JYU DISSERTATIONS 832

Maria Kasanen

Aspects of Early Childhood Fundamental Movement Skills in Longitudinal Pathways to Physical Activity and Health-Related Fitness

UNIVERSITY OF JYVÄSKYLÄ
FACULTY OF SPORT AND HEALTH SCIENCES

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ABSTRACT

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This dissertation investigates the longitudinal relationships from early childhood fundamental movement skills (FMS) to various outcomes, including accelerometer-based time spent in different physical activity (PA) intensities, body mass index (BMI), cardiorespiratory fitness (CRF), and muscular fitness (MF). The FMS are categorized into locomotor skills (LMS) and object control skills (OCS) and are assessed using the process-oriented Test of Gross Motor Development third edition (TGMD-3) and the product-oriented Körperkoordinationstest Für Kinder (KTK). The study focuses on children aged 3-8 years living in Finland, with a follow-up period ranging from 3 to 6 years.

The results of this dissertation are based on the findings of three sub-studies. Analyses were conducted using two-level regression analysis, along with its extensions including the cross-lagged model and the Cholesky decomposition approach. The findings indicate that higher process-oriented LMS scores, not OCS scores, significantly predict greater engagement in moderate-to-vigorous PA and less sedentary behavior over time. Furthermore, process-oriented LMS were found to be more prominent predictors of later CRF and MF than OCS, while product-oriented LMS overshadowed the predictive power for these fitness components. Additionally, no significant longitudinal relationship was found between BMI and process-oriented FMS or their skill domains.

These comprehensive analysis reveals that the longitudinal relationships from FMS to PA intensities and investigated health outcomes are not straightforward. The findings suggest that LMS may be a more prominent predictor than OCS, and that the physical capacity characteristics included in the product-oriented LMS may overshadow the effects of process-oriented methods. However, the overall contribution of FMS may remain relatively minor when most of the variance in outcomes remains unexplained.

Keywords: motor skills, physical activity, fitness, body mass index, children, longitudinal research

TIIVISTELMÄ (ABSTRACT IN FINNISH)

Kasanen, Maria
Varhaislapsuuden motoriset taidot, niiden osa-alueet ja erilaiset mittausmenetelmät myöhemmin lapsuudessa mitatun fyysisen aktiivisuuden ja terveyskunnon taustalla
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Tämän kolmesta osatutkimuksesta koostuvan väitöskirjan tavoitteena oli tutkia varhaislapsuuden motoristen taitojen pitkittäisyhteyttä kestävyys- ja lihaskuntoon, painoindeksiin ja kiihtyvyysmittarilla mitattuun ja intensiteeteittäin tarkasteltuun fyysiseen aktiivisuuteen. Motoriset taidot jaettiin liikkumis- ja välineenkäsittelytaitoihin, ja mitattiin suorituksen laatuun (TGMD-3) ja määrälliseen lopputulokseen (KTK) perustuvilla testeillä. Alkumittauksiin osallistui 3–8-vuotiaita Suomessa varhaiskasvatukseen osallistuvia lapsia. Tutkimuksen seuranta-aika vaihteli kolmesta kuuteen vuoteen osatutkimuksittain.

Tilastollisena menetelmänä käytettiin kaksitasoista regressioanalyysiä ja sen laajennuksia. Painoindeksin ja liikkeen laatuun perustuvien motoristen taitojen välillä ei havaittu pitkittäisyhteyttä. Sen sijaan suorituksen laatuun perustuvat liikkumistaidot ennustivat välineenkäsittelytaitoja paremmin kohtalaista ja rasittavaa fyysistä aktiivisuutta ja paikallaanoloa sekä kestävyys- ja lihaskuntoa myöhemmin lapsuudessa. Kuitenkin suorituksen määrälliseen lopputulokseen perustuvat liikkumistaidot ennustivat kestävyys- ja lihaskuntoa paremmin kuin suorituksen laatuun perustuvat liikkumistaidot.

Tämän tutkimuksen tulokset tukevat aikaisempia havaintoja siitä, että pitkittäissuhteet varhaislapsuuden motorisista taidoista tässä tutkimuksessa käytettyihin lopputulosmuuttujiin eivät ole yksiselitteisiä. Varhaislapsuuden liikkumistaidot saattavat olla välineenkäsittelytaitoja merkittävämpi fyysisen aktiivisuuden ja kunto-ominaisuuksien ennustaja. Erityisesti suorituksen määrälliseen lopputulokseen perustuvien liikkumistaitojen fyysistä kuntoa kuvaava osuus voi selittää sen suorituksen laatuun perustuvia liikkumistaitoja merkittävämmän pitkittäisvaikutuksen kestävyys- ja lihaskuntoon. Motoristen taitojen ennustusvaikutus tutkittuihin lopputulosmuuttujiin saattaa kuitenkin kokonaisuutena olla suhteellisen vähäinen, sillä suurin osa lopputulosmuuttujien vaihtelusta jää tarkastelluissa malleissa selittämättä.

Asiasanat: motoriset taidot, fyysinen aktiivisuus, kunto, painoindeksi, lapset, pitkittäistutkimus

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My dissertation began with a life change: a move to the north and a change in my work situation. Change always brings something good and interesting. Completing this dissertation has been a challenging yet deeply rewarding journey, and I have many people to thank for their invaluable support and guidance.

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Maria Kasanen

ORIGINAL PUBLICATIONS AND AUTHOR CONTRIBUTION

This dissertation is based on the following three original peer-reviewed scientific publications of the sub-studies, referred to in the text by their Roman numerals.

I. Kasanen, M., Laukkanen, A., Niemistö, D., Kotkajuuri, J., Luukkainen, N., & Sääkslahti, A. (2023). Do fundamental movement skill domains in early childhood predict engagement in physical activity of varied intensities later at school age? A 3-year longitudinal study. *Journal of Motor Learning and Development*, *11*(3), 424–443. https://doi.org/10.1123/jmld.2023-0004

II. Kasanen, M., Laukkanen, A., Niemistö, D., Tolvanen, A., Ortega, F., & Sääkslahti, A. (2024). Bidirectional relationship over time between body mass index and fundamental movement skill domains measured by a process-oriented method in childhood: A 3-Year longitudinal study. *Journal of Motor Learning and Development, 12*(2), 347–365. https://doi.org/10.1123/jmld.2023-0044

III. Kasanen, M., Sääkslahti, A., Niemistö, D., Tolvanen, A., Luukkainen, N. M., Meklin, E., & Laukkanen, A. (2024). Process- and product-oriented fundamental movement skills in early childhood as predictors of later health-related fitness. *Medicine & Science in Sports & Exercise, 56*(9), 1722–1731. https://doi.org/10.1249/MSS.0000000000003458

Maria Kasanen was responsible for planning the dissertation and drafting the articles. As the first author of the original publications, she formulated the study questions and designs, prepared the data collected by the research group for statistical analysis, conducted the analysis with assistance from a statistician, and incorporated feedback and guidance from her co-authors throughout the research process and in the final decision-making. She also took primary responsibility for writing the manuscripts.

FIGURES

TABLES

ABBREVIATIONS

BMI	body mass index
CI	confidence interval
CRF	cardiorespiratory fitness
CRF_{adj}	cardiorespiratory fitness adjusted for age and maturation
CrI	credibility interval
FMS	fundamental movement skills
FMS_{adj}	FMS adjusted by age
HRF	health-related fitness
ICC	intraclass correlation
KTK	Körperkoordinationstest für Kinder
LMS	locomotor skills
LMS_{adj}	locomotor skills adjusted for age
LPA	light physical activity
LVPA	light-to-vigorous physical activity
MAD	mean amplitude deviation
MCAR	missing completely at random
MF	muscular fitness
MF_{adj}	muscular fitness adjusted for age and maturation
MPA	moderate physical activity
MVPA	moderate-to-vigorous physical activity
OCS	object control skills
OCS_{adj}	object control skills adjusted for age
PA	physical activity
PHV	peak height velocity
PPP	posterior predictive probability
PSR	potential scale reduction
R^2	coefficient of determination
SB	sedentary behavior
SD	standard deviation
SDS	standard deviation score
SEE	standard error of estimate
TENK	The Finnish National Board on Research Integrity
TGMD-2	Test of Gross Motor Development-second edition
TGMD-3	Test of Gross Motor Development-third edition
VPA	vigorous physical activity
WHO	World Health Organization

CONTENTS

1 INTRODUCTION

Global concern regarding children's insufficient levels of physical activity (PA) continues to rise (Farooq et al., 2020; Guthold et al., 2018; Lounassalo et al., 2019), and the amount of sedentary behavior (SB) increases with age during childhood (Kontostoli et al., 2021). Recent decades have also seen a decline in health-related fitness (HRF) components (Caspersen et al., 1985), such as cardiorespiratory fitness (CRF) (Fühner et al., 2021; Masanovic et al., 2020) and muscular fitness (MF) (Masanovic et al., 2020), among children and adolescents across various countries, including Finland. Additionally, deteriorating body composition has contributed to the increasing prevalence of childhood overweight and obesity, which is a major global concern (NCD Risk Factor Collaboration, 2017).

A sufficient amount of PA (Pate et al., 2019; World Health Organization [WHO], 2019, 2020), a low degree of SB (Park et al., 2020), sufficient levels of CRF (Hauser et al., 2023; Lang et al., 2018, 2024; Mintjens et al., 2018; Ortega et al., 2008) and MF (García-Hermoso et al., 2018; Ortega et al., 2008; Smith et al., 2014), and a healthy body composition (Bhaskaran et al., 2018; Rokoff et al., 2019; Shaban Mohamed et al., 2022) have been linked to various positive health outcomes, such as improved cardiovascular and bone health, enhanced psychosocial well-being from childhood to adulthood, and a lower risk of mortality. The benefits of PA (Wang et al., 2024; Zhao et al., 2024), CRF (Zhan et al., 2020), and MF (Zeng et al., 2023) have also been found for executive functions. Conversely, overweight and obesity may negatively affect executive functions, leading to impairments in cognitive processes such as working memory, attention, and inhibitory control (Reinert et al., 2013; Yang et al., 2018). Inadequate levels of PA, SB, CRF, MF, and an unhealthy body composition affect health and well-being negatively, and the costs associated with physical inactivity (Kari et al., 2023; Kolu et al., 2018), low CRF (Chaput et al., 2023a) and MF (Chaput et al., 2023b), overweight, and obesity (Mahase, 2023) are significant. Considering these connections, it can be stated that the benefits of a sufficient amount of PA, a low degree of SB, sufficient levels of CRF and MF, and healthy body composition are extensive and manifold. Therefore, understanding the mechanisms behind these outcomes is crucial.

Theoretical models and frameworks suggest that a higher fundamental movement skills (FMS) level could be an underlying variable of positive PA behavior, higher CRF and MF, and a healthy body composition (Robinson et al., 2015; Stodden et al., 2008). This makes FMS, defined as the neural, muscular, mechanical, and perceptual mechanisms underlying gross motor movement (Goodway et al., 2019), a particularly interesting research subject.

However, theoretical models and frameworks (Robinson et al., 2015; Stodden et al., 2008) are mainly based on the results of cross-sectional studies. This dissertation primarily focuses on the longitudinal relationships from early childhood FMS to PA behavior, including SB, and HRF components, such as CRF and MF, while also investigating the bidirectional longitudinal relationship with body composition beginning in early childhood, defined as children under the age of 8 years (UNICEF, 2022). The limited amount of research on longitudinal relationships, especially beginning with early childhood FMS (Barnett et al., 2021; Jones et al., 2020; Xin et al., 2020), underscores the importance of further investigation. Additionally, early childhood is a crucial period for the development of FMS (Brian et al., 2020; Goodway et al., 2019).

Early childhood is also seen as a significant period that influences children’s health behaviors (Goldfield et al., 2012). Previous studies have evidenced that PA behavior, including SB (Biddle et al., 2010; Malina, 1996, 2001; Schmutz et al., 2020), and CRF and MF levels (García-Hermoso et al., 2022; Kolunsarka et al., 2022) in childhood can be predictive of health behaviors later in life. A strong longitudinal relationship has also been found between obesity in childhood and adulthood, which begins in early childhood (Rooney et al., 2011). Investigating FMS in early childhood as an underlying variable in these outcomes may provide a way to promote positive health behaviors from an early age.

However, because of different aspects of FMS, longitudinal relationships from early childhood FMS to PA behavior, CRF, MF, and body composition may not be straightforward. FMS can be measured and categorized in various ways, which may affect the longitudinal relationships from FMS to outcomes. Using accurate categories of FMS skill domains, such as locomotor skills (LMS), which involve moving the body from one place to another, and object control skills (OCS), which involve imparting or receiving force on an object during movement (Barnett et al., 2021; Barnett, Lai, et al., 2016; Goodway et al., 2019), can provide a clearer understanding of the longitudinal relationships from FMS to PA behavior, CRF, MF, and body composition. Additionally, employing different measurement methods, such as process-oriented methods focused on movement quality and product-oriented methods based on movement outcomes (Barnett et al., 2021; Palmer et al., 2021; Ré et al., 2018), can enhance this understanding. Furthermore, considering different PA intensities, including SB (Barnett, Lai, et al., 2016; Barnett, Salmon, et al., 2016; Xin et al., 2020), along with HRF components, such as CRF, MF, and body composition (Barnett et al., 2021), may provide a more detailed understanding of the relationship, starting from early childhood FMS and refining previous theoretical models and frameworks.

The aim of this dissertation was to investigate the longitudinal relationship from total FMS and its skill domains, assessed using process- or product-oriented methods in early childhood, to subsequent engagement in various PA intensities, encompassing SB, and HRF components that include CRF, MF, and body composition, in later childhood. The theoretical foundation of this dissertation builds on previous evidence exploring the longitudinal relationship from early childhood FMS to PA and the HRF components focused on CRF, MF, and body composition in later childhood. The findings of this dissertation are derived from three sub-studies: (I) the longitudinal relationship from process-oriented FMS or skill domains to PA intensity, including SB; (II) the bidirectional relationship between BMI and process-oriented FMS or skill domains; and (III) the longitudinal pathways from process- and product-oriented FMS to CRF and MF. This dissertation offers a new perspective on early childhood FMS, highlighting its aspects within skill domains and process- and product-oriented approaches as underlying variables in children's PA behavior, CRF, MF and body composition in later childhood. The final discussion integrates the results of this dissertation with previous research on skill domains, and process- and product-oriented measurements of FMS.

2 THEORETICAL BACKGROUND

The theoretical background of this dissertation encompasses several key concepts, including FMS and their various aspects, such as skill domains and process- and product-oriented measures, PA behavior and its intensities, and components of HRF, such as CRF, MF, and body composition. Following this, information is presented on the theoretical frameworks, as well as current evidence of the longitudinal relationships from early childhood FMS to PA, CRF, and MF, and the longitudinal bidirectional relationship between early childhood FMS and weight status. The theoretical background concludes with a summary of and rationale for the dissertation.

2.1 Aspects of early childhood fundamental movement skills

When assessing children's movement abilities, various terms are used. Robinson et al. (2015) utilize the concept of motor competence, which encompasses terms such as motor proficiency, motor performance, motor ability, and motor coordination, as well as fundamental movement or motor skills. Hulteen et al. (2018) also refer to these as foundational skills. Although these terms often overlap, they may emphasize slightly different aspects. For instance, motor skills and movement skills are often used interchangeably, but motor skills assessment tends to focus on measuring the neural, muscular, biomechanical, and perceptual mechanisms underlying movement, while movement skill assessment focuses on the observable skill itself (Goodway et al., 2019).

In this dissertation, the term fundamental movement skills, as well as its abbreviation FMS, is used to denote skills that incorporate the visible aspects of movement's underlying mechanisms (neural, muscular, biomechanical, and perceptual) that can be observed outside a laboratory setting (Goodway et al., 2019). Assessment involves evaluating movement quality and outcomes. This dissertation focuses specifically on early childhood gross motor skills, which involve the large muscles of the body, arms, and legs, rather than fine motor skills, which require precise movements produced by small muscles in the hands and wrists (Goodway et al., 2019). This theoretical background draws on the previous literature and studies that align with this definition, regardless of the terminology used.

Particular attention is given to the development phase of FMS (Figure 1), which typically occurs between the ages of 2 and 7 years, following the reflexive and rudimentary phases, according to the hourglass model of motor development (Goodway et al., 2019). Motor development is broadly defined as a lifelong change in an individual’s level of functioning over time due to human biology, maturation, task demands, and learning environment characteristics, with their contributions being inseparable (Goodway et al., 2019). The age-appropriate placement of the FMS development phase and the correlation between FMS proficiency and age (Barnett, Lai, et al., 2016) show that FMS development is age-related (Goodway et al., 2019). Furthermore, despite lifelong changes, FMS may remain relatively stable and consistent with age during childhood compared to peers (Chen et al., 2023; Kolunsarka et al., 2022; Schmutz et al., 2020). The developmental phase (Goodway et al., 2019) and tracking of FMS (Chen et al., 2023; Kolunsarka et al., 2022; Schmutz et al., 2020) underscore the importance of studying longitudinal relationships from early childhood.

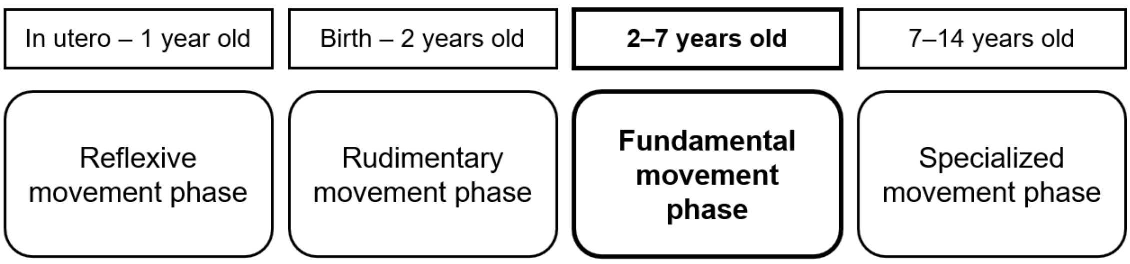


FIGURE 1 Phases of motor development and their timing in childhood according to Goodway et al. (2019). This dissertation focuses on the fundamental movement phase of motor development in children aged 2–7 years.

FMS may be examined through different skill domains (Figure 2). Usually, FMS include the skill domains of stability, LMS, and OCS, as described by Goodway et al. (2019). Stability refers to any movement emphasizing balance against gravity and is a prerequisite for all movements. Examples of stability skills include sitting, standing, bending, and twisting. LMS enable movement of the body relative to a fixed point, transitioning from one location to another, such as walking, running, and jumping. OCS, also called manipulative skills, involve imparting force on an object, as in projection skills (e.g., throwing), or receiving force from an object, as in receiving skills (e.g., catching). This division is not strictly limited; stability is a prerequisite for LMS and OCS, and OCS also require LMS (Goodway et al., 2019). This suggests that LMS might be more advanced than OCS in early childhood since OCS rely on LMS and develop later. This dissertation focuses on LMS and OCS within the FMS skill domains. Analyzing these skill domains separately can provide a more comprehensive understanding of how FMS and their skill domains relate longitudinally to other variables (Barnett et al., 2021; Barnett, Lai, et al., 2016; Goodway et al., 2019).

