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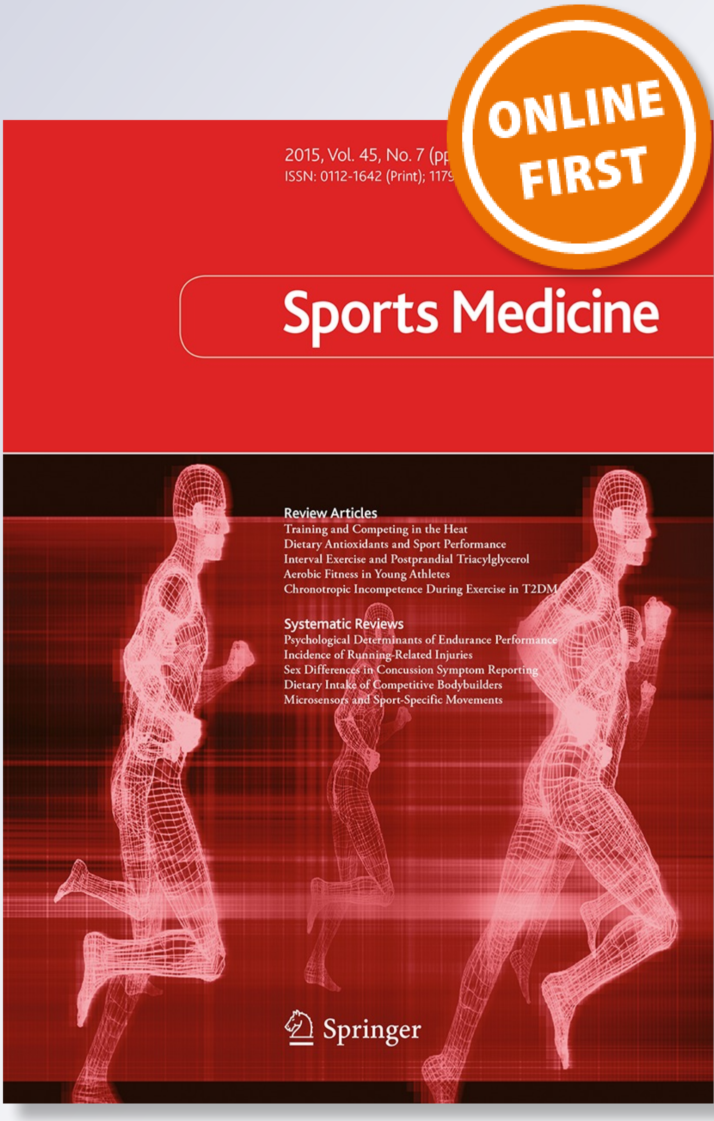

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REVIEW ARTICLE

Motor Competence and its Effect on Positive Developmental Trajectories of Health

Leah E. Robinson[1] · David F. Stodden[2] · Lisa M. Barnett[3] · Vitor P. Lopes[4] · Samuel W. Logan[5] · Luis Paulo Rodrigues[6] · Eva D'Hondt[7,8]

Abstract In 2008, Stodden and colleagues took a unique developmental approach toward addressing the potential role of motor competence in promoting positive or negative trajectories of physical activity, health-related fitness, and weight status. The conceptual model proposed synergistic relationships among physical activity, motor competence, perceived motor competence, health-related physical fitness, and obesity with associations hypothesized to strengthen over time. At the time the model was proposed, limited evidence was available to support or refute the model hypotheses. Over the past 6 years, the number of investigations exploring these relationships has increased significantly. Thus, it is an appropriate time to examine published data that directly or indirectly relate to specific pathways noted in the conceptual model. Evidence indicates that motor competence is positively associated with perceived competence and multiple aspects of health (i.e., physical activity, cardiorespiratory fitness, muscular strength, muscular endurance, and a healthy weight status). However, questions related to the increased strength of associations across time and antecedent/consequent mechanisms remain. An individual's physical and psychological development is a complex and multifaceted process that synergistically evolves across time. Understanding the most salient factors that influence health and well-being and how relationships among these factors change across time is a critical need for future research in this area. This knowledge could aid in addressing the declining levels of physical activity and fitness along with the increasing rates of obesity across childhood and adolescence.

L. E. Robinson, D. F. Stodden and L. M. Barnett were equal first authors and equally contributed.

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Key Points

A positive relationship exists between motor competence and physical activity across childhood.

The strength of associations between motor competence and both cardiorespiratory endurance and muscular strength/endurance tends to increase from childhood into adolescence.

Motor competence is both a precursor and a consequence of weight status and demonstrates an inverse relationship across childhood and adolescence.

