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www.PES-Journal.com
A NOTE FROM THE PUBLISHER

Pediatric Exercise Science, 2014, 26, 231-241
http://dx.doi.org/10.1123/pes.2013-0027
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Dynamic Relationships Between Motor Skill Competence and Health-Related Fitness in Youth

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This cross-sectional study examined associations among motor skill competence (MSC) and health-related fitness (HRF) in youth. A convenient sample of 253 boys and 203 girls (aged 4–13 years) participated in the study. Associations among measures of MSC (throwing and kicking speed and standing long jump distance) and a composite measure of HRF (push-ups, curl-ups, grip strength and PACER test) across five age groups (4–5, 6–7, 8–9, 10–11 and 12–13 yrs.) were assessed using hierarchical regression modeling. When including all children, throwing and jumping were significantly associated with the composite HRF factor for both boys and girls (throw, $t = 5.33$; jump, $t = 4.49$) beyond the significant age effect ($t = 4.98$) with kicking approaching significance ($t = 1.73$, $p = .08$). Associations between throwing and kicking speed and HRF appeared to increase from early to middle to late childhood age ranges. Associations between jumping and HRF were variable across age groups. These results support the notion that the relationship between MSC and HRF performance are dynamic and may change across childhood. These data suggest that the development of object control skills in childhood may be important for the development and maintenance of HRF across childhood and into adolescence.

Components of health-related physical fitness (HRF; i.e., muscular strength/endurance and cardiorespiratory endurance) have been identified as independent factors for predicting risk of chronic disease and other health outcomes in children, adolescents and adults (5,19,21,32,38). In addition, the associations of HRF to health markers/outcomes may be as important as associations between general physical activity to health markers/outcomes (34,48). Thus, understanding correlates and mechanisms that promote the development of multiple measures of HRF in children and adolescents is critical. Unfortunately, we do not fully understand how to promote and maintain adequate HRF in youth (20,26). It has been suggested that the development of motor competence in a variety of forms across childhood may provide a foundation for promoting positive trajectories of fitness and physical activity behaviors across childhood, adolescence and into adulthood (39).

Motor competence, as a global term relating to development and performance of human movement, has been defined as relating to proficiency in fundamental motor skills (i.e., locomotor and object control skills; 39). Thus, the term motor skill competence (MSC), as referenced in this paper, refers to competence in selected object control and locomotor skill performance. Context-specific experiences including practice, instruction, and structured training are critical for the acquisition of these types of skills as they do not "naturally" develop over time. Without this skill foundation, youth are less likely

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to be physically fit (17,28,40). In addition, we believe current evidence on promoting long-term HRF in youth have produced equivocal results because researchers have not addressed this question from a developmental perspective (9,15,39).

The Physical Activity Guidelines for Children (46) propose the adoption of "developmentally appropriate" activities (e.g., tennis, basketball, baseball, soccer, hop-scotch etc.) to promote HRF. Such activities inherently require a certain degree of proficiency in MSC (e.g., kicking, throwing and jumping) for successful participation. Unfortunately, many youth do not attain adequate proficiency in MSC (17,30). We contend the lack of proficiency in MSC may severely hinder youth participation in many diverse types of leisure physical activities, games and sports that demands continued practice and participation, which in turn will hinder the development of HRF.

Dynamic Relationship Between MSC and HRF

MSC is assessed by various process- and product-oriented measures including the performance scores of many fundamental object control (e.g., throwing, striking, and kicking) and locomotor (e.g., running, jumping and hopping) skills (39). Published data have demonstrated weak to strong positive associations (i.e., correlations [$r = .01$ to .74] and explained variance [r^2 =1–79%]) among single or composite measures of MSC and HRF in children, adolescents and young adults (8,17,15,16,31,40,45). Studies examining these relationships vary greatly on the type of motor skill assessment batteries used (e.g., process vs. product; 1,6,8, 30,15,31,40), skills tested (e.g., locomotor, object control, fine and gross skills; 1,8,15) and differences in ages (i.e., childhood, adolescence, and adults). Such variability makes it difficult to compare and interpret findings across studies. Previous studies have not provided a clear picture of the strength of relationships between MSC and HRF across time.