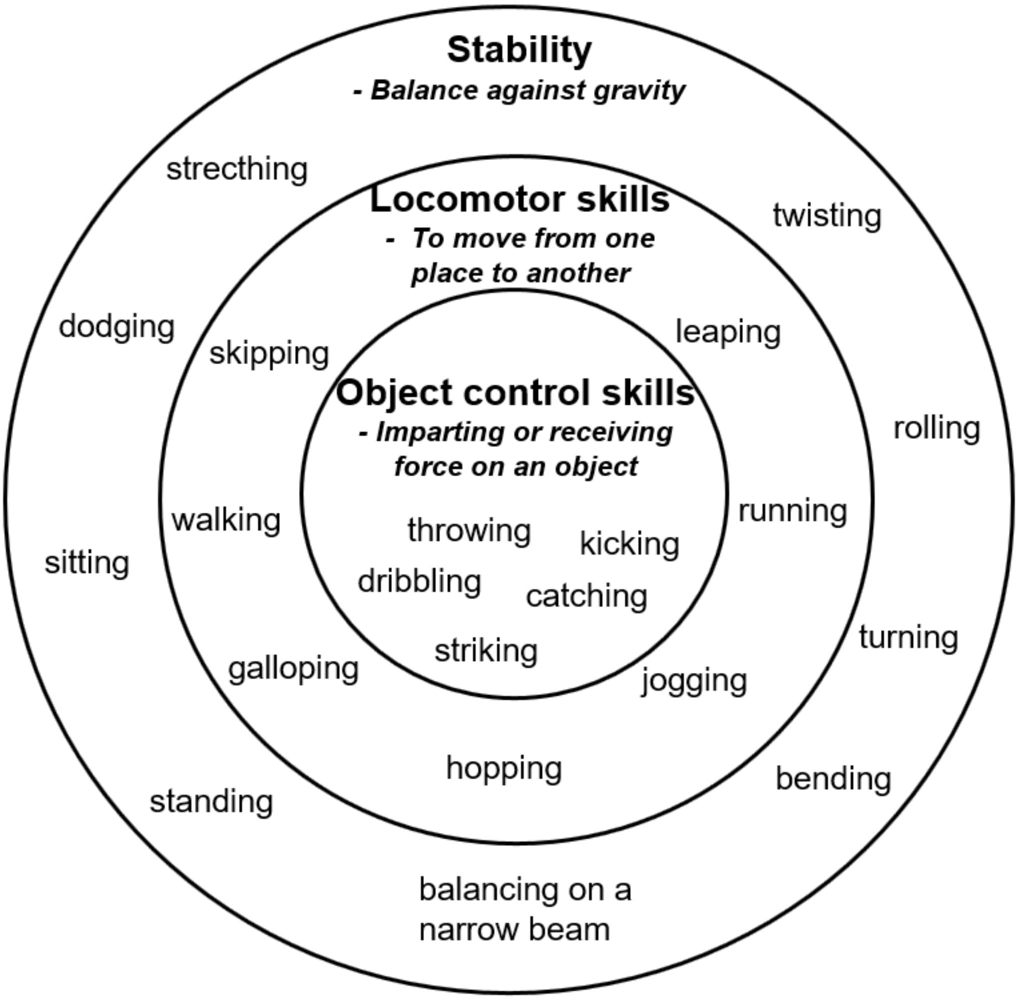


FIGURE 2 Skill domains of fundamental movement skills with examples of movements (Goodway et al., 2019). The nesting of the skill domains describes their dependence on each other; all movements require stability, and object control skills require locomotor skills.

Beyond skill domains, FMS can be assessed through process- and product-oriented methods, each examining different aspects of FMS (Palmer et al., 2021; Ré et al., 2018), although measurements may include the same skills. Process-oriented assessments focus on the qualitative aspects of movement, such as patterns and techniques, while product-oriented assessments emphasize quantitative results, such as speed, distance, height, or the number of repetitions (Williams & Monsma, 2006). Both measurement types are recommended for comprehensively determining FMS levels (Logan et al., 2017; Ré et al., 2018), but they are not interchangeable (Palmer et al., 2021), with generally low to moderate correlations between them (Logan et al., 2017; Ré et al., 2018).

These different approaches (i.e., process- and product-oriented methods) also require different attributes. A product-oriented measure that emphasizes the outcome of performance may demand more physical fitness attributes than a process-oriented measure based on the quality of movement, and the differences between these methods (Logan et al., 2017; Palmer et al., 2021; Ré et al., 2018; Williams & Monsma, 2006) could significantly impact their longitudinal relationships. The resemblance of product-oriented FMS measures to CRF and MF (Cattuzzo et al., 2016; Utesch et al., 2019) may further influence these relationships. For example, the Test of Gross Motor Development-third edition (TGMD-3) is a process-oriented test, while the Körperkoordinationstest für Kinder (KTK) is an example of a product-oriented test. The TGMD-3 and KTK are used in this dissertation and are presented in detail in the Section 4.3.5.

2.2 Accelerometer based physical activity and sedentary behavior

PA refers to any movement of the body generated by skeletal muscles that leads to energy expenditure (Caspersen et al., 1985). While moderate-to-vigorous physical activity (MVPA) is recommended to promote children's health and well-being, lower levels of activity, such as light physical activity (LPA), are also beneficial (World Health Organization, 2019, 2020). Additionally, physically active children do not necessarily demonstrate reduced SB (Pearson et al., 2014), which is described as any waking activity with low energy expenditure ($\leqslant$ 1.5 METs), typically performed while sitting, reclining, or lying down (Sedentary Behaviour Research Network, 2012; Tremblay et al., 2017).

Given the health benefits of different PA intensities (Pate et al., 2019; WHO, 2019, 2020) and the drawbacks of SB (Park et al., 2020), this dissertation focuses on accelerometer-based measurements of PA intensities, including SB, for a more nuanced understanding of the longitudinal pathways from FMS to PA and SB (Barnett, Lai, et al., 2016; Barnett, Salmon, et al., 2016; Xin et al., 2020). Accelerometer-based PA intensities can be categorized into SB, LPA, moderate physical activity (MPA), and vigorous physical activity (VPA), and their combinations, such as MVPA and light-to-vigorous PA (LVPA) (Aittasalo et al., 2015). By examining the intensities of PA, it is possible to identify high-intensity movements more precisely, which may provide clearer insight into the connection, particularly between high-intensity PA and FMS (Laukkanen et al., 2014). However, this approach also emphasizes the importance of even low-intensity activities and the need to consider the negative impact of excessive SB.

2.3 The components of health-related fitness - Cardiorespiratory fitness, muscular fitness, and body composition

HRF, as a subset of physical fitness (Figure 3), includes components such as cardiorespiratory endurance, muscular endurance, muscular strength, body composition (e.g., overweight and obesity), and flexibility (Caspersen et al., 1985).

Some of these components may be referred to using slightly different terms, which are synonyms. In this dissertation, the focus within the HRF components is on cardiorespiratory endurance, which is referred to as cardiorespiratory fitness (CRF), and muscular endurance, which is referred to as muscular fitness (MF). Additionally, body composition, as measured by BMI, is considered.

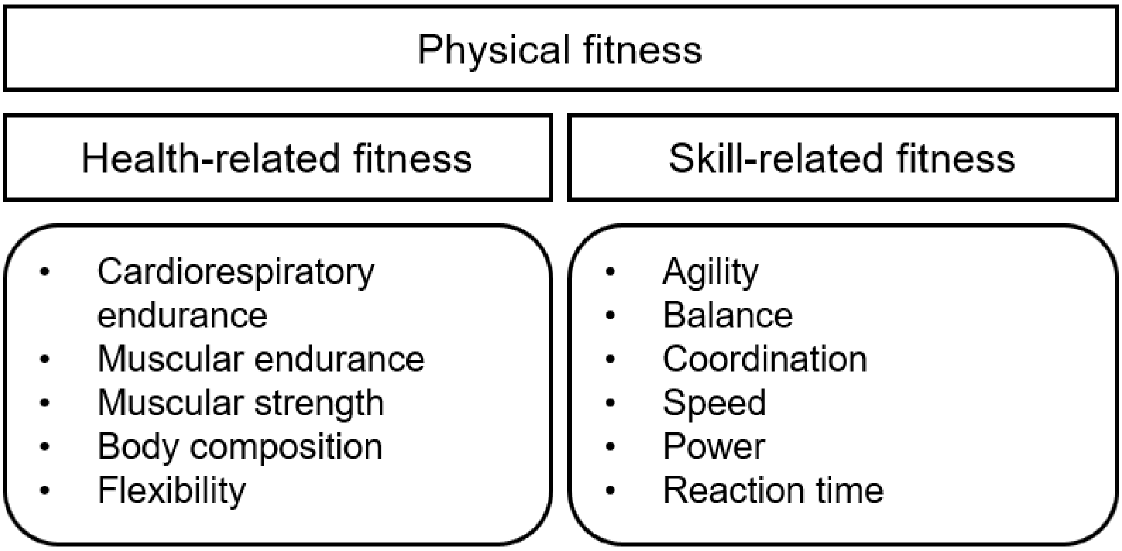


FIGURE 3 Physical fitness components divided into health-related fitness components and skill-related fitness components, as determined by Caspersen et al. (1985).

CRF, MF, and body composition represent different aspects of HRF. Considering these components separately helps to clarify the longitudinal relationship from FMS to HRF, as each component represents unique physical attributes and contributes differently to overall HRF. CRF is defined as the ability of the circulatory and respiratory systems to supply fuel and oxygen to muscles during prolonged PA and to aid recovery by removing the by-products of fatigue. MF, on the other hand, refers to the ability of various muscle groups to exert force, either through repeated actions or sustained effort (Caspersen et al., 1985). Meanwhile, body composition is defined as the relative amounts of muscle, fat, bone, and other vital body parts (Caspersen et al., 1985). BMI is widely used to determine weight status and body composition (Martin-Calvo et al., 2016), such as overweight and obesity in children, which are characterized by abnormal or excessive fat that can negatively affect health (WHO, 2024). BMI is a good technique for defining body composition, although it does not directly measure the amounts of specific body components (Martin-Calvo et al., 2016).

2.4 Early childhood fundamental movement skills as an underlying variable of physical activity and health-related fitness

Many previous frameworks have described the relationships between FMS and PA (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Stodden et al., 2008) and between FMS and HRF (Robinson et al., 2015; Stodden et al., 2008). Robinson et al. (2015) placed FMS at the center of their theoretical framework. This dissertation focuses on the part of the framework (Robinson et al., 2015) that contains the relationships between FMS and the outcomes of this dissertation (Figure 4).

Robinson et al. (2015) described positive relationships between motor competence—defined as a global term for goal-directed human movement—and PA and HRF such as CRF and MF. In addition, the framework describes, separately from HRF, an inverse relationship between motor competence and weight status. The relationships between FMS and PA behavior, CRF, MF, and body composition may be reciprocal and strengthen during childhood (Robinson et al., 2015; Stodden et al., 2008). It has also been suggested that a low level of FMS may form a proficiency barrier that leads to lower levels of PA (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Seefeldt, 1980; Stodden et al., 2008), CRF, MF, as well as an unhealthy weight status (Robinson et al., 2015; Stodden et al., 2008). Conversely, developing a higher FMS level may promote continued and longer engagement in various PA due to a wider skill set and positive neuromotor development leading to the promotion of CRF, MF, and a healthy body composition (Robinson et al., 2015; Stodden et al., 2008).

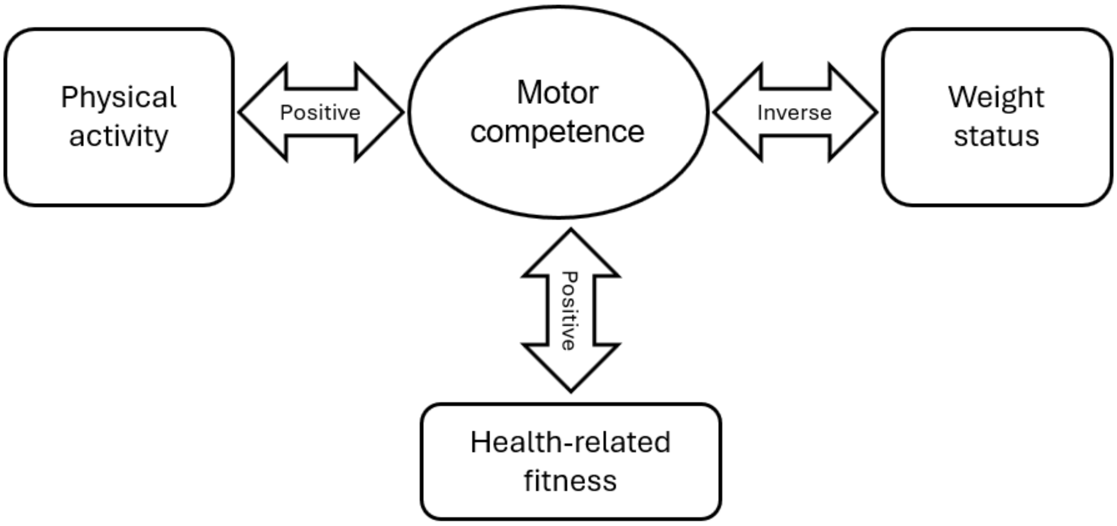


FIGURE 4 Relationships between motor competence and physical activity, health-related fitness, and weight status, following Robinson et al.'s (2015) framework.

FMS, which typically develop in early childhood (Goodway et al., 2019), have been described as the alphabet of PA (Stodden et al., 2008). These skills, along with PA behavior, are effectively promoted during early childhood, a period that can shape children's future PA levels (Goldfield et al., 2012). According to various models and frameworks (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Stodden et al., 2008), higher levels of FMS may encourage engagement in various physical activities because children possess the necessary skills to choose more physically active behaviors. Conversely, if children's FMS are underdeveloped, PA engagement may be low due to a lack of success, confidence, and enjoyment in participating in activities. In addition, children's opportunities for PA, play, and games, are limited due to the absence of these foundational skills (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Stodden et al., 2008).

Alongside PA, Robinson et al.'s (2015) theoretical framework suggests that FMS play a foundational role in HRF components such as CRF, MF, and body composition. Improving FMS can lead to better CRF and MF while preventing obesity and overweight through increased PA and neuromotor development. Moreover, there may be a dynamic and reciprocal inverse relationship between FMS and body composition, including overweight and obesity in children. Higher FMS levels may help prevent overweight and obesity through PA, while a higher body weight can lead to a decline in proficiency in FMS, particularly in activities that require managing overall body mass.

Previous reviews have supported longitudinal relationships from FMS to PA (Barnett et al., 2021; Jones et al., 2020; Xin et al., 2020), as well as from FMS to CRF or MF (Barnett et al., 2021; Cattuzzo et al., 2016; Utesch et al., 2019). Additionally, a systematic review (Barnett et al., 2021) demonstrated a bidirectional longitudinal relationship between a child's weight status and their level of FMS. However, the evidence of longitudinal relationships from FMS to various outcome variables remains limited and inconsistent (Barnett et al., 2021; Cattuzzo et al., 2016; Jones et al., 2020; Utesch et al., 2019; Xin et al., 2020) and a relatively small amount of longitudinal research begins in early childhood. This dissertation explores therefore previous research findings on the longitudinal relationships from FMS to outcome variables, specifically in light of the results from studies beginning in early childhood.

Longitudinal relationships have been further examined from the perspectives of LMS, OCS, and the process- and product-oriented approaches of FMS. This division is necessary due to the requirements and developmental orders of the skill domains (Goodway et al., 2019) and the noninterchangeable nature of process- and product-oriented FMS approaches (Palmer et al., 2021), although the use of both approaches has been suggested (Logan et al., 2017; Ré et al., 2018). Building on this foundation, the longitudinal relationships from early childhood FMS to later childhood PA, CRF, and MF can be examined in greater detail, including the bidirectional relationship with weight status.

2.4.1 Locomotor and object control skills as predictors of physical activity intensities and health-related fitness

As mentioned, examining LMS and OCS separately may provide a more nuanced understanding of the longitudinal relationship between early childhood FMS and other variables (Barnett et al., 2021; Barnett, Lai, et al., 2016). Despite some conflicting research results (Liu et al., 2023), LMS may be a more prominent predictor of PA intensities and HRF compared to OCS in early childhood, regardless of the skill domain measurement methods used (Chen et al., 2023; Duncan et al., 2021; Gu, 2016). This may be because LMS develop earlier in childhood, while OCS require LMS and thus develop later (Goodway et al., 2019). Additionally, it may also be due to the similar characteristics shared by LMS and PA (Pearson et al., 2014).

LMS characteristics, involving body movement relative to a fixed point on a surface and against gravity (Goodway et al., 2019), are often present in PA (Pearson et al., 2014). This may explain the significant relationship between LMS and PA intensities (Duncan et al., 2021; Gu, 2016; Lima, Pfeiffer, Larsen, et al., 2017), particularly VPA (Gu, 2016; Lima, Pfeiffer, Larsen, et al., 2017) and MVPA (Duncan et al., 2021; Gu, 2016). Some evidence also shows a longitudinal relationship from early childhood LMS to LPA (Duncan et al., 2021; Gu, 2016) and, inversely, SB (Duncan et al., 2021). Conversely, an inverse relationship has been found between LMS and LPA (Gu, 2016), and some studies have not found statistically significant longitudinal relationships from early childhood LMS to accelerometer-based PA intensities (Foulkes et al., 2021; Melby et al., 2021; Nilsen et al., 2020).

The movements against gravity inherent in LMS may also contribute to the evidence of a significant inverse longitudinal relationship between LMS and body composition (Barnett et al., 2021; Okely et al., 2004), as well as the evidence of a positive longitudinal relationship from LMS to CRF or MF (Chen et al., 2023). However, some findings remain inconclusive regarding the longitudinal relationship between LMS and PA intensities or HRF components. A previous meta-analysis (Liu et al., 2023) found that OCS, not LMS, are associated especially with MVPA in early childhood. This may be because OCS are often linked to sports and activities that involve MVPA (Liu et al., 2023).

The order in which skill domains develop and their different characteristics, along with conflicting research results, offer an interesting perspective to this dissertation's hypothesis that LMS may be a more prominent predictor of PA, body composition, CRF, and MF compared to OCS. The importance of OCS may become more pronounced later in childhood, particularly in adolescence (Barnett et al., 2008, 2009, 2021; Cohen et al., 2014; Okely et al., 2004; Vlahov et al., 2014).

2.4.2 Longitudinal relationships of fundamental movement skills - Process- and product-oriented perspectives

In addition to the LMS and OCS approaches, process- and product-oriented methods of measuring FMS may provide insights into longitudinal relationships due to their differing measurement characteristics, movement quality, and quantitative outcomes (Logan et al., 2017; Palmer et al., 2021; Ré et al., 2018). Both methods are used to measure FMS, but the product-oriented method may require more physical capacity (Cattuzzo et al., 2016; Utesch et al., 2019). Moreover, different constructs and metrics may overlap, especially FMS and HRF components such as CRF and MF, depending on the measurement approach.