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1 Introduction

Promoting and sustaining health-enhancing physical activity (PA), health-related physical fitness (HRF), and healthy body weight in children and adolescents is a global pursuit. Over the past few decades, a wealth of research has been conducted in an attempt to alleviate the disturbing trends in these health domains. However, research indicates that these interventions have had limited success [1–4]. Largely unexplored is the understanding of how the development of multiple health-related variables may synergistically impact each other to promote either positive or negative trajectories of health. Conceptualizing this complex problem using a developmental framework may provide valuable insight as to why researchers have had limited success in increasing PA and HRF and decreasing obesity rates.

In 2008, Stodden et al. [5] suggested that previous research had "…failed to consider the dynamic and synergistic role that motor competence (MC) plays in the initiation, maintenance, or decline of physical activity…" (p. 90). 'Motor competence' is a global term used in this paper to reflect various terminologies that have been used in previous literature (i.e., motor proficiency, motor performance, fundamental movement/motor skill, motor ability, and motor coordination) to describe goal-directed human movement. Using a unique developmental approach, a conceptual model was proposed by Stodden et al. [5] that addresses the potential role the development of MC may have on promoting either positive or negative trajectories of PA and weight status (see Fig. 1). In addition, HRF and perceived motor competence were suggested as mediating variables in the model. While different causal pathways are hypothesized across different phases of childhood, the development of reciprocal relationships and increasing strengths of associations among the variables across time are critical assumptions within this model. The synergistic nature of relationships among variables is suggested to promote either positive or negative trajectories of PA, HRF, and weight status across childhood and into adolescence. Ultimately, the lack of an adequate foundation of MC may be linked to a hypothetical 'proficiency barrier' [6] where low-MC individuals may not demonstrate health-enhancing levels of PA and HRF later in life [7]. These low-skilled individuals may also be at greater risk for obesity across childhood and adolescence. Overall, the model provides a testable framework focusing on multiple individual, behavioral, and psychological constraints.

It is imperative to note that indirect support for the development of actual MC is evident in many theoretical models as it relates to the development of positive health-enhancing behaviors across the lifespan. When examining health behavior change, prominent theories consider an individual's psychological disposition to be physically active. Many of these theories, including Self-Determination Theory [8], Achievement Goal Theory [9], Theory of Planned Behavior [10], the Transtheoretical Model [11], and Social Cognitive Theory [12], address some form of an individual's perceptions of competence, physical

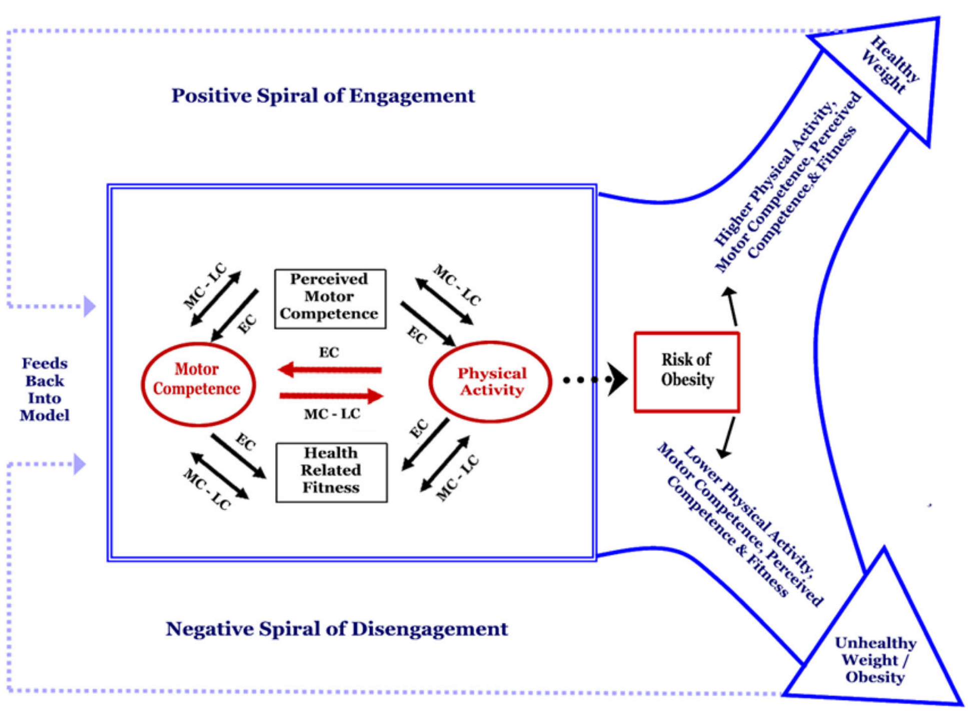

Fig. 1 Developmental model proposed by Stodden et al. [5] hypothesizing developmental relationships between motor competence, health-related physical fitness, perceived motor competence, physical activity, and risk of obesity. *EC* early childhood, *MC* middle childhood, *LC* late childhood. Reprinted from Stodden et al. [5] with permission from Taylor & Francis (http://www.tandfonline.com)