Stodden et al. (39) proposed that the strength of relationships between MSC and HRF will increase across age and suggest the development of MSC may be a causal mechanism to promote either positive or negative trajectories of HRF as well as physical activity and body composition status across time (see Figure 1). We propose the positive or negative trajectories of MSC and HRF will hold true because the development of advanced coordination patterns and higher performance levels for object control and locomotor skills involve ballistic actions of the body that directly increase demand on the neuromuscular system (e.g., changes in motor unit recruitment rate and thresholds, coactivation of agonists/antagonists, central drive, altered sensitivity of proprioceptors, cross-lateral education; 12,33,44,47), as well as perceptual motor integration (e.g., object control skills; 9). Advanced levels of coordination and control demanded for the development of many fundamental motor skills requires the effective integration and manipulation of one's entire body mass and extremities and involves high eccentric/concentric muscle activity levels and is related to strength/power output (7,13,22,36,40–42). Repeated high muscular activity levels associated with practice and performance of fundamental motor skills in leisure and

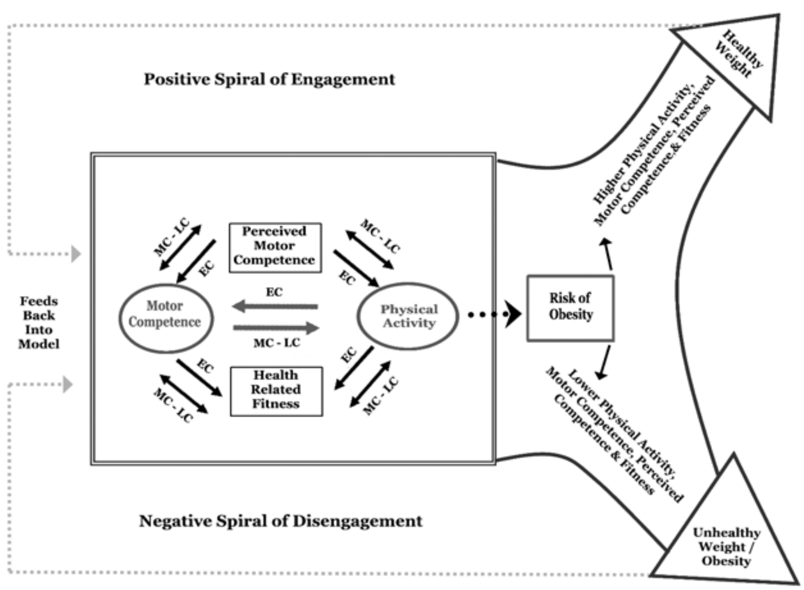

Figure 1 — Developmental model proposed by Stodden et al. (39) hypothesizing developmental relationships between motor competence, health-related physical fitness, perceived motor competence, physical activity and risk of obesity. EC = early childhood, MC = middle childhood, LC = late childhood. A developmental perspective on the role of motor skill competence in physical activity: An emergent relationship, Stodden, Quest. Reprinted by permission of Taylor & Francis (http://www.tandfonline.com).

sport activities promotes muscular endurance. In addition, regular participation in many games and sports includes continued muscular activation (i.e., aerobic activities) that promotes cardiorespiratory endurance (e.g., physical education games, soccer, aerobic dance, tennis, basketball, baseball). Thus, movement experiences associated with the development of proficient levels of MSC should both directly and indirectly support the development of various components of HRF.

In contrast, it is likely that low MSC proficiency negatively influences a child's persistence in many physical activities that promote aspects of HRF because a low skilled child: a) believes he/she is not as competent as peers, b) does not want to demonstrate low MSC, and (c) having fewer movement options and movement opportunities, he/she is less motivated to participate in various physical activities because they are less enjoyable (39). The relationship among MSC and aspects of HRF also may be viewed as recursive in nature promoting either positive or negative HRF trajectories across childhood and adolescence (1). If associations among MSC and HRF increase in strength across childhood and into adolescence (as proposed by the Stodden et al. model), then it would seem logical to promote a strong foundation of MSC across childhood, even if the associations are not well established early in life. In essence, weak associations in early childhood may not be a good indicator of the potential longitudinal impact of MSC on HRF and other health-related variables (e.g., physical activity and obesity). The development of MSC and its potential linkage to lifespan trajectories of HRF and related constructs such as physical activity and obesity across childhood (6,10,11,17,23,28,47), adolescence (1,15,16,31), and even into adulthood (40) needs to be addressed.