Although they are conceptually distinct constructs, CRF, MF, and FMS share a foundation in neuromuscular connections, which can promote greater participation in PA (Cattuzzo et al., 2016; Utesch et al., 2019). The use of goal-directed movements to measure FMS, CR, and MF, which require similar abilities (Cattuzzo et al., 2016; Robinson et al., 2015; Utesch et al., 2019), such as physical capacity, has led to overlapping terminology (Utesch et al., 2019) and metrics across these constructs (Cattuzzo et al., 2016). For example, similar metrics, such as jumping sideways or the standing long jump, are used to measure both FMS and fitness components (Barnett et al., 2021; D'Hondt et al., 2014; Lima et al., 2019; Oberer et al., 2018; Ruedl et al., 2022). Similarities may be especially apparent between product-oriented FMS and fitness components due to their physical capacity requirements.

Furthermore, the different scoring systems—value-limited scoring and the possible ceiling effect of the process-oriented method compared to value-unlimited scoring of the product-oriented method—can cause differences in longitudinal relationships. These differences also relate to the specific target groups and purposes for which the tests are designed. In this dissertation's analysis, the focus is on the process-oriented TGMD-3 (Ulrich, 2019) and product-oriented KTK (Kiphard & Schilling, 2007) measures. However, other process- and product-oriented measurements have been used in previous studies, and both process- and product-oriented early childhood FMS measurements offer conflicting evidence on the longitudinal relationships with PA and HRF.

Regarding PA intensities, Foulkes et al. (2021) and Nilsen et al. (2020) found no evidence of a longitudinal relationship between FMS, based on the process-oriented TGMD-3 or second edition (TGMD-2), and accelerometer-based PA intensities. Duncan et al. (2021) found positive longitudinal relationships from some subtests of LMS, measured by the TGMD-2, to time spent engaged in MVPA, LPA, and SB. In contrast, a product-oriented measurement using the KTK showed that the total scores for FMS significantly predicted VPA but not MVPA (Lima, Pfeiffer, Larsen, et al., 2017). Product-oriented PE metrics scores, related to physical education, also predicted the time spent in MVPA during the school day, along with a negative relationship with SB (Gu, 2016; Gu et al., 2018). However, other studies (Bürgi et al., 2011; Melby et al., 2021; Schmutz et al., 2020) investigating longitudinal relationships from product-oriented early childhood FMS to accelerometer-based PA intensities found no evidence of a longitudinal relationship.

For body composition, prior research exploring the longitudinal relationship from the process-oriented TGMD-2 to weight status (Duncan et al., 2021; Foulkes et al., 2021; Vlahov et al., 2014) or the reverse (Lopes et al., 2020;

Spring et al., 2023) found mixed results. Some studies identified inverse relationships from process-oriented FMS to BMI or body fatness (Duncan et al., 2021; Vlahov et al., 2014), while others did not find significant relationships from FMS to weight status (Foulkes et al., 2021) or the reverse direction (Lopes et al., 2020; Spring et al., 2023), except that a fat-free body mass predicted LMS and OCS (Spring et al., 2023). From a product-oriented perspective, some previous studies starting in early childhood found significant inverse bidirectional longitudinal relationships between FMS, as assessed with the KTK, and BMI (D'Hondt et al., 2014), or body fatness (Lima et al., 2019). On the other hand, a longitudinal relationship was not found to be statistically significant from the KTK to BMI-based class (Lopes et al., 2020).

Longitudinal relationships from early childhood FMS to CRF (Chen et al., 2023; Lima, Pfeiffer, Bugge, et al., 2017; Vlahov et al., 2014) or MF (Chen et al., 2023; Vlahov et al., 2014) have been investigated in few studies. All these studies found a statistically significant relationship from FMS to CRF (Chen et al., 2023; Lima, Pfeiffer, Bugge, et al., 2017; Vlahov et al., 2014) or MF (Chen et al., 2023; Vlahov et al., 2014) regardless of whether process-oriented FMS (Chen et al., 2023; Vlahov et al., 2014) or product-oriented FMS (Lima, Pfeiffer, Bugge, et al., 2017) were used. In addition, some studies have found a positive longitudinal relationship from specific product-oriented FMS level categories to CRF or MF (Fransen et al., 2014; Haugen & Johansen, 2018).

To the best of our knowledge, comparable studies using process- and product-oriented FMS methods have not been conducted. The lack of research, the inconsistent previous research results, the differences between process- and product-oriented FMS measurement methods, the similarities between constructs, such as FMS, CRF, and MF, and the overlap in measuring these constructs all highlight the need for further study.

2.5 Summary of the theoretical background and rationale of the dissertation

According to various theoretical models and frameworks, FMS may serve as the foundation for PA (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Stodden et al., 2008) and HRF components, such as CRF, MF, and body composition (Robinson et al., 2015). However, previous research findings are somewhat inconclusive due to contradictory results or a limited number of studies, indicating the need for further research (Barnett et al., 2021; Cattuzzo et al., 2016; Jones et al., 2020; Utesch et al., 2019; Xin et al., 2020).

Given global concern about insufficient PA in childhood (Farooq et al., 2020; Guthold et al., 2018; Lounassalo et al., 2019), alongside the increased prevalence of childhood overweight and obesity (NCD Risk Factor Collaboration, 2017) and the observed declines in CRF (Fühner et al., 2021; Masanovic et al., 2020) and MF (Masanovic et al., 2020) among children and adolescents, it is crucial to determine whether FMS may be an underlying variable influencing PA, CRF, and MF levels and maintaining a healthy weight status.

Early childhood is a crucial period for influencing children's health behaviors (Goldfield et al., 2012), including establishing stable patterns of PA and SB (Biddle et al., 2010; Malina, 1996, 2001; Schmutz et al., 2020). This stage also impacts CRF and MF levels (García-Hermoso et al., 2022; Kolunsarka et al., 2022) and plays a role in overweight and obesity development (Rooney et al., 2011) in later life. FMS development is another critical aspect during early childhood (Goodway et al., 2019), making it an optimal time to promote these skills (Brian et al., 2020), which tend to remain stable throughout childhood (Chen et al., 2023; Kolunsarka et al., 2022; Schmutz et al., 2020).

However, FMS can be assessed in various ways, and the methods of categorizing and measuring FMS can lead to different, even contradictory, results. In this longitudinal study, skill domains, such as LMS and OCS, were examined, and the use of process- and product-based measurement tools was compared. This comprehensive approach aimed to provide a more accurate depiction of FMS as an underlying variable influencing PA, CRF, MF, and weight status.

3 DISSERTATION AIMS

The aims of this dissertation were to investigate the longitudinal relationship from FMS in early childhood to time spent in PA intensities (Sub-study I) and health-related fitness components, such as BMI (Sub-study II), CRF, and MF (Sub-study III), in later childhood. This dissertation specifically aimed to understand the differences in skill domains, such as LMS and OCS (Sub-studies I, II, and III), and in process- and product-oriented measurements of FMS as predictors (Sub-study III).

The objectives of the original sub-studies were as follows:

I. To study how the total FMS score, measured in a process-oriented way during early childhood, along with the separate LMS and OCS scores, predicts the time spent engaged in specific-intensity accelerometer-measured physical activities (SB, LPA, MPA, VPA, MVPA, and LVPA) three years later in children living in Finland.

II. To investigate the bidirectional longitudinal relationship between BMI and process-oriented FMS, including LMS and OCS, in children living in Finland from early to later childhood over a three-year follow-up period.

III. To examine the longitudinal relationship of early childhood FMS, focusing on the skill domains of LMS and OCS, evaluated using a process-oriented method, and compare the perspectives of both process- and product-oriented measurements of FMS with respect to CRF and MF in late childhood over a six-year follow-up period.

4 MATERIALS AND METHODS

4.1 Longitudinal data and participants

The longitudinal data of this dissertation come from three research projects. The baseline data for this thesis (Figure 5) were collected from the Skilled Kids study (2015–2016), funded by the Finnish Ministry of Education and Culture (OKM/48/626/2014) (Sääkslahti, 2017). The follow-up data, also funded by the Finnish Ministry of Education and Culture, were collected in the Active Family study (2018-2020, OKM/59/626/2017) (Sääkslahti et al., 2022) for Sub-studies I and II and the Skills, Support, and Physical Activity — TAITURIT study (2021–2023, OKM19/626/2021) (Laukkanen et al., 2023) for Sub-study III.

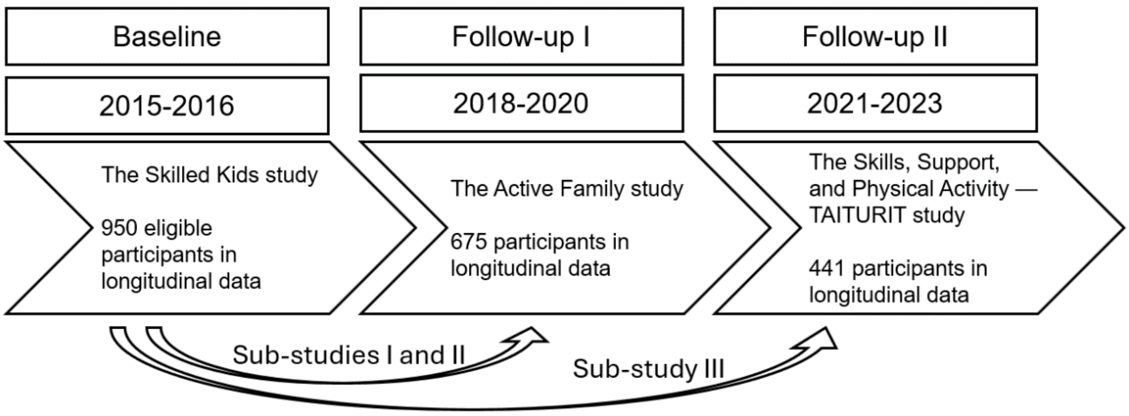


FIGURE 5 Timeline and number of participants in the baseline and follow-up data collection.

The baseline study was a geographical cluster randomized trial, and 1238 children attending 37 childcare centers in Finland were initially measured (Laukkanen et al., 2018; Niemistö, 2021). Of these 1238 participants, 950 participants with comprehensive data available on the main study variables of the follow-up studies (parental support for child physical activity and child outdoor time) were contacted for the follow-ups (Figure 5). Only children who participated in the follow-up studies had permission to combine their follow-up data with their baseline data. Table 1 presents the descriptive statistics regarding the exact age of the participants and the follow-up durations for Sub-studies I–III.

The first follow-up, the Active Family study, included 675 children from 97 schools approximately 3 years after the baseline study. In the analysis of Sub-study I (Table 1), participants (n = 441) from 52 schools with results available for the model-involved variables were included. The complete case analysis was valid (Ross et al., 2020) because data for model-involved variables were missing completely at random (Little's test for missing completely at random, MCAR, chi-square = 31.983, df = 22, p = .078), indicating that the observations of the included participants (n = 441) represent a random subset of all the original participants (n = 675) and that the distributions of the missing and observed values would be comparable (Bhaskaran & Smeeth, 2014).

In the follow-up phase of Sub-study II, which was also based on the Active Family study, all 675 children (Table 1) who participated in the follow-up approximately 3 years after the initial phase were included in the analysis. The rate of loss from baseline to follow-up (29%) was considered acceptable from a bias perspective (Kristman et al., 2004). Additionally, the data were missing completely at random (Little's MCAR test chi-square = 118.773, df = 141, p = .913), considering the missing data for all the model-involved variables. The Sub-study II participants were clustered within 36 childcare centers and 97 schools.

Approximately 6 years after the baseline study, in the Skills, Support, and Physical Activity — TAITURIT study, 441 children (representing 46.4% of the initial cohort of 950 participants) were included in the Sub-study III analysis (Table 1). The model-included variable data were found to be missing completely at random (Little's MCAR test chi-square = 86.672, df = 69, p = .074). The participants were nested within 37 childcare centers at baseline and within 80 schools at the follow-up phase in Sub-study III.

TABLE 1 Participants' age at baseline and follow-up and time between baseline and follow-up measurements in Sub-studies I-III based on the participants with no missing data.

	Sub-study I					Sub-study II					Sub-study III				
Variable[a]	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max
Age at baseline	441	5.60	1.05	2.97[b]	7.80	675	5.53	1.09	2.97[c]	7.80	440	5.51	1.08	3.03	7.44
Girls	228	5.57	1.03	2.97	7.23	341	5.48	1.10	2.97	7.29	218	5.47	1.12	3.10	7.29
Boys	213	5.62	1.08	3.10	7.80	334	5.58	1.08	3.10	7.80	222	5.55	1.08	3.03	7.44
Age at follow-up	441	8.81	1.07	6.67	11.44	674	8.76	1.08	6.33	11.44	440	11.65	0.91	9.06	13.33
Girls	228	8.80	1.04	6.76	11.44	341	8.72	1.08	6.72	11.44	218	11.60	0.93	9.06	13.33
Boys	213	8.85	1.10	6.67	11.28	333	8.80	1.09	6.33	11.28	222	11.70	0.89	9.55	13.28
Time to follow-up	441	3.22	0.37	2.39	4.55	674	3.23	0.37	2.39	4.55	441	6.14	0.52	5.24	7.45
Girls	228	3.22	0.35	2.45	4.55	341	3.23	0.36	2.45	4.55	219	6.14	0.50	5.24	7.39
Boys	213	3.23	0.39	2.39	4.55	333	3.23	0.37	2.39	4.55	222	6.15	0.55	5.24	7.45

[a]Gender differences (p = .303–.935) between these variables were not found in Sub-studies I–III.
[b]The baseline data included measurements from one girl aged 2.97 years.
[c]The baseline data included measurements from two girls aged 2.97 years.

4.2 Study ethics

Responsible research conduct according to the Finnish National Board on Research Integrity TENK (2023) was adhered to in the Skilled Kids, Active Family, and Skills, Support, and Physical Activity – TAITURIT studies, as well as throughout the process of this dissertation. The processing of personal data complies with Regulation (EU) 2016/679 of the European Parliament and of the Council (European Union, 2016). The University of Jyväskylä owns the research data for all three study projects, and the research group has agreed to the use of the data in this dissertation. The principles of open science (Avoimen tieteen ja tutkimuksen koordinaatio, 2020) were followed in the publication of the sub-studies.

The Skilled Kids study, the Active Family study, and the Skills, Support, and Physical Activity – TAITURIT study each received ethical approval from the Ethics Committee of the University of Jyväskylä on October 30, 2015, June 28, 2018, and May 21, 2021, respectively. Children, as the target group, were considered in accordance with the guidelines of the Finnish National Board on Research Integrity TENK (2019). The children were informed about the study in a manner appropriate for their understanding, and participation in the studies was voluntary. Written informed consent was obtained from the guardians of the participants for both their own and their children's participation and data use, and for merging the data in the follow-up phases. The data used in the analysis were pseudonymized.

4.3 Measurements

4.3.1 Gender, age, and time between baseline and follow-up measurements

The gender of the children was reported by their parents (options: girl or boy) when completing a questionnaire at the baseline. The parents also reported their children's dates of birth in the baseline questionnaire. The exact age of each child at every measurement point was calculated by comparing the children's birth dates with their respective test dates at the baseline and follow-ups.

The time between the baseline and follow-up measurements varied among the participants and was calculated by comparing the baseline and follow-up test dates. Exact age, alongside time between the baseline and follow-up measurements, was used as a covariate in Sub-study I. In the other sub-studies, variances between the exact age and follow-up time were considered by adjusting the age-related measurements. This is explained in more detail in the Section 4.3.8.2.

4.3.2 Body dimensions

The children's body mass and height were measured directly to the nearest decimal at every measurement point using a scale (seca 877, seca GmbH & Co. KG, Hamburg, Germany) for body mass and a portable stadiometer (HM200P, Charder Electronic Co., Ltd., Taichung City, Taiwan, R.O.C.) for height. During these measurements, the children were lightly dressed and barefoot.

In Sub-study III, the sitting height and leg length were also determined. The sitting height was calculated by subtracting the measured chair height from the total height while sitting. Both the chair height and height while sitting were measured using a portable stadiometer (HM200P, Charder Electronic Co., Ltd., Taichung City, Taiwan, R.O.C.). The leg length was calculated by subtracting the sitting height from the child's overall height. Sitting height and leg length, alongside other variables, were used when calculating the maturation offset equations (Mirwald et al., 2002).

4.3.3 Body mass index

Body mass and height, along with the children's exact age and gender, were utilized to determine the BMI-for-age standard deviation scores (BMI SDSs) using the Finnish national standards (Saari et al., 2011) and were determined at the baseline for all the sub-studies, as well as at follow-up in the Active Family study for Sub-study II. BMI SDSs were used as a covariate in Sub-study I. In Sub-studies II and III, BMI SDS values were further standardized into BMI SDS z-scores, with distinct calculations for boys and girls to ensure that gender-specific differences in the interpretation of BMI did not affect the results. In Sub-study II, the International Obesity Task Force BMI categories (Cole & Lobstein, 2012) were described according to a classifier (Sanchez-Delgado et al., n.d.) in the supplemental material of original article for international comparison of the number of children in different BMI categories.

4.3.4 Maturation

In Sub-study III, which involved participants aged 9.1–13.3 years during the follow-up phase, maturation offset was determined using the method outlined by Mirwald et al. (2002). This calculation, which is applicable to both genders, takes into account age, weight, height, sitting height, and leg length. The maturation offset equations provide a noninvasive, practical, and reliable means of evaluating maturation in terms of years from peak height velocity (PHV), with a model accuracy of $R^2 = 0.92$ and a standard error of estimate (SEE) of 0.49 for boys and $R^2 = 0.91$ and SEE = 0.50 for girls. A negative maturation offset indicates a pre-PHV stage, while a positive offset suggests a post-PHV stage. Although these equations may not perfectly align with biological maturity, they offer a valuable assessment tool for estimating maturity-related PHV (Mirwald et al., 2002).

4.3.5 Fundamental movement skills

FMS served as the main predictor in all the sub-studies of this dissertation. The process-oriented TGMD-3 (Ulrich, 2019) was used to measure FMS at the baseline in the Skilled Kids study, divided into LMS and OCS, and these baseline results were utilized in all three sub-studies. TGMD-3 was also partly used at follow-up in the Active Family study, and these results contributed to Sub-study II. Additionally, in Sub-study III, the product-oriented body coordination test for children, the KTK (Kiphard & Schilling, 2007), was employed at the baseline.

The assessment of FMS was carried out over two distinct days at the baseline (Sääkslahti, 2017). Initially, on the first day, the KTK measurements were administered to the children over 5 years old, adhering to the validated age range for the KTK (Kiphard & Schilling, 2007). On the subsequent day, the TGMD-3 test was conducted for children older than 3 years (see the Table 1 notes), aligning with the TGMD-3's intended age group (Ulrich, 2019). The same team of researchers carried out all these tests. In the Active Family study, all the abbreviated TGMD-3 subtests were carried out in one day (Sääkslahti et al., 2022).

4.3.5.1 TGMD-3 process-oriented manner

The process-oriented TGMD-3 (Ulrich, 2019) evaluates qualitative information on children's overall FMS levels and, separately, their LMS and OCS levels. The TGMD-3 is designed for children aged 3–11 years and includes 6 LMS subtests (run [0–8 points], gallop [0–8], hop [0–8], skip [0–6], horizontal jump [0–8], and slide [0–8]) that produce a maximum of 46 points. Additionally, the TGMD-3 contains 7 OCS subtests (a 2-hand strike of a stationary ball [0–10 points], a 1-hand forehand strike [0–8], a 1-hand stationary dribble [0–6], a 2-hand catch [0–6], kicking a stationary ball [0–8], an overhand throw [0–8], and an underhand throw [0–8]) producing a maximum of 54 points. The total FMS score (maximum of 100 points) is defined as the sum of the LMS and OCS subtest scores.