capability, or self-efficacy. Perceptions of competence and/or self-efficacy, which are situated within the context of an individual's actual competence (either globally or specific to an activity), are noted as important factors for promoting engagement in various leisure physical activities [5]. In addition, these psychological factors support other psychological health outcomes that are critical for promoting a positive environment of social interaction and acceptance in childhood, which also are important to promote PA [13]. For instance, obese youth are more likely than healthy-weight peers to encounter psychosocial problems such as lower health-related quality of life, anxiety, poor self-esteem, depression, lower social competence, and negative family interactions [14–17]. Additionally, physical literacy has emerged as a prominent theoretical paradigm since 2008 [18]. The focus of physical literacy is on the development of self and social awareness, self-regulation, and responsible decision making to foster overall personal well-being. In turn, this reinforces the notion of the integration of physical, psychological, and social traits and behaviors for healthy development. The physically literate individual is a physically educated person with the ability to use these skills in everyday life and who has the disposition towards purposeful physical activity as an integral part of daily living [19]. Therefore, when addressing long-term behavioral change, the linkage of positive psychological and social development, which is related to an individual's belief in their actual competence, should be valued.

1.1 Importance of Motor Competence

A majority of psychology-based behavior change theories address the concept of individual perceptions of competence from a motivation standpoint. However, it is also essential to understand the importance of actual MC and its relationship to PA, HRF, and weight status from both a movement and a developmental perspective. Childhood is a critical time for the development of MC [20], which enables children and adolescents to successfully participate in various types of PA [20, 21]. For example, successful participation in many structured and non-structured activities, games, and sports (e.g., hopscotch, cricket, four-square, tennis, basketball, dance, etc.) demands a certain degree of competence in many fundamental motor skills (e.g., running, catching, throwing, hopping, balance, and striking). However, multiple enabling and disabling constraints are present across childhood and adolescence that influence a child's developmental trajectory. Biological and environmental constraints [22] affect changes in growth and MC, and these constraints can either positively or negatively affect PA participation. There is a clear connection between the environmental context (e.g., aspects of the home, school, culture, psychological, and social influences) to MC, and this connection is supported by Bronfenbrenner's Ecological Systems [23], Gibson's Ecological Perspective [24], and Newell's Constraints Model [25]. One common thread among these approaches is that the human system is not pre-wired for ontogenetically defined skilled movement behaviors. Rather, these behaviors are adaptable properties promoted through complex interactions of biological, psychological, instructional, and environmental constraints that change across time. One important distinction noted in this paper is that development is age-related and not age-determined. Thus, the expression of different phases of physical, cognitive, social, and psychological development across childhood (which for the purposes of this paper will be generally defined as early childhood [2–5 years], middle childhood [6–9 years], late childhood [10–13 years], and adolescence [14–18 years]) can be ambiguous and are relative to the development of an individual child. It is also important to understand that the development and learning of MC is a process that ultimately results in a relatively permanent change in an individual's behavioral capability [26–29]. This is in contrast to PA level, HRF, and weight status, which are more adaptable and/or transient outcomes.

Recent meta-analyses and reviews highlight the idea that motor skills need to be taught and reinforced and do not develop 'naturally' or automatically over time [30–32]. Robinson and colleagues [29, 33–35] found that children who are directed by specialists to learn motor skills display greater increases in MC than children who engage in free play. Work from Robinson et al. [29, 33, 34] also notes that the instructional approach used to teach motor skills along with basic learning principles and the amount and context of experiences influence the stability of MC. Thus, it is important to foster continued learning and development of MC through practice and participation in developmentally appropriate activities that demand more advanced movement patterns and higher levels of performance in a variety of movement contexts [21, 27–29].

When the model by Stodden et al. [5] was published, limited research was available to indicate whether hypotheses of the proposed model were plausible. In the 6 years since, research in this area has greatly expanded and, thus, it is an opportune time to revisit the data that both directly or indirectly relate to the model hypotheses and determine whether the hypotheses are supported from a developmental perspective. Therefore, the purpose of this narrative review is to explore the direct and indirect synergistic relationships among motor competence and PA, HRF, perceived motor competence, and weight status. We generally focused on related articles published from 2008 to 2014 (i.e., published since the previous model by Stodden et al. [5]), accessing relevant databases, including

Academic Search Premier, CINAHL, PsycINFO, PubMed/MEDLINE, ERIC, Cochrane, SPORTDiscus, and author references, to review articles that provided a balanced picture of the literature.

Recent systematic reviews [30, 36–39] relating to individual model pathways and key cross-sectional, longitudinal, and experimental data are highlighted in subsequent sections to provide a global picture of data relating to the model hypotheses. In addition, we cite emerging evidence demonstrating that these factors are critical for promoting positive trajectories of growth, development, and health across childhood and for an individual's health and quality of life.

