measure qualitative aspects of movement regarding *how* a task is performed (i.e., process-oriented) and/or quantitative information concerning the *outcome* of the performed task (i.e., product-oriented; Logan et al., 2017; Barnett et al., 2020). Differences in the information garnered by process- versus product-oriented measures suggest the inclusion of both types of measures to provide a more complete representation of MC (Logan et al., 2017; Barnett et al., 2020).

Throwing is one of the most studied motor skills because of its evolutionary history and relevance to various physical activities and sports across many cultures. There are 33 known unique assessments that have been used in the field of motor development with distinct methods for evaluating throwing skill level (Barnett et al., 2020). For example, many throwing assessments designed to differentiate between throwing movement patterns vary in selection of specific indicators or movement characteristics as well as the number of indicators used to classify the skill level of the performance (e.g., Test of Gross Motor

Development [TGMD]; Ulrich & Sanford, 1985; Ulrich, 2017; Get Skilled Get Active [GSGA]; New South Wales Department of Education and Training, 2006; Children's Activity and Movement in Preschool Study Motor Skill Protocol [CMSP]; Williams et al., 2009; Component developmental sequences; Roberton & Halverson, 1984). Differences in task goals (e.g., throwing for maximum effort/speed, throwing for accuracy) among various throwing assessments can differentially affect both process (movement patterns) as well as product (e.g., projectile speed, hitting a target) outcomes used to evaluate skill level (Williams et al., 1996; Barrett & Burton, 2002; van den Tillaar & Ettema, 2006; Langendorfer et al., 2011). The wide-range of methods used to measure throwing skill may contribute to the inconsistent evidence regarding the relationship between process- and product-oriented assessments of throwing skill, and other outcomes (e.g., physical activity, fitness, obesity, self-concept) of interest (Haapala, 2013; Leondard & Hill, 2014; Logan et al., 2017; Barnett et al., 2020; Pesce, Vazou et al., 2021). Assessments of throwing skill are mostly performed under closed-skill environmental contexts (i.e., stable/unchanging task demands or static environment and consistent task demands), limiting the extent to which other critical elements of skillfulness (e.g., adaptability, consistency) are demonstrated by the performer (Clark & Metcalfe, 2002; Barnett et al., 2020). As such, many throwing assessments may be limited in how performance can be generalized to more dynamic, real-world contexts inherent in games, sports, and other physical activities (i.e., ecological validity).

The questionable ecological validity in currently implemented throwing assessments coincides with motor development research that differentiates "fundamental" or "foundational" motor skills in how they are applied in specific physical activity contexts.

Specifically, the concept of fundamental motor skills implies that a primary level of competence in select skills provides a basis for the subsequent acquisition of more complex transitional context-specific skills necessary for successful participation in many different physical activity contexts (Seefeldt, 1980; Clark & Metcalfe, 2002; Stodden et al., 2008; Newell, 2020). Ironically, this emphasis on fundamental motor skills has promoted widespread use of assessments in which these skills are often isolated from ecologically relevant task demands (Barnett et al., 2020; Newell, 2020; Rudd et al., 2020).

1.2 Environmental Testing Context

Closed performance contexts that characterize many throwing assessment environments limit the generalizability of demonstrated movement patterns and outcome performance to real-world situations (e.g., physical education, sport, structured and unstructured play). For example, in handball, a player may effectively utilize different throwing patterns within their skill repertoire to throw the ball at the goal or pass to a teammate. Nuanced, yet critical, adjustments to throwing patterns are dictated by context-specific task constraints of gameplay (e.g., distance from teammate/ goal, position of defenders) that are situationally unique, thus requiring performers to create novel solutions (i.e., adaptation).

Effective throwing performance requires ball speeds and trajectories (i.e., task constraints) suited for the specific characteristics of the performance context. Specifically, the trajectory of a thrown ball is determined by characteristics of both force production and release angle. For example, when passing to a teammate, one situation may call for a "lofted" pass to a teammate in which the ball is thrown over an opposing player, while another situation may demand a pass thrown with more speed to avoid a defender. Thus, a varied throwing coordination pattern repertoire and the ability to regulate forces and directionality to produce different ball speeds with accuracy and consistency (e.g., throw to a target) and/or variability (e.g., throw with different speeds to a batter/defender) are necessary to effectively perform based on different task demands of a particular activity. Even still, these examples are too simplistic as they do not account for actions preceding (e.g., catching/ initial possession of the ball, running prior to throw) or immediately following a throw performance. In addition, time constraints typical of most physical activities necessitate a rapid performance of throwing, which can influence which throwing patterns can be used to demonstrate a successful outcome in a particular situation (Barrett & Burton, 2002). Overall, a performer who lacks a diverse repertoire of throwing coordination patterns and lacks the ability to regulate forces within a specific pattern is limited to the extent they can adapt and successfully perform in real-world throwing contexts. Specifically, there may be multiple solutions to a movement problem with several different throwing patterns and force regulation parameters that can produce successful outcomes.

1.3 Development of a Throwing Skill Repertoire

The development of throwing skill is associated with age, with boys generally demonstrating initial characteristics of more advanced throwing patterns at the age of 5.5 years and girls at 8.5 years (Seefeldt & Haubenstricker, 1982; Williams & Monsma, 2007). Similarly, throwing force (i.e., speed/distance) and directionality generally increase as individuals age, with boys demonstrating higher levels of performance at an earlier age (Nelson et al., 1986; Nelson et al., 1991; Roberton & Konczak, 2001). However, children display differing developmental trajectories and pathways in achieving more advanced throwing patterns (Langendorfer & Roberton, 2002). Though biological determinants (e.g., anatomical structure, maturation) contribute to the development of throwing performance and the noted gender differences in product measures of forceful throwing (e.g., throwing speed, throwing distance; Nelson et al., 1991; Lombardo & Deaner, 2018), this evidence provides little insight to explain differences in throwing speed and distance between boys and girl prior to puberty (Blanksby et al., 1986). Overall, it is generally held that the development of forceful throwing is most attributable to practice and experience in throwing tasks which promote the development of higher-level throwing patterns (Sakurai & Miyashita, 1983; Thomas & French, 1985; Butterfield & Loovis, 1993; Thomas et al., 1994; Stodden et al., 2006a, 2006b; Lorson et al., 2013), though little is known about factors underlying the development of throwing accuracy.

Advanced throwing patterns are differentiated from less-advanced patterns by the extent to which the performers exploit neuromuscular and mechanical properties of the body's kinetic link system during the performance of a throw (Stodden et al., 2006a, 2006b; Langendorfer et al., 2011). As individuals develop throwing skill, they progress through a sequence of throwing pattern combinations that initially demonstrate a disjointed pattern of component interactions to a more effective, proximal to distal kinetic chain sequence. This progression is reflective of the incorporation of higher magnitudes of force production, larger joint ranges of motion, and more efficient transfer of energy from the lower extremities to the throwing hand, resulting in higher throwing velocities (Fleisig et al., 1999; Stodden et al., 2006a, 2006b; Fleisig et al., 2016; Fleisig et al., 2018). As more advanced throwing patterns emerge, the potential repertoire of throwing patterns that can be effectively implemented to context-specific goals accumulates (Urbin et al., 2012). That is, previous throwing pattern combinations are not "lost" and can be effectively implemented to produce a successful performance depending on the context of performance. In many situations, an individual can apply one or more previously acquired throwing patterns and variable force parameterization characteristics within patterns based on his/her perceptions of the performance context (i.e., interaction between task, individual, and environmental constraints; Barrett & Burton, 2002; Urbin et al., 2012; Ranganathan et al., 2020; Rudd et al., 2020). When throwing with the intent of producing higher projectile speeds or longer distances, more advanced throwing patterns emerge (Roberton, 1996; Barrett & Burton, 2002; Southard, 2006). Unfortunately, little research has addressed how performers alter kinematics and coordination to adapt to changing task constraints, such as accuracy and time, which are critical to throwing performance in most real-world scenarios.

It is generally accepted that movement accuracy is sacrificed when task goals necessitate higher movement speeds (Fitts, 1954). Though the inverse relationship between the movement speed and accuracy, known as "Fitts Law," has been demonstrated during many motor tasks, there is evidence to suggest that the speed-accuracy trade-off may not apply to multi-joint ballistic motor skills, such as throwing (Urbin et al., 2012; Molina & Stodden, 2018; Molina et al., 2019). In addition, the variability in performance outcomes (e.g., throwing speed) across a spectrum of percentage effort in ballistic skills may not increase at a linear rate, even with differences in movement pattern dynamics that occur across different performance speeds; thus, individuals are able to organize their coordination and control of segmental interactions and its output (i.e., both speed and accuracy) without compromising performance (van den Tillaar & Ettema, 2006; Urbin et al., 2012; Molina & Stodden, 2018). These adaptation capabilities speak to the potential environmental constraints that promote the use of different movement patterns and force parameterization for successful performance in a variety of contexts. Specifically, decreased variability in segmental acceleration forces and relative timing that are demonstrated at higher speeds suggest spatial error produced when throwing at higher percentages of maximum speed may be more attributable to variability in preparatory alignment of segments and timing of ball release (Urbin et al., 2012).

Since accuracy and variability in performance may not necessarily be compromised across a spectrum of movement speeds in throwing performance, an individual may effectively adapt performance via both coordination patterns (i.e., use previously learned throwing patterns within their movement repertoire) or regulate magnitudes and durations of force application within the same pattern to create accurate and consistent movement outcomes (Schmidt et al., 1985; Barrett & Burton, 2002; Urbin et al., 2012; Molina & Stodden, 2018). A low-skilled thrower will, however, have a limited range of throwing patterns they can demonstrate, thus limiting the extent to which they may be able to adapt their performance. For example, due to the integrated nature of joint interactions during throwing, the lack of higher-level trunk patterns during throwing limits the availability of high-level distal segment dynamic interactions (e.g., humerus and forearm lag) critical to higher throwing speeds (Langendorfer & Roberton, 2002). Thus, low-level throwers lack potential for adapting throwing patterns that they do not have in their repertoire, specifically in tasks requiring relatively high throwing speeds. Overall, the capability of an individual who has a limited skill pattern repertoire within a skill (i.e., a less skilled performer) to consistently demonstrate a successful outcome is not known. Investigating the throwing strategies of differentially skilled throwers and how they may or may not adapt to ecologically relevant task conditions to successfully accomplish a task will provide more authentic and generalizable information relating to skilled movement.

1.4 Advancing assessment from an Ecological Dynamics perspective

To effectively capture adaptational capabilities of individuals' motor skill performance, motor skill assessment must provide dynamic performance environments where individuals have the capability to choose how the goal is attained and relinquish the rigid interpretations of movement patterns according to predefined "optimal" movement templates that currently dominate the field of motor development assessment. But how can we create assessment tasks capable of promoting adaptive movement solutions while maintaining the standardization necessary to reliably differentiate between various skill levels? An intentional and direct appreciation for the link between perception and action in the design of MC assessment may assist in identifying the functional movement solutions specific to the performer in a particular context (i.e., affordances; Gibson, 1979). Deliberate selection of specific task constraints and a performance environment that provides the potential for a wide range of movement solutions can allow for a greater understanding of the movement capabilities of the performer (Rudd et al., 2020). In essence, while the assessment task and environment are standardized, the "open-ness" is brought to the assessment context by the performer and shaped by the performer's perceptions of the task/environment and their own performance capabilities. In theory, the highest possible level of performance would result from the selection of the most appropriate movement solution (i.e., flexibility to choose) within the performer's repertoire for the given context.

Further, performers of higher skill will possess a larger collection of viable movement solutions and thus, would have a higher potential for performance success in environments that inherently require adaptability in performance.

The ability of assessments to capture performers' adaptational performance capacities is critical from an ecological validity standpoint (Barnett et al., 2020). Assessment of throwing performance in sport and gameplay reflect the highest form of ecological validity. Observation in these settings demonstrate the need for performers to adapt a variety of throwing characteristics, including force, distance, repeatability, and accuracy to meet the various demands encountered in real-world settings (Barrett & Burton, 2002; Hamilton & Tate, 2002). Comparison of throwing patterns in these contexts to those deemed "ideal" is inappropriate because a) throwing form is trivial relative to the achievement of the intended task goal (Barrett & Burton, 2002) and b) conceptualizations of "ideal" throwing patterns formed through the observation of throwing for maximal force may not align with the various performance contexts encountered in authentic settings (Buekers et al., 1999). Analyses of throwing behavior should instead account for the constraints imposed by the task/environment and the performer's ability to exploit movement variability to achieve task success (Buekers et al., 1999). Careful manipulation of constraints related to the force and accuracy demands in throwing assessments may provide more generalizable results (i.e., ecologically valid) in terms of assessing throwing skill.