Although girls lag behind in object control skill performance from an early age, longitudinal data indicate performance trajectories (i.e., rate of change) of both MSC and fitness measures across childhood are quite similar in boys and girls through early and middle childhood (25). The approach to adolescence demonstrates a more visible delineation in performance trajectories between boys and girls with boys' performance changes markedly outpacing girls' performance changes (25). Alternatively, the development of qualitative coordination patterns has not been demonstrated to be different between boys and girls; rather, they simply develop at different rates of longitudinal change (14). As prepubescent girls and boys are similar in physical characteristics, there are no anatomical or physiological reasons why their development during early and middle childhood should be altogether different (3). However, previous studies have not examined the strength of associations between MSC and HRF in both boys and girls across the entire age range from early childhood into early adolescence using the same assessments.

The purpose of this study was to examine the relationship among selected measures of MSC and HRF in youth, ages 4–13 years. An additional unique aspect of this study was to examine the hypothesis by Stodden et al. (39) whose model proposed that the strength of associations among MSC and HRF would increase across childhood and adolescence and that boys and girls would demonstrate similar associations among these variables across age groups.

Methods

Two convenient samples of youth (263 and 193), ages 4–13 years (253 boys, 203 girls; Mean = 8.84 years, *SD* = 2.64), were included in the final data set. We classified subjects according to five age groups for data analysis (see Table 1 for descriptive characteristics of age, sex, and fitness changes across the five age groups). One sample ($n = 263$) was selected from a suburban school district in northwest Ohio and tested in the Fall of 2007. This sample was predominantly non-Hispanic White. The second sample ($n = 193$) was selected from a rural school in northwest Texas and tested in the Fall of 2009. The second sample was 58% Hispanic with the remaining subjects being predominately non-Hispanic White. Overall, both schools provided adequate physical education time during the school year (Ohio cohort 120 min/wk; Texas cohort 150 min/wk) and promoted similar curricular emphases (i.e., sports games and fitness). Before participation we obtained permission from the school districts and institutional human subjects review boards to conduct the study. Parental consent and child assent also were obtained. Youth with any physical disability or health condition that prevented completion of any of the motor skill or fitness tests were not allowed to participate in testing.

We measured maximum speed for throwing (using tennis balls) and kicking (20cm diameter playground balls) and maximum jump distance/height (standing long jump) from a total of five trials of each skill (40,43). We measured ball speeds using a radar gun (JUGS Co., Tualatin, OR; Stalker Radar, Plano, TX). The radar guns were accurate to at least ± 0.22 m/s (0.5 mph). Jump distance was measured to the nearest centimeter. We assessed MSC using product scores because they are sensitive discriminators among competence levels across childhood and early adolescence (18,24,27,35,41,42).

We conducted fitness testing using *FITNESSGRAM* (29) protocols for curl-ups (abdominal strength/endurance), pushups (upper body strength/endurance), and PACER (cardiorespiratory endurance) tests. We also included grip strength as a measure of total body strength. Previous research has demonstrated acceptable validity and reliability of these tests (29,37). Curl-ups were performed to a cadence on a CD (i.e., "up; down") while fingers slid forward across a 7.6 cm (4–9 year olds) or 12.7 cm (10–14 year olds) rubber strip. The recorded score was the maximum number performed or until two form breaks occurred. 90° pushups were performed to a cadence on a CD (i.e., "up; down"). The recorded score was the maximum number performed or until two form breaks occurred. The PACER test is an interval cardiorespiratory endurance test that includes running back