2 Motor Competence and Physical Activity

The Stodden et al. [5] model suggests PA in early childhood will initially promote the development of MC as basic motor patterns are developed through a variety of exploratory movement experiences. However, as children enter middle and late childhood, the model suggests the MC/PA relationship becomes more reciprocal due to the continued development and importance of more complex movement patterns (e.g., fundamental motor skills), which is suggested to augment success and the development of HRF and perceived competence (see Sects. 3 and 4). This progression fosters continued participation in a variety of physical activities as children enjoy success and are motivated to continue to improve. A lack of MC development is hypothesized to lead to a negative spiral of disengagement in PA as children lack the competence and confidence to move and will not enjoy participation in activities where they understand they will not be successful.

While limited data on associations between MC and PA were available in 2008, recent investigations have shed additional light on this aspect of the model. When considering recent evidence, a picture begins to emerge that provides a deeper level of understanding about how the relationship between MC and PA changes over time. Three review articles have examined the relationship between MC (differentially defined) and PA in children and adolescents. Lubans et al. [36] reviewed 21 studies that included both product- and process-oriented assessments of MC (i.e., specifically fundamental motor skills) in relation to a variety of health-related outcomes, including PA. Of the 21 studies, 13 specifically examined the relationship between MC and PA. Of the 13 studies, 12 found a positive association between MC and PA, and this review concluded that a positive association between MC and PA exists. However, strengths of associations were not provided to describe the magnitude of associations. For the remainder of the paper, strength of associations will be defined as noted by Cohen [40]: 0.10–0.29 = low; 0.30–0.49 = moderate; and $\geq$0.50 = strong.

Holfelder and Schott [37] also reviewed the relationship between MC and PA. Similar to Lubans et al. [36], product- and process-oriented assessments of MC were administered in the papers reviewed. However, the Holfelder and Schott [37] review included measures of motor abilities, motor coordination, as well as fundamental motor skills, and found that 12 of the 23 studies had positive associations between MC and PA ($r = 0.10$ to $r = 0.92$). The authors concluded that evidence suggests a cause–effect relationship between MC and PA, but the relationship has yet to be conclusively demonstrated as experimental data are limited. Recently, Logan et al. [41] published a similar review that focused on only process-oriented assessments to measure MC (i.e., fundamental motor skills). Of the 13 studies noted in the review, 12 reported a positive correlation between MC and PA ($r = 0.16$ to $r = 0.55$) [41].

Two longitudinal studies appear to provide the support for the developmental trajectory hypothesis between MC and PA. Barnett et al. [26] found that object control skills in childhood accounted for 3.6 and 18.2 % of participation in moderate-to-vigorous PA and organized PA, respectively, during adolescence. However, childhood locomotor skill competence was not related to adolescent PA. Additionally, Lopes et al. [42] found that children with high MC at the age of 6 years demonstrated sustained high self-reported levels of PA after 3 years compared with children of low and moderate MC, who exhibited declines in PA over this time. It is important to note that whilst these longitudinal studies provide stronger evidence than cross-sectional studies, only one found that object–control skills in childhood explained a significant but small proportion of the variance in moderate–vigorous physical activity during adolescence [26]. Also, both studies collected information on PA via self-report rather than using objective measures. Nevertheless, the follow-up time for both studies was extensive and, considering all the other factors that have been shown to influence PA, these studies still suggest a causal relationship between MC and PA. Furthermore, these findings are supported by recent randomized clinical trials. The SCORES (Supporting Children's Outcomes Using Rewards Exercise and Skills) study was a multicomponent school intervention that resulted in improvements in fundamental motor skill competence and maintenance of PA levels in the intervention group compared with a decline in the control group [43].

Overall, data strongly support a positive relationship between MC and PA across childhood. Data indicate low to moderate associations from early childhood through middle childhood years. During adolescence, there are simply not enough studies to make any reasonable conclusions about the relationship between MC and PA strengthening over time. In addition, methodological issues limit the ability to compare findings across studies. PA in previous studies has been assessed in many different ways (i.e., self-report questionnaires, objective measures such as pedometers and accelerometers, and direct observation). PA is also operationalized differently in terms of intensity, steps, leisure participation, and patterns throughout the day (i.e., weekday vs. weekend, e.g. Foweather et al. [44]). MC also was measured using many different assessments (i.e., qualitative and quantitative outcomes) that emphasized a variety of aspects of the motor domain. Additionally, some MC assessment data were norm- or criterion-referenced, and individual or composite measures of a variety of MC outcomes were noted in other studies. These measurement factors are important to consider for future investigations. For example, one recent study reported no association between MC and PA in middle childhood, with authors speculating this may have occurred because (1) a majority of the children were highly active (i.e., mean per day 1.5 h), thus limiting the opportunity to discriminate based on MC; and (2) there may have been a ceiling effect with the Test of Gross Motor Development—second edition (TGMD-2) scoring based on the age of the children tested [45].