There are examples of assessment tasks that better capture the essence of an ecologically valid task as they combine multiple skills and are inherently more complex from a performance perspective. The throw-catch (TC) assessment published by Terlizzi et al. (2022) provides a context in which performers may choose to demonstrate numerous coordination patterns (if they have that capability) to successfully complete the assessment task. Participants are tasked to repeatedly throw a tennis ball against a wall from approximately three-times their standing height and catch it on its return as many times as possible in a 30 second trial. Performers are not provided with instruction on how the task must be completed, except that the thrown ball must first hit the wall in the air. As such, the task demands that the performer integrate multiple task (e.g., distance from wall, size and percussion characteristics of the ball and wall), environmental (e.g., gravity, ball/wall percussion dynamics) and individual (e.g., perception-action capabilities, throwing and catching skill repertoire, agility) constraints to produce as many throw/catch combinations as possible in 30 seconds. The performer may choose to apply any number of throwing pattern (i.e., "advanced" or "rudimentary") and catching (e.g., with one or two hands) behavioral combinations that promote successful goal achievement based upon individual's perceptions of their own capabilities and the constraints of the task. Maximum performance of the current throw-catch (TC) task includes effective integration of information based on the linkage of multiple constraints with an individual optimizing both throwing speed and release angle to consistently create ball trajectories that allow not only for the ball to be caught on its return, but also minimizes both the time the ball is not in the performers possession and the time needed to transition (i.e., preparatory body segment and postural configuration) into the next throw. Because multiple task performances are incorporated within each trial, the TC task captures the performer's ability to consistently achieve successful outcomes, a key component of MC absent from many other assessment contexts (Barnett et al., 2020). Thus, a lack of consistent and accurate throwing trajectories may dictate that the performer adapts different coordinative and control strategies in subsequent throws to effectively respond to perturbations (e.g., change in orientation of the body for catching, throw at a different speed, throw with a different coordination pattern) while still performing the throw quickly with an effective and repeatable trajectory.

Overall, this assessment has the potential to advance MC assessment strategies by addressing characteristics of skilled behavior that are not currently measured in most individual assessments. In essence, the TC task provides a more complex gross motor task environment that places greater perception-action coupling demands on the individual and integrates force regulation, accuracy, consistency, and adaptability demands in one task that incorporates multiple fundamental movement skills.

Not known is whether performance on this task is developmental in nature (i.e., demonstrates increased performance across age) and whether it is associated with other developmentally valid throwing skill assessments (e.g., component developmental sequences and maximum throwing speed). The purposes of this study are to examine the developmental validity (using a pre-longitudinal screen) of the TC task based on the scores across ages 8 to 22 years and examine the association between TC scores with validated product- and process-oriented measures of throwing skill in a sample of young adults.

CHAPTER 2

LITERATURE REVIEW

The assessment of skilled movement is a complex endeavor and has recently gained increased attention in the field of motor development with research noting its importance to other critical developmental and health outcomes (Haapala, 2013; Leondard & Hill, 2014; Ré et al., 2018; Barnett et al., 2020; Pesce, Vazou et al., 2021). Thus, the need to fully realize the contribution of motor development to other developmental domains (i.e., predictive utility) will continue to be a focus in the field of motor development. Overall, there is little consensus on testing protocols and assessment designs for evaluating MC. In addition, there is a relative lack of agreement among assessments purporting to measure the same construct (Logan et al., 2017; Re et al. 2018; Barnett et al., 2020). These inconsistencies result in a range of assessments that prioritize different types of skills and different aspects of skilled behavior. To comprehensively evaluate and differentiate between levels of skill, assessments must account for the multidimensional nature of skilled performance.

The following chapter is separated into four sections. The first section summarizes current literature on the assessment of MC. The next section describes the importance of Ecological Dynamics as a contemporary alternative theoretical framework for evaluating skilled movement. The third section provides a synopsis of research concerning the development of skillful throwing. The final section describes the limitations of previous assessments of throwing skill and potential for the TC task to fulfill those needs based on the theoretical underpinnings of Ecological Dynamics framework.

2.1 Current State of Motor Competence Assessment

It is important to understand the nuanced, yet critical differences between terms that are used consistently in motor development literature, as they have significant implications when considering the intent of assessment. The study of *Motor Development* investigates the *process of changes* in motor behavior over the lifespan that are sequential, cumulative, continuous, and age-related. The study of the process of change also includes the underlying mechanisms and interactions with the various contextual factors that influence changes (Clark & Whitall, 1989; Barnett et al., 2020; Haywood & Getchell, 2021). *Motor Competence* (MC), on the other hand, speaks to the degree of *skillfulness* in a wide range of motor tasks (D'Hondt et al., 2013). In this context, MC can be viewed as the outcome of motor development, or the manifestation of biological, cognitive, and perceptual processes, their interactions, and interactions with environmental factors (i.e., individual experiences; Clark & Whitall, 1989; Clark & Metcalf, 2002).

MC is assessed using either product- (i.e., measures which describe movement outcomes) and process-oriented (i.e., measures which describe the actions or movement patterns that produce an outcome) measures of human movement, or a combination of both process- and product-oriented measures (Clark & Whitall, 1989; Barnett et al., 2020). While use of the term "motor competence" has been used in contemporary literature in the field of motor development, it is reflective of various product- and process-oriented measures of motor skill performance that have historically been used to assess change in various motor behaviors (Clark & Whitall, 1989). In addition, various terminology has been used to describe skilled behavior (i.e., motor proficiency, motor coordination, motor ability, motor fitness, motor performance), yet there is no valid distinction among these various terms and how they are purportedly assessed. Motor development researchers also have used many different product-oriented and process-oriented assessments that were reflective of the dominant perspectives and goals of motor development research across the 20th Century and the beginning of the 21st Century (Clark & Whitall, 1989; Thelen, 2000; Barnett et al., 2020). While movement outcomes were prioritized and examined to produce normative data during early motor development research, the introduction of the dynamical systems perspective on the underlying processes of motor development (Bernstein, 1967) drove the development and use of process-oriented measures (Clark & Whitall, 1989; Thelen, 2000) and testing batteries to study changes in movement patterns (e.g., TGMD, GSGA, CMSP, Motorische Basiskompetenzen [MOBAK]; Herrmann et al., 2019; Herrmann & Seelig, 2017a, 2017b, developmental sequences; Wickstrom, 1977; Seedfeldt, 1980; Roberton & Halverson, 1984). While the use of process-oriented measures remains the predominate method used by current researchers to assess motor competence (Logan et al., 2017), product-oriented assessments also are common and are increasingly used to examine MC (e.g., Korperköordinations Test für Kinder [KTK]; Schilling & Kiphard, 1974; Kiphard & Schilling, 2007; KTK3+ Eye Hand Coordination [KTK3+]; Platvoet et al., 2018; Coppens et al., 2021; Motor Competence Assessment [MCA]; Luz et al., 2016; Bruininks-Oseretsky Test of Motor Proficiency [BOT]; Bruininks & Bruininks, 1978, 2005), specifically as they are more feasible for large-scale data collections.

The development of MC assessments and selection of specific motor skills of interest have been heavily influenced by the work of Wickstrom (1977) and Seefeldt (1980), amongst others, who identified specific motor skills as being "fundamental" to further skill development and its application. According to this view, fundamental motor skills are common skills viewed as the basis, or "building blocks", for the subsequent development of more complex, context-specific skills utilized in many physical activity contexts (e.g., games, sports, dance; Wickstrom, 1977; Seefeldt, 1980; Clark & Metcalfe, 2002; Logan et al., 2018). Fundamental motor skills are classified as either object manipulation (e.g., throwing, kicking, striking, catching), locomotor (e.g., running, hopping, skipping, galloping, jumping), or postural control/stability skills (e.g., rolling, bending, twisting, dodging, balancing) according to interpretation of the movement action and outcome (Goodway et al., 2019; Newell, 2020). Notably, the performance of many skills, especially in real-world contexts, involve the performance of multiple skills in series that span more than one classification of fundamental motor skills (Newell, 2020). Nevertheless, commonly used process-oriented (e.g., TGMD, GSGA, CMSP, MOBAK, Component Developmental Sequences) and product-oriented assessment methods (e.g., KTK, KTK3+, MCA, BOT) assess competency in fundamental motor skills independently and isolated from other skills and dynamic task constraints. Though there are differences in the specific skills assessed across various MC test batteries based on interpretations of their fundamental nature and views of cultural appropriateness of specific skills (Barnett et al., 2016), assessment batteries generally are designed to "cover the most representative or salient skills that, if mastered, will give children the best possible chance to *successfully* *and persistently participate* [italics added] in a range of health-enhancing behaviors" (Barnett et al., 2016, p. 220).

The use of fundamental motor skill assessments to estimate motor competence has been instrumental in advancing motor development theory and research relating the development of MC to various health-related and developmental outcomes (e.g., physical fitness, obesity, self-concept; Stodden et al., 2008; Haapala, 2013; Leondard & Hill, 2014; Robinson et al., 2015; Pesce, Vazou et al., 2021). Recently, developmentalists have suggested limitations of this approach in terms of its ability to represent and predict motor skill performance in real-world contexts and fully capture and appreciate the multifaceted/dimensional nature of skilled movement (e.g., variability/consistency of skill performance, adaptability; Barnett et al., 2020; Hulteen et al., in press). This critique of the traditional fundamental motor skill approach to evaluate MC aligns with an Ecological Dynamics conceptualization of MC, specifically, the impact of perception on movement behaviors (Rudd et al., 2020). From this perspective, the assessment of skills performed in isolated and closed contexts that emphasize "optimal" kinematic characteristics minimizes the extent we are able determine performers' abilities to integrate and adapt movement to perceptual information (Rudd et al., 2020; Seifert et al., 2013).

2.2 An Ecological Dynamics Approach to Motor Competence Assessment

The assessment of movement behavior in an "authentic" environment is a key tenet of the Ecological Dynamics framework. Ecological Dynamics incorporates perspectives from Ecological Psychology and Dynamical Systems theory to characterize the emergence of movement behaviors through reciprocal relationships between the performer and characteristics of the task and environment (Buekers et al., 1999; Seifert et al., 2013; Rudd et al., 2020). The performer's perceived "actionable properties" of a specific context (i.e., affordances) are defined by the perceptions of the task and environment relative to perceptions of their own performance dispositions (i.e., intrinsic dynamics; Gibson, 1979; Seifert & Davids, 2017; Adolph & Hoch, 2019). As such, the ecological dynamics conceptualization of skilled movement embraces an individual's ability to "explore" or interact with the environment in multiple ways as a characteristic of expert behavior (Rudd et al., 2020; Stodden et al., 2021).

Observation of movement behaviors in outward-facing, open, and informationally rich environments provides the opportunity for performers to demonstrate the flexibility within their current movement repertoire, or the ability to achieve the same task goal in multiple ways (Rudd et al., 2020; Seifert et al., 2018; Ranganathan et al., 2020; Hacques et al., 2021). In this way, exploration or flexible behavior suggests an enhanced ability to recognize relevant information regarding possible movement solutions (Gibson, 1979; Araujo et al., 2006; Ranganathan et al., 2020). Flexible behavior illustrates the performer's ability to exploit redundant degrees of freedom and degeneracy within the human movement and environmental systems (Gibson & Carmichael, 1966; Bernstein, 1967; Gibson, 1979; Edelman & Gally, 2001) as well as the potential to adapt performance to meet a diverse range of environmental and task conditions (Ranganathan et al., 2020). The ability to adapt performance effectively in a variety of contexts is a hallmark of skillful or expert behavior (Clark & Metcalfe, 2002; Seifert et al., 2013; Barnett et al., 2020).

In most real-world performance contexts, technical aspects of movement (i.e., process-oriented qualities) may be trivial relative to the achievement of specific outcome-related task goals (Barrett & Burton, 2002). Thus, in many cases, there is an indefinite number of possible movement patterns that may produce successful task outcomes depending on the specific capabilities of the performer (Seifert & Davids, 2017). For example, when using an overarm throw to pass to a teammate in handball, a skilled thrower may be able to alter their throwing kinematics to produce either a linear trajectory or a more lofted pass to reach the same terminal location at the teammate to successfully accomplishing the task goal. In this example context, the capability to utilize multiple movement strategies to accomplish the overall task goal reflects a degree of flexibility within the within the performers throwing repertoire (Ranganathan et al., 2020). Alternatively, in the presence of a defender, the performers perceptions of the defender's proximity and potential for intercepting the ball may dictate that the more linear, high-speed throwing trajectory be used to decrease the amount of time needed to successfully pass to the teammate to minimize defender disruption. In this case, the expanded throwing repertoire demonstrated by ability to utilize throwing kinematics that produce higher ball speeds would enable the performer to successfully adapt to the additional task constraint presented by the defender.