Table 1 Descriptive Statistics for the Normalized and Raw Scores by Age Group

	4–5 yrs (*n* = 68)		6–7 yrs (*n* = 82)		8–9 yrs (*n* = 84)		10–11 yrs (*n* = 143)		12–13 yrs (*n* = 79)	
	B = 30 G = 38		B = 54 G = 28		B = 41 G = 43		B = 70 G = 73		B = 58 G = 21	
Variables	M/*SD* Normalized Score	M/*SD* raw score	M/*SD* Normalized Score	M/*SD* raw score	M/*SD* Normalized Score	M/*SD* raw score	M/*SD* Normalized Score	M/*SD* raw score	M/*SD* Normalized Score	M/*SD* raw score
Throw (m/s)	38.17/4.12	**9.33/2.14**	44.72/5.85	**12.83/3.12**	48.20/5.46	**14.69/2.92**	53.46/7.43	**17.42/3.87**	61.36/9.70	**21.76/5.31**
Kick (m/s)	36.34/4.55	**7.99/1.87**	42.82/6.78	**10.65/2.78**	49.54/5.01	**13.41/2.06**	54.37/5.32	**15.35/2.15**	61.68/7.01	**18.34/2.90**
Jump (cm)	39.20/9.81	**74.37/21.82**	52.04/8.15	**118.41/15.58**	52.76/8.05	**123.01/18.76**	51.09/8.33	**134.56/22.87**	52.34/10.81	**146.53/31.48**
HRF	39.71/2.37	-	44.80/3.68	-	48.79/4.47	-	53.99/6.03	-	58.31/6.56	-
Grip (kg)	36.36/4.63	**9.64/2.99**	43.67/4.44	**14.36/2.87**	47.78/4.35	**17.01/2.81**	55.31/6.18	**21.88/5.43**	61.15/8.41	**25.65/5.43**
Sit-ups	40.17/1.17	**2.04/3.17**	42.99/3.11	**9.71/8.45**	47.36/6.76	**21.56/18.35**	54.06/8.97	**39.77/23.95**	60.90/8.82	**48.35/23.95**
Push-ups	41.94/4.17	**1.79/3.11**	47.27/8.85	**5.77/6.6**	50.60/8.34	**8.25/6.21**	51.66/10.45	**9.04/7.69**	55.79/10.32	**12.12/7.69**
PACER (laps)	40.37/2.47	**8.07/3.18**	45.28/5.15	**14.41/6.67**	49.42/7.86	**19.77/10.16**	54.90/9.78	**26.86/15.16**	55.01/11.73	**27.00/15.16**

Note. B = Boy, G = Girl. M = mean; *SD* = standard deviation.

and forth across a 20-m shuttle course in progressively shorter time intervals. For younger children (4–6 years), we adapted the original PACER test protocols by having research staff run individually with children or in groups of two or three children until the test ended. A recent study using 4–6 year old children (6) demonstrated high reliability for this adapted protocol ($r = .84$, $p < .001$). We examined grip strength using a children's hand grip dynamometer (Lafayette Instrument, Lafayette IN). The best score of three trials for each hand was averaged and used for data analysis (4).

Procedures

Children completed a general warm-up routine before any testing session and also 3–5 practice trials before each motor skill test. We conducted MSC testing in a school gymnasium. Children performed throwing and kicking with maximum effort to an unmarked wall from a distance of approximately nine meters. Children were instructed to throw or kick the ball as hard or as fast as they could to the wall. For the standing long jump, children stood behind a line and were instructed to jump as far as they could. Distance from the line to the back of the heel at landing closest to the line was measured in centimeters. Children received speed/distance feedback on each trial and were prompted to see if they could do better on subsequent trials.

We tested younger children (ages 4–6) individually on pushups, curl-ups, grip strength and the PACER test. We tested children ages 7–13 in groups of two or three. Instruction and modeling for all children were provided on curl-ups, pushups, grip strength and the PACER test. Children also were prompted to demonstrate correct technique, if possible, on curl-ups and pushups (one or two trials) before the actual testing. HRF tests were performed in a school gymnasium or in an all-purpose room during their normal physical education time. In general, subjects completed the HRF and MSC tests during three testing sessions. Children completed the PACER test on a separate day from all other fitness and MSC tests. It is important to note that formal testing using the *FITNESSGRAM* is not recommended until the fourth grade (29) as many younger children, specifically ages 4–6, have difficulty in performing any pushups or curl-ups. A lack of experience, strength, and/or coordination and control in younger children may influence technical completion of pushup and curl-up tests.