Until a consensus is reached relative to MC, and PA measurement methodology and measures are consistently used in the literature, it will be difficult to examine whether changes in strengths of associations occur across time. We recommend as a start that researchers use assessments that have been used outside of their own country to collect MC data. If countries only use their own specific instrument to assess MC, it does not help move the field forwards. We suggest that both process (e.g., the TGMD) and product measures (e.g., the Körperkoordination Test für Kinder) of MC will provide a more comprehensive assessment of MC than either alone. Further reliability and validity studies of these more well-used instruments in a range of countries will mean we will be better able to compare children's MC across the globe and compare the findings. Furthermore, as the objective measurement of PA improves and becomes more sophisticated, it is possible that pattern recognition will help isolate the aspects of PA behavior that link to MC by accurately identifying activity recognition and activity level assessment [46]. In summary, evidence indicates a positive association between MC and PA. However, the strength of associations across developmental time remains unclear.

3 Motor Competence and Health-Related Fitness

The relationship between MC and multiple aspects of HRF (i.e., cardiorespiratory fitness, muscular strength, muscular endurance, and flexibility) has a storied history [47]. Explaining associations between these two distinct yet related constructs is multifaceted, as complex neuromuscular function is inherently integrated within both constructs [48]. In essence, many MC and HRF tests commonly promoted in youth populations involve complex goal-directed movements that require concentric and eccentric muscle actions that produce moderate to high force, speed, precision, or a combination of these attributes.

The Stodden et al. [5] model suggests that the development of MC will initially promote HRF in early childhood and, in middle and late childhood, HRF would mediate the relationship between MC and PA as increased fitness would hypothetically facilitate continued engagement in PA for longer periods. While no studies have directly addressed the mediating aspect of the model, a recent review article [39] generally noted strong evidence of a positive association between MC and cardiorespiratory fitness ($r = 0.32$ to $r = 0.57$) and muscular strength/endurance ($r = 0.27$ to $r = 0.68$) in childhood and adolescence. Data on flexibility were limited, and results were inconclusive. Only a few studies in this review noted null associations between MC and either cardiorespiratory endurance or muscular strength/endurance, and these were generally in younger children. As noted by the model hypotheses, the strength of associations between MC and both cardiorespiratory endurance and muscular strength/endurance tends to increase from childhood (null to moderate correlations) into adolescence (mostly moderate correlations) [39]. Evidence supports that these associations may be sustained even into young adulthood (moderate correlations) [7, 49].

While most evidence demonstrates that these trends are cross-sectional, recent longitudinal and experimental data provide stronger scientific evidence for associations among these variables in both childhood and adolescence [50–53]. Both direct (i.e., improved neuromuscular function) and indirect (i.e., motivation and choice of participation in various types of physical activities) associations suggest that a synergistic mechanism may be the most plausible explanation to understand the increased strength of associations between these factors across childhood and into adolescence [48]. Finally, maturational status [54] and its association with MC and HRF is important to address in future research. Maturation is the timing (e.g., specific maturational events like the appearance of secondary sex characteristics) and tempo (e.g., rate at which maturation progresses—how quickly or slowly an individual goes through sexual maturity) of progress toward a mature biological state that occurs in all tissues, organs, and organ systems, affecting enzymes, chemical compositions, and functions [55]. However, maturation may have a limited impact on different aspects of MC, as Freitas et al. [56] noted that the influence of maturation (i.e., skeletal age interacting with body size) has a negligible influence on MC in children aged 7–10 years.

4 Motor Competence and Perceived Competence

Perceived competence refers to an individual's perception of their actual movement capabilities [57] and is highlighted in the Stodden et al. [5] model as an important factor that mediates the role between actual MC and PA. In other words, an indirect relationship exists between MC and PA through an individual's perception of their competence. For this to occur, perceived competence needs to be associated with actual MC and PA. Associations are purported to increase in strength as children age, as the development of a child's cognitive ability to accurately assess their competence becomes more established in middle childhood. Thus, middle childhood is proposed to be a critical time where the positive or negative trajectories of PA, HRF, and weight status (related to MC) begin to diverge. At the time the model was published, limited evidence was cited to support this [58, 59]. More recent work provides additional support regarding the differential role of perceived competence as it relates to both actual MC and PA in children and adolescence.