In the Ecological Dynamics framework, the emergence of behavior in specific contexts is viewed as a function of the performer's intrinsic dynamics at a specific point in time (Southard, 2006). A performer's intrinsic dynamics capture changes in the way which laws of motion and perceptions interact to influence the stability of coordinative structures, or the likelihood of a specific coordinative pattern to materialize under specific task and environmental conditions (Kelso, 1995, 2012). The degree of movement pattern stability is affected by the intent to act according to perceptions of relevant task conditions, termed control parameters, which possess the potential to bring about changes in the movement patterns (i.e., relative timing of neighboring segments) when intent is scaled to a critical value (Southard, 2006; Kostrubiec et al., 2012). In the previous handball example, this can be understood by the performers intent to throw at a higher speed to avoid the defender, as throwing speed has been identified as a control parameter in throwing performance (Southard, 1998, 2006; Barrett & Burton, 2002; Hamilton & Tate, 2002;). However, the scaling of intent itself does not dictate a transition to a new coordinative pattern as only those patterns which possess the requisite degree of stability in the given performance context can be produced by the performer (Kelso et al., 1993; Kostrubiec et al., 2012). In this way, an individual's intrinsic dynamics can be considered synonymous with their repertoire of potential movement solutions in a specific context (Zanone & Kelso, 1997; Corbetta & Vereijken, 1999; Kostrubiec et al., 2012). Due to the reciprocal relationship between perception and action, the ability of the performer to detect environmental information, which specifies the potential movement solution(s) or movement parameters, is a fundamental component of an individual's intrinsic dynamics or functional movement repertoire (Seifert et al., 2013). Thus, assessment of throwing in open environments, which provide abundant sources of environmental information, may provide a means to better understand the performers' abilities to integrate perceptual information to produce successful throwing outcomes.

2.3 The Development of Skillful Throwing

Throwing has been suggested as a phylogenic feature of human behavior due to its early and universal emergence across children of different cultures and ethnicities (Young, 2009). Though rudimentary throwing actions are commonly demonstrated around the age of six months, the extent to which higher level throwing patterns are developed in childhood is influenced by factors dictating opportunities for skill development (e.g., practice, modeling, societal and cultural expectation, rearing factors, motivation; Sakurai & Miyashita, 1983; Thomas & French, 1985; Young, 2009), which demonstrate an ontogenetic process of development. Such factors that influence the volume of throwing experiences in childhood are suggested as major contributors to the well-documented gap between male and female throwing performance (Sakurai & Miyashita, 1983; Thomas & French, 1985). Throwing outcomes are most widely assessed in terms of the speed and/or spatial accuracy of the projected object. Though rarely assessed concurrently for assessing MC, the simultaneous control of both throwing speed and accuracy is critical to success in most real-world throwing contexts.

In forceful throwing, the ability to throw for maximal speed and/or distance generally increases across childhood into young adulthood (Sakurai & Miyashita, 1983; Roberton & Konczak, 2001; Lorson et al., 2013). The ability to throw with greater speed is inextricably linked to changes in the spatiotemporal characteristics of forces produced during the skill performance, which progressively integrate neuromuscular and mechanical properties of the musculoskeletal system to maximize the transfer of energy through the body's kinetic chain (Sakurai & Miyashita, 1983; Roberton & Konczak, 2001; Stodden et al., 2006a, 2006b; Lorson et al, 2013). Roberton and Halverson's (1984) component developmental sequences for the development of overarm throwing illustrate a sequential continuum by which developing throwers progressively utilize larger ranges of motion to increase linear and rotational velocities of proximal and distal segments (Roberton & Konczak, 2001; Stodden et al., 2006a, 2006b; Langendorfer et al., 2011). Children can demonstrate highly advanced throwing patterns as early as 8 years of age (Langendorfer & Roberton, 2002;

Roberton & Konczak, 2001), but less than 20% of children demonstrate highly advanced throwing patterns by the age of 15 years. While improvements in throwing accuracy are also presumed to increase with age, the underlying mechanisms by which accuracy improves are less clear.

Although conceptually independent constructs, it is impossible to separate projectile speed from accuracy when both are required due to the inherent impact of projectile speed on the projectile's spatial location at a given point in time (i.e., trajectory) in a gravity-based environment. Thus, throwing accuracy is a product of concurrent control of both projectile speed and directionality in a complementary fashion according to a specific terminal location.

Identifying specific skill-related determinants of throwing accuracy is difficult due to the complex interaction between throwing speed and accuracy. Individuals attune their movements to accuracy constraints during throwing through both alterations in movement patterns and magnitudes of systemic force production (i.e., ball speeds; Williams et al., 1996; van den Tillaar & Ettema, 2006; Langendorfer et al., 2011). The presumption of an inverse relationship between throwing speed and accuracy dominated early research on throwing accuracy. The speed-accuracy trade-off (i.e., Fitts Law) assumes a relatively constant capacity of the sensory-motor systems in which movement speed and precision compete for resources (Fitts, 1954). Etnyre (1998) observed both increased average error and variable error in dart throwing when throwing with the intent of maximal force when compared to the participants' typical throwing approach, regardless of skill level. In contrast, van den Tilaar and Ettema (2006) observed no differences in overhead throwing accuracy when comparing between tasks emphasizing accuracy or throwing speed in expert and non-expert handball throwers despite both groups demonstrating self-directed decreases in throwing speed. The authors suggested that the incorporation of trunk movement in overarm throwing introduced additional degrees of freedom when compared to dart throwing may have contributed to the differential findings (van den Tilaar & Ettema, 2006), which were in direct contradiction to the rationale underpinning Fitts Law.

Urbin and colleagues (2012) similarly found no differences in the spatial accuracy across various throwing speeds in either expert or non-expert young adults when examining the application of the impulse-variability theory to overarm throwing. The impulse variability theory proposes variability in muscular forces as primary contributors to error in limb spatial trajectories (Schmidt et al., 1979; Sherwood & Schmidt, 1980; Urbin et al., 2012). The study demonstrated an "inverted-U", parabolic relationship between the percentage of max throwing speed and the variability of throwing speeds, suggesting individuals are better able to regulate force consistently at lower and higher percentages of max throwing speed, while maximum throwing speed variability occurred around 65% of maximal throwing speed, providing support for the application of the impulse-variability theory to overhead throwing (Sherwood & Schmidt, 1980; Urbin et al., 2012). Given the decreased variability in throwing speeds as speeds approach maximum, there was an assumed consistency on the throwing trajectories when throwing at higher percentages of maximal throwing speed. However, no relationship was observed between relative throwing speed and spatial accuracy across all percentages of maximum speed (Urbin et al., 2012). Variability in the timing of ball release and preparatory segmental alignment have demonstrated an impact on throwing accuracy and may have contributed to the accuracy results demonstrating no change across throwing speeds (Chowdhary & Challis, 1999; Stodden et al., 2001; Jegede et al., 2005; Urbin et al., 2012). In general, these data demonstrate that individuals were able to modify both their speed and ball trajectories without a change in accuracy, which speaks to the capability of the system to modify parameters to demonstrate consistent accuracy.

Interestingly, less-skilled throwers in the study demonstrated less variability in throwing speed when throwing at speeds below 90% of maximal when compared to skilled throwers. The authors proposed more throwing experience had likely enabled skilled throwers the capability to build a wider range of movement options for producing the same relative speed (e.g., manipulating preparatory positions, force magnitudes, and temporal relationships between body segments), and thus, resulted in higher variability in throwing speeds (Urbin et al., 2012). Similarly, Molina & Stodden (2018) observed higher variability at various percentages of throwing speeds in high-skilled children compared to lower skilled children however, there was no relationship between proportion of maximal throwing speed and speed variability, nor spatial accuracy, in either the high- or low-skilled children.

While the higher variability in throwing speed observed in skilled throwers when throwing at speeds below 90% would seem to suggest a detrimental impact on spatial accuracy, a larger throwing skill repertoire provides a wider range of movement solutions to compensate for the impact of speed on throwing trajectories. In a task requiring participants to throw to a series of target locations, Garcia and colleagues (2013) observed that both novice and expert participants produced lower throwing speeds when accuracy was the only emphasis of the task, compared to when instructed to “throw the ball at more than 90% of their maximum speed trying to be as accurately as possible” (García et al., 2013). However, contrary to the findings of Urbin et al. (2012), and van den Tilaar and Ettema (2006), novice throwers experienced reduced accuracy when throwing under the higher speed condition, while the accuracy of the expert participants was not affected by the higher throwing speed. The varying target locations used in this study may have contributed to the differences between skill levels. As suggested by Urbin et al. (2012), expert performers likely possessed a larger repertoire of throwing patterns allowing them to adapt aspects of their throwing action (e.g., throwing speed, preparatory position, timing of ball release) to better produce throwing trajectories for the different target locations at higher relative speeds.

To produce accurate throwing trajectories, the timing of ball release must be synced with the speed and spatial trajectory of the throwing hand (Jegede et al., 2005). Essentially, the timing of ball release relative to instantaneous hand velocities and movement paths dictates both ball speed and direction (Freeston et al., 2015; Jegede et al., 2005). Jegede et al. (2005) demonstrated that coordination of timing ball release becomes more consistent in skilled throwers, reducing the potential impact on throwing speed variability. While participants in the study were instructed to “throw as hard and accurately as possible” while throwing at a target, the study did not assess the relationship between the timing of ball release and spatial accuracy, nor differences in hand path characteristics between skilled and non-skilled throwers.

Freeston and colleagues (2015) investigated the presence of a speed-accuracy trade-off in throwing in elite level baseball players with regards to the “launch window hypothesis” first proposed by Calvin (1983), which describes the critical, finite time frame during throwing in which ball release would result in hitting a target. As hand-trajectories increase in speed, the timing window of successful ball release shrinks because of the decreased movement time during the arm acceleration phase (Calvin, 1983; Freeston et al., 2015). Kinematic data of the throwing performances was used to describe characteristics of the hand-path and speed to calculate a successful launch window for each throw. The researchers observed increased average throwing error when throwing at 100% versus 80% maximal throwing speed, in support of a speed-accuracy trade-off. Interestingly, the decrease in throwing accuracy from 80% to 100% effort was only demonstrated in the vertical direction. The throwing error was evaluated in terms of both hand-path error and release-timing error in relation to the calculated launch window. Their findings suggested errors in timing of ball release as the primary contributor to decreased throwing accuracy at maximal throwing speed, although absolute time of release error did not vary significantly between throwing conditions. Rather, resulting from the decreased movement time when throwing at higher speeds, the vertical component of the calculated launch windows “shrunk”, increasing the resultant error in ball trajectory per unit time. The increase cost of timing error for ball release, however, was not demonstrated with regards to throwing accuracy in the horizontal direction, which remained consistent across throwing conditions. The authors proposed that the participants may have altered their throwing kinematics across conditions to maintain the horizontal component of the launch window (Freeston et al., 2015).

The ability to adapt characteristics of throwing performance to a range of task and environmental conditions, such as various speed/distance and accuracy requirements, may signify an individual’s capability to integrate environmental stimuli more effectively at higher levels of skill (Barnett et al., 2020; Hulteen et al., in press). Real-world performance settings, such as gameplay, provide task and environmental constraints that can elicit variations in throwing patterns, including those that are considered less advanced developmentally (Newell, 1984; Barrett & Burton, 2002), yet still effectively accomplish the goal of the task. For example, in elite college baseball players, infield positions players utilize an advanced throwing pattern less than fifteen percent of their throws during gameplay (Barrett & Burton, 2002). Throwing patterns during gameplay were observed to vary according to the amount of time to relay the ball (e.g., to beat a baserunner), distance of the throw, and posture of the performer (Barrett & Burton, 2002). Importantly, all throws during active gameplay in baseball and most throwing scenarios that are sport/game-related or not, possess accuracy-related tasks goals which constrain throwing performance characteristics. The various situational contexts encountered in real-world throwing environments necessitate that a skillful thrower coordinate and control multi-joint systemic force production, hand-path, and release timing to produce throwing trajectories that meet unique task demands (e.g., distance, speed, and directionality). Thus, the ability to effectively utilize any number of throwing patterns (both highly- or less-advanced) would expand the range of task and environmental conditions in which the performer has the potential to navigate successfully. Current throwing assessment methods, especially those widely used to assess change in MC, are designed in a way that does not effectively integrate all necessary constraints that impact throwing performance, a critical aspect inherent in the concept of skillfulness (Clark & Metcalfe, 2002; Barnett et al., 2020).

2.4 Assessment of Throwing Skill

Throwing skill and its development has been studied extensively in the field of motor development. The use of both process- and product-oriented assessments have provided valuable information regarding the development of critical movement characteristics related to advanced levels of throwing speeds (Roberton & Konczak, 2001; Stodden et al., 2006a, 2006b). As such, many commonly used process-oriented assessment methods (e.g., TGMD, GSGA, CMSP, component developmental sequences) have emphasized maximum speed as a task constraint that enables the emergence of advanced throwing patterns, characterized by the exploitation of kinetic chain principles (e.g., proximal to distal sequencing, segmental lag) during overarm throwing (Kelso et al., 1993; Southard, 1998, 2002, 2006; Roberton & Konczak, 2001; Stodden et al., 2006a, 2006b). To promote the use of more advanced throwing patterns in speed-focused assessments, performers are instructed to perform with high effort (e.g., "throw as hard and fast as possible") while limiting potential disabling task constraints (e.g., target/accuracy, time to throw) that may influence throwing speed and the aligned movement parameter characteristics (Williams et al., 1996; Roberton & Konczak, 2001; Southard, 2006; Stodden et al., 2006a, 2006b; van den Tillaar & Ettema, 2006; Langendorfer et al., 2011). In addition, the relationship between throwing patterns and speed has provided support for throwing assessments utilizing only throwing speed as an outcome measure in terms of assessing development of throwing skill (e.g., MCA). The use of product-oriented measures provides a higher level of measurement sensitivity than process-oriented assessments (e.g., summed dichotomous or ordinal levels), especially at higher skill levels, avoiding potential "ceiling effects" that may occur with process-oriented assessments (Barnett et al., 2020). While the high level of standardization in speed-focused throwing assessments has contributed to our understanding of the relationship kinematic characteristics and throwing speeds, the lack of accuracy constraints for throwing in many assessments limits the predictive utility to performance success in real-world contexts. Further, the use of speed-focused assessment as rationale for the hierarchical classification of throwing patterns (i.e., less- or more advanced) disregards the impact of additional task constraints relevant to adapting throwing performance in more dynamic settings.