Statistical Analyses

A power calculation to predict HRF by the three MSC predictors with alpha set at p £ .05, and an f^2 of .28 yielded a sample size of 43 with a power estimate of .80. Thus, sample sizes for each age group had sufficient statistical power for all analyses to detect significant and meaningful differences if they existed. The data were analyzed in four steps. First, we examined the global construct of HRF using the four fitness measures (40). Initially, we calculated the mean and *SD* for each HRF and MSC test and then normalized the scores by converting them to T-scores. Pearson's bivariate correlations were then calculated to assess the relationships between MSC (throw, kick, and jump) and HRF within the subsamples. To glean the most parsimonious construct for physical fitness, we used a principal component analysis to examine the relationships among the four fitness measures (40). The principal component analysis was conducted using the SAS 9.1 system's PROC FACTOR, with the normalized scores to the four HRF measures as prior communality estimates. Only the first factor displayed eigen values greater than 1. Thus, we kept only the first component in the analysis. This component explained 99.94% of the total variance. In this study, a loading of .40 or greater was used to identifying items to factors. According to the criteria, all four HRF measures loaded on the first factor (loadings from .66, .78, .67, and .76 for grip, curl-up, pushup, and PACER, respectively). We also examined construct reliability of these measures using Cronbach's alpha (.81), which indicated that all four measures significantly added to the factor. Removing any of the measures significantly reduced Cronbach's alpha. Thus, the HRF factor was comprised of the mean of the T-scores of the four physical fitness components.

Second, a one-way analysis of covariance (ANCOVA) was conducted to examine if relationships among HRF and MSC differed across age groups. In the ANCOVA, the dependent variable was HRF and the independent variable was age group. The covariates were: age by throw, age by kick, and age by jump. If the effects of the covariates were significant, then it was meaningful to further investigate the relationship differences between HRF and each MSC by each age group. Third, a hierarchical multiple regression was performed with all children to assess the predictive utility of MSC (all three skills included) performance (independent variable) to HRF (dependent variable) after controlling the effect of age, sex and height. Finally, we implemented hierarchical regressions to assess the relative contribution of each individual motor skill (independent variable) to HRF (dependent variable) after controlling the effect of sex and height for each age group. We conducted this procedure to understand individual relationships of each skill to HRF and to determine whether those relationships changed across the five age groups. SAS Version 9.1 was used for all analyses. We set a traditional alpha level of a = .05 to determine significance.

Results

Descriptive statistics and bivariate correlations for each age group are provided in Tables 1 and 2, respectively. Descriptive data indicated that object control skills and HRF scores generally increased across age groups in both boys and girls, which is generally consistent with previous longitudinal HRF and motor skill performance data (24). Correlation analyses revealed that throwing speed was positively related to HRF for all groups except for 4–5 year-olds ($p < .01$ for all; see Table 2). Kicking speed

Table 2 Correlation Matrices for MSC and HRF by Age Group

	4–5 yrs (*n* = 68)				6–7 yrs (*n* = 82)				8–9 yrs (*n* = 84)				10–11 yrs (*n* = 143)				12–13 yrs (*n* = 79)			
Variables	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1. Throw	-				-				-				-				-			
2. Kick	.43**	-			.59**	-			.62**	-			.60**	-			.78**	-		
3. Jump	.11	.43**	-		.06	-.03	-		-.05	.08	-		.40**	.10	-		-.002	-.001	-	
4. HRF	.23	.38**	.55**	-	.39**	.37**	.02	-	.42**	.42**	.18	-	.47**	.44**	.34**	-	.65**	.59**	-.006	-

** $p < .01$.

was positively associated with HRF for all age groups ($p < .01$). Jump distance was positively correlated to HRF for 4–5 year-olds and 10–11 year-olds. In general, significant correlations between individual skill performance and HRF were low to moderate ($r = .34$–$.65$) across all age groups and correlations between throwing and kicking speed skills generally demonstrated stronger correlations ($r = .43$–$.78$) across all age groups. In contrast, correlations between jump distance and throwing and kicking speed were lower with only 2/10 correlations (across each age groups) being significant.

Results of the ANCOVA indicated there were significant effects for all the covariates including age by throw ($F(5, 425) = 6.19$, $p < .01$), age by kick ($F(5, 425) = 4.56$, $p < .01$), and age by jump ($F(5, 425) = 4.04$, $p < .01$). Therefore, further analyses were conducted to examine associations between HRF and MSC for the entire sample and across different age groups by individual skills.

In the first step of the hierarchical regression including the entire sample, age and sex were significant predictors of HRF, but height was not a significant predictor (see Table 3). When the three skills were added in the second step, throwing and jumping were significant predictors for HRF beyond the significant age effect with sex and height not being significant predictors (see Table 3). Kicking approached a significant level ($p = .08$) for prediction. Overall, this model predicted 65% of the variance in HRF. As kicking was moderately correlated to HRF in all age groups ($r = .38$–$.59$) and correlations increased across each age group, the individual hierarchical regressions for kicking across age also were conducted.