A recent systematic review by Babic et al. [38] noted that perceived competence had the strongest relationship to PA compared with other aspects of self-concept. This review also found that age moderated the relationship. Both of these findings align with the Stodden et al. [5] hypotheses. However, this review only included one study of perceived competence in children, with the remainder in adolescents, and found that the strongest association was in early adolescence, not later adolescence. Sex was not found to be a moderator in the Babic et al. [38] review, although studies in children have found the relationship between perceived competence and PA did differ according to sex. For example, in older Portuguese boys (aged 8–10 years) an association existed between perceived competence and self-reported PA, but not for girls [60].

During early childhood, evidence of positive associations between perceived and actual MC has been noted across various cultures including Canadian [61], American [34], and Danish children [62]. In contrast, a study in young Brazilian children found no relationship [63]. It is difficult to truly ascertain strengths of association between perceived competence and actual competence as assessments of perceived competence do not closely align with assessments of MC in terms of particular skill domains [64] or even general measures of self-concept [38]. For instance, surveys assessing physical self-perceptions tend to include broader questions relating to general competency in the physical domain [65, 66] as opposed to assessments of actual MC that might be targeted to particular competence sub-domains such as object control and locomotor competence [67]. It is likely that children at different levels of cognitive development may have different perceptions of their ability in specific physical domains (e.g., MC, PA, or HRF), and future research should explore the alignment of actual competence and perceived competence assessments [64]. Two recent Australian articles align measures of actual and perceived skill competence in young children, finding positive associations [68, 69], but further research is needed to see whether the strength of association differs for different skill or activity types and across age.

There is also preliminary support for perceived competence as a mediator. Barnett et al. [70] found perceived competence mediated children's object control competence (but not locomotor competence) and self-report PA during the adolescence years 6 years later. In addition, perceived competence mediated object control competence and self-report PA in adolescence, and this relationship also worked in the reverse direction (when PA was the predictor) [71], providing support for the model in that these pathways may be reciprocal. However, a recent study in young children did not find this to be the case [72], which follows the model hypothesis that relationships between these constructs emerge as children age. The systematic review by Babic et al. [38] did note that, whilst sufficient evidence exists to conclude a bi-directional relationship between PA and physical self-concept, future researchers could seek to further explore mediation analyses.

5 Motor Competence and Weight Status

As initially hypothesized, an important outcome of the model is the development of a healthy or unhealthy weight status [5]. Research documenting associations between MC and various measures of weight status has increased substantially since 2008. Evidence from several cross-sectional studies with large samples of children, adolescents, and young adults clearly demonstrates an inverse association ($r = -0.20$ to $r = -0.62$) between both factors using various MC and weight status measures [7, 42, 73–76]. In addition, differences in MC levels of overweight/obese children as compared with healthy weight peers are more evident in tasks requiring manipulation of total body mass [74, 77, 78]. Inverse associations between MC and weight status emerge at pre-school age [76, 79, 80] and become stronger during elementary school years [42, 75]. Beyond this age, evidence is less conclusive. Some studies indicate that the strength of association tends to decline again with puberty into adolescence [42, 73], whereas others found strong(er) correlations in adolescents [81] and young adults [7] than in childhood.

Many authors have stressed the crucial need for longitudinal and experimental research to examine a possible antecedent/consequent mechanism between MC and weight status. One explanation is that excess mass impedes stabilization and/or propulsion of the body, promoting lower actual and perceived MC, which decreases the likelihood of overweight/obese individuals being physically active [59, 82–85]. It has been suggested that the weight status of infants (i.e., being overweight) is related to motor development impairment [86]. Likewise, body mass index was noted to be an important predictor of future MC in childhood [85, 87]. Alternatively, children's MC level was also suggested to be a significant predictor of adiposity [85, 88–90]. Unfortunately, no experimental designs can corroborate causal pathways.

Diverse pathways of MC across childhood and adolescence are associated with higher or lower levels of PA, and that pathway also may assist in the development of differential trajectories of weight status over time. Most studies reporting an adverse association between MC and weight status did not adjust for PA, but when PA was taken into account its role turned out to be rather limited [84, 85, 88, 91]. A longitudinal study by D'Hondt et al. [87] demonstrated an increasingly wide gap in gross motor coordination, with overweight and obese children showing poor MC as well as reduced age-related progress compared with normal-weight peers. Children's body mass index at baseline negatively predicted and explained 37.6 % of the variance in gross motor coordination over time, while participation in organized sports were a positive predictor. D'Hondt et al. [85] also found that the level of MC negatively influences body mass index over time, while baseline PA did not mediate the adverse relationship between weight status and MC. Unfortunately, no longitudinal evidence on associations of MC and weight status is available in early childhood or adolescent age ranges. However, the strongest inverse correlations reported between MC and a measure of weight status (i.e., % body fat) were in young adults aged 18–25 years ($r = 0.56$ to $r = 0.73$) [7].