Throwing accuracy is utilized by, or integrated in, relatively fewer MC assessment batteries as a product-oriented measure of throwing performance in children and adolescents (e.g., MOBAK, BOT, PE Metrics; Dyson et al., 2011). Throwing in these assessments is performed in similarly closed-environmental contexts as those used in speed-focused assessments. In general, these assessments utilize a static target of varying size and location (i.e., height on wall, distance from performer) for each assessment. Performers are tasked with hitting the target over multiple trials in which the total number of target hits is recorded. In addition to the limitations previously discussed concerning the assessment of adaptability in closed contexts, the implementation of these assessments is adapted by the age of performer. Target distances are selected based upon notions of performance capabilities specific to the age of the intended assessment populations, thus limiting their utility for comparison across different age groups. However, the manipulation of target distance is an important concept due to the integrated nature of speed and spatial accuracy. As higher throwing speed capabilities may be necessary to successfully hit targets at longer distances, careful consideration must be made with regards to minimal force requirements when creating throwing assessments that include an accuracy constraint. This consideration is especially important when process-oriented measures are assessed concurrently during an accuracy-focused throwing assessment (e.g., PE Metrics), as the minimal force requirements needed to reach the target may not necessarily demand the use of throwing patterns deemed optimal in terms of producing high throwing speeds (Barrett & Burton, 2002; Dyson et al., 2011; Hulteen et al., in press).

One method that has been used in the assessment of throwing skill to enhance ecological validity of the throwing task is the incorporation of multiple skills within the assessment context. For example, the Dragon Challenge assessment tool (DC; Tyler et al., 2018) and Canadian Assessment of Physical Literacy (CAPL; Longmuir et al., 2015) both instruct performers to run with a ball to a designated throwing area and throw to a target. Both assessments require the performance of a series of fundamental motor skills with an overall goal of completing the assessment as quickly as possible. Thus, specific to the throwing portion of the assessments, the time constraint rewards performers for quickly transitioning from a running posture to throwing. This condition emphasizes the performer's ability to adapt preparatory segmental configurations for effective throwing accuracy based upon the initial posture assumed by running, thus increasing its relevancy to performance in real-world contexts (Barrett & Burton, 2002). In both assessments, points are awarded for throwing accuracy (i.e., successfully hitting the target) as well the throwing pattern demonstrated according to specific criteria. However, in both cases, process-oriented criteria are somewhat reflective of segmental coordination patterns that are necessary to produce high throwing speeds (e.g., DC: Arm moves backwards in arc to initiate throw, steps with opposite foot toward target; CAPL: Arm comes from behind and hand goes over the shoulder, transfer of weight and rotates body to assist throw; Roberton & Konczak, 2001; Stodden et al., 2006a, 2006b). The selection of criteria related to forceful throwing may not be relevant to the specific performance context as there is no incentive from the performers perspective to produce higher throwing speeds beyond that which is necessary to reach the target (DC: 4.65m; CAPL: 5m). Since performers do not need to wait for the ball to hit the target before moving to the next task, performers are instead oriented to decrease the overall time necessary to complete the throwing *action*, which may not promote throwing characteristics related to higher projectile speeds given the relatively short target distances. Rather, to meet the demands of the communicated task constraints, the performer may utilize any throwing pattern within their repertoire capable of quickly producing throwing trajectories effective for hitting the target. A further limitation of both assessments is throwing is only performed one time. Thus, it is impossible to make conclusions concerning spurious performance outcomes or the consistency at which the performer can produce effective throwing trajectories.

The combination of catching and throwing in assessments may provide a superior alternative in terms of predicting throwing performance capabilities in authentic performance contexts due to their ecological relevance in many sport/practice contexts (e.g., baseball, American football, handball, cricket) and play (e.g., playing "catch") contexts. One such assessment is included in the Movement Assessment Battery for Children, 2nd edition (MABC-2), designed for assessing catching skillfulness across the age band from 11-16 years (Henderson et al., 2007). In the assessment, performers throw a tennis ball at a wall from behind a line two meters away and attempt to catch it with the throwing hand on its return before it touches the ground. There are ten discrete (i.e., isolated) performances for using each the dominant and non-dominant hand. The number of successful, "clean" catches (i.e., without use of any other body part) are recorded for each hand. In terms of assessment outcomes being related specifically to throwing skill, the assessment is limited due to short target distance, which decidedly limits the use of more advanced throwing patterns. The use of “advanced” throwing patterns could unnecessarily increase ball speeds and thus, the difficulty of catching the ball on its return. However, although not measured directly and with no explicit target, the assessment does incorporate an accuracy constraint as initial throwing trajectories would directly relate to the balls trajectory after contacting the wall. Thus, throwing accuracy may influence the ability to successfully catch the ball on its return. In support of this assumption, Dirksen and colleagues (2016) found that variable error in terms of the spatial location of the balls contact with the wall was related to catch success in the MABC-2 catching task.

Variations of another throw and catch combination task have been used in Finland (Jaakkola, Hakonen, et al., 2019; Jaakkola et al., 2015; Jaakkola, Huhtiniemi, et al., 2019; Jaakkola et al., 2012; Jaakkola et al., 2020; Joensuu et al., 2018). In the Finnish throwing-catching combination task performers have 20 attempts to throw a tennis ball from behind a marked line, hit a target area, and catch the ball after one bounce. Attempts are deemed successful if the hit both the target area and the ball is caught after one bounce. The distance between the designated throwing line and the target generally is manipulated between seven and ten meters based upon the participants’ age and gender; however, specific distances have varied across studies. Additionally, characteristics of the target location and size are not fully described across all studies. To successfully complete the task, the performer must produce ball trajectories that not only hit the target, but also allow for the ball to bounce only once on its return in a way that is conducive for catching. The interaction between accuracy and force regulation constraints in the assessment make this task unique from many other throwing contexts, both in assessments and real-world environments. The unique task constraints may be considered a strength of the assessment, as the performer is tasked with solving a relatively novel task, thus challenging the performer's ability to apply parameters of throwing performance to conform to the specific demands of the task. The concept of task novelty in may improve the ability of throwing assessments to predict performance under various conditions given the real-world performance contexts are widely variable.

A similar task is included in a recent version of the Korperköordinations Test für Kinder (KTK3+; Platvoet et al., 2018; Coppens et al., 2021). Adopted from Faber and colleagues (Faber et al., 2014), the Eye Hand Coordination (EHC) task places the performer one meter away from a wall. Using a throwing pattern (e.g., overhand, or underhand) and hand (dominant or non-dominant) of their choosing, the performer is to throw a tennis ball against the wall and catch it cleanly with the opposite hand (i.e., non-throwing) before it hits the ground. This task is completed as many times as possible in a 30s span, while alternating the hand that is used to throw each sequence. Performers are allowed freedom of movement for catching but must throw the ball from behind the one-meter line. Two trials are performed, and the highest number of catches is recorded. Like the Finnish combination task, the EHC incorporates an accuracy constraint (1m x 1m target). The continuous nature of the task simultaneously encourages a quick transition from catching to throwing and minimizing the time from ball release until the next catch. Thus, performers may minimize the time it takes to complete each throw catch sequence by scaling up on their throwing speed. However, the short distance between the performer and target (1m) and may limit the range of applicable throwing speeds and movement pattern dynamics given the associated cost in reaction time for catching.

A consistent limitation of the previously discussed assessments which combine throwing and catching in terms of assessing throwing skill is the presence of a somewhat finite upper limit of applicable throwing speeds. This limitation is significant when considering ecological validity as minimal force producing requirements in sport and play contexts may greatly exceed those present in the assessment context. Further, conditions that inhibit high throwing speeds restrict the ability to make conclusions concerning performers' development of throwing patterns related to high levels of force/speed. Thus, assessments that significantly constrain throwing speeds may limit the discriminatory power of the assessment between performers of higher throwing skill.

The throw-catch (TC) assessment published by Terlizzi et al., (2022) addresses potential ceiling effects with regards to throwing speed in while incorporating previously noted strengths of assessment tasks that combine throwing and catching for assessing throwing skill. In the assessment, performers are positioned behind a line approximately three-times their standing height from a wall and tasked with throwing a ball against the wall and catching it as many times as possible in 30 seconds. To successfully complete the task, the throw must result in the ball hitting the wall in the air (i.e., without bouncing) and the rebound must be caught using only the hands (one or two hands). Performers may utilize any throwing pattern of their choosing to create a throwing trajectory that hits the wall. The rebounded ball may be caught directly off the wall or after one or multiple bounces (but not rolling) for a successful throw-catch sequence. Additionally, performers are allowed freedom of movement when catching the ball but must throw from behind the designated throwing line. Two thirty-second trials are performed in which the highest number of throw-catch sequences is recorded.

The limitations in other assessments with regards to throwing speed is addressed in multiple ways. First, the distance between the performer and the wall ("target") is considerably further than that of the MABC-2 and KTK3+ combination tasks, minimizing the detrimental impact of higher throwing speeds on the reaction time needed for catching. Like the KTK3+, the incorporation of a time constraint and the opportunity for multiple performances within each trial links the performance of consecutive throw and catch sequences. Thus, in addition to the need to quickly transition from body configurations used to catch the previously thrown ball to throwing postures, performers are incentivized to throw at higher speeds to reduce the time between ball release to the next catch. Finally, as performers are given freedom to choose from multiple strategies for catching the ball on its return (e.g., catching directly off the wall or after one or multiple bounces) and the accuracy constraint is relatively ambiguous compared to the Finnish throw-catch combination and KTK3+ tasks, higher ball speeds may be utilized in multiple ways to reduce the time the ball is out of the performers hand. Ultimately, the interaction of these constraints may improve the sensitivity of the assessment at higher levels of throwing skill ability. Similarly, the opportunity to make use of one or multiple bounces after rebounding off the wall and/or throwing trajectories of various heights reduces the minimal throwing speed threshold for meeting the accuracy demands of the task (i.e., contacting the wall in the air). The scaling of the throwing of the performer provides a developmentally appropriate performance context across age based on standing height to maintain a wide range of possible performance solutions across participants. Thus, the TC may be adequate for assessing the throwing skill across performers with a wide range of force producing capabilities.

An additional strength of the TC assessment is the open-ended nature of the assessment context which provides performers with a range of possible strategies for completing the task successfully. As performers can select from various movement (e.g., throwing pattern, catching strategy) and task (e.g., use of bounce) strategies based upon their perceptions of the environmental conditions and own capabilities, this can be regarded similarly to the advantage of "outward-facing and informationally rich" assessment contexts described from by Rudd and colleagues (2020). Thus, the TC may provide a window for understanding performers' ability to recognize context-specific properties of the performance environment (e.g., distance from wall; size, weight, and percussion characteristics of the ball/wall; body configurations), what these properties offer in terms of possible throwing strategies (i.e., affordances), and align movement and task strategies optimally to achieve maximum number of successful throw-and-catch sequences. This ability to conform or adapt movement optimally to specific task and environmental constraints (i.e., attunement to affordances) is a critical feature of increasing levels of expert performance (Clark & Metcalfe, 2002; Fajen et al., 2008; Seifert et al., 2013) and speaks to the overall repertoire of throwing patterns that can be functionally demonstrated by the performer.

As was observed in the MABC-2 catching task, catching success and overall score in the TC is influenced by accurate throwing trajectories. As such, maximal performance demands the ability to effectively and consistently control characteristics of the throwing action suggested to vary between skilled and non-skilled throwers (e.g., systemic force production [Roberton & Konczak, 2001; Stodden et al., 2006a, 2006b], hand-trajectories [Urbin et al., 2012; Urbin et al., 2013; Freeston et al., 2015], and timing of ball release

[Jegede et al., 2005]). To create a higher potential number of catches, these features of throwing performance must be harmonized in a way that consistently creates ball trajectories that allow for the ball to be caught on its return and minimizes the time needed to transition (i.e., preparatory body configuration) over the performance of multiple throws. While these demands offer rationale for the importance of throwing skill for high TC scores, the impact of catching skill may hinder the ability to make strong conclusions about throwing skill solely based upon TC score. In the TC, performers with relatively low catching abilities may need to use a compensatory throwing strategy (e.g., decrease throwing speeds) to decrease the difficulty successive catch attempts. While the use of a compensatory strategy in and of itself may speak to a flexible and adaptable throwing repertoire, it may or may not be reflected in the number of successful throw-catch sequences. Thus, research is needed to evaluate the potential for the TC to provide information about the performer's throwing and catching skills individually.