Assessing performance through direct observation with the naked eye is an effective method for evaluating FMS levels (Goodway et al., 2019). Performance is assessed through direct observation by trained observers, who assign one point for each criterion met, based on three to five qualitative performance criteria, depending on the skill. Initially, children undergo a practice round for each subtest, followed by two official attempts. The aggregate of points from these attempts forms the overall score for each skill (Ulrich, 2019).

In Sub-studies I and III, all the TGMD-3 subtests were used. However, in Sub-study II, only two LMS subtests (skip and 1-legged hop, 0–14 points) and two OCS subtests (an overhand throw and a 1-handed stationary dribble, 0–14 points) were utilized to derive the total FMS level (0–28 points) and skill domain levels. These subtests were selected for their strong representation of the skill domains (Wagner et al., 2016) and were measured during the follow-up phase in the Active Family study. The other subtests were not included in the follow-up measurements and therefore could not be used in the analysis.

The TGMD-3 is highly favored for FMS assessment due to its low cost, feasibility, and robust psychometric properties. A meta-analysis revealed that the inter- and intra-rater reliabilities of the TGMD-3 were greater than 0.9, while the test–retest reliability exceeded 0.8 (Rey et al., 2020). In the context of the Skilled Kids study, the TGMD-3 demonstrated commendable inter-rater reliability (interclass correlation coefficient = 0.88, 95% CI = 0.85–0.92), as evidenced by the evaluation of 167 children before the initial data collection phase (Niemistö et al., 2019). The internal consistency of the TGMD-3 ranged from acceptable to excellent, with Cronbach's alpha values of between 0.7 and 0.9 (Rey et al., 2020).

Despite these strengths, caution is advised when comparing results across different studies and research groups. In one study, intraclass correlation coefficients (ICC) indicated fair consistency (ICC = 0.730–0.757) across different research teams for FMS, LMS, and OCS scores, while the agreement ICCs (0.363-0.478) were considered poor (Hulteen et al., 2023). Thus, comparisons between studies employing the TGMD-3 might not always yield consistent results. However, since the research team remained the same in all three research projects from which the longitudinal data used in this dissertation come, the TGMD-3 results between the Skilled Kids study and the Active Family study are assumed to be comparable. However, comparing these results with those obtained by other research groups could be unreliable, due to different research teams.

4.3.5.2 KTK product-oriented manner

The product-oriented KTK (Kiphard & Schilling, 2007), known for assessing motor coordination, includes 4 distinct subtests: 1) walking backwards along balance beams of varying widths, scoring up to a maximum of 72 points; 2) hopping for height on 1 foot, with a potential score of 78 points; 3) jumping sideways for 15 seconds, where the score is based on the number of correct jumps over 2 attempts; and 4) moving sideways with wooden plates, aiming for the highest possible score within a 20-second timeframe, scored over 2 trials.

The KTK has become a respected, user-friendly, and standardized tool with high reliability in the realm of product-oriented FMS assessment (Iivonen et al., 2016). Its inter-rater reliability surpasses 0.85, reflecting a strong consensus among different evaluators. The KTK also demonstrates impressive intra-rater reliability with an interclass correlation coefficient of 0.97, ensuring consistent assessments across multiple observations. Its test–retest reliability is equally noteworthy, exceeding 0.85 and showing no significant variance between initial and subsequent tests, thus underlining the KTK's reliable nature over time (Cools et al., 2009).

4.3.6 Measurement of engagement in different physical activity intensities using accelerometers

The participants' engagement in various PA intensities, including SB, was measured in the Active Family study using triaxial accelerometers (model UKK RM-42, UKK Terveyspalvelut Oy, Tampere, Finland), and these data were utilized in Sub-study I. Pate et al. (2010) have confirmed the reliability of accelerometers in measuring the duration and intensities of children's PA.

The children participating in the Active Family study wore accelerometers for seven consecutive days. They were instructed to wear the device on the right side of their waist, secured with an elastic belt, and to use it during their waking hours. Additionally, the children were advised to remove the accelerometer at bedtime, as well as for activities such as showering, visiting saunas, and swimming, and if they were ill.

For the analysis, only accelerometer data recorded between 6 a.m. and 10 p.m. were considered. Any period in which the mean amplitude deviation (MAD) of acceleration fell below 0.02 g for 60 continuous minutes was classified as non-wear time. To be deemed acceptable for analysis, the accelerometer data had to satisfy 2 criteria: a minimum daily recording time of 10 hours, following the recommended standards (Migueles et al., 2017, and the presence of valid data from at least 2 weekdays (averaging 4.2 weekdays) and 1 weekend day (averaging 1.9 weekend days). According to Penpraze et al. (2006), this combination of daily wear time and number of days provides an acceptable level of reliability, estimated to be around 62%.

A well-established method based on MAD (Aittasalo et al., 2015; Gao et al., 2019) was employed to assess the children's PA intensities. For the analysis of the accelerometer data, MATLAB software was used, in which data were sampled at 100 Hz and categorized based on the MAD over non-overlapping 5-second epochs. The MAD cut points were set as follows: below 29 for SB, 29 for LPA, 338 for MPA, and 604 for VPA, as per Aittasalo et al.'s (2015) guidelines. The total time spent in LPA, MPA, and VPA was collectively calculated to determine the time engaged in varying intensities of PA (i.e., LVPA).

4.3.7 Cardiorespiratory and muscular fitness

The tests for CRF and MF are part of the Finnish physical fitness monitoring system named Move! (Jaakkola et al., 2012). These tests were performed after a warm-up, starting with MF tests that included push-ups and curl-ups and followed by the CRF tests.

The recognized and reliable 20-meter shuttle run test (Léger & Lambert, 1982) was used to evaluate the children's CRF (Liu et al., 1992; Selland et al., 2022) in the Skills, Support, and Physical Activity – TAITURIT study. The test begins with a beep signal. Upon hearing this signal, children must run a distance of 20 meters until the next beep, which indicates the start of a new lap. The test starts at a running speed of 8.5 km/h, increasing by approximately 0.5 km/h every minute. Performance is quantified by counting the total number of laps completed according to the beep signals (Léger & Lambert, 1982).

The children's MF results were based on the combined results of the push-up and curl-up tests, in this order. The push-up test (Jaakkola et al., 2012) is known to be a reliable indicator of upper body muscle strength in children (Fernandez-Santos et al., 2016; Jaakkola et al., 2012). Boys start the push-up test on their toes, with arms straight and hands on the floor next to their shoulders, fingers pointing forward. Girls start with their weight on their knees instead of their toes. Participants keep their bodies straight and face down, lowering themselves until their upper arms are horizontal and parallel to the floor, elbows bent at 90°, then pushing back up to full arm extension. Each return to the starting position counts as one completed push-up. The test measures the number of correctly executed push-ups within a 60-second timeframe (Jaakkola et al., 2012).

The curl-up test is known for its ability to evaluate the endurance of the abdominal muscles and has acceptable measurement properties (Jaakkola et al., 2012). Children start lying on their backs with their heads, straight arms, and soles of the feet flat on the mat and knees bent at a 100° angle. Fingertips are positioned at the edge of a marked 8-cm-wide tape. During the exercise, children lift their upper bodies from the mat until their fingertips reach the opposite edge of the tape, engaging the abdominal muscles. They return to the starting position after each repetition. The goal is to perform as many correct curl-ups as possible in time with an audio tape, with a maximum achievable score of 75 repetitions.

4.3.8 Statistical analysis

4.3.8.1 Statistical software and two-level regression analysis as the sub-studies' statistical method

The Sub-study I analysis was conducted using SPSS software (version 28, IBM, Armonk, NY, USA). Descriptive statistics and preliminary analyses, such as tests for normality, Mann–Whitney U-tests, and data transformation, standardization, and residualizing for all the sub-studies, were also computed using SPSS. Further analyses of Sub-studies II and III were performed using Mplus statistical software (version 8.8, Muthén & Muthén, Los Angeles, CA, USA).

Two-level regression analysis was utilized in all the sub-studies to accommodate the clustered data. In Sub-study I, the analysis considered only the participants (Level 1) nested within 52 schools (Level 2), with an average of 5.3 students per school (range 1–23) (Hox et al., 2010). The clustering of children within childcare centers at the baseline was not considered due to the limitations of the SPSS software. The two-level regression analyses in Sub-study I employed a linear mixed model approach, using restricted maximum likelihood estimation and the Satterthwaite approximation.

In Sub-studies II and III, two-level, cross-classified regression analyses (Finch & Bolin, 2017) were employed, allowing for the consideration of children clustered both at the childcare centers at the baseline and the schools at the follow-up. The participants comprised level 1 and were cross-classified at level 2 by 36 childcare centers (average 18.1 participants, range 5–35) and 97 schools (average 6.9 participants, range 1–31) in Sub-study II and by 37 childcare centers (average 12 participants, range 1–22) and 80 schools (average 5.6 participants, range 1–22) in Sub-study III.

The two-level, cross-classified analysis in Sub-study II (Finch & Bolin, 2017) used a cross-lagged approach (Kearney, 2017) to investigate the bidirectional relationship. Furthermore, a two-level cross-classified regression analysis (Finch

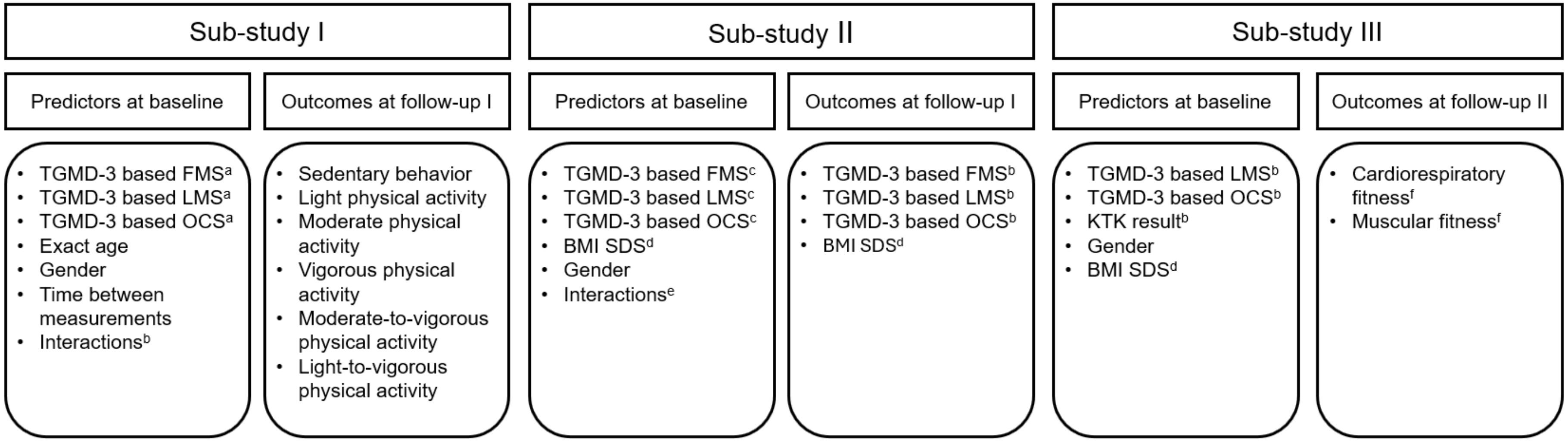
& Bolin, 2017) and Cholesky decomposition approach (De Jong, 1999) were utilized in Sub-study III to investigate correlated observed predictors and their unique contributions to outcome variables, as indicated by an increased R^2 value, beyond the effects of other correlated predictors in the model. All predictors were grand mean centered in these analyses, and all variables were allowed to correlate at the between level due to the data's multilevel structure. The models for Sub-studies II and III were executed using Bayesian analysis (an iterative Markov chain Monte Carlo method: GIBBS[PX1], point estimate—median, two parallel chains, 18,000–110,000 iterations; burn-in: half of the iterations; and thinning rate = 1), with prior distributions (mean 0, variance ∞) employed to derive parameter estimates from the observed data.

The statistical significance level for all analyses was set at a probability of less than .05. Credibility intervals (CrIs) in the Bayesian analysis were interpreted similarly to confidence intervals (CIs) in the frequentist models. The convergence of the posterior distribution was assessed using potential scale reduction (PSR) coefficients—targeted below 1.1—along with trace plots. Acceptable autocorrelation levels were verified through autocorrelation plots (Finch & Bolin, 2017).

The model fit in the Bayesian analysis was evaluated by comparing the posterior predictive probability value (PPP) and the 95% CI for the difference between the observed and replicated chi-square values. PPP values near 0.5 indicated an optimal model fit, while a 95% CI including zero signified a fitting model (Finch & Bolin, 2017).

4.3.8.2 Used variables and their modification for statistical analysis

In all the sub-studies, only individual-level (Level 1) variables were included in the analysis (Figure 6). In Sub-study I, the predictor variables measured at the baseline included standardized values of the total FMS score, LMS, and OCS scores, along with the main effects of age and gender, and their interactions with FMS, LMS, and OCS scores to account for differences in gender and age within the models. Interaction terms, such as total FMS score and gender, LMS and gender, and OCS and gender, as well as similar interactions with age, were utilized. BMI SDS was used as a covariate. Additionally, the time between the baseline and follow-up measurements was considered a covariate due to notable variations among the participants. The outcome variables were standardized variables of the time spent engaged in PA at different intensities.



TGMD-3 = Test of Gross Motor Development, third edition, FMS = fundamental movement skills, LMS = locomotor skills, OCS = object control skills, BMI SDS = body mass index, standard deviation score, KTK = Körperkoordinationstest für Kinder.
[a]Standardized values, [b]Interaction terms FMS*gender, LMS*gender, OCS*gender, FMS*age, LMS*age, OCS*age, [c]Adjusted by exact age in measurement point, [d]Standardized for boys and girls, [e]Interaction terms FMS*gender, LMS*gender, OCS*gender, BMI SDS*gender, [f]Adjusted by exact age in measurement point and maturation.

FIGURE 6 Predictors at baseline and outcomes at follow-up of Sub-studies I–III.

In Sub-study II, the bidirectional relationship between the BMI for age and FMS, as well as LMS and OCS, was investigated. The main effects of the same variables were also of interest in the outcomes. In Sub-study III, the predictors were LMS and OCS, as measured by the TGMD-3, and KTK result. The BMI SDS z-scores and gender were used as covariates, with CRF and MF as the outcome variables.

The participants' exact ages and the individually varying times between the baseline and follow-up measurement points were adjusted for in the age-related FMS variables (Barnett, Lai, et al., 2016) in Sub-studies II and III and further adjusted for in Sub-study III for age-related CRF (Roberts et al., 2012) and MF (Beunen & Thomis, 2000). Additionally, in Sub-study III, the age-adjusted CRF (Roberts et al., 2012) and MF (Beunen & Thomis, 2000) results were also residualized by maturity to eliminate the effects of maturation offset on CRF and MF. These adjusted residuals, abbreviated using the subscript "adj" (FMS_{adj}, LMS_{adj}, OCS_{adj}, CRF_{adj}, and MF_{adj}), were utilized in the analyses. Residualization allowed for an understanding of the participants' deviations from the average FMS, LMS, and OCS scores typical for their age at the measurement point and, in addition to age, for maturity in CRF and MF. Positive residuals indicated a performance exceeding the predicted norm, while negative residuals denoted a performance falling short of the expected level.

4.3.8.3 Executed models in the analysis

In all the sub-studies, an intercept-only model with no predictors was first implemented to determine whether multilevel analytic techniques were warranted. If a two-level regression analysis was not required, a linear regression analysis was used. After establishing the intercept-only model, the analysis continued with the inclusion of individual-level predictors (Figure 6) in the models of the sub-studies. The outcome variables were based on follow-up I from the Active Family study for Sub-studies I and II, and on follow-up II from the Skills, Support, and Physical Activity – TAITURIT study.

In Sub-studies I and II, the models also included interaction terms. Detailed analyses were conducted if an interaction showed statistical significance. For significant interactions, separate models for girls and boys with individual-level predictors were implemented in Sub-studies I and II. In cases where interactions were not significant, they were excluded from the analysis, which focused instead on reporting the main effects of the predictors.

In Sub-study III, a model including only the covariates was implemented initially. Afterward, the predictors KTK_{adj}, LMS_{adj}, and OCS_{adj}, which were correlated with each other, were added separately and simultaneously to a model that already included the covariates. The models included two specific models focusing on LMS^{adj} to reveal their unique contributions, even when considered together. Finally, three additional models incorporating LMS_{adj}, OCS_{adj}, and KTK_{adj} were executed. In each model, one of KTK_{adj}, LMS_{adj}, or OCS_{adj} was included after controlling for the effects of the other variables and covariates, thereby revealing the unique contributions of all the predictors.

5 RESULTS

5.1 Rationale for the two-level regression analysis and detailed analysis for gender differences

In all the sub-studies of this dissertation, multilevel analytic techniques were warranted due to the intercept-only models and the statistically significant results ($p < .05$) of the between-level variances. Intercept-only models were executed for all the outcome variables. Only in Sub-study I, where the outcome as SB between levels was not statistically significant, was linear regression analysis performed instead.

In Sub-studies I and II, the interaction terms of FMS or skill domains with gender were found to be statistically significant, and separate models for girls and boys were executed. In Sub-study I, a detailed analysis was conducted for the longitudinal relationship from the total FMS score to LPA, where the interaction term was statistically significant ($\beta = -0.177$, $p < .05$). In Sub-study II, all the models were computed separately for the girls and the boys according to the statistically significant interaction terms ($\beta = -0.080$ to 0.141, $p < 0.05$). In cases where the interactions were not significant, only the main effects were reported.

5.2 Longitudinal relationship from process-oriented fundamental movement skills to time spent in physical activity intensities

Table 2 presents the descriptive statistics of Sub-study I. Gender differences were found in the skill domains and PA behavior variables, excluding LVPA and SB.

TABLE 2 Descriptive statistics of Sub-study I (n = 441, 228 girls and 213 boys).

Variable	Mean	SD	Min	Max	Gender Differences (p-value)
Baseline					
BMI SDS	0.19	1.05	−4.55	3.23	.443
Girls	0.22	1.13	−4.55	3.23	
Boys	0.16	0.96	−3.36	2.47	
TGMD-3 FMS (0–100 points)	54.94	13.85	8	88	**.037**
Girls	53.75	12.57	8	84	
Boys	56.22	15.03	14	88	
TGMD-3 LMS (0–46 points)	28.95	7.33	2	46	**<.001**
Girls	30.23	6.88	2	46	
Boys	27.57	7.57	7	43	
TGMD-3 OCS (0–54 points)	26.00	8.71	6	49	**<.001**
Girls	23.52	7.59	6	44	
Boys	28.65	9.06	6	49	
Follow-up					
SB (mins/day)	334.02	59.22	184.20	529.71	.482
Girls	336.24	60.52	184.20	513.57	
Boys	331.65	57.84	186.33	529.71	
LPA (mins/day)	282.44	44.55	162.67	433.57	**<.001**
Girls	293.45	42.25	180.25	433.57	
Boys	270.66	44.03	162.67	382.00	
MPA (mins/day)	156.18	36.01	54.80	289.57	**<.001**
Girls	147.23	33.44	74.71	289.57	
Boys	165.76	36.27	54.80	274.71	
VPA (mins/day)	13.48	10.50	0.00	74.43	**<.001**
Girls	11.51	9.50	0.83	74.43	
Boys	15.59	11.11	0.00	58.00	
MVPA (mins/day)	169.66	41.89	55.20	331.29	**<.001**
Girls	158.74	38.62	82.50	305.29	
Boys	181.35	42.18	55.20	331.29	
LVPA (mins/day)	452.10	60.74	287.00	612.17	.993
Girls	452.19	60.25	300.50	612.17	
Boys	452.01	61.41	287.00	587.43	

Note. P-values of gender differences <.05 are shown in bold.
BMI SDS = body mass index standard deviation score, TGMD-3 = Test of Gross Motor Development-third edition, FMS = fundamental movement skills, LMS = locomotor skills, OCS = object control skills, SB = sedentary behavior, mins = minutes, LPA = light physical activity, MPA = moder-ate physical activity, VPA = vigorous physical activity, MVPA = moderate-to-vigorous physical activity, LVPA = light-to-vigorous physical activity.