Based on the available data, MC may be considered both a precursor and a consequence of weight status in childhood. As hypothesized by Stodden et al. [5], this reciprocal relationship is likely to be synergistically influenced by PA, HRF, and perceived competence, leading to a variety of individual trajectories across developmental time as noted by Rodrigues et al. [92]. Additional longitudinal research (including evidence from intervention studies) should take into account any additional variables (including but not limited to diet, genetics, growth, and maturation) that may influence the inverse associations between MC and weight status throughout childhood, adolescence, and (young) adulthood, and examine the individual developmental pathways of change conceptualized in the original model [5].

6 Future Directions

Overall, there is a strong consensus that MC is positively associated with all health-related variables within the model [5]. Based on the research that has been published

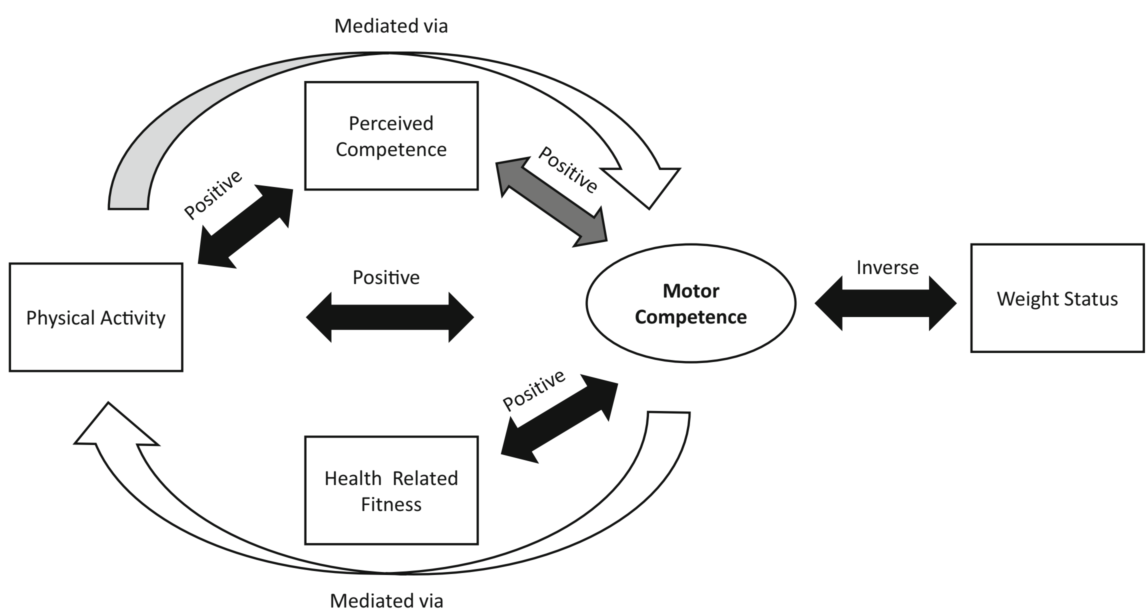

Fig. 2 Research consensus on motor competence and health-related variables. *Black arrow* indicates extensively tested: consistent relationship; *dark grey arrow* indicates moderately tested: variable relationship; *partial grey arrow* indicates partially tested: some evidence; *white arrow* indicates limited testing. The direction of the relationship is indicated above the *arrows*

since 2008 (see Fig. 2), the model hypotheses have initial empirical support. Data for some pathways are stronger than others, and some pathways have yet to be tested. Emerging evidence also indicates increasing strength in associations between MC and weight status (inverse) and HRF (direct) across childhood into adolescence, while associations between MC and PA and perceived competence are variable across time. In addition, perceived competence has been identified as a potential mediator (as noted in the model) in the MC and PA pathway.

To promote future research as it relates to Fig. 2, several model hypotheses have yet to be confirmed and warrant exploration. The original model [5] situated HRF as a mediator between MC and PA. This is yet to be confirmed empirically. Perceived motor competence was also situated as a mediator and there is emerging evidence of this hypothesis, although further research could seek to explore this aspect further. Whilst research on perceived physical competence (in terms of general physical perceptions) and actual MC has been conducted, there is less research on perceived MC and actual MC, so the specificity of these relationships could be further investigated. In terms of MC and PA, future studies may wish to examine different contexts of PA. It seems plausible that MC will only be related to discrete time periods for PA, and perhaps the nature of the association between MC/PA is diluted by examining daily averages of PA outcomes (which includes periods such as school that tend to encourage sedentary behavior). For example, weekday and weekend variations [44], or focusing on segments on the day that are critical periods for PA such as recess and afterschool [93], may help to further illuminate the relationship between MC and PA.