Throwing and catching coincide in many real-world sport/practice and game contexts. The coexistence of throwing and catching in many contexts may facilitate the concurrent development of both skills, as performers are presented with opportunities for practice with both skills. A positive relationship between throwing and catching skill would offer support for the use of assessments that include both skills as it would suggest that the presence of both skills in the assessment context would not greatly limit the ability to make conclusions regarding the respective skill abilities of throwing and catching. To date, surprisingly little research has reported the relationship between measures throwing and catching skill. In general, weak to moderate positive correlations have been observed between throwing and catching skills across children and adolescents three to twelve years of age (*r* = .234 - .410; Garn & Webster, 2018; Herrmann et al., 2019; Herrmann & Seelig, 2017a, 2017b). However, the limited number of studies to report these relationships and differing methods of assessment (i.e., process- versus product-oriented outcomes) warrant further investigation of the relationship between throwing and catching. Further, comparison of performance in throw and catch combination tasks, such as the TC, with other validated process and product-oriented measures of throwing skill are needed support for the use of combination tasks for evaluating throwing skill.

CHAPTER 3
STUDY 1: PRE-LONGITUDINAL SCREEN OF PERFORMANCE IN THE THROW-CATCH ASSESSMENT

3.1 Introduction

The development of Motor Competence (MC) is a progressive and cumulative process that occurs over time and thus, is inherently related to age. However, the development of advanced skill levels in specific motor domains becomes increasingly related to experiences unique to the individual over time (Clark & Metcalfe, 2002). These context-specific experiences shape the development of perceptuomotor capabilities underlying the performance of gross motor skills (Clark & Metcalfe, 2002; Seifert et al., 2013). With continued and persistent experience in a variety of contexts, individuals can build upon a basic foundation of movement options to create a versatile repertoire within a specific skill domain and increase the range of task and environmental constraints to which they can successfully adapt (Clark & Metcalfe, 2002; Araujo et al., 2006; Seifert et al., 2013).

The assessment of MC requires an appreciation not only for the dynamic nature by which underlying physical and perceptual abilities interact, but also how these abilities affect skill performance over time (Roberton, 1980; Rudd et al., 2020). As such, the ability to adequately represent developmental change is a critical feature of quality MC assessments. The Throw-Catch (TC) assessment (Terlizzi et al., 2022) is a product-oriented assessment of object manipulation skill with potential for use across a wide range of ages and developmental levels due to its open-ended and informationally rich performance context. The TC performance context offers an indefinite number of possible movement solutions (both "rudimentary" and "advanced"), emphasizing the abilities of the performer to integrate information from the task environment (e.g., distance from target, percussion characteristics of ball/wall) to select an appropriate movement strategy with respect for their own physical performance capabilities (e.g., throwing- and catching-related skillfulness). The ability to recognize relevant environmental information and align, or adapt, movement performance to successfully meet task goals is developed through extensive practice and experience and is a hallmark of expert movement behavior (Clark & Metcalfe, 2002; Fajen et al., 2008; Seifert & Davids, 2017). As the task environments encountered real-world performance contexts are varied and diverse, the demand for perceptuomotor integration in the TC assessment may speak to the ability to relate TC performance to real-world contexts (i.e., ecological validity).

The interplay between the performance of both throwing and catching skills (i.e., adapting throwing trajectories to accommodate catching skill) provides an additional level of ecological validity as the performance of both skills coincide in many real-world contexts (e.g., baseball, cricket, handball, playing catch). The TC assessment task concurrently stresses the ability to consistently throw with accuracy and speed to decrease the overall time of each throw-catch sequence. Use of higher throwing speeds would also increase the difficulty of the catch due to the associated cost in reaction time to catch the returning ball, especially in the presence of spatial error (i.e., an inaccurate throw). Thus, being able to throw with greater speed and catch the ball that is returning quickly speaks to increased competence levels of each skill. Alternatively, performers may utilize lower throwing speeds to accommodate for low-level throwing accuracy or catching abilities. Although the highest levels of performance may be created by increasing throwing speeds and thus, increasing catching difficulty, performers are granted to opportunity to scale their performance according to perceptions of their own abilities to find the most appropriate solution to the TC task.

Combination tasks including the performance of both throwing and catching are used as part of existing MC assessment batteries (e.g., MABC-2 [Henderson et al., 2007], KTK3+ [Coppens et al., 2021; Platvoet et al., 2018], Finnish throwing-catching combination task [Jaakkola et al., 2012; Jaakkola et al., 2015; Joensuu et al., 2018; Jaakkola, Hakonen, et al., 2019; Jaakkola, Huhtiniemi, et al., 2019;; Jaakkola et al., 2020]). Both the KTK3+ and MABC-2 assessments utilize much shorter throwing distances (one and two meters respectively) which dissuade the use of "advanced" throwing patterns related to high ball speeds which would unnecessarily increase the difficulty of the catching portion of the task. As the ability to throw with higher speed is a critical aspect of throwing skill (Roberton & Konczak, 2001; Stodden et al., 2006a, b), the incentive to produce high throwing speed in the TC assessment provides greater potential for estimating throwing skill than the MABC-2 and KTK3+ throwing and catching assessments. The Finnish throwing-catching combination task utilizes similar distances to that of the TC assessment (7-10 meters) to combine the performance of throwing and catching; however, the discrete performance context (i.e., one performance per trial) of the Finnish assessment provides minimal reward for demonstrating a flexible throwing and catching skill repertoires. Alternatively, the "linked" nature of successive performances of the TC assessment within each trial emphasizes the performer's ability to adapt both throwing and catching performance based upon previous performance (e.g., postures assumed for throwing/catching, accuracy of throw). We propose that the design of the TC task constraints provides the opportunity assess motor performance in a more authentic context that will enable participants of various ages and skill levels to display skill abilities related to throwing and catching. As the developmental validity of an assessment should be addressed from a lifespan perspective, understanding whether performance in the TC increases from childhood to young adulthood is an important consideration.

The purpose of this study is to examine the developmental validity of the TC assessment performance using a pre-longitudinal screening method. Pre-longitudinal screening uses cross sectional data to investigates the age-related validity of process- (; Messick, 1991; Strohmeyer et al., 1991; Roberton, et al., 2017; Lane et al., 2018; Nesbitt et al., 2018;; Sacko et al., 2021;) and product-oriented (Lorson et al., 2013; Nesbitt et al., 2018; Rodrigues et al., 2019; Coppens et al., 2021) motor assessment outcomes. This study examined how age-related development of skills included in the throw-catch assessment concurrently interact with the task and environmental constraints to influence TC score. We hypothesized that there would be a positive relationship between TC score and participant age. In addition, as the development of throwing coordination patterns occurs similarly in both males and females (but generally accelerated in males), we hypothesized a positive relationship between TC score and age in both genders.

3.2 Methods

Participants and Setting

This study included a convenience sample and secondary data analysis from multiple projects in the Southeast U.S. and Canada from 2018 – 2020. Data was collected on 873 individuals from the ages of 8-22 years old (M_{age} = 14.7 ± 4.2; females: n = 320, M_{age} = 14.1 ± 4.0; males: n = 553, M_{age} = 15.9 ± 4.2).

Procedures

The TC assessment was completed at each location as part of larger gross motor skill testing batteries. Participants who were under the care of a physician due to medical conditions (e.g., heart condition, chest pain, injury, pregnancy, chronic illness) that prevented them from physical activity were excluded from participation. Human-Subjects Review Board approval was obtained at each location prior to data collection.

Throw-Catch Assessment (TC)

Each participant stood behind a line that was scaled to a distance at least three-times the performer's standing from a solid wall. The scaling of the throwing of the performer provides a developmentally appropriate performance context across age based on standing height to maintain a wide range of possible performance solutions across participants. The floor and wall surfaces used were solid, flat, and free of any surface alterations that may cause a ball to rebound and bounce in an unexpected way. Walls were a minimum of 6.1m height to limit a restriction on participants throwing form and ball trajectories. Performers were asked to throw and catch a standard tennis ball (6.6 cm diameter, 56g) against the wall as many times as possible in 30 seconds. A score was awarded based on the number of successful throw and catch sequences completed during the 30-second trial. Throw-catch sequences were deemed successful if: 1) the ball is thrown from a position with both feet behind the tapeline and struck the wall in the air with no bounce, 2) the ball is caught in the air without contacting any body part other than the performer's hand(s) from a position with both feet behind the tapeline. During the assessment, the performers were allowed to use any method of throwing the ball to the wall (i.e., overhanded or underhanded), so long as the ball contacted the wall directly after the throw. When catching the ball on the return, performers could use either one or two hands to catch the ball directly off the wall or indirectly by allowing the ball to bounce one or multiple times (but not roll) on the floor prior to catching it. A "bobbled" ball was still considered a catch if it did not contact any other part of the body or the floor before being secured with the hands. A basket containing at least five tennis balls was be placed at the distance of the throwing line, approximately 2m to the participant's right. Participants were instructed to retrieve another ball from the basket if a returning ball is uncatchable and/or bounced too far away from them during the trial. Research staff retrieved missed balls and replaced them in the bucket to ensure balls are continuously available during each trial performance. Prior to their first trial, participants were provided with a short demonstration to clarify the rules of the task. Participants were then allowed a maximum of five throw practice attempts prior to the start of the assessment to familiarize themselves with the task constraints. The number of successful throw-catch sequences was scored during the assessment. Each participant completed two 30-second trials of the TC and the maximum score was used for data analysis.

Data Analysis

Descriptive statistics for TC scores were calculated for the overall sample, stratified by both gender and age. Pearson correlations were used to evaluate the relationship between age and TC score in the overall sample and within each gender subgroup. Additionally, partial correlations were used to evaluate the relationship between age and TC score while controlling for gender. Lastly, to understand the relationship between age TC score over the range of ages included in the study, we explored the utility of linear and nonlinear regression models with age and gender as predictors of TC score. Correlation coefficients were interpreted using guidelines set forth by Cohen (1988; weak: $r < .300$, moderate: $.300 \leq r < .500$, strong: $r \geq .500$). Significant relationships between variables were assessed using alpha level < .05. All statistical analyses were conducted using R Statistical Software, version 4.0.3.

3.3 Results

Mean TC score for the sample was 11.34 ± 5.44 ($M_{\text{female}} = 9.18 \pm 4.80$; $M_{\text{male}} = 12.59 \pm 5.40$; Table 3.1). Bivariate Pearson correlations demonstrated strong positive relationships between TC score and age in the sample overall ($r = .743$, 95% CI: .712 - .771, $p < .001$) and within each gender subgroup ($r_{\text{female}} = .698$, 95% CI: .637 -.749, $p < .001$; $r_{\text{male}} = .746$, 95% CI: .707 -.781, $p < .001$). Partial correlation of the relationship between participant age and TC score, controlling for gender, demonstrated a strong relationship between the two variables ($r_{\text{partial}} = .730$, 95% CI: .697 - .759; $p < .001$). Results of the linear regression ($R^2 = .575$, $F_{2,870} = 589.7$, $p < .001$) demonstrated positive effects on TC score by age ($\beta = .913$, $\sigma = .028$, $p < .001$) and gender ($\beta_{\text{male}} = 1.78$, $\sigma = .255$, $p <$

.001), suggesting an advantage for male performers. The polynomial model demonstrated a slightly better fit to the data (R^2 = .584, $F_{2,870}$ = 406.7, p < .001). Age (β = 2.01, σ = .261, p < .001), gender (β_{male} = 1.95, σ = .256, p < .001), and the quadratic term for age (β = -.039, σ = .009, p < .001) significantly contributed to the amount of explained variance.

3.4 Discussion

The purpose of the current study was to conduct a pre-longitudinal screen to evaluate the relationship between age and performance on the TC assessment. Overall, strong positive relationships between age and TC score were found in the total sample (r = .743; $r_{partial}$ = .730) and within both female and male subgroups (r_{female} = .698; r_{male} = .746), confirming our hypothesized relationship between age and TC score. Secondarily, we aimed to explore the nature of the effect of age on TC score across the range of ages in the sample. Regression analyses that included both linear and polynomial models demonstrated similar results with the quadratic model (negatively accelerating across age) indicating a slightly stronger model fit whereby the rate at which TC scores improved slowed at higher ages.

Overall, these cross-sectional data provide preliminary support that the TC assessment is a developmentally valid assessment of MC, as participant age was positively associated with an increase in TC scores. Increases in mean TC score for the overall sample were consistently observed across ages 8-17 years except in the 14- and 16-year-olds. The deviation from the increasing trend observed in these two ages may be confounded by the gender make-up of the 14- and 16-year-old participants, both of which consisted of a much higher proportion of females than the ages between 8-17-year-old (n_{age16} = 67% females;

n_{age14} = 79% females). As males generally had greater success at the TC task, especially at ages greater than 14 years, the higher proportion of females in these two age groups likely contributed to lower scores observed at these ages.