Tables 3 and 4 present an overview of the results from Sub-study I. The process-oriented total FMS score and LMS based on TGMD-3 significantly predicted MPA and VPA, both separately and together (i.e., MVPA). LMS also significantly predicted SB inversely. However, the LVPA and LPA results were not significantly predicted by FMS or LMS. Despite statistically significant interaction terms ($\beta = 0.178$, $p = .043$), the total FMS score did not significantly predict LPA in either gender in the detailed analysis. Moreover, no statistically significant results were found for the longitudinal relationship from OCS to any PA intensities, including SB.

The covariates in the FMS and skill domain models, such as age at baseline and the time between the baseline and follow-up measurements, indicated that time spent engaged in PA intensities generally decreased with age, except with respect to LVPA, and decreased with longer follow-up time. Conversely, SB increased with age and with a longer follow-up time. Additionally, higher BMI SDS scores predicted greater time spent engaged in SB. Gender was not a statistically significant predictor of LVPA or SB, but it predicted time spent engaged in other PA intensities.

The models included covariates, and the total FMS score or skill domains explained overall the variability in time spent engaged in PA intensities by 5.1%–11.8%. The models explained 14.3%–14.4% of the variability in SB.

TABLE 3 Longitudinal relationship between total fundamental movement skills score or skill domain-based TGMD-3 values and time spent engaged in physical activity intensities (n = 441, 52 schools).

	LPA			MPA			VPA			MVPA			LVPA		
Models of the total FMS score	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p- value
TGMD-3 FMS	0.061[a] −0.117[b]	0.0778 0.068	.434 .087	0.177	0.058	**.003**	0.201	0.06	**<.001**	0.203	0.058	**<.001**	0.112	0.059	.057
Gender	−0.479[c]	0.087	**<.001**	0.489	0.088	**<.001**	0.312	0.090	**<.001**	0.502	0.087	**<.001**	0.001	0.089	.987
Age	−0.252	0.059	**<.001**	−0.328	0.060	**<.001**	−0.179	0.062	**.004**	−0.323	0.060	**<.001**	−0.419	0.0589	**<.001**
Time to follow-up	−0.164	0.049	**.001**	−0.116	0.054	**.033**	−0.102	0.055	.067	−0.124	0.054	**.023**	−0.196	0.046	**<.001**
BMI SDS	−0.016	0.044	.721	−0.036	0.044	.412	−0.047	0.045	.298	−0.044	0.043	.311	−0.042	0.044	.340
R^2		11.5			11.4			5.1			11.8			7.8	
	LPA			MPA			VPA			MVPA			LVPA		
Models of the skill domains	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value
TGMD-3 LMS	−0.022	0.057	.701	0.140	0.057	**.014**	0.156	0.059	**.008**	0.164	0.057	**.004**	0.096	0.057	.092
TGMD-3 OCS	−0.030	0.064	.645	0.059	0.065	.362	0.070	0.067	.291	0.065	0.064	.310	0.029	0.065	.651
Gender	−0.476	0.100	**<.001**	0.536	0.100	**<.001**	0.363	0.103	**<.001**	0.559	0.099	**<.001**	0.039	0.101	.703
Age	−0.249	0.060	**<.001**	−0.320	0.061	**<.001**	−0.170	0.062	**.006**	−0.314	0.060	**<.001**	−0.412	0.059	**<.001**
Time to follow-up	−0.166	0.049	**<.001**	−0.115	0.054	**.034**	−0.101	0.055	.069	−0.123	0.054	**.024**	−0.196	0.046	**<.001**
BMI SDS	−0.015	0.044	.740	−0.032	0.044	.459	−0.043	0.045	.339	−0.040	0.044	.359	−0.040	0.045	.369
R^2		10.3			11.2			5.1			11.8			7.9	

Note. Statistically significant (p-value <.05) longitudinal relationships are shown in bold.
LPA = light physical activity, MPA = moderate physical activity, VPA = vigorous physical activity, MVPA = moderate-to-vigorous physical activity, LVPA = light-to-vigorous physical activity, FMS = fundamental movement skills, SE = standard error, TGMD-3 = Test of Gross Motor Development third edition, Time to follow-up = time between baseline and follow-up measurements, BMI SDS = body mass index standard deviation score, LMS = locomotor skills, OCS = object control skills
[a]Estimates in girls. [b]Estimates in boys. [c]Gender is reported with girls as the reference group.

TABLE 4 Longitudinal relationship from TGMD-3 total fundamental movements skill score or skill domains to sedentary behavior (n = 441).

	Variable	Estimate	SE	p-value
Model of the total FMS score	TGMD-3 FMS	−0.107	0.059	.070
	Gender	−0.079	0.089	.372
	Age	0.408	0.059	**<.001**
	Time to follow-up	0.176	0.045	**<.001**
	BMI SDS	0.099	0.044	**.027**
	R^2 = 0.152, adjusted R^2 = 0.143 F(5, 435) = 15.631, p <.001, SEE = 0.926			
Model of the skill domains	TGMD-3 LMS	−0.116	0.057	**.042**
	TGMD-3 OCS	−0.001	0.065	.991
	Gender	−0.139	0.101	.168
	Age	0.398	0.059	**<.001**
	Time to follow-up	0.176	0.045	**<.001**
	BMI SDS	0.095	0.045	**.034**
	R^2 = 0.155, Adjusted R^2 = 0.144 F(6, 434) = 13.302, p < 0.001, SEE = 0.925			

Note. Statistically significant (p-value <.05) longitudinal relationships are shown in bold. SE = standard error, FMS = fundamental movement skills, TGMD-3 = Test of Gross Motor Development third edition, Time to follow-up = time between baseline and follow-up measurements, BMI SDS = body mass index standard deviation score, LMS = locomotor skills, OCS = object control skills.

5.3 Bidirectional longitudinal relationship between body mass index and process-oriented fundamental movement skills

Table 5 presents the descriptive statistics for the BMI SDS and TGMD-3-based FMS, LMS, and OCS at baseline and follow-up. Gender differences were found in FMS and the skill domains, but not in BMI SDS. The TGMD-3 FMS and skill domains are based only on two LMS subtests and two OCS subtests, which is why many participants reached the minimum and maximum values (Table 5). However, only a few girls and boys reached the minimum or maximum points across all four TGMD-3-based FMS assessments.

TABLE 5 Descriptive statistics of Sub-study II based on the participants with no missing data.

	N	Mean	SD	Min	Max	Gender differences (p-value)
Baseline						
TGMD-3 FMS (0–28 points)[a]	596	12.2	5.4	0	27	.439
Girls	299	12.3	4.9	0	24	
Boys	297	12.0	5.8	0	27	
TGMD-3 LMS (0–14 points)[b]	602	7.0	3.5	0	14	**<.001**
Girls	304	7.7	3.3	0	14	
Boys	298	6.4	3.5	0	14	
TGMD-3 OCS (0–14 points)[c]	604	5.1	3.1	0	14	**<.001**
Girls	302	4.6	2.6	0	12	
Boys	302	5.7	3.3	0	14	
BMI SDS	621	0.18	1.05	-4.55	3.24	.325
Girls	311	0.21	1.13	-4.55	3.24	
Boys	310	0.14	0.95	-3.37	2.47	
Follow-up						
TGMD-3 FMS (0–28 points)[d]	643	17.2	5.0	0	28	**.002**
Girls	328	16.7	4.3	5	27	
Boys	315	17.8	5.5	0	28	
TGMD-3 LMS (0–14 points)[e]	645	8.9	2.9	0	14	**<.001**
Girls	330	9.5	2.5	2	14	
Boys	315	8.3	3.2	0	14	
TGMD-3 OCS (0–14 points)[f]	648	8.3	3.3	0	14	**<.001**
Girls	329	7.2	2.8	0	14	
Boys	319	9.4	3.3	0	14	
BMI SDS	641	0.22	0.99	-3.43	3.22	.580
Girls	328	0.25	1.02	-3.01	3.22	
Boys	313	0.19	0.96	-3.43	2.51	

Note. Statistically significant p-values of gender differences (<.05) are shown in bold.
TGMD-3 = Test of Gross Motor Development-third edition, FMS = fundamental movement skills, LMS = locomotor skills, OCS = object control skills, BMI SDS = body mass index standard deviation score
[a]One girl and four boys reached the minimum points, while one girl and one boy reached the maximum points, [b]15 girls and 30 boys reached the minimum points, while 6 girls and 2 boys reached the maximum points, [c]3 girls and 10 boys reached the minimum points, while 3 girls and 7 boys reached the maximum points, [d]One girl and one boy reached the minimum points, while two girls and four boys reached the maximum points, [e]1 girl and 5 boys reached the minimum points, while 15 girls and 14 boys reached the maximum points, [f]5 girls and 4 boys reached the minimum points, while 2 girls and 39 boys reached the maximum points.

Detailed analysis did not reveal any statistically significant bidirectional longitudinal relationships between the BMI SDS z-scores and FMS_{adj} or skill domains for either gender (Table 6). Conversely, the baseline BMI SDS z-scores, FMS_{adj}, and LMS_{adj} predicted their follow-up values statistically significantly in both genders. Additionally, OCS_{adj} at baseline statistically significantly predicted its follow-up value only for the boys.

The models accounted for 57.2%–61.5% of the variance in the BMI SDS z-scores, 7.8%–27.1% of the variance in FMS_{adj}, and 4.0%–18.9% in LMS_{adj} and OCS_{adj}. The executed models were well fitted to the data according to the PPP value and 95% CI for the difference between the observed and replicated chi-square values.

TABLE 6 The bidirectional longitudinal relationship between BMI and process-oriented TGMD-3-based FMS or skill domains in girls and boys.

Individual-level predictors	Outcomes at follow-up					
	Girls (n = 340, 36 childcare centers, 76 schools)			Boys (n = 332, 36 childcare centers, 76 schools)		
Model of the total FMS score	BMI SDS s-scores (95 % CrI)	FMS_{adj} (95 % CrI)		BMI SDS z-scores (95 % CrI)	FMS_{adj} (95 % CrI)	
BMI SDS z-scores	0.757* (0.700, 0.805)	−0.056 (-0.175, 0.066)		0.780* (0.727, 0.824)	0.037 (−0.066, 0.140)	
FMS_{adj}	0.063 (-0.018, 0.145)	0.262* (0.142, 0.376)		−0.079 (−0.158, 0.001)	0.516* (0.417, 0.603)	
R-square within level	0.573* (0.492, 0.647)	0.077* (0.026, 0.152)		0.614* (0.536, 0.683)	0.271* (0.179, 0.369)	
Model of the skill domains	BMI SDS z-scores (95 % CrI)	LMS_{adj} (95 % CrI)	OCS_{adj} (95 % CrI)	BMI SDS z-scores (95 % CrI)	LMS_{adj} (95 % CrI)	OCS_{adj} (95 % CrI)
BMI SDS z-scores	0.756* (0.700, 0.804)	−0.090 (−0.208, 0.032)	0.002 (−0.116, 0.120)	0.776* (0.722, 0.820)	−0.013 (−0.124, 0.097)	0.060 (−0.049, 0.167)
LMS_{adj}	0.064 (−0.017, 0.145)	0.219* (0.097, 0.336)	0.158* (0.034, 0.273)	−0.079 (−0.160, 0.002)	0.229* (0.113, 0.337)	0.212* (0.096, 0.321)
OCS_{adj}	0.019 (−0.062, 0.099)	0.121 (−0.002, 0.240)	0.070 (−0.055, 0.189)	−0.018 (−0.098, 0.061)	0.315* (0.201, 0.421)	0.299* (0.186, 0.409)
R-square within level	0.573* (0.493, 0.646)	0.088* (0.033, 0.164)	0.040* (0.008, 0.095)	0.616* (0.537, 0.683)	0.188* (0.108, 0.278)	0.173* (0.096, 0.262)

CrI = credibility interval, BMI SDS = body mass index standard deviation score, FMS_{adj} = fundamental movement skill adjusted by age, LMS_{adj} = locomotor skills adjusted by age, OCS_{adj} = object control skills adjusted by age, * = significant to at least $p < .05$.

5.4 Longitudinal relationship from process- and product oriented fundamental movement skills to cardiorespiratory and muscular fitness

Table 7 presents the descriptive statistics of Sub-study III's main variables at the baseline and follow-up. Gender differences were found in the TGMD-3 based skill domains, CRF, and MF but not in the KTK result or BMI SDS.

The initial phase of the analysis (Table 7) indicated that when the predictors were analyzed independently, LMS_{adj}, OCS_{adj}, and KTK_{adj} each predicted CRF_{adj} and MF_{adj}. More detailed analysis of LMS_{adj} and OCS_{adj} revealed that only LMS_{adj} made a statistically significant unique contribution to both outcomes: CRF_{adj} ($\Delta R^2 = 0.016$) and MF_{adj} ($\Delta R^2 = 0.014$).

Further analysis that also included KTK_{adj} revealed that KTK_{adj} had a specific independent effect, contributing uniquely to CRF_{adj} ($\Delta R^2 = 0.092$) and MF_{adj} ($\Delta R^2 = 0.032$), while controlling for process-oriented TGMD-3-based LMS_{adj} and OCS_{adj}, as well as covariates. Neither LMS_{adj} nor OCS_{adj} retained a role as statistically significant predictors in the Cholesky decomposition approach.

Gender and BMI SDS z-scores were statistically significant predictors of CRF_{adj} across all the executed models. Regarding MF_{adj}, gender was a statistically significant predictor in all the models. In contrast, BMI SDS z-scores were significant predictors only in the model that included the covariates alone and not in the models that contained LMS_{adj}, OCS_{adj}, or KTK_{adj}.

The models aligned well with the data, as indicated by the PPP values and 95% CIs. The potential scale reduction coefficients fell within an acceptable range, and the convergence of the models was visually confirmed by trace plots that consistently centered the curves along the y-axis.

TABLE 7 Descriptive statistics of Sub-study III based on the participants with no missing data.

		N	Mean	SD	Min	Max	Gender differences (p-value)
Baseline							
TGMD-3 LMS[a] (0–46 points)		393	28.3	7.8	6	46	**.002**
	Girls	193	29.5	7.3	6	45	
	Boys	200	27.1	8.0	6	46	
TGMD-3 OCS (0–54 points)		394	25.9	8.8	4	49	**<.001**
	Girls	194	23.4	8.0	4	44	
	Boys	200	28.4	8.8	5	49	
KTK		183	107.3	34.2	27	189	.257
	Girls	88	109.9	31.4	49	182	
	Boys	95	104.8	36.6	27	189	
BMI SDS		410	0.17	1.04	−3.41	3.13	.815
	Girls	201	0.19	1.10	−3.41	3.13	
	Boys	209	0.16	0.98	−3.29	2.50	
Follow-up							
BMI SDS		424	0.14	1.05	−6.37	2.46	.493
	Girls	212	0.17	1.12	−6.37	2.46	
	Boys	212	0.12	0.99	−2.33	2.34	
Maturity		417	−2.46	0.74	−4.35	0.17	.320
	Girls	210	−2.44	0.72	−4.35	−0.79	
	Boys	207	−2.48	0.76	−3.96	0.17	
CRF		323	33.1	15.7	5	81	**.002**
	Girls	157	30.0	13.2	6	64	
	Boys	166	36.1	17.2	5	81	
MF[b]		401	57.4	29.1	0	127	**.007**
	Girls	203	61.3	26.5	4	127	
	Boys	198	53.3	31.1	0	110	

TGMD-3 = Test of Gross Motor Development-third edition, LMS = locomotor skills, OCS = object control skills, KTK = Körperkoordinationstest Für Kinder, BMI SDS = body mass index standard deviation score, CRF = cardiorespiratory fitness, MF = muscular fitness.

[a]Only one participant reached maximum points in the TGMD-3 LMS.

[b]In the push-up test, the boys started with their weight on their toes and the girls on their knees.

TABLE 8 Unique contributions of three age-adjusted fundamental movement skill variables to predicting age- and maturity-adjusted cardiorespiratory fitness and muscular fitness while controlling for other predictors and covariates based on Cholesky decomposition analysis.

	Outcome variables (N = 441, 37 childcare centers, 80 schools)				Model fit information		
	CRF_{adj}	95 % CrI	Mf_{adj}	95 % CrI	PPP	95% CI	PSR
Unique contributions of TGMD-3 LMS_{adj} and OCS_{adj}							
TGMD-3 LMS_{adj}[a]	0.126*	(0.011, 0.239)	0.117*	(0.014, 0.220)	0.219	(−22.607, 59.950)	1.094
TGMD-3 OCS_{adj}[b]	0.055	(−0.067, 0.172)	0.084	(−0.024, 0.189)	0.222	(−23.618, 58.402)	1.094
Unique contributions of KTK_{adj}, TGMD-3 based LMS_{adj} and OCS_{adj}							
TGMD-3 LMS_{adj}[c]	0.021	(−0.112, 0.146)	0.042	(−0.073, 0.156)	0.122	(−19.332, 74.907)	1.098
TGMD-3 OCS_{adj}[d]	−0.017	(−0.139, 0.105)	0.045	(−0.064, 0.152)	0.128	(−19.767, 73.381)	1.097
KTK_{adj}[e]	0.304*	(0.147, 0.433)	0.178*	(0.022, 0.348)	0.134	(−18.373, 74.151)	1.094

CRF_{adj} = cardiorespiratory fitness adjusted for age and maturity, MF_{adj} = muscular fitness adjusted for age and maturity, CrI = credibility interval, PPP = posterior predictive probability value, CI = confidence interval, PSR = potential scale reduction coefficient, TGMD-3 = Test of Gross Motor Development-third edition, LMS_{adj} = locomotor skills adjusted for age, OCS_{adj} = object control skills adjusted for age, KTK_{adj} = Results of Körperkoordinationstest Für Kinder adjusted for age, * = significant to at least $p < .05$.

[a]Controlled by TGMD-3 OCS_{adj} and covariates, [b]Controlled by TGMD-3 LMS_{adj} and covariates, [c]Controlled by TGMD-3 OCS_{adj}, KTK_{adj} and covariates, [d]Controlled by TGMD-3 LMS_{adj}, KTK_{adj}, and covariates, [e]Controlled by TGMD-3 LMS_{adj} and OCS_{adj} and covariates.