With respect to the prediction of HRF by each individual skill for each age group, throwing speed was a significant predictor for HRF for all groups except 4–5 year-olds (see Table 4) with *t* values increasing across each age group. Height emerged as the lone significant predictor for 4–5 year-olds. Sex was not a significant predictor for any age group with throwing. Explained variance in HRF by throwing speed generally increased across age groups (i.e., $r^2 = 0$–39%) except for age 8–9 and 10–11 year-olds where it was approximately equal ($r^2 = 19\%$ and 18%, respectively; see Table 4).

Kicking speed also was a significant predictor for HRF for all age groups except 4–5 year-olds, where height was the sole predictor of HRF in that age group. Similar to throwing results, *t* values increased across each age group for kicking. In addition, sex emerged as an additional significant predictor of HRF for the 12–13 year-old group. Explained variance in HRF by kicking speed generally increased across age except for age groups 8–9 and 10–11 where explained variance was approximately equal ($r^2 = 15\%$ and 14%, respectively; see Table 4). Sex contributed (along with kicking performance) to the rather dramatic increase in explained variance ($r^2 = 37\%$) in the 12–13 year old group. Thus, the trend for increasing variance explained in HRF by kicking speed across age groups was similar to throwing speed across age.

Jump distance was a significant predictor for HRF for the 4–5, 8–9, and 10–11 year-old groups although the overall explained variance was lower in the 8–9 and 10–11 age groups. Height also was a significant predictor of HRF in the 4–5 age group and approached significance ($p = .06$) in the 8–9 age group. There was sex effect in the individual model regressions for jumping in the 10–11 and 12–13 year-old age groups and sex

Table 3 Multiple Regression Analyses for three MSC to HRF for the Entire Sample

Step	Independent Variables	*F*	R^2	*T*
1		202.07**	.58	
	Age			9.54**
	Sex			6.30**
	Height			-.08
2		132.73**	.65	
	Age			4.98**
	Sex			1.18
	Height			-.31
	Throw			5.33**
	Kick			1.73 (p=.08)
	Jump			4.49**

Note. $F = F$ value for the model; R^2 values are cumulative, with each incremental step adding to the variance explained; ** $p < .01$.

Table 4 Regression Analyses for Individual MSC to HRF

MSC	Age Group	Independent Variables	*F*	*R2*	*T*
Throw	4–5 yrs		5.18	.20	
		Sex			.64
		Height			3.25**
		Throw			.63
	6–7 yrs		3.06**	.11	
		Sex			.83
		Height			–.96
		Throw			2.38*
	8–9 yrs		6.37**	.19	
		Sex			–.17
		Height			.48
		Throw			3.72**
	10–11 yrs		9.63**	.18	
		Sex			.24
		Height			–.54
		Throw			4.10**
	12–13 yrs		15.29**	.39	
		Sex			.85
		Height			–.04
		Throw			4.37**
Kick	4–5 yrs		5.28**	.21	
		Sex			.52
		Height			2.99**
		Kick			.79
	6–7 yrs		2.93**	.10	
		Sex			.81
		Height			–1.24
		Kick			2.30*
	8–9 yrs		4.55**	.15	
		Sex			.66
		Height			.10
		Kick			2.94**
	10–11 yrs		7.49**	.14	
		Sex			1.40
		Height			–1.16
		Kick			3.45**
	12–13 yrs		13.93	.37	
		Sex			2.67**
		Height			–.59
		Kick			3.99**
Jump	4–5 yrs		12.34**	.38	
		Sex			–.06
		Height			3.54**
		Jump			4.20**
	6–7 yrs		1.45	.05	
		Sex			1.84(p = .07)
		Height			.10
		Jump			1.01
	8–9 yrs		4.55**	.14	
		Sex			1.38
		Height			1.92(p = .06)
		Jump			2.85**
	10–11 yrs		7.50**	.14	
		Sex			2.20*
		Height			.90
		Jump			3.55**
	12–13 yrs		7.75**	.26	
		Sex			4.31**
		Height			1.35
		Jump			.93

Note. F = F value for the model; R^2 values are cumulative, with each incremental step adding to the variance explained;

* $p < .05$.