The significant effect of the quadratic term for age in the polynomial regression model suggests a non-linear relationship between age and TC score where improvements in TC performance diminish in early adulthood ($\beta_{age^2} = -.039$, $p < .001$). Increases in mean TC score across the 18-22-year-olds were less consistent than those observed across 8-17-year-olds, supporting the developmental nature of skills incorporated within the TC assessment. In a cross-sectional study performed by Lorson et al., (2013), enhanced throwing speed and movement pattern characteristics of forceful throwing peaked in young adults (ages 18-25 years) as compared to adolescent (ages 14-17 years) and older adult (35-55 years) groups. The TC data also seem to support the lifespan perspective of development as multiple other studies that have examined product or process data in specific cross-sectional samples across early childhood to the elderly (approximately 75 years) have demonstrated skill levels being the most advanced in early adulthood (Roberton, 1987; MacWilliams et al., 1998; Runionet al., 2003; Butterfield et al., 2012). While curvilinear trajectories have also been suggested to describe the relationship between age and catching skill across childhood and adolescence (Thomas & French, 1985; Williams, 1992; Butterfield et al., 2012), the negatively accelerating relationship between age and catching performance may have been exaggerated by the predominate use of process-oriented measures of catching skill, which could have limited discriminatory power in older, presumably more skilled, age-groups, contributing to ceiling-effects (Logan et al., 2017; Barnett et al., 2020).

While results of the polynomial regression demonstrate a curvilinear relationship between age and TC score, the model (R^2 = .584) explained less than 1% more of the total variance in TC scores than linear model (R^2 = .575). The negligible difference in explanatory power between the two predictive models is significant from a practical perspective and speaks to the relative ease at which age-specific performance benchmarks may be identified using the TC assessment. For example, after controlling differences associated with gender, the linear model predicted an increase of approximately 1 point in TC score for each year increase in age. This consistent metric for improvement can be quite useful from a practical perspective as physical education teachers and interventionists would be able to clearly align scores with grade/age level improvements. More research is needed with larger samples at each age-group to produce normative data to identify potential performance benchmarks more clearly.

Gender Differences

Results of the both the polynomial and linear models suggest a significant gender effect when controlling for age (polynomial model: $\beta_{male} = 1.95$, $p < .001$; linear model: $\beta_{male} = 1.78$, $p < .001$). Male participants outperformed females from age 14-22 years. This result was expected, as previous literature has consistently indicated males possess higher levels of throwing skill (Thomas & French, 1985; Roberton & Konczak, 2001; Runion et al., 2003; ; Ehlet al., 2005; Barnett et al., 2010; Lorson et al., 2013; Angell et al., 2018) and catching skill (Thomas & French, 1985; Barnett et al., 2010; Butterfield et al., 2012). Interestingly, mean TC scores for females exceeded or were approximately the same as males at every age from 8-13 years, except for the 9-year-olds (Table 3.1). This result may largely be a consequence of the low sample sizes at each of these ages (n = 13-33);

however, understanding what specific gender-related differences may have contributed to this finding are not clear. In contrast to previous research on throwing and catching, the general lack of a gender difference at earlier ages may be, in part, due to the open-ended nature of the assessment task, which allows the performer to choose between any number of task strategies (e.g., use various throwing trajectories to catch directly off the wall or after a bounce) to successfully complete a throw-catch sequence. In these earlier age groups, females were able to choose and perform throwing strategies and regulate throwing speed that enabled them to catch the ball similar to males, which aligns with data from Langendorfer and Roberton (2002) that demonstrates boys and girls learn to throw similarly from a coordination pattern (i.e., profile development) standpoint but at different rates. Future research should investigate different task strategies (i.e., throwing form, speed, number of unsuccessful catches, and consistency and accuracy in throwing to the wall) used during the TC assessment and how they relate to task success at different ages.

Conclusion, Limitations, and Future Directions

The results of this pre-longitudinal screen of the TC assessment suggest its potential as a developmentally valid assessment of MC across ages 8-22 and demonstrates the assessments' practicality in settings relevant to motor development and physical education research and application. While the overall sample size was adequate to make preliminary conclusions regarding the relationship between age and TC score, the current study was limited in that the subsamples at specific ages were limited, and the distribution of male and female participants was not balanced in the sample overall. This limitation and the lack of longitudinal data hinders the ability to make robust conclusions about the results observed at specific ages, such as comparing mean scores between males and females.

Finally, the current sample was limited to ages 8-22 years. It is unclear how these results may relate to performances demonstrated in early childhood and mid-to-late adulthood. Future research on the TC assessment should expand upon the current study by including larger samples of male and female participants that encompass different races, ethnicities, cultures, and economic statuses, across childhood (i.e., < 8 years) and later adulthood (i.e., > 22 years) to provide further generalizability evidence for its use as a measure of MC across the lifespan. Longitudinal studies will provide further evidence for the assessment's validity with regards to development at the individual level. Finally, there is a need to establish the content validity of the TC by evaluating the concurrent validity of the TC assessment with other assessments of MC, specifically, those involving the performance of throwing and catching skills.

Table 3.1 Descriptive Statistics of Throw-Catch Performances Across Age

	Total			Females			Males		
Age	*n*	*M*	*SD*	*n*	*M*	*SD*	*n*	*M*	*SD*
8	33	4.06	3.59	15	4.87	4.45	18	3.39	2.63
9	159	5.26	3.44	70	4.03	2.89	89	6.22	3.54
10	32	6.62	4.41	12	6.67	3.75	20	6.60	4.86
11	17	6.71	4.16	10	8.00	4.67	7	4.86	2.61
12	16	10.20	3.19	7	10.30	3.90	9	10.10	2.76
13	13	11.20	3.67	5	12.40	4.51	8	10.40	3.11
14	64	9.73	3.04	43	9.44	2.79	21	10.30	3.50
15	61	11.30	4.07	36	10.70	4.17	25	12.20	3.82
16	24	10.50	3.18	19	10.20	2.90	5	11.60	4.28
17	27	13.11	4.00	12	10.00	3.88	15	15.60	1.72
18	221	14.87	3.59	36	12.33	3.35	185	15.36	3.43
19	115	14.66	3.50	38	13.68	3.13	77	15.14	3.51
20	36	14.94	3.66	8	13.38	2.56	28	15.39	3.83
21	42	16.05	4.21	7	13.14	4.45	35	16.63	3.99
22	13	15.54	2.79	2	14.50	2.12	11	15.73	2.94
Total	873	11.34	5.44	320	9.18	4.80	553	12.59	5.40

Note. *M* = mean, *SD* = standard deviation

CHAPTER 4
STUDY 2: CONCURRENT VALIDITY OF THE THROW-CATCH ASSESSMENT

4.1 Introduction

Commonly used assessments of motor competence (MC) generally involve the individual assessment of locomotor, object manipulation, and dynamic stability skills in prescribed and closed environment contexts (e.g., TGMD [Ulrich & Sanford, 1985; Ulrich, 2017], GSGA [New South Wales Department of Education and Training, 2006], CMSP [Williams et al., 2009], component developmental sequences [Roberton & Halverson, 1984]). The assessment of skill performance in such closed contexts (i.e., static task and environmental conditions) limits the extent to which performers can demonstrate their ability to recognize and integrate relevant information in the performance environment (Rudd et al., 2020). In addition, most MC assessments contexts do not enable the emergence of creative movement solutions used to adapt their performance to meet various task demands (Rudd et al., 2020; Pesce, Stodden et al., 2021). Adaptability in motor skill performance is an advanced level of MC; however, it is rarely assessed (Barnett et al., 2020; Stodden et al., 2021).

Throwing is one of the most widely studied gross motor skills as it is fundamental for participation many ontogenic activities (e.g., sports, games; Lombardo & Deaner, 2018). Common assessments of throwing skill used in motor development research require repeated performances emphasizing either throwing speed (e.g., TGMD, GSGA, CMSP, component developmental sequences, MCA) or throwing accuracy (e.g., MOBAK [Herrmann et al., 2019; Herrmann & Seelig, 2017a, 2017b], BOT [Bruininks & Bruininks, 1978, 2005], PE Metrics [Dyson et al., 2011]). However, performances in most real-world contexts demand performers concurrently regulate coordinative movement, throwing speed and projectile accuracy. Further, successive performances are rarely identical, necessitating a degree of adaptability to consistently produce successful throwing outcomes. These limitations pose a threat to the ecological validity of many commonly used throwing assessments.

Previous research has demonstrated the sequential and progressive (i.e., via accumulation of practice) integration of neuromuscular and mechanical properties of the musculoskeletal system to maximize the transfer of energy through the body's kinetic chain that result in advanced movement patterns and higher throwing speeds over the course of development (Roberton & Konczak, 2001; Stodden et al., 2006a, 2006b; Lorson et al., 2013). However, the underlying mechanisms involved in coordination and control of throwing actions to meet spatial task demands (i.e., throwing accuracy) are less clear. Due to the impact of projectile speed on projectile trajectory, throwing accuracy is inherently linked to the regulation of throwing speed. Accurate throwing trajectories are created through the concurrent coordination and control (i.e., directionality and speed) of the throwing hand (Freeston et al., 2015), and timing of ball release (Jegede et al., 2005; Freeston et al., 2015). The redundancy within the human movement system enables performers utilize any number of throwing patterns to control the directionality of the throwing hand to produce an accurate throw, as long as minimal force requirements are met with regards to the distance of the target and ball release is adequately timed. It is assumed that highly skilled throwers can alter throwing coordination patterns and force regulation to accommodate for differences in task constraints (Barrett & Burton, 2002; Urbin et al., 2012; Seifert et al., 2013; Barnett et al., 2020). Unfortunately, the closed performance contexts utilized in most throwing assessments limit opportunities for performers to display the flexibility of their throwing skill repertoire (i.e., different qualitative coordination patterns) and adaptability within a specific coordination pattern (i.e., force regulation, relative timing, ball release).

The Throw-Catch (TC) assessment, published by Terlizzi et al. (2022), provides a more open context that allows performers to demonstrate flexibility and adaptability during performance. Participants repeatedly throw a tennis ball against a wall from approximately three-times their standing height and catch it on its return as many times as possible in a 30 second trial. Performers are not provided with instruction on how the task must be completed, except that the thrown ball must first hit the wall in the air. As such, the task demands that the performer integrate multiple task (e.g., distance from wall), environmental (e.g., gravity, ball/wall percussion dynamics) and individual (e.g., throwing and catching skill repertoire, agility, balance and stability) constraints to produce as many throw-catch combinations as possible in 30 seconds. Performers are able to use any throwing pattern within their skill repertoire ("advanced" or "rudimentary") to create various throwing trajectories and resulting trajectories of the ball off the wall (with or without a bounce on the floor) that will effectively and consistently enable them to catch the ball on its return. Though there is no explicitly defined accuracy constraint in the task, participants with higher throwing skill abilities may have a higher potential for success with the assessment as the speed and initial trajectory of the thrown ball will dictate the return speed and direction of the ball after contacting the ball; thus, influencing the difficulty of the catch. Individuals who are unable to consistently perform accurate throwing trajectories, or effectively adapt performance based on prior performances may have to make larger body adjustments to catch the ball, increasing the time needed to reconfigure their preparatory stance for each throw-catch sequence. Further, as multiple performances are included within the 30s trial, performers are incentivized to decrease the time needed for each performance, including timespans when the performer is in possession of the ball (e.g., transitioning from catching postures to throwing preparatory configurations, and the throwing action) and when the ball is not in the performer's possession (i.e., by increasing throwing speeds). Thus, performers with higher levels of throwing skill will have a wider range of functional throwing options to create optimum throwing trajectories while also compensating for potential task-related perturbations caused by previous throws/catches.

While the incorporation of multiple skills in the assessment (e.g., throwing and catching) can be viewed as a strength from an ecological validity perspective (Hulteen et al., in press), catching abilities limit the ability to make direct conclusions regarding the performers' highest level throwing performance. Throwing "skill" is traditionally assessed by demonstrating the highest level of an individual's coordination pattern profile (e.g., TGMD, GSGA, CMSP, component developmental sequences), and/or maximum throwing speed (Stodden et al., 2014) which demands that the performer include preparatory and follow through actions that require additional time. In addition, advanced follow through movements may place the body in a position (e.g., unilateral stance with body rotating away from the wall) in a non-optimal position to respond to the trajectory of the ball off the wall (e.g., need to translate the entire body to the left or right) and return the entire body to the initial throwing stance. Thus, the incorporation of catching and throwing in the TC task demands that an individual continually integrates perceptual information relating to the speed and directionality of the ball after each throw and use performance feedback to regulate throwing speed and its trajectory for each successive throw. The TC assessment also continually demands the integration of environmental and task contexts, promoting a disabling constraint with respect to individuals' maximal effort throwing to produce a maximum number of throw/catch combinations.