6 DISCUSSION

The aim of this dissertation was to focus on the critical period of early childhood for the development and promotion of FMS (Goodway et al., 2019), examining how these skills impact future time spent engaging in various accelerometer-based PA intensities (Sub-study I) and HRF components, such as body composition measured by BMI (Sub-study II), CRF, and MF (Sub-study III). The main findings suggest that FMS may predict time spent engaged in PA intensities, including SB, CRF, and MF, but not BMI. However, the results especially support previous studies suggesting that the longitudinal relationship from FMS to PA, BMI, or CRF and MF may not be straightforward (Barnett et al., 2021; Barnett, Lai, et al., 2016; Cattuzzo et al., 2016; Utesch et al., 2019).

Regarding the investigated outcomes, the current results partly contradict previous findings. First, while previous theories have suggested that early childhood FMS may predict PA intensities in later childhood (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Stodden et al., 2008), findings from other studies (Barnett et al., 2021; Duncan et al., 2021; Gu, 2016; Gu et al., 2018; Lima, Pfeiffer, Larsen, et al., 2017) and the current results suggest that this longitudinal relationship is tenuous. Additionally, some findings do not support a longitudinal pathway from early childhood FMS to PA intensities in later childhood at all (Barnett et al., 2021; Bürgi et al., 2011; Foulkes et al., 2021; Melby et al., 2021; Nilsen et al., 2020; Schmutz et al., 2020), and some studies suggest that the pathway may be either reciprocal (Lima, Pfeiffer, Larsen, et al., 2017) or from PA to FMS (Bürgi et al., 2011; Nilsen et al., 2020; Reyes et al., 2019). The longitudinal relationship from FMS to PA intensities remains unclear, but LMS may be a more prominent predictor of PA than OCS in early childhood.

Second, the longitudinal relationship from early childhood FMS to CRF and MF in later childhood is supported by the current results, as well as previous theories (Robinson et al., 2015), reviews (Barnett et al., 2021; Cattuzzo et al., 2016; Utesch et al., 2019), and studies beginning in early childhood (Chen et al., 2023; Lima, Pfeiffer, Bugge, et al., 2017; Vlahov et al., 2014). However, the results of this dissertation also indicate that skill domains and the measurement method of FMS may confound the relationship, as previous studies have suggested (Cattuzzo et al., 2016; Utesch et al., 2019).

Third, the current results do not support an inverse bidirectional relationship between weight status and process-oriented FMS starting from early childhood, although previous theories (Robinson et al., 2015) and research evidence (Barnett et al., 2021; D'Hondt et al., 2014; Duncan et al., 2021; Lima et al., 2019; Vlahov et al., 2014) support such relationships. However, some evidence that does not support a longitudinal relationship between FMS and weight status (Foulkes et al., 2021; Lopes et al., 2020; Spring et al., 2023) aligns with the current results.

The results of this dissertation highlight and support previous findings that FMS, as categorized into LMS and OCS (Barnett et al., 2021; Barnett, Lai, et al., 2016; Goodway et al., 2019) or measured in both process- and product-oriented ways (Barnett et al., 2021; Palmer et al., 2021; Ré et al., 2018), may provide more detailed insights into their longitudinal relationships with the outcomes. This closer examination may provide some explanations for this dissertation's findings.

6.1 Early childhood locomotor skills as an underlying variable of physical activity and health-related fitness components

The results of this dissertation support previous evidence that early childhood LMS may be a prominent predictor of accelerometer-based PA intensities (Barnett et al., 2021; Duncan et al., 2021; Gu, 2016), as well as CRF and MF (Chen et al., 2023), compared to OCS in early childhood. However, the current results are inconsistent with studies beginning from early childhood that did not find longitudinal pathways, even from LMS to varying PA intensities (Foulkes et al., 2021; Melby et al., 2021; Nilsen et al., 2020), or that suggested a longitudinal relationship, along with LMS, from OCS to CRF and MF (Vlahov et al., 2014) or a relationship from OCS to PA in principally cross-sectional studies (Liu et al., 2023).

The development of LMS may explain their more prominent status compared to OCS, especially in early childhood. OCS require LMS, and thus LMS must develop earlier, while OCS are still developing (Goodway et al., 2019). Some previous findings have suggested that the role of OCS increases as children age towards adolescence (Barnett et al., 2008, 2009, 2021; Cohen et al., 2014; Okely et al., 2004; Vlahov et al., 2014), probably alongside LMS (Vlahov et al., 2014).

In addition, the characteristics of LMS may explain the relationships. LMS require body movements against gravity from point A to point B compared to more static OCS and might have a greater influence on pathways to PA (Rainham et al., 2012), CRF, and MF (Chen et al., 2023). Additionally, LMS, rather than OCS, may be more closely aligned with the abilities assessed in fitness tests (Chen et al., 2023). This perspective offers the potential for more accurate predictions of fitness outcomes and, probably, predictions of PA due to the relationship between PA and fitness outcomes (Serrano-Gallén et al., 2022). An LMS subtest such as running is an essential component of CRF tests, such as the shuttle run, while hopping and jumping reflect MF through lower limb strength (Castro-Piñero et al., 2010; Shinkle et al., 2012). Skill domains' different requirements, such as LMS with body movements against gravity and more static OCS, may also be related to other variables such as BMI (Barnett, Lai, et al., 2016) and gender (Zheng et al., 2022) in different ways, which may be revealed in models and affect relationships. BMI may have a greater impact on LMS compared to OCS (Barnett, Lai, et al., 2016). Additionally, boys tend to exhibit higher levels of OCS, whereas girls generally show stronger LMS (Zheng et al., 2022). However, this dissertation did not find gender differences, and bidirectional longitudinal relationships were not found between BMI and LMS or OCS for either gender.

Measurements of outcomes may also affect the relationships. Previous studies (Cohen et al., 2014) have supported LMS as a statistically significant predictor of MVPA measured by total amount during the day and amount after school, but not for MVPA during school breaks. OCS may be associated with games that involve MVPA (Barnett et al., 2009; Cohen et al., 2014), especially during school breaks (Cohen et al., 2014). Considering the total amount of PA in a day, as in this dissertation, children's time spent outside school hours, such as commuting between home and school, may be linked to a higher amount of MVPA (Rainham et al., 2012). In Finland, over 80% of primary school children actively travel (e.g., walking or cycling) to and from school (Turunen et al., 2023), which may emphasize LMS as a predictor of PA and the inverse association with SB, as well as the positive relationship with CRF (Ruiz et al., 2006) uncovered in this dissertation. Additionally, the most common PAs in their free time among 7–15-year-old children living in Finland include soccer, skating, ice hockey, skiing, swimming, cycling, and disc golf, depending on the time of year (Martin et al., 2023). All these activities require LMS, and some of these activities require OCS along with LMS. Along with children's PA, CRF and MF can be maintained at a good level (Serrano-Gallén et al., 2022) by using LMS. This may emphasize LMS as a predictor of PA, CRF, and MF.

Although LMS seem to be a stronger predictor of PA intensities, CRF, and MF than OCS, this does not explain all this dissertation's results. Sub-study III indicated that the product-oriented KTK, which includes locomotor-only subtests (Kiphard & Schilling, 2007), surpassed even process-oriented LMS as a predictor of CRF and MF when process-oriented LMS and OCS were controlled. This suggests that differences in process- and product-oriented measures of FMS may affect these relationships, especially with CRF and MF, aligning with the current results, as well as with body composition assessed by BMI, according to previous studies. The pathway from FMS to PA intensities remains indeterminate.

6.2 Longitudinal relationship from process- and product oriented fundamental movement skills to cardiorespiratory and muscular fitness

The results of this dissertation indicate that the early childhood product-oriented KTK independently predicts CRF and MF in later childhood, even when process-oriented LMS and OCS are controlled. These findings support the evidence that process- and product-oriented measures of FMS are not interchangeable (Logan et al., 2017; Palmer et al., 2021; Ré et al., 2018; Williams & Monsma, 2006). Comparing them could offer more detailed information and possible explanations for contradictory findings on the longitudinal relationships from FMS to outcomes. Comparing the results of Sub-study III to previous findings (Barnett et al., 2021; Cattuzzo et al., 2016; Utesch et al., 2019) supports the notion that product-oriented early childhood FMS may especially predict CRF and MF. However, to the best of our knowledge, a comparison of process- and product-oriented methods in this longitudinal aspect has not been done earlier.

Previous studies have found a statistically significant longitudinal relationship from early childhood FMS to CRF (Chen et al., 2023; Lima, Pfeiffer, Bugge, et al., 2017; Vlahov et al., 2014) or MF (Chen et al., 2023; Vlahov et al., 2014), regardless of the use of process-oriented (Chen et al., 2023; Vlahov et al., 2014) or product-oriented FMS (Lima, Pfeiffer, Bugge, et al., 2017). Statistically significant longitudinal relationships from specific product-oriented FMS-level groups to CRF or MF have also been found in previous studies (Fransen et al., 2014; Haugen & Johansen, 2018). These results align with the results of this dissertation because, regardless of the measurement method, FMS alone predict CRF and MF. However, process- and product-oriented measurements of FMS have not previously used in the same analysis, so the possible overshadowing effect of product-oriented FMS cannot be analyzed in previous studies.

The overshadowing effect of the product-oriented KTK compared to process-oriented skill domains as a predictor of CRF and MF may be related to the physical capacity component of product-oriented FMS that has characteristics similar to CRF and MF (Cattuzzo et al., 2016; Utesch et al., 2019). Although a comparison of process- and product-oriented FMS methods was absent in previous results regarding CRF and MF, the physical capacity component of FMS has been suggested to significantly influence, for example, the relationship between product-oriented FMS and executive functions (Malambo et al., 2022).

Similarities between the characteristics of product-oriented FMS and CRF or MF (Cattuzzo et al., 2016; Utesch et al., 2019), as well as differences between process- and product-oriented FMS measurement methods (Logan et al., 2017; Palmer et al., 2021; Ré et al., 2018; Williams & Monsma, 2006), such as the TGMD-3 and KTK, may explain the current results. Product-oriented tests may include, more so than process-oriented tests, physical capacity components alongside elements of fitness testing such as high force, speed, and muscular endurance, offering stronger predictive power for CRF and MF. Conversely, the process-oriented view of FMS, such as the TGMD-3 (Ulrich, 2019), emphasizes the quality of movement and observed movement patterns, execution methods, body positioning, and motion engagement (Williams & Monsma, 2006). These tests are brief and do not demand high physical capacity, unlike product-oriented measures, which often overlap with the physical capacity components of fitness tests (Utesch et al., 2019). At the same time, it is suggested that, along with FMS (Chen et al., 2023; Kolunsarka et al., 2022; Schmutz et al., 2020), CRF (Kolunsarka et al., 2022) and MF (García-Hermoso et al., 2022) remain quite stable from childhood into adulthood, which may support the significant relationship observed from the KTK to CRF and MF with similar characteristics.

Due to its similar characteristics, the product-oriented KTK may broadly measure MF (Utesch et al., 2019) compared to the process-oriented TGMD-3. The KTK subtests, especially jumping sideways and hopping for height on one foot, require, in addition to skills, a notable degree of lower limb muscular fitness. Further, core strength plays a significant role in the ability to create and transfer force in the lower limbs (Shinkle et al., 2012), and core strength was measured through an endurance approach using curl-ups in Sub-study III. The outcomes of jump tests have been found to relate to the results of push-ups (Castro-Piñero et al., 2010) by which MF was determined, along with curl-ups, in the current study.

Similar elements can also be found in both the KTK and CRF tests. The KTK (Moreira et al., 2019) and the 20-meter shuttle run test (Tomkinson et al., 2019), which was used in the current study, both involve balance, rhythm, speed, and agility, especially when changing direction. Poorer agility, which affects the ability to quickly change direction or speed in the 20-meter shuttle run test, can increase the oxygen cost of running, thereby challenging CRF assessment performance (Tomkinson et al., 2019). The KTK subtests, especially jumping sideways and moving sideways, are also thought to evaluate anaerobic capacity due to their brief but intense nature (Green & Dawson, 1993). Further, maximal aerobic performance in the 20-meter shuttle run test could be influenced by anaerobic capacity (Bassett & Howley, 2000). This capacity plays a key role in tests such as the 20-meter shuttle run because it provides the energy required for short, high-intensity activities. Reduced anaerobic capacity limits the energy available from anaerobic metabolism, which becomes crucial in the test’s final stages. This is particularly relevant for children nearing the end of the test or those who can complete only a few stages due to a weak condition (Tomkinson et al., 2019).

In addition to the physical capacity component, the process-oriented TGMD-3 (Ulrich, 2019) and product-oriented KTK (Kiphard & Schilling, 2007) are scored differently and were developed for different target groups. The TGMD-3 has a value-limited scoring system, creating a potential ceiling effect (Ulrich, 2019) that may restrict variability among participants. In contrast, the KTK (Kiphard & Schilling, 2007) includes only time constraints, without a maximum score limit in the moving sideways and jumping sideways subtests. These differences in scoring may allow the KTK to capture a broader range of

CRF and MF than the TGMD-3. Differences in scoring and the possible ceiling effect between the TGMD-3 and KTK, along with differences due to the designed target group of the tests (Kiphard & Schilling, 2007; Ulrich, 2019), show that the TGMD-3 may be more suitable for younger children compared to the KTK. Additionally, it is notable that the KTK subtests, such as walking backwards, might not challenge older children as much (Utesch et al., 2018), leading to less variability in older children's KTK results. However, in Sub-studies I and III, the ceiling effect of TGMD-3 was not detected according to a comparison of the participants' scores with the maximum test scores. In Sub-study II, regarding only the four subtests of the TGMD-3 used, a ceiling effect may be more likely to have occurred because of narrower variation in the results.

Only longitudinal relationships from process- and product-oriented FMS to CRF and MF, not PA intensities or BMI, were analyzed in this dissertation. However, the current findings of longitudinal relationships between process-oriented FMS and body composition (Sub-study II), along with previous findings, may support the effect of the measurement method on the bidirectional relationship between BMI and FMS.

6.3 Fundamental movement skills as a predictor of body composition

Regarding the bidirectional longitudinal relationship between FMS and BMI, previous findings are contradictory. As in this dissertation, previous studies starting from early childhood (Foulkes et al., 2021; Lopes et al., 2020) that used process-oriented FMS to examine pathways from FMS to BMI (Foulkes et al., 2021) or the reverse pathway (Lopes et al., 2020) found no statistically significant relationships. Notably, contradictory results have been reported from process-oriented early childhood FMS to BMI (Duncan et al., 2021) or body fatness (Vlahov et al., 2014), although these studies did not account for the baseline values of the predictive variables. As previous studies and the results of Sub-study II have shown, baseline BMI (Rooney et al., 2011; Simmonds et al., 2016), as well as FMS (Chen et al., 2023; Kolunsarka et al., 2022; Schmutz et al., 2020), predict themselves at follow-up. The absence of baseline values potentially overlooks changes or developments in these variables, which could have impacted the results of statistically significant longitudinal relationships (Vickers & Altman, 2001) and partly explain these contradictory findings. Most longitudinal and cross-sectional studies starting in early childhood that were included in Trecroci et al.'s (2021) systematic review reported a negative relationship between FMS and weight status. However, the evidence remains uncertain and lacking due to the risk of bias (Trecroci et al., 2021).

In light of this dissertation's results, it cannot be directly inferred that product-oriented FMS, which includes a physical capacity component, would predict BMI more significantly than qualitative process-oriented FMS because comparable analyses have not been performed. Regarding outcomes such as CRF and MF, process-oriented FMS alone predicted these outcomes, and only the comparative analyses revealed the overshadowing effect of product-oriented FMS, probably due to the physical capacity component. In this dissertation, the longitudinal relationship between FMS and BMI (Sub-study II) was analyzed only with the process-oriented TGMD-3 and not the product-oriented KTK, as was done for CRF and MF (Sub-study III). However, the current results mirror previous findings and reflect the use of different FMS measurement methods.

According to previous studies, the physical capacity component of product-oriented FMS may primarily drive the bidirectional longitudinal relationship between BMI and FMS, beginning in early childhood. Previous findings suggest that bidirectional longitudinal relationships may occur, especially between product-oriented FMS and weight status measured by BMI (D'Hondt et al., 2014) or body fatness (Lima et al., 2019). Additionally, previous studies have demonstrated an inverse longitudinal relationship between weight status and physical fitness tests in early childhood (Ortega et al., 2013; Silva-Santos et al., 2017), which may be explained by increased muscle mass leading to higher calorie expenditure (Ortega et al., 2013). However, there are also conflicting results regarding the relationship between BMI and physical fitness (Lopes et al., 2020).

Overweight and obesity can pose challenges for children moving body mass against gravity in the tests (Cattuzzo et al., 2016), which can partly explain differences between process- and product-oriented methods of measuring FMS and its relationship to weight status. The presence of overweight or obesity may negatively influence the performance of product-oriented FMS in children (D'Hondt et al., 2011), while the relationship between process-oriented FMS and overweight or obesity is not as clear-cut and may exist only for LMS (Ma & Luo, 2023; Webster et al., 2021).

The results of the bidirectional longitudinal relationship between FMS and body composition are indeterminate, but it may be that the physical capacity component of FMS drives these relationships. However, the stability of FMS (Chen et al., 2023; Kolunsarka et al., 2022; Schmutz et al., 2020) and obesity (Rooney et al., 2011; Simmonds et al., 2016), even beginning in early childhood, highlight the importance of investigating longitudinal relationships beginning in the early childhood years.

6.4 Fundamental movement skills as an underlying variable in time spent engaging in physical activity intensities

The longitudinal relationship from early childhood FMS or skill domains to time spent engaging in different PA intensities remains unclear. As mentioned, according to the current results and previous studies, LMS may be a more prominent predictor than OCS. However, the longitudinal relationship from

FMS, regardless of the measurement method, to PA intensities may still be tenuous, according to the current and previous results.

Some previous studies did not find a statistically significant longitudinal relationship from early childhood FMS to PA intensities (Barnett et al., 2021; Bürgi et al., 2011; Foulkes et al., 2021; Melby et al., 2021; Nilsen et al., 2020; Schmutz et al., 2020), while a statistically significant longitudinal pathway from PA to FMS has also been found (Estevan et al., 2022; Lima, Pfeiffer, Larsen, et al., 2017; Nilsen et al., 2020; Reyes et al., 2019). Other studies found no relationship in either direction (Schmutz et al., 2020).

However, other studies (Duncan et al., 2021; Gu, 2016; Gu et al., 2018; Lima, Pfeiffer, Larsen, et al., 2017), as well as the results of Sub-study I, support a longitudinal relationship from early childhood FMS to PA intensities, especially to VPA (Lima, Pfeiffer, Larsen, et al., 2017), MVPA (Duncan et al., 2021; Gu, 2016; Gu et al., 2018), LPA (Duncan et al., 2021), and, inversely, SB (Duncan et al., 2021; Gu, 2016; Gu et al., 2018). After controlling for BMI, Gu (2016) also reported a statistically significant longitudinal relationship from FMS to VPA and, inversely, LPA. However, all the variations of PA intensities were not used in the analyses of previous studies, but the findings align with Sub-study I, which found a tenuous but statistically significant longitudinal relationship from FMS, particularly LMS, to MPA, VPA, MVPA, and, inversely, SB.