Following the developmental underpinnings of this model, data from a few studies indicate that object control/manipulation skills may be more salient predictors of PA [26, 93] and HRF [48, 52, 53] in later childhood and early adolescence. However, data support that locomotor skills are critical during the early childhood years for PA [33, 94]. This aligns with motor development literature, as locomotor skills generally develop earlier than object control/manipulation/ball skills. Further examination of this question is important, as some MC assessments are limited in their testing of object control/manipulation skills (i.e., Körperkoordination Test für Kinde, Bruininks-Oseretsky Test of Motor Proficiency). In addition, measurement issues are important to address, as a wide variety of PA, MC, perceived competence, and weight status assessments are used in the literature, which makes it difficult to accurately ascertain the strength of associations across age. However, longitudinal data [39, 42, 85, 87] provide valuable insight on the hypothesized positive or negative developmental trajectories of PA, HRF, and weight status based on the tracking of MC levels.

Recent years have seen increased interest in the area of cognitive function/health. Research clearly supports the positive benefits of PA on cognitive function, and emerging evidence supports the connection of MC to cognition [95–104]. This connection seems intuitive based on the complex and multilevel cognitive involvement inherent in neuromotor 'learning.' A growing body of literature also indicates cognitive/executive function (e.g., attentional control, working memory, and inhibition) [95, 97, 98, 101–103] and academic performance [96, 97, 99, 105] is positively associated with cardiorespiratory fitness, weight status, and PA in youth and adults.

A review by Haapala [106] examined associations between MC and aspects of cognitive function and academic achievement. Ten of the included articles focused on some aspects of MC, and eight studies noted positive associations between MC and cognitive tests that included tasks for IQ, attention, inhibitory control, item memory, and academic performance. More specifically, correlational studies indicate children with higher levels of MC exhibit higher order cognitive function [107], working memory, and processing speed [108] as well as various measures of academic achievement [109–111]. Haapala et al. [112] recently found children, aged 6–8 years, with poor motor skill competence also exhibited worse cognition, and this relationship was more pronounced in boys. The effect of motor skill interventions on cognitive and executive functioning is limited, but emerging findings are also positive [113–115]. Examining whether improved cognition and executive function outcomes in children result from both persistent PA (i.e., due to the act of PA) as well as cognitive neural development associated with various types of context-specific motor development warrants further attention [116–118]. In addition, if the strength of associations between MC and HRF, weight status, and PA increase across time, would the associations between MC and cognitive factors also increase across developmental time?

Specifically related to the demonstration of positive or negative developmental trajectories is an untested hypothesis relating to a 'proficiency barrier.' In 1980, Seefeldt [6] proposed the idea of a critical level of MC that would be related to participation in activities requiring the application of MC. Thus, if an individual were below this proficiency barrier, they may be at greater risk for decreased PA and HRF. A recently published paper by Malina [54] also noted this topic was related to a "top ten" question for understanding the development of obesity. Limited preliminary data indirectly support the proficiency barrier hypothesis with young adults. Only 3 % of a sample of 18–25 year olds with "low" MC demonstrated "good" fitness, as defined by a composite measure of muscular strength, muscular endurance, and cardiorespiratory endurance [49]. Thus, Seefeldt's proficiency barrier hypothesis is a logical and critically important extension of the positive or negative trajectory hypotheses of the Stodden et al. [5] model, not only for PA, HRF, and weight status, but also for long-term health-related outcomes. To our knowledge, the association of MC with long-term health outcomes has not been addressed in the MC literature [3]. As a greater percentage of the population is approaching elderly status, would the development of MC (analogous to functional capacity) in childhood and adolescence promote long-term functional capacity and independence and decreased chronic disease and all-cause mortality in an aging population? As noted previously in Sects. 1 and 1.1, the development and learning of MC is associated with a relatively permanent change in behavior, and MC can be defined as an individual's capacity to coordinate and control their center of mass and extremities in a gravity-based environment [7]. Thus, highly developed MC in childhood/adolescence has the potential to foster lifelong functional independence and quality of life.

7 Conclusions

Based on the increased interest of the scientific community and data linking MC to various aspects of health across childhood, adolescence, and young adulthood, further testing of the specific hypotheses (i.e., differential trajectories and causal pathways) within the model is warranted. We believe this approach should continue to be tested, modified, or adapted to examine its feasibility and predictive utility. As noted in many cross-sectional and longitudinal studies, demonstrating antecedent/consequent relationships among variables in the model remains speculative without well-conducted experimental evidence. Interventions targeting young children should be initiated during the early childhood years, as MC and PA behaviors should be established early in life and they often track into the adult years.

Collectively, children's physical and psychological development is a complex labyrinth of biological, environmental, psychosocial, and behavioral factors that synergistically evolve across developmental time. Additionally, the rationale for causal pathways in the model may not be unidirectional across time. These are two critical features that separate it from other theoretical models that are used as paradigms to promote various aspects of health. Understanding the most salient factors that influence health and well-being of individuals and how relationships among these factors change across time is a worthwhile endeavor that should be approached in both a developmental and a systematic manner.

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