The performance of throwing and catching coexist in many real-world contexts (e.g., baseball, handball, cricket, "playing catch", etc.) and promotes the concurrent development of both skills. While a positive association between the development of throwing and catching performance would generally allow us to make conclusions about each skill using tasks which combine throwing and catching, relatively little research has examined the relationship be individuals' throwing and catching skill. The design of the TC task promotes a novel and more complex integration of constraints over multiple performances where a highly advanced motor skill repertoire allows for increased flexibility and adaptability in throwing form and speed. For example, a highly skilled catcher is able to compensate by utilizing various catching strategies (e.g., catching with one or both hands, catch from different body positions/postures, intercept ball at various positions relative to body) to both increase chances of catch success and minimize the time needed to transition to the next throw. This flexibility and adaptability in performance results from a plethora of opportunity to practice and perform the skills that promotes progressive improvements in skill. The flexibility in catching granted to performers in the TC differs from other assessments of catching, which often dictate the use of specific hands (e.g., BOT, KTK3+) or include the use of two hands for catching as a criterion for higher level performance (e.g., TGMD, CMSP, GSGA). As catching skills likely develop alongside throwing skill, we propose that the inclusion of catching in the TC assessment will not greatly detract from the sensitivity of the assessment's outcomes to differences in throwing skill.

Thus, the purpose of the current investigation is to evaluate the concurrent validity of the TC assessment with previously validated process- and product-oriented assessments of throwing skill in young adults. It was hypothesized that TC scores would demonstrate positive relationships with both component developmental sequences for forceful throwing (Roberton & Halverson, 1984) and maximal throwing speed during maximal effort performance.

4.2 Methods

Participants and setting

In total, 130 participants (M_{age} = 22.02 ± 3.35 years) were recruited from a university in the southeastern U.S. (Caucasian = 64.8%, African American = 23.2%, Hispanic = 7.2%, Other = 4.8%). Participants completed the assessments in an indoor gymnasium at the university as part of a larger motor skill testing battery.

Procedures

Prior to participation, informed consent from all participants and approval from the human subjects' review board was obtained. All participants completed the Physical Activity Readiness Questionnaire to be eligible for the study. Participants who were under the care of a physician due to medical conditions (e.g., heart condition, chest pain, injury, pregnancy, chronic illness) that prevented them from physical activity were excluded from participation. Additionally, any participant who reported current throwing shoulder pain or discomfort were excluded from the throwing assessments. All assessments were performed as a part of a larger motor skill testing battery.

Throwing Speed

Participants threw a standard tennis ball (size) toward a wall approximately 10m away (Stodden et al., 2014). Participants were instructed to "throw the ball as fast as possible," but were not given any instruction on how to perform the throw. Each participant performed five throws with maximum effort. Performers were allowed (and encouraged) to perform warm-up throws as needed prior to the assessment. Ball speeds were measured using a radar gun (Stalker inc., Plano, TX) and recorded by research staff. The maximal throwing speed demonstrated across the five trials was used for data analysis (Stodden et al., 2014). Throwing performances were also video recoded for later coding of process-oriented measures.

Component Developmental Sequences

A digital video camera (Sony Handycam HDR-CX380; Tokyo, Japan) was placed approximately 3 m perpendicular to the throwing area to capture the performer's entire throwing performance. Videos were saved to an encrypted external hard drive and kept for further analysis of process-oriented throwing measures by trained research staff. Process-oriented throwing skill measures were scored using the component developmental sequences for overhand throwing, developed by Roberton and Halverson (1984; Table 3.1), using Dartfish video analysis software (30 frames per second, Dartfish TeamPro 7.0, Copyright 2014). Component developmental sequence (DS) modal profiles were established for each participant using the most demonstrated developmental sequence score combination (i.e., trunk, humerus, and forearm components combined) across the five max-effort trials, which were then summed to create the modal profile (i.e., out of 9) and used for data analysis (Logan et al. 2017). Inter-rater reliability between two trained research staff was calculated for each component using the proportion of agreement adjusted for chance (*kappa* [*k*] coefficient; Safrit & Wood, 1995) on 27 randomly selected participants (20% of the total sample). Results of the inter-rater reliability for each component were: a) Trunk Action: k = .92, b) Humerus action: k = .94, c) Forearm action: k = .86.

Throw-Catch Assessment (TC)

Each participant stood behind a line that was scaled to a distance at least three-times the performer's standing from a solid wall. The scaling of the throwing of the performer provides a developmentally appropriate performance context across age based on standing height to maintain a wide range of possible performance solutions across participants. The floor and wall surfaces used were solid, flat, and free of any surface alterations that may cause a ball to rebound and bounce in an unexpected way. Walls were a minimum of 6.1m height to limit a restriction on participants throwing form and ball trajectories. Performers were asked to throw and catch a standard tennis ball (6.6 cm diameter, 56g) against the wall as many times as possible in 30 seconds. A score was awarded based on the number of successful throw and catch sequences completed during the 30-second trial. Throw-catch combinations were deemed successful if: 1) the ball is thrown from a position with both feet behind the tapeline and struck the wall in the air with no bounce, 2) the ball is caught in the air without contacting any body part other than the performer's hand(s) from a position with both feet behind the tapeline. During the assessment, the performers were allowed to use any method of throwing the ball to the wall (i.e., overhanded or underhanded), so long as the ball contacted the wall directly after the throw. When catching the ball on the return, performers could use either one or two hands to catch the ball directly off the wall or indirectly by allowing the ball to bounce one or multiple times (but not roll) on the floor prior to catching it. A "bobbled" ball was still considered a catch if it did not contact any other part of the body or the floor before being secured with the hands. A basket containing at least five tennis balls was be placed at the distance of the throwing line, approximately 2m to the participant's right. Participants were instructed to retrieve another ball from the basket if a returning ball is uncatchable and/or bounced too far away from them during the trial. Research staff retrieved missed balls and replaced them in the bucket to ensure balls are continuously available during each trial performance. Prior to their first trial, participants were provided with a short demonstration to clarify the rules of the task. Participants were then allowed a maximum of five throw practice attempts prior to the start of the assessment to familiarize themselves with the task constraints. The number of successful throw-catch sequences was scored during the assessment. Each participant completed two 30-second trials of the TC and the maximum score was used for data analysis.

Data Analysis

Descriptive statistics were calculated for TC scores, maximum throwing speeds and DS modal profiles, stratified by gender. Analysis of variance (ANOVA) was implemented to evaluate gender differences in TC scores, maximum throwing speeds, and DS modal profiles. Pearson correlations were used to evaluate the relationship between maximal throwing speed and TC score. Spearman correlations were used to evaluate the relationships between TC score and ordinal DS modal profiles, as well as maximal throwing speeds and DS modal profiles.

To evaluate maximal throwing speed as a predictor of performance on the TC assessment, linear regression was performed with maximal throwing speed and gender as independent variables on the dependent variable of TC score. The inclusion of gender as a predictor in this model was used to account for physiological differences between genders that impact force capabilities that may contribute to the well-documented discrepancy in throwing speed between males and females (Thomas & French, 1985; Lorson et al., 2013; Lombardo & Deaner, 2018). Additionally, linear regression analysis was used to evaluate DS modal profile as a predictor of TC score. Gender was not included as a predictor in the model as there is little theoretical or empirical rationale to suggest a unique limiting factor to females' ability to achieve advanced throwing patterns. Correlation coefficients were interpreted using guidelines set forth by Cohen (1988; weak: $r < .300$, moderate: $.300 \leq r < .500$, strong: $r \geq .500$). Significant relationships between variables were assessed using alpha level < .05. All statistical analyses were conducted using R Statistical Software, version 4.0.3.

4.3 Results

Overall, data was collected on 130 participants. During initial data screening, two male participants were identified as outliers in terms of TC performance, demonstrating TC scores less three standard deviations below the mean (i.e., TC score < 3). After removing data from the two outliers, the remaining dataset met all statistical assumptions for the methods of analysis. Final data analysis was performed on the remaining 128 participants with a mean age of 22.1 ± 3.4 years (females: $n = 30$; $M_{age} = 21.8 \pm 4.0$; males: $n = 98$, $M_{age} = 22.1 \pm 3.2$). Descriptive statistics for each of the assessments are provided in Table 4.2. Mean TC score for the sample was 13.9 ± 3.3 ($M_{\text{females}} = 12.2 \pm 2.2$, $M_{\text{males}} = 14.5 \pm 3.3$). The mean maximum throwing speed for the sample was 26.1 ± 5.9 m/s ($M_{\text{females}} = 21.2 \pm 4.9$; $M_{\text{males}} = 27.6 \pm 5.3$). DS modal profiles for the sample ranged from 5-9, with a mean score of 7.4 ± 1.4 ($M_{\text{females}} = 6.7 \pm 1.3$, $M_{\text{males}} = 7.5 \pm 1.4$). ANOVA suggested a main effect for gender on TC score ($F_{1,28} = 8.32$, $p < .01$, $\eta = .06$), maximum throwing speed ($F_{1,28} = 35.79$, $p < .001$, $\eta = .22$), and DS modal profiles ($F_{1,28} = 7.53$, $p < .01$, $\eta = .06$).

Calculated Pearson correlations demonstrated a strong relationship between TC score and maximum throwing speeds in the sample overall ($r = .640$, 95% CI: .525 - .732, $p < .001$) and in the male subgroup ($r = .619$, 95% CI: .480 - .728, $p < .001$), while a moderate relationship was observed in females ($r = .496$, 95% CI: .165 - .726, $p = .005$). Spearman correlations demonstrated significant strong relationships between TC score and DS modal profiles for the sample overall ($r = .588$, 95% CI: .464 - .719, $p < .001$) and within the male subsample ($r = .607$, 95% CI: .464 - .719, $p < .001$), while the weak relationship observed in the female subsample was not statistically significant ($r = .260$, 95% CI: -.111 - .567, $p = .165$).

Results of the linear regression analysis with both gender and throwing speed as independent variables on the dependent variable of TC score explained approximately 41% of variance in TC scores in the sample overall (R^2 = .410, $F_{2,125}$ = 43.45, p < .001). Throwing speed significantly contributed to the model (β = .161, σ = .019, p < .001), but gender did not (β_{male} = -.072, σ = .600, p = .905). The linear model predicting TC score from DS modal profiles explained approximately 32% of variance in TC scores (β = 1.32, σ = .171, p < .001; R^2 = .322, $F_{1,126}$ = 59.83, p < .001).

4.4 Discussion

The purpose of the current study was to examine the concurrent validity of the TC assessment with previously validated methods of assessing throwing skill, maximal throwing speed and component developmental sequences. Overall, the strong correlations observed between maximal throwing speed (r = .640) and DS modal profiles (r = .588) with TC scores indicate that the traditional measures of throwing skill that assess individuals' movement patterns and throwing speed with maximal effort are strongly related to performance on the TC assessment in young adults with generally stronger associations in males. Further, results of the linear regressions demonstrate that throwing for maximal speed, but not gender, predicted 41% of the variance in TC scores (β = .119, σ = .021, p < .001). Similarly, movement pattern modal profiles predicted 32% of variance in TC scores in the total sample (β = 1.32, σ = .171, p < .001).

When addressing the throwing aspect of the TC assessment, high levels of success require the ability to throw for accuracy, consistency, optimal ball speed, and the ability to adapt throwing performance during the assessment based upon catching postures from previous performances. Results between TC scores and maximal throwing speeds and DS modal profiles speak to the concurrent nature in which these aspects of throwing skill develop with capabilities to throw for maximal speed. Higher capabilities for maximum throwing speed in and of itself expands the flexibility by which a performer may successfully accomplish the TC tasks because the performer possesses the minimal force production capabilities needed for a larger range of throwing strategies. Further, the ability to throw for higher speeds enables the emergence of more advanced coordination patterns, thus expanding the base of functional throwing patterns within the performer's repertoire (Southard, 1998, 2002, 2006; Roberton & Konczak, 2001; Langendorfer & Roberton, 2002; Stodden et al., 2006a, 2006b) and the potential movement patterns by which the performer can regulate throwing speed and control throwing accuracy (Urbin et al., 2012). The strong relationship between the TC score and traditional throwing skill assessments suggest that the participants' skill related to catching the ball (e.g., catching, agility) did not greatly detract from the assessment's ability to differentiate between participants of various levels of throwing skill. Overall, these data suggest that the TC score strongly aligns with estimates of other validated throwing skill assessments in young adults.