As reported in previous reviews (Barnett et al., 2021; Jones et al., 2020; Xin et al., 2020), comparing study results is complicated, for example, by variability in target groups (e.g., age and gender), differences in the measurements of FMS and PA, and variations in follow-up periods. Moreover, cultural variations may occur (Adeyemi-Walker et al., 2018; Barnett et al., 2021; Cordovil et al., 2022; Jeong et al., 2023; Robinson et al., 2015).

FMS can be measured using numerous different metrics and interpreted in different ways (Hulteen et al., 2020; Palmer et al., 2021). Regarding the longitudinal relationship from process- and product-oriented FMS to PA intensities, previous results seem to present contradictory aspects of process- and product-oriented FMS methods. Both process- (Duncan et al., 2021; Foulkes et al., 2021; Gu, 2016; Gu et al., 2018; Nilsen et al., 2020; Schmutz et al., 2020) and product-oriented (Bürgi et al., 2011; Lima, Pfeiffer, Bugge, et al., 2017; Melby et al., 2021) FMS measurements have produced indeterminate findings regarding the longitudinal relationship with PA intensities when different FMS measurements were used, beginning in early childhood. Possibly, the relationship is like the pathway from FMS to CRF and MF, in which case a statistically significant longitudinal relationship can be found for both measurement methods, even if the measurement method containing physical capacity may be more prominent or overshadowing.

It should also be noted that not all product-oriented measures contain a strong physical capacity component, which is proposed to explain the longitudinal relationship from early childhood FMS to PA. For example, Bürgi et al. (2011) used short agility (obstacle course) and dynamic balance (balance beam) tests and did not find a relationship from these test results to PA intensities. On the other hand, Schmutz et al. (2020) measured skill outcomes, but the performance scores ranged only between 0 and 4. The physical capacity component may be significant as well as the broader variability of FMS metrics. However, studies comparing process- and product-oriented FMS measurements that included a physical capacity component have not been found with aspects of PA intensities.

In addition to the contradictory nature of previous results, most of the variation in PA remained unexplained in the models (R^2 range 5.1%–14.4%) examined in Sub-study I. In addition, Sub-study I did not account for the baseline values of the outcome as predictors, nor did some previous studies (Duncan et al., 2021; Gu, 2016; Gu et al., 2018), which may overlook significant results (Vickers & Altman, 2001) with quite stable FMS values (Chen et al., 2023; Kolunsarka et al., 2022; Schmutz et al., 2020) and PA intensities (Malina, 1996, 2001; Schmutz et al., 2020) that included SB (Schmutz et al., 2018) in childhood.

Instead of the evidenced stable nature of FMS (Chen et al., 2023; Kolunsarka et al., 2022; Schmutz et al., 2020) and PA (Malina, 1996, 2001; Schmutz et al., 2020), the cross-sectional relationship between the FMS level and time spent engaging in PA may be stronger than the longitudinal relationship between these variables (Nilsen et al., 2020). The follow-up period varied quite a lot in previous studies, but a short follow-up period (≤1 year) does not explain the indeterminate findings on the pathway from early childhood FMS to PA found in some short longitudinal studies (Duncan et al., 2021; Gu, 2016; Gu et al., 2018) but not in others (Bürgi et al., 2011; Schmutz et al., 2020). Nor did a longer follow-up period evidence a statistically significant pathway from early childhood FMS to PA (Foulkes et al., 2021; Melby et al., 2021; Nilsen et al., 2020).

FMS seem to be more stable than PA in childhood (Schmutz et al., 2020). FMS develop in childhood (Barnett, Lai, et al., 2016), while time spent engaging in PA decreases with age (Farooq et al., 2020; Lounassalo et al., 2019) and may also be rather unstable in childhood (Telama, 2009), for example, depending on the time of year (Martin et al., 2023). This partly supports the notion that FMS does not strongly relate to time spent engaging in PA intensities. It also suggests that variables other than FMS, such as age and gender (Schmutz et al., 2018), and some variables that were excluded from the models in Sub-study I, play a significant role in the time spent engaged in PA at varying intensities. Due to numerous biological, psychological, sociocultural, and environmental variables that impact the amount of PA (Li & Moosbrugger, 2021), along with effects of age and gender, the influence of FMS may remain small. It is also possible that a longitudinal relationship from FMS to outcomes does not yet appear in early childhood (Barnett et al., 2021; Melby et al., 2021; Robinson et al., 2015) or that the suggested proficiency barrier of FMS (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Seefeldt, 1980; Stodden et al., 2008) was exceeded among the participants of this study.

6.5 Strengths and limitations of the dissertation

The strength of this dissertation lies in its investigation of longitudinal data on young children in early childhood, with an average follow-up period of 3 years (Sub-studies I and II) or 6 years (Sub-study III). The use of clustered data accounted for two-level regression analysis (Sub-study I) or its extensions—two-level, cross-classified, and cross-lagged regression analysis (Sub-study II)—and two-level cross-classified regression analysis with Cholesky decomposition analysis (Sub-study III) was also a strength.

The use of total FMS scores and skill domains (Sub-studies I and II), comparing process- and product-oriented measurements of FMS (Sub-study III), as well as PA intensities (Sub-study I) and HRF components (Sub-studies II and III), offered more specific information on the pathways beginning in early childhood FMS. Additionally, controlling for age and the varied time between baseline and follow-up measurements as predictors (Sub-study I), or through residualization (Sub-studies II and III), accounted for the age-related characteristics of FMS (Barnett, Lai, et al., 2016). Maturity (Mirwald et al., 2002) was also controlled due to residualization in the follow-up when it could have affected the results in Sub-study III.

Along with its strengths, there are also limitations in the current dissertation. A comparison of FMS's process- and product-oriented measurement methods was done only in Sub-study III. However, in this study, it was not possible to compare skill domains measured in a product-oriented way. Furthermore, in Sub-study II, LMS and OCS levels were each based only on two TGMD-3 subtests, resulting in the total FMS level being based on the results of four subtests. Although these subtests have been found to describe the skill domains well (Wagner et al., 2016), they may provide a limited picture of the longitudinal relationship between BMI and FMS. Additionally, the possible ceiling effect of TGMD-3 might have influenced the results (Ulrich, 2019), especially when only four subtests were used in total. However, regarding Sub-studies I and III, the possible ceiling effect of TGMD-3 does not seem realistically to have affected the results because only very few children achieved the maximum score for LMS, and no one did for OCS, which was based on all TGMD-3 subtests.

The PA, CRF, and MF results were not evaluated at baseline, making it impossible to use the baseline value of the outcomes as a predictor. For stability of outcomes (García-Hermoso et al., 2022; Kolunsarka et al., 2022; Malina, 1996, 2001; Schmutz et al., 2020), obtaining detailed information on longitudinal relationships could be beneficial. Despite the use of high-quality measures, these have their own challenges. Accelerometer-based PA does not account for the quality, context, or type of PA (Barnett, Salmon, et al., 2016). For instance, it does not account for water activities because the device must be removed during such activities. Additionally, the analysis period of two weekdays and one weekend day for PA in Sub-study I may not have offered a representative picture of habitual PA, although it may provide an acceptable level of reliability (Penpraze et al., 2006).

The data in the current dissertation included children living in Finland. The possible cultural characteristics and homogeneity of this sample compared to international studies, particularly regarding BMI, could also impact the findings. Dropout is usually a challenge in the voluntary participation of longitudinal studies (Hogan et al., 2004), as in the current research. However, the longitudinal data of the studies were missing completely at random.

6.6 Future perspectives

In the future, the results of this dissertation suggest examining the longitudinal bidirectional relationship between FMS and PA intensities, as well as HRF components, beginning from early childhood to adolescence and beyond, considering the stability of the variables. Comparing process- and product-oriented ways of measuring FMS or tests that require physical capacity or not, as well as skill domains, may provide detailed information on these relationships. Additionally, considering detailed outcomes, PA intensities, and HRF components may offer a more accurate picture of longitudinal relationships beginning in early childhood FMS.

However, measurement methods should be chosen carefully because numerous metrics of FMS (Hulteen et al., 2020), PA (Jones et al., 2020), body composition (Jeong et al., 2023; Meyers et al., 2013), CRF (Bruggeman et al., 2020; Léger & Lambert, 1982), and MF (Jaakkola et al., 2012; Marques et al., 2021) are available. Moreover, a comparable FMS test method suitable from early childhood to adolescence and beyond is not available (Hulteen et al., 2022). Thus, reliable comparisons of measurements of longitudinal data should be noted, considering variations in study samples and follow-up periods (Barnett et al., 2021; Jones et al., 2020; Xin et al., 2020). Even using the same test in different studies may not guarantee reliable comparisons. For instance, the TGMD-3 may vary among different research teams (Hulteen et al., 2023), and the different versions of the test, TGMD-2 and TGMD-3, are not completely aligned in terms of their subtests and scoring, particularly in OCS (Field et al., 2020). Furthermore, considering cultural variations (Hulteen et al., 2022) and different target groups or study populations, such as different ages, genders, ethnicities, and the number of overweight or obese children, makes comparing results more complex (Adeyemi-Walker et al., 2018; Jeong et al., 2023).

Thus, follow-up data should collect high-quality measures from the same study population at multiple time points, enabling the use of growth curve analysis methods. It is also important to determine constructs carefully (Logan et al., 2018) and describe what characteristics have been measured, as overlap between variables, for example, between the physical capacity component of FMS and CRF or MF (Cattuzzo et al., 2016; Utesch et al., 2019), may confuse relationships.

7 CONCLUSION

The results of this dissertation suggest that the measurement method of early childhood FMS can influence their predictive power regarding outcome variables in later childhood. The findings underscore the importance of recognizing skill domains and determining whether the measurement of FMS using both process- and product-oriented methods includes a physical capacity component. This is crucial for gaining a clearer understanding of their relationships with outcome variables.

Despite some partly contradictory evidence from previous studies (Foulkes et al., 2021; Liu et al., 2023; Melby et al., 2021; Nilsen et al., 2020; Vlahov et al., 2014), this dissertation's results suggest that early childhood LMS, compared to OCS, is a more important predictor of PA throughout the day, including SB and health-related components such as CRF and MF, due to the developmental order and requirements of skill domains (Goodway et al., 2019). When investigating the bidirectional longitudinal relationship between skill domains and BMI, with baseline and follow-up values of all variables accounted for, LMS do not appear to be a statistically significant predictor of BMI.

In this research, most of the variance in PA, SB, CRF, and MF remained unexplained in the executed models. This suggests that the effect of FMS, along with other variables included in the models, could be minor and that external variables may significantly influence these outcomes. On the other hand, higher levels of PA, lower levels of SB, good CRF and MF, and a health-promoting body composition may be achieved even with lower levels of FMS, as long as the child finds suitable ways to be active in daily life and other lifestyle factors support these attributes. It is also possible that the longitudinal relationship of FMS has not yet manifested in early childhood (Barnett et al., 2021; Melby et al., 2021; Robinson et al., 2015).

When promoting children's FMS, PA, and HRF components, it is important to focus on their growth environments, including families, childcare centers, and schools. The results of this dissertation highlight the fact that individual differences alone may not fully explain the variation, and variables related to childcare centers and schools should also be considered due to statistically significant between-level variances. A more holistic picture of variables that predict outcomes is needed, including a variety of biological, psychological, sociocultural, and environmental variables (Li & Moosbrugger, 2021; McPhee et al., 2023; Veldman et al., 2023; Weihrauch-Blüher & Wiegand, 2018). Especially in early childhood, the influence of the family may also be significant (Kondolot et al., 2017; Rooney et al., 2011; Schmutz et al., 2018; Scott-Sheldon et al., 2020). Adults have the responsibility to set an example and support children's health behaviors.

The current results and previous findings do not provide strong and straightforward evidence of longitudinal relationships from differently measured FMS to outcomes. The predictive power of baseline values (Chen et al., 2023; García-Hermoso et al., 2022; Kolunsarka et al., 2022; Malina, 1996, 2001; Rooney et al., 2011; Schmutz et al., 2018, 2020; Simmonds et al., 2016) for later life suggests that these variables may develop independently or that longitudinal relationships might be in the opposite direction, if they exist at all, or may occur between outcomes, such as from PA to physical fitness (Ortega et al., 2008). However, the current and previous results highlight the importance of investigating longitudinal relationships starting in early childhood, as this period may predict outcomes in later life (Chen et al., 2023; García-Hermoso et al., 2022; Kolunsarka et al., 2022; Malina, 1996, 2001; Rooney et al., 2011; Schmutz et al., 2018, 2020; Simmonds et al., 2016).

SUMMARY IN FINNISH

Varhaislapsuuden motoriset taidot, niiden osa-alueet ja erilaiset mittausmenetelmät myöhemmin lapsuudessa mitatun fyysisen aktiivisuuden ja terveyskunnon taustalla

Fyysisen aktiivisuuden väheneminen ja passiivisen paikallaanolon lisääntyminen, kestävyys- ja lihaskunnon lasku sekä ylipainon ja lihavuuden lisääntyminen lapsuudesta alkaen ovat maailmanlaajuisia ongelmia, jotka aiheuttavat terveysriskejä, heikentävät toimintakykyä ja aiheuttavat suuret kustannukset yhteiskunnalle. Vastaavasti riittävän fyysisen aktiivisuuden, suositusten mukaisen paikallaanolon, hyvän kestävyys- ja lihaskunnon sekä normaalipainon rajoissa pysyvän painoindeksin hyödyt ovat laajat ja terveydellisesti merkittävät.

Teoreettiset viitekehykset ovat ehdottaneet, että lapsuuden hyvät motoriset taidot, yksilön kyky suorittaa tarkasti ja koordinoidusti silmin havaittavia karkeamotorisia liikkeitä isoilla kehon tai raajojen lihaksilla hermo- ja lihasjärjestelmien sekä biomekaanisten- ja havaintomekanismien ohjaamana, voivat olla merkittävä muuttuja terveyden kannalta riittävän fyysisen aktiivisuuden ja terveyskunnon osa-alueiden, kuten hyvän kestävyys- ja lihaskunnon sekä terveyttä edistävän kehonkoostumuksen taustalla. Pitkittäistutkimuksia erityisesti varhaislapsuuden motorisista taidoista alkaen on toteutettu kuitenkin varsin rajallinen määrä ja tulokset ovat epäjohdonmukaisuudessaan ristiriitaisia.

Varhaislapsuus nähdään merkittävänä motoristen taitojen kehittymisen ja lasten terveyskäyttäytymiseen vaikuttamisen ajanjaksona. Lisäksi motoriset taidot säilyvät melko vakaana suhteessa vertaisiin koko lapsuuden ajan. Näin ollen jo varhaislapsuuden motoristen taitojen pitkittäisyhteydet fyysiseen aktiivisuuteen ja paikallaanoloon, kestävyys- ja lihaskuntoon sekä kehonkoostumukseen ovat tärkeä tutkimuskohde, jotta näihin lopputulosmuuttujiin voitaisiin vaikuttaa riittävän ajoissa ja ennustaa myös muuttujien tasoa myöhemmin elämässä.

Motoristen taitojen jakaminen liikkumis- ja välineenkäsittelytaitoihin tai motoristen taitojen arviointi suorituksen laatuun ja määrälliseen lopputulokseen perustuen voivat selkiyttää varhaislapsuuden motoristen taitojen pitkittäissuhdetta fyysiseen aktiivisuuteen, paikallaanoloon, kestävyys- ja lihaskuntoon sekä kehonkoostumukseen. Terveyskunnon valittujen osa-alueiden lisäksi fyysisen aktiivisuuden intensiteettien käyttö lopputulosmuuttujina voi myös antaa tarkempaa kuvaa pitkittäisyhteyksistä.

Tämän väitöskirjan tulokset perustuvat kolmeen osatutkimukseen. Väitöskirjan tavoitteena oli varhaislapsuuden motoristen taitojen jaottelulla liikkumis- ja välineenkäsittelytaitoihin (osatutkimukset I-III), tai motorisen suorituksen laatuun ja määrälliseen lopputulokseen perustuvien motoristen taitojen vertailun avulla (osatutkimus III) tarkentaa motoristen taitojen pitkittäisyhteyttä fyysiseen aktiivisuuteen ja paikallaanoloon (osatutkimus I) sekä kestävyys- ja lihaskuntoon (osatutkimus III). Lisäksi väitöskirjan tarkoituksena oli tarkastella motoristen taitojen ja painoindeksin molemmin suuntaista pitkittäisyhteyttä varhaislapsuudesta alkaen (osatutkimus II).

Tämän väitöskirjan pitkittäisaineisto perustui kolmessa toisiaan seuranneessa Opetus- ja kulttuuriministeriön rahoittamassa tutkimusprojektissa kerättyyn aineistoon. Tutkittavien varhaislapsuuden (3–8-vuotiaat) alkutilanne, jota on hyödynnetty kaikissa tämän väitöskirjan osatutkimuksissa, koostuu Taitavat tenavat (2015–2016, OKM/48/626/2014) -tutkimukseen osallistuneiden 950 tutkittavan kysely- ja mittaustuloksista. Ensimmäinen seuranta toteutettiin noin kolmen vuoden päästä alkutilanteesta Liikkuva perhe (2018–2020, OKM/59/626/2017) -tutkimuksessa, johon tavoitettiin 675 alkutilanteeseen osallistunutta tutkittavaa. Liikkuva perhe -tutkimuksen aineistoa käytettiin seurantapisteenä tämän väitöskirjan I (n=441) ja II (n=675) osatutkimuksessa. Toinen pitkittäisaineiston seurantapiste toteutui noin kuuden vuoden päästä alkutilanteesta Taidot, sosiaalinen tuki ja liikunta-aktiivisuus - Taiturit (2021–2023, OKM19/626/2021) -tutkimuksessa, johon osallistui 441 pitkittäisaineistoon kuuluvaa tutkittavaa. Tätä seurantapistettä käytettiin osatutkimuksessa III (n=441).

Osatutkimuksissa käytettiin kaksitasoista regressioanalyysiä, jossa huomioitiin tutkittavien jakautuminen kouluihin (osatutkimukset I-III) ja päiväkoteihin (osatutkimukset II ja III). Kuitenkin vain yksilötason muuttujia käytettiin analyyseissä. Osatutkimuksessa II sovellettiin cross-lagged mallia molemmin suuntaisen pitkittäissuhteen selvittämiseksi motoristen taitojen ja painoindeksin välillä, ja osatutkimuksessa III hyödynnettiin Choleskin decomposition -mallia selvitettäessä suorituksen laatuun ja lopputulokseen perustuvien motoristen taitojen itsenäistä vaikutusta kestävyys- ja lihaskuntoon.

Suorituksen laatuun perustuvana motorisen taidon mittarina käytettiin kaikissa osatutkimuksissa Test of Gross Motor Development -testin kolmatta versiota (TGMD-3). Suorituksen määrälliseen lopputulokseen perustuvana motorisen taidon mittarina käytettiin puolestaan neljästä osatestistä koostuvaa Körperkoordinationstest Für Kinder (KTK) -testiä. Fyysisen aktiivisuuden määrä, eri intensiteetit huomioituna, perustui kiihtyvyysanturilla (RM-42, UKK Terveyspalvelut Oy, Tampere) suoritettuihin mittauksiin. Painoindeksi kuvattiin suomalaisten lasten kasvukäyriin perustuvina keskihajonta-arvoina, jotka laskettiin tutkittavan sukupuolta, ikää, kehon massaa ja pituutta hyödyntämällä. Kestävyyskunto määritettiin 20 metrin viivajuoksutestillä ja lihaskunnon tulos perustui punnerrus- ja vatsalihastestien yhteistulokseen.