** $p < .01$.

approached significance in the 6–7 year-old group (p = .07). Jump distance actually demonstrated the strongest relationship to HRF in the 4–5 year-old age group (t = 4.20) along with height (t = 3.54). Explained variance in HRF by jump distance and/or height and sex was variable across age groups.

Discussion

The purpose of this cross-sectional study was to examine associations among selected measures of MSC and HRF in boys and girls, ages 4–13 years. In general, associations between object control skills and HRF increased across age. Associations between jump distance and HRF were variable across age and strongest in the 4–5 year-old group.

Overall, the object control skill data indirectly support the hypotheses posited by the Stodden et al. (39) model, which suggests associations among MSC and HRF in both boys and girls will be stronger across time. The increase in explained variance for HRF across age (see Table 4) for the object control skills suggests the development of proficiency in a variety of skills may provide multiple avenues for engaging in various physical activities and sports linked to the development of multiple components of fitness (1,39,46). The improvement in mean raw scores for object control skills and the general increased explained variance in HRF across age groups in these skills, aligned with the lack of consistency in explained variance in HRF by jump distance across ages, indirectly support Barnett et al.'s (1) conclusion that object control skills may be better indicators to explain associations between MSC and HRF across childhood and into adolescence. Having greater proficiency in object control skills in adolescence may promote continued participation in a wider variety of physical activities, sports and games that inherently demand these skills and higher levels of HRF for successful performance. Alternatively, developing advanced locomotor movement patterns, which generally develop earlier than advanced object control skills, may have a greater influence on HRF in early childhood where the practical use of context-specific object control skills is not as critical for success in various games and sports. In addition, neuromotor development (i.e., coordination and control) in childhood provides support for the impact of skill on jump distance in early childhood. That is, the development of coordination and control of multiple body segments or lack-thereof in early childhood (related to experience) for projecting the entire body may be more critical for, and a better discriminator of, global HRF development in early childhood. The application of muscular force and rate of force development promoted by increases in lean muscle mass with growth and the concomitant neural adaptations related to the development of coordination and control may play a larger role in jump distance as children age.

However, data from Stodden et al. (40) indicated throwing, kicking and jumping performance predicted 79% of the variance in a similar composite measure of health-related fitness young adults (18–25 years) with men and women demonstrating similar linear relationships. Interestingly, jump distance predicted the highest amount of unique variance in both men and women in that sample. Thus, continuing to develop and perform multiple skills (both locomotor and object control) in various activities may both directly and indirectly augment or assist in maintaining multiple components of HRF across time. Moreover, because multiple aspects of neuromuscular development are integrated within the development of both MSC and multiple aspects of HRF, these relationships may reciprocally influence each other across time (39).

When aligning the individual regression model results with the mean raw score performance increases across age group, data indicated that performance increases in object control MSC and HRF were similar in boys and girls in the early and middle childhood groups. Sex significantly influenced HRF in the individual regression models for jumping in the 10–11 and 12–13 age groups and for kicking in the 12–13 age group (see Table 3). The transition from middle to late childhood and adolescence is an important time where children's biological age may impact both HRF and skill development (26,40,48). When including the entire sample, further examination of mean raw skill jump data by sex across age groups (data not shown) demonstrated that girls did not consistently increase their raw jump distance across age groups, as compared with the more consistent improvement by boys across age groups. Girls jump performance was quite similar between the 6–7 and 8–9 year-old groups and also between the 10–11 and 12–13 year-old groups. The difference in mean jump performance increases by sex across age may have influenced the differences in explained variance of HRF by jump distance across age groups. While not significant across all age groups, sex generally demonstrated stronger associations to HRF in the individual regression models for jumping for most age groups (see t-scores in Table 4) as compared with the object control skill regression models.

It is also important to note that perceived competence may play a role in the associations between MSC and HRF, specifically for object control skills. Highly developed MSC may promote continued participation in various types of activities via increased perceived competence throughout adolescence and into adulthood. Perceived competence has been shown to mediate the associations between object control skill and cardiorespiratory endurance and PA from childhood into adolescence (1,2). As the development, or lack of development, of MSC promotes enhanced or decreased perceived competence, it is another indirect pathway that may assist in promoting either positive or negative reciprocal spirals of engagement in physical activity and concomitant HRF levels (1,2,16,17,23,39).