TC scores demonstrated stronger correlations with maximal throwing speed than DS modal profiles within the sample overall and within each gender group. The differences in the strength of the relationship between the product- and process-oriented assessments can be partially explained by the sensitivity of maximal throwing speed measurements compared to ordinal DS modal profiles in terms of differentiating performers, especially within gender subgroups. For example, DS modal profiles ranged between 5-9 with approximately 73% of the current sample demonstrating one of two DS modal profile scores (DS modal profile 6 -- 37.5% and DS modal profile 9 – 35.2%). Further, within the female sample, two-thirds demonstrated a DS modal profile ≤ 6, with 60% of the female sample demonstrating a DS modal profile 6, contributing to the non-significant weak relationship observed between DS modal profiles and TC scores in this female sample. Alternatively, 40% of the male sample demonstrated a max DS modal profile of 9. Overall, 95% of the young adult (males = 95%, females = 93%) sample most often demonstrated (i.e., mode) at least two on each of the components (i.e., DS modal profile ≥ 6; Appendix B). These findings are supported by previous investigations utilizing Roberton & Halverson's (1984) component developmental sequences in adolescents and young adults. Lorson and colleagues (2013) similarly observed over 80% of individuals 14 years and older demonstrated the at least a developmental level of 2 for the trunk, humerus, and forearm components, which is also the most commonly demonstrated modal profile in young adolescent samples (Halverson et al., 1982; Langendorfer & Roberton, 2002). Essentially, 95% of the current sample was differentiated by only four levels of the DS modal profile variable in their maximal effort trials. While the Roberton and Halverson (1984) component developmental sequences used in this study demonstrate greater levels of sensitivity than other process-oriented measures of throwing skill (e.g., TGMD, GSGA; Logan et al., 2017), when taken together with previous research, these results speak to the limited sensitivity of process-oriented measures of throwing. Further, our results suggest that process-oriented assessment of throwing skill during maximal effort throwing tasks in closed contexts may provide no additional value than maximal throwing speed in terms of predicting success in more complex throwing tasks. More research is needed across different age groups, cultures, socio-economic statuses, and with the use of alternative throwing tasks to provide further support for this proposition and to demonstrate further developmental validity for the TC task across the lifespan.

The task constraints of the TC task incentivize the use of higher throwing speeds to decrease the timespan needed for each throw-catch sequence, likely contributing to the predictive utility of maximal throwing speed in terms of predicting TC success. However, it is likely that that the relationship between maximal throwing speeds and TC score is also influenced by covariates of maximal throwing speed, which may have also influenced TC success (e.g., throwing accuracy, catching abilities). Further, though not directly measured, it is unlikely the throwing speeds during the utilized during performance of the TC were similar to the maximal throwing speeds of the individual performers, which exceeded 31.3 m/s (70 mph) for over 20% of the current sample. While males demonstrated higher performance across all assessments, gender was not a significant predictor of TC score (β_{male}= -.072, σ = .600, p = .905) after controlling for maximal throwing speed, suggesting that if maximal throwing speed is known, gender is an irrelevant predictor of success on the TC task. Biological factors have been frequently suggested as contributors to the difference throwing speeds between male and females (Thomas & French, 1985; Lombardo & Deaner, 2018); however, as throwing speeds used during higher levels of performance in the TC assessment in females would not exceed those demonstrated during maximal throwing tasks, factors more attributable to differences in throwing experience and practice (e.g., catching skill, throwing accuracy; Thomas & French, 1985) may better explain the differences in TC performance between males and females. Future research should examine the relationship between TC performance and assessments throwing accuracy and catching skill, as well as the throwing speeds used during the TC assessment to further investigate the impact of throwing speed capabilities on TC scores.

Conclusions and Limitations

Overall, the results of this study indicate performance on the TC assessment is indicative of throwing skill in young adults, as demonstrated by the strong correlations with both maximal throwing speed and DS modal profiles overall, although, the relationship between throwing speed was weaker in females and females' DS modal profiles were not significantly related to TC score. The study had a few limitations. While performance environment used in the TC assessment is effective for determining aspects of throwing skill related to maximal performance (i.e., maximal throwing speed and the component developmental sequences), specific information related to other throwing performance capabilities that impact successful performance in the TC assessment, such as throwing accuracy, consistency and adaptability, were not assessed. Future research should investigate the relationship between TC performance and these measures. Additionally, it would be valuable to investigate the various forms of throwing patterns and speeds utilized by performers in the TC to better understand how performers adapt throwing performance to cope with the constraints of the assessment and how they relate to task success. Second, the sample used in the current study was limited to college-aged young adults, thus, we cannot assume that similar relationships between maximal throwing tasks and the TC assessment would be observed across childhood, adolescence, or older adults. Future research should examine the relationship between performance on the TC assessment, maximal throwing tasks, and throwing accuracy tasks in samples with diverse ages.

Table. 4.1 Throwing Component Developmental Sequences

Humerus Action
H1. *Humerus Oblique.* The humerus moves forward to ball release in a plane that intersects the trunk obliquely above or below the horizontal line of the shoulders. Occasionally, during the backswing, the humerus is placed at a right angle to the trunk, with the elbow pointing toward the target. It maintains this fixed position during the throw.

H2. *Humerus aligned but independent*. The humerus moves forward to ball release in a plane horizontally aligned with the shoulder, forming a right angle between humerus and trunk. By the time the shoulders (upper spine) reach front facing, the humerus has moved independently ahead of the outline of the body (as seen from the side) via horizontal adduction at the shoulder
H3. *Humerus lags*. The humerus moves forward to ball release horizontally aligned, but at the moment the shoulders (upper spine) reach front facing, the humerus remains within the outline of the body (as seen from the side). No horizontal adduction of the humerus occurs before front facing

Forearm Action
F1. *No forearm lag*. The forearm and ball move steadily forward throughout the throwing motion
F2. *Forearm lag.* The forearm and ball appear to 'lag', i.e., to remain stationary behind the child or to move downward or backward in relation to the performer. The lagging forearm reaches its farthest point back, deepest point down, or last stationary point *before* the shoulders (upper spine) reach front facing
F3. *Delayed forearm lag*. The lagging forearm delays reaching its final point of lag until the moment of front facing

Trunk (pelvis-spine) action
T1. *No trunk action or forward-backward movements*. Mainly the arm is active in force production. Sometimes, the forward thrust of the arm pulls the trunk into passive rotation, but no twist-up precedes that action. If trunk action occurs, it accompanies the forward thrust of the arm by flexing forward at the hips. Preparatory extension sometimes precedes forward flexion.
T2. *Upper trunk rotation or total-trunk, "block" rotation*. The spine and pelvis both rotate away from the intended line of flight and then simultaneously begin forward rotation, acting as a unit or "block" Occasionally, only the upper spine twists away, then toward the direction of force. In this latter case, the pelvis remains fixed, facing the line of flight, or joins the rotary movement after forward spinal rotation has begun.
T3. *Differentiated rotation*. The pelvis precedes the upper spine in initiating forward rotation. The performer twists away from the intended line of ball flight and, then, begins forward rotation with the pelvis while the upper spine is still twisting away.

Adopted from Roberton & Halverson, 1984

Table 4.2 Means and Standard Deviations of Assessment Performances

	Total *n* = 128		Females *n* = 30		Males *n* = 98	
	M	SD	*M*	SD	*M*	SD
TC Score	13.9	3.3	12.2	2.2	14.5	3.4
Max Speed (m/s)	26.1	5.9	21.2	4.9	27.6	5.3
DS Profile	7.4	1.4	6.7	1.3	7.5	1.4

Note. Max speed = maximum throwing speed; TC Score = Max Throw-Catch score; DS Profile = Component developmental sequence modal profile

CHAPTER 5
CONCLUSIONS AND FUTURE DIRECTIONS

This dissertation investigated the potential for the TC assessment to produce a valid estimate of MC across the life span. In contrast with traditional assessments of motor competence performed in static and unchanging performance environments, the TC performance context incorporates a larger range of environmental degrees of freedom, thereby emphasizing the abilities of the performer to sense and interpret characteristics of the performance context. The results of the current research provide strong preliminary evidence to support the potential of the TC assessment as a valid estimate of throwing and catching development and its ability as an integrative assessment of object projection/reception skills across the life span. Through interaction with an informationally rich performance environment, the open-ended and unrestricted nature of the TC task offers performers the opportunity to demonstrate the range of movement capabilities they accumulate over the course of development.

The combination of throwing and catching in the assessment contributes to the complexity of the task as performers must sync throwing and catching performances in a complementary fashion to achieve high levels of success. TC performance also demonstrates similar negatively accelerating developmental trends to those observed across childhood into young adulthood in both throwing and catching (Thomas & French, 1985; Butterfield et al., 2012; Lorson et al., 2013). The overall impact of throwing skill on

TC performance was demonstrated via positive relationships between TC scores and maximal throwing speed and developmental sequence modal profiles.

While there is no shortage of different MC assessment tools, the TC provides an assessment option that is highly feasible and aligns with contemporary conceptualizations of MC from an ecological perspective and aligns with a developmental perspective. As TC performances are easily live-scored and require minimal equipment (e.g., bucket, tennis balls, timekeeping, location with solid floors and wall of adequate height), the lack time needed outside of the actual administration of the assessment (e.g., for data coding, staff training) and the use of equipment common to many physical activity contexts (e.g., physical education) eliminates common barriers to assessment and makes the TC a viable means for assessing object projection/reception skills. This type of assessment is needed, specifically in physical education as assessment barriers limit the ability to consistently provide nationally representative data on the potential effectiveness of physical education and positively impact lives of children and adolescents (Ferkel et al., 2022).

The use of a more dynamic and open performance context in the TC assessment separates it from traditional assessments of MC; however, does not limit the tasks capability to produce results that depict the developmental nature of MC and adequately represent the degree of competence in specific motor skills incorporated in the assessment task. Further, the TC assessment addresses weaknesses in traditional MC assessment methods by offering a performance context that allows individuals to demonstrate the flexibility within their motor repertoire and capability to adapt performance during the assessment (Barnett et al., 2020; Rudd et al., 2020). In this way, the TC assessment appeals to the Ecological Dynamics conceptualization of skillful behavior, emphasizing the relationship between movement behavior and the performance environment (Seifert et al., 2017; Rudd, 2020). Designing assessments of MC which incorporate task and environmental constraints reflective of those encountered in real-world contexts (i.e., incorporation of multiple skills, multiple “linked” performances) may enhance the ability of MC assessments to predict performance in other contexts (i.e., ecological validity); and thus, better represent the relationship between MC and various correlates of interest to motor development researchers (e.g., physical activity, physical fitness, self-concept, cognition).

The unrestricted nature of the TC performance context also supports its use beyond assessment and its potential to facilitate throwing and catching-related skill development. As there is no “right” way (i.e., process) to perform during the assessment, practitioners, such as physical educators, can encourage performers to explore alternative throwing and catching strategies and/or movement patterns that can be used during the task, promoting the development of a larger movement repertoire. Accordingly, the task-focused design allows performers the autonomy to choose their own performance strategies and aligns with characteristics of mastery performance experiences which promote higher levels of enjoyment and motivation (Ames, 1992). In contrast to traditional practice of throwing and catching to another individual who may have differing levels of skill, the TC task allows performers to advance performance at their own rate by manipulating task difficulty according to their own respective abilities (e.g., throwing speed, use of a bounce, catching with one or two hands). Further, task constraints (e.g., dictating throwing/catching strategies) can easily be manipulated to augment skill-related development, as well as those in affective domains (e.g., cooperation with others; addition of multiple performers active in task). As such, the TC task can offer multiple avenues of formative assessment of student learning in the physical education context.

Future research on the TC tasks should continue to investigate validity of the TC assessment across the lifespan. While the first study in this dissertation demonstrates that higher performance on the TC assessment is associated with age, longitudinal research is needed to further support the developmental validity of the TC assessment. Further, while the second study provides initial evidence in support of the content validity of the TC assessment as it relates to throwing skill in young adults, future research should aim to investigate the presence this relationship with additional measures of throwing skill (e.g., accuracy and consistency assessments) and catching skill across a wider range of participant ages. Confirming these relationships across age would support the use of the TC assessment as a lifelong measure of MC. Lastly, researchers should investigate the development and implementation of assessments of MC that are designed to embrace inter-individual differences in motor performance through the use of more dynamic and open performance contexts in other domains of MC.

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APPENDIX A

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: Answer YES or NO.

1. Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?

2. Do you feel pain in your chest when you do physical activity?

3. In the past month, have you had chest pain when you were not doing physical activity?

4. Do you lose your balance because of dizziness or do you ever lose consciousness?

5. Do you have a bone or joint problem (for example, back, knee, or hip) that could be made worse by a change in your physical activity?

6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

7. Do you know of <u>any other reason</u> why you should not do physical activity?

APPENDIX B

STUDY 2 SUPPLEMENTARY DATA

Component Level Developmental Sequence Profiles

	H1-F1	H1-F2	H2-F1	H2-F2	H3-F1	H3-F2	H3-F3
Total (*n* =128)							
T2	-	3.1%	0.8%	36.7%	0.8%	6.3%	3.1%
T3	-	0.8%	-	4.7%	-	7.8%	35.9%
Females (*n* = 30)							
T2	-	3.3%	-	63.3%	-	3.3%	3.3%
T3	-	-	-	-	-	6.7%	20.0%
Males (*n* = 98)							
T2	-	3.1%	1.0%	28.6%	1.0%	7.1%	3.1%
T3	-	1.0%	-	6.1%	-	8.2%	40.8%

Note. T = Trunk component, H = Humerus component, F = Forearm Component; Number after each component indicates the component developmental sequence level as defined by Roberton and Halverson (1984). Example: T2-H1-F1 = Trunk level 2, Humerus level 1, Forearm level 1