Tämän väitöskirjan tulokset korostavat, että pitkittäissuhteet varhaislapsuuden motorisista taidoista tässä tutkimuksessa käytettyihin lopputulosmuuttujiin eivät ole yksiselitteisiä. Tulokset tuovat esille, että varhaislapsuuden motorisista taidoista liikkumistaidot voivat olla välineenkäsittelytaitoja merkittävämpi kestävyys- ja lihaskunnon sekä fyysisen aktiivisuuden ennustaja, erityisesti kohtalaisen ja rasittavan fyysisen aktiivisuuden sekä paikallaanolon osalta. Liikkumistaidot mahdollisesti korostuvat varhaislapsuudessa niiden ollessa tuolloin kehittyneemmät kuin välineenkäsittelytaidot. Lisäksi suomalaisten lasten suosimat liikkumisen muodot ja koulumatkojen kulkeminen aktiivisesti korostavat erityisesti liikkumistaitoja fyysisen aktiivisuuden taustalla. Liikkumistaidoissa on myös samankaltaisia ominaisuuksia kuin kestävyys- ja lihaskuntotesteissä, jonka vuoksi liikkumistaidot voivat näyttäytyä merkittävämpänä ennustajana aikaisempien tutkimusten mukaan melko pysyville kestävyys- ja lihaskuntomuuttujille.

Lisäksi tämän väitöskirjan tulokset osoittavat motorisen suorituksen määrälliseen lopputulokseen perustuvien liikkumistaitojen säilyttävän itsenäisen vaikutuksen kestävyys- ja lihaskuntoon suoritukseen laatuun perustuvien motoristen taitojen ollessa kontrolloituna. Myös tältä osin suorituksen määrälliseen lopputulokseen perustuvan motorisen taidon päällekkäisyys ja fyysiseen kuntoon liittyvien vaatimusten samankaltaisuus kestävyys- ja lihaskuntotestien kanssa voivat selittää suorituksen määrälliseen lopputulokseen perustuvien motoristen taitojen merkittävämmän ennustusvaikutuksen. Painoindeksin ja fyysisen aktiivisuuden osalta suorituksen laatuun ja määrälliseen lopputulokseen perustuvia motorisia taitoja ei vertailtu analyyseissä, mutta tässä väitöskirjassa saatujen tulosten ja aikaisempien tutkimustulosten valossa voidaan ehdottaa motorisen taidon mittaustavan mahdollisesti vaikuttavan myös näihin pitkittäisyhteyksiin.

Yhteenvetona voidaan todeta tämän väitöskirjan tulosten ehdottavan, että varhaislapsuuden motoristen taitojen tarkempi määrittely ja jaottelu voi tuottaa selkeämmän kuvan motorisista taidoista lopputulosmuuttujien ennustajana. Motoristen taitojen ennustavuus tutkittuihin lopputulosmuuttujiin saattaa kuitenkin olla suhteellisen vähäinen, sillä suurin osa fyysisen aktiivisuuden ja paikallaanolon sekä kestävyys- ja lihaskunnon vaihtelusta jää tarkastelluissa malleissa selittämättä ja pitkittäisyhteyttä painoindeksin ja motoristen taitojen välillä ei havaittu lainkaan. On myös mahdollista, että pitkittäisyhteydet ovat havaittavissa vasta varhaislapsuuden jälkeen, mikäli yhteydet voimistuvat myöhemmin lapsuudessa. Toisaalta terveyden kannalta riittävä fyysinen aktiivisuus, suositusten mukainen paikallaanolo, hyvä kestävyys- ja lihaskunto sekä terveyttä edistävä kehonkoostumus voivat olla saavutettavissa alhaisemmillakin motorisilla taidoilla, mikäli lapsi löytää itselleen sopivan tavan liikkua arjessa ja muut elämäntavat tukevat näiden ominaisuuksien saavuttamista.

Todennäköisesti pelkät motoristen taitojen kaltaiset yksilölliset tekijät eivät riitä selittämään tarkasteltuja lopputulosmuuttujia, sillä myös päiväkoti- ja kouluympäristöt näyttäisivät vaikuttavan lopputulosmuuttujiin. Aikaisempien tutkimusten valossa erityisesti varhaislapsuudessa myös perheen vaikutus lapsen fyysiseen aktiivisuuteen ja terveyskuntoon voi olla merkittävä. Näin ollen lapsen kasvuympäristön aikuisilla voidaan nähdä olevan tärkeä tehtävä, velvollisuus ja vastuu edistää lasten fyysistä aktiivisuutta ja terveyskuntoa omalla esimerkillään ja toiminnoillaan jo varhaislapsuudesta alkaen.

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ORIGINAL PAPERS

I

DO FUNDAMENTAL MOVEMENT SKILL DOMAINS IN EARLY CHILDHOOD PREDICT ENGAGEMENT IN PHYSICAL ACTIVITY OF VARIED INTENSITIES LATER AT SCHOOL AGE? A 3-YEAR LONGITUDINAL STUDY

by

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Human Kinetics
ORIGINAL RESEARCH

Do Fundamental Movement Skill Domains in Early Childhood Predict Engagement in Physical Activity of Varied Intensities Later at School Age? A 3-Year Longitudinal Study

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This study was conducted to determine how total fundamental movement skill (FMS) score and, separately, locomotor skill (LMS), and object control skill scores in children 3–8 years old predicted their specific-intensity physical activity 3 years later. Overall, 441 Finnish children (51.7% female, baseline mean age of 5.6 years) participated in the study. Total FMS, LMS, and object control skill scores were assessed using the Test of Gross Motor Development, third edition. The time spent engaged in physical activity of different intensities (light, moderate, vigorous, moderate-to-vigorous, light-to-vigorous, and sedentary behavior) was determined using accelerometers. A two-level regression model was used in the analysis, considering potential covariates and interactions. The results showed that moderate physical activity, vigorous physical activity, and moderate-to-vigorous physical activity were predicted by the total FMS score ($\beta = 0.177$ to 0.203, $p = .001–.003$) and the LMS score ($\beta = 0.140$ to 0.164, $p = .004–.014$), but not the object control skill score. Moreover, the LMS score inversely predicted sedentary behavior ($\beta = -0.116$, $p = .042$). In conclusion, higher FMS and, specifically, LMS scores seem to predict more engagement in moderate-to-vigorous physical activity and less sedentary behavior over time. However, most of the variance in physical activity remains unexplained.

Keywords: children, infancy, motor development

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Evidence has shown the health benefits (e.g., bone health, reduced risk for being overweight) of engaging in physical activity (PA) during childhood (Pate et al., 2019; World Health Organization, 2019, 2020). While moderate-to-vigorous physical activity (MVPA) is recommended to promote children's health and well-being, lower levels of activity, such as light physical activity (LPA) are also beneficial (World Health Organization, 2019, 2020). However, the amount of PA that children engage in seems to decrease with age (Cooper et al., 2015; Farooq et al., 2020; Lounassalo et al., 2019), starting at an average age of 7.7 years (Lounassalo et al., 2019). Hence, insufficient PA as a risk factor for noncommunicable diseases and reduced quality of life is a global concern (Guthold et al., 2020; Tucker, 2008). In addition, reducing sedentary behavior (SB) also is important to preventing disease and improving public health (Park et al., 2020). For these reasons, the underlying mechanisms of PA behaviors are important to understand.

Understanding that the underlying mechanisms of PA, such as fundamental movement skills (FMS), start in early childhood is crucial. FMS refer to the performance level of the neural, muscular, biomechanical, and perceptual mechanism involved in movement; the FMS development phase occurs in early childhood (Goodway et al., 2019, pp. 36, 118–119), in children aged eight or younger (UNICEF, 2022). Many theoretical models and frameworks (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Seefeldt, 1980; Stodden et al., 2008) have suggested that children with limited FMS in early childhood may have restricted opportunities for engagement in PA later in childhood because they lack the skills necessary to be adequately physically active. Early childhood is considered an effective period for promoting FMS (Brian et al., 2020) and PA behavior, as it can influence children's future PA levels (Goldfield et al., 2012).

According to systematic reviews, evidence of a longitudinal pathway from FMS score to PA level in early childhood (Jones et al., 2020; Xin et al., 2020), as well as across childhood (2–18 years old; Barnett et al., 2021), is limited, and more longitudinal studies on the link between FMS and PA are needed (Barnett et al., 2021; Jones et al., 2020; Xin et al., 2020). FMS include the skill domains of stability, locomotor skills (LMS), and object control skills (OCS; Goodway et al., 2019, pp. 36, 118). Considering the skill domains separately (Barnett et al., 2021) and considering different intensities of PA, including SB (Barnett, Lai, et al., 2016; Barnett, Salmon, & Hesketh, 2016; Xin et al., 2020), may provide a more detailed picture of the relationship between FMS and PA levels. In this study, FMS is defined in terms of gross motor skills, focusing on LMS and OCS.

LMS and OCS may exhibit different longitudinal relationships with PA. LMS enable body movement relative to a fixed point on a surface, from point A to point B (Goodway et al., 2019, pp. 44, 118), which PA often necessitates. Thus, a lack of LMS can hinder PA engagement and increase SB, although physically active children do not necessarily demonstrate decreased SB (Pearson et al., 2014). This also supports considering SB as an independent outcome variable. From the perspective of OCS, Barnett et al. (2009) and Cohen et al. (2014) suggested that OCS are particularly related to MVPA via many games and activities (e.g., soccer), as measured by data gathered through questionnaires as part of a 6-year longitudinal study (baseline mean age = 10.1 years, range = 7.9–11.9 years; Barnett et al., 2009) and through accelerometers worn by students during the school day ($n = 460$, mean age = 8.5 years, $SD = 0.6$) in a cross-sectional study (Cohen et al., 2014).

Based on longitudinal studies initiated in early childhood, the relationship between FMS or skill domains and PA measured by accelerometer does not entirely conform to previous findings. Multiple studies (Bürgi et al., 2011; Duncan et al., 2021; Foulkes et al., 2021; Gu, 2016; Gu et al., 2018; Lima et al., 2017; Melby et al., 2021; Nilsen et al., 2020; Schmutz et al., 2020) have investigated this relationship, beginning in early childhood. The findings have been partly contradictory regarding the pathways from FMS or LMS to PA, and none of the studies provided evidence of a longitudinal relationship from OCS to PA measured by accelerometer.

A few studies (Duncan et al., 2021; Gu, 2016; Gu et al., 2018; Lima et al., 2017) evidenced at least some statistically significant longitudinal pathways from total FMS or skill domain scores to PA measured by accelerometer. Lima et al. (2017) discovered that the total FMS score, measured by Körperkoordinationstest für Kinder, was associated with vigorous PA (VPA) but not with MVPA in Danish children ($n = 298$, baseline mean age = 6.75, $SD = 0.37$) over a 7-year follow-up. Duncan et al. (2021) found that some subtests of LMS, measured by the Test of Gross Motor Development 2nd edition (TGMD-2) at baseline, significantly predicted time spent engaged in MVPA, LPA, and SB 1 year later in British preschoolers ($n = 177$, baseline mean age = 4.46 years, $SD = 0.70$). Gu et al. (2018) observed a positive longitudinal link from FMS total score, measured by PE Metrics related to physical education, to MVPA in school days, as well as a negative relationship to SB in Hispanic children ($n = 141$, baseline mean age = 5.37 years, $SD = 0.485$) over a 1-year follow-up. Another study (Gu, 2016) involving Hispanic children ($n = 256$, baseline mean age = 5.37 years, $SD = 0.48$) also provided evidence of a statistically significant positive longitudinal pathway from FMS to MVPA and SB measured in the same manner used by Gu et al. (2018). This study also revealed that only higher LMS scores predicted a statistically significant greater degree of engagement in MVPA and VPA, and inversely LPA, after controlling for body mass index (BMI; Gu, 2016).

On the other hand, some studies (Bürgi et al., 2011; Foulkes et al., 2021; Melby et al., 2021; Nilsen et al., 2020; Schmutz et al., 2020) did not find a longitudinal association between total FMS or skill domain scores and engagement in various PA intensities. Bürgi et al. (2011) and Schmutz et al. (2020) found no statistically significant relationship when FMS were measured by agility and dynamic balance test (Bürgi et al., 2011) or using the Zurich neuromotor assessment (Schmutz et al., 2020) in Swiss children ($n = 217$–550) aged 2–6 years old (baseline) during a 9- to 12-month follow-up. Moreover, Melby et al. (2021) found no statistically significant relationship between FMS measured by Körperkoordinationstest für Kinder at 6 years old and MVPA at 9 and 13 years ($n = 654$). At the same time, Foulkes et al. (2021) found no longitudinal relationship between FMS, LMS, or OCS measured by TGMD-2 and MVPA in British preschoolers ($n = 75$, baseline mean age = 4.5 years, $SD = 0.6$) over a 5-year follow-up. Similarly, Nilsen et al. (2020) reported finding no longitudinal relationship based on an examination of LMS and OCS measured by the TGMD-3 as predictors, with PA intensity and SB as outcome variables in Norwegian children ($n = 230$, baseline mean age = 4.7 years, $SD = 0.9$) over a 2-year follow-up.

The related literature lacks comprehensive longitudinal studies examining pathways from total FMS or skill domains scores to PA of varied intensities in early childhood; furthermore, existing results are contradictory. The current study aimed to provide a more accurate picture of the longitudinal pathways from FMS scores to accelerometer-measured PA levels utilizing skill domains and multiple PA intensities (light-to-vigorous PA [LVPA], LPA, moderate PA [MPA], MVPA, VPA, and SB), considering the effect of age (Barnett, Lai, et al., 2016; Farooq et al., 2020; Lounassalo et al., 2019; Valentini et al., 2022), gender (Barnett, Lai, et al., 2016; Ricardo et al., 2022; Zheng et al., 2022), and BMI (Jago et al., 2020; Lopes et al., 2021). This study was guided by two research questions that asked how total FMS score and, separately, LMS and OCS scores in children 3–8 years old predict time spent engaged in PA at different intensities 3 years later. Social-level factors, like school, may interact with individual-level factors to determine children's PA (Duncan et al., 2004); this is considered in a two-level regression analysis (Hox et al., 2010) in this study. Despite contradictory research results, the authors hypothesized a positive longitudinal pathway from total FMS score to time spent engaged in various PA intensities based on previous literature (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Seefeldt, 1980; Stodden et al., 2008) and research findings (Gu, 2016; Gu et al., 2018; Lima et al., 2017). The authors also hypothesized that LMS may have a statistically significant longitudinal relationship with engagement in various PA intensities according to previous research results (Duncan et al., 2021; Gu, 2016), as opposed to the link to OCS, of which no evidence was found in previous studies (Duncan et al., 2021; Foulkes et al., 2021; Gu, 2016; Nilsen et al, 2020).

Materials and Methods

Design and Participants

The baseline (T1) data for this longitudinal study were derived from the Skilled Kids study (2015–2016, $n = 1{,}238$), which was based on a geographic cluster randomization of childcare centers in Finland (Laukkanen et al., 2018). Of the children who participated in the measurement at T1, only 950 were contacted in the follow-up (T2) for the Active Family study (2018–2020) because complete data on the main study variables of the Active Family study (parental support for child's PA and child's outdoor time on weekdays and weekends) were available at T1. Among these 950 children, 675 (from 97 schools) participated in the follow-up assessment, and only for this group did researchers have permission to combine T1 and T2 data. The difference between the contacted and participating children (275 out of 950) was acceptable (29%) from the bias perspective in the follow-up (Kristman et al., 2004).

However, out of these 675 participants, LMS and OCS levels were measured in 592 children. Acceptable PA measurements (at least 10 hr recording time per day on at least two weekdays and one weekend day) were missing for 144 participants, and data on at least one other model-involved variable were missing for seven children. All participants with available results for all variables used in the analysis were included in the study ($n = 441$, 46.4% of initial sample of T2, girls = 228 [51.7%]; at T1: mean age = 5.6 years, $SD = 1.1$, in 37 childcare centers; at T2: mean age = 8.8 years, $SD = 1.1$, in 52 schools). The data were missing completely at random (Little's missing completely at random (MCAR) test chi-square = 31.983, $df = 22$, $p = .078$), considering all model-involved variables. This indicates that the model included observations ($n = 441$) represent a random subset of all the observations ($n = 675$) and that the distributions of the missing and observed values will be comparable (Bhaskaran & Smeeth, 2014). Thus, the complete case analysis is valid (Ross et al., 2020).

Both T1 and T2 studies received ethical approval from the Ethics Committee of the University of Jyväskylä, on October 30, 2015, for T1 and on June 28, 2018, for T2. Participation was voluntary, and appropriate permissions were obtained to conduct the research from the parents for their own and their children's participation before the beginning of data collection at both T1 and T2.

Measurements

Fundamental Movement Skills

FMS were measured using the TGMD-3 (Ulrich, 2013, 2019), a process-oriented measure developed for children aged 3–11 years old, which included six LMS subtests that produced a maximum total of 46 points and examined the following skills: run (0–8 points), gallop (0–8), hop (0–8), skip (0–6), horizontal jump (0–8), and slide (0–8). OCS levels were measured by seven subtests (two-hand strike of a stationary ball [0–10 points], one-hand forehand strike [0–8], one-hand stationary dribble [0–6], two-hand catch [0–6], kicking a stationary ball [0–8], overhand throw [0–8], and underhand throw [0–8]) for a maximum total score of 54 points. Total FMS score was defined by the gross motor index of the TGMD-3 measure, reflecting a sum of the LMS and OCS subtest scores; the maximum score was 100 points (Ulrich, 2013, 2019).

The TGMD-3 evaluates qualitative information on children's total FMS level and, separately, their LMS and OCS levels. The qualitative evaluation of each skill is based on three to five performance criteria, depending on the skill (Ulrich, 2013, 2019). Observing performance with the naked eye is effective for investigating FMS levels (Goodway et al., 2019, p. 36). Each performance is scored according to the defined criteria by a trained observer. If the criterion is met, one point is allocated instead of zero, and vice versa. Children perform each activity twice. The sum of the scores from these two trials for each performance criterion constitutes the total score for the skill (Ulrich, 2013, 2019).

The TGMD-3 is recommended for FMS testing because of low cost, feasibility, and strong psychometric properties. According to one meta-analysis, the interrater reliability of TGMD-3 was above 0.9 in about 70% of the reported statistics (19 studies; Rey et al., 2020). Regarding data collection for the current study, the interrater reliability was determined to be good (interclass correlation = .88, 95% confidence interval [.85, .92]) based on the performance of 167 children before data collection in T1 (Niemistö et al., 2019). According to the meta-analysis, the intrarater reliability of the TGMD-3 was greater than 0.9 in 85% of reported statistics ($n = 13$ studies). Moreover, the internal consistency of the TGMD-3 was between acceptable and excellent (Cronbach's alpha .7–.9), and test–retest reliability was over 0.8 (Rey et al., 2020).

Accelerometer-Based Physical Activity Intensities

An accelerometer can reliably measure the PA of children (Pate et al., 2010). PA was measured at T