The increasing strength of association between object control skills and HRF across age groups and the increased influence of sex as children approach adolescence mirrors both MSC and HRF longitudinal normative data. As sex differences in HRF and physical activity (i.e., boys higher than girls) generally increase over time, specifically during adolescence, MSC may be a missing link to understand why these trends occur as MSC performance aligns with these trends. As such, the object control skill data from this study indirectly support the developmental trajectory hypotheses of Stodden et al. (39) proposing that the strength of association between MSC and HRF will increase across time. The jumping data do not support the hypotheses.

While it is clear that relationships among MSC and HRF are complex and that multiple factors impact overall physical development during childhood and adolescence, these data indicate that associations between MSC and HRF are dynamic across age. And, these associations may be dependent on the type of skill performed. More importantly, similarities in direct and indirect mechanisms underlying the development of MSC and HRF from a neuromuscular and neuromotor control development standpoint indicate unidirectional causal pathways may not be the most prudent explanation for the development of these two separate, yet integrated constructs (12,28,33,39,40,47). As improvement in MSC or HRF may reciprocally influence each other during childhood and adolescence (28,39,47), promoting the development of both MSC and fitness would seem to be mutually beneficial. Based on the results from these data, promoting locomotor skill early in childhood may be more beneficial for promoting global HRF during early and middle childhood, while the development of object control skills in early childhood may be more beneficial to help promote and/or maintain HRF during later childhood and into adolescence. As early and middle childhood are critical periods for promoting the acquisition of MSC and the development of perceived competence, a concerted focus on the development of both types of skills as well as aspects of HRF should be promoted.

Several methodological limitations of this study should be noted. The cross-sectional nature of the sample for this study cannot justify causation. Statements alluding to the effects of MSC on HRF remain speculative. Long-term longitudinal experimental designs with a strong focus on MSC or HRF development are needed to understand the effect of developing MSC on HRF and HRF on MSC, as there is a paucity of experimental data on this topic (28). We did not assess sexual maturity or skeletal maturity in this sample and biological maturation effects likely would provide additional insight on the dynamic relationships among measures of MSC and HRF, specifically during the transition from childhood to adolescence (25,47). In addition, we did not control for the effect of body mass on the associations between MSC and HRF for three reasons. First, we did not assess % body fat in these samples and the influence of increased body fat as children age may have directly impeded children's ability to perform the standing long jump, pushup, curl-up, and the PACER tests as these field tests require the manipulation of total or a majority of body mass (10,11,47). This may have been more important for the last two age groups (ages 10–13 years) as many children may have been transitioning into adolescence. Second, lean mass has two important characteristics that relate to the idea of force/torque production (i.e., strength), specifically for developing children. While lean mass is a good predictor of strength potential, the contribution of the development of inter- and intramuscular coordination (i.e., motor unit recruitment, motor unit firing rate, optimal coactivation of agonist & antagonist muscles, and synergistic muscle contractions of similarly functioning muscle groups) to force/torque output (i.e., strength) is not well understood (12,33). Thus, integrated within the concept of increased lean mass with growth is improved coordination and control (i.e., neural attributes) promoted by practice and experiences that are related to both the HRF and MSC movements tested in this study. Third, since we used a composite fitness variable as the dependent variable that included cardiorespiratory endurance, and muscle endurance assessments, it is difficult to estimate the influence of overall mass on this global factor as evidence on the relative contribution of muscle mass on muscular endurance and cardiorespiratory endurance is limited (19). Lastly, while data in this study included only three fundamental motor skills, they do represent the larger class of fundamental locomotor and object control skills. The outcome measures examined in this study align with process-oriented (i.e., qualitative coordination) assessments associated with skill development (14,18,27,35,41,42).

This study is unique in that it is the first to demonstrate that the strength of associations among object control skill performance and a composite HRF index, which included measures of muscular strength, muscular endurance, and cardiorespiratory endurance, increase across age in both boys and girls. These data and other related research indicate the development of higher levels of object control skill are associated with higher levels of HRF in childhood (16,28), adolescence (2,15,31,47) and into young adulthood (40). As such, the potential significance of promoting the development of object control skill as well as HRF across childhood may take on greater significance from a health promotion perspective across the lifespan.

Acknowledgments

This work was funded by the National Institutes of Health grant1R21HD055621-01A2 and the National Association for Sport and Physical Education Research Grant Program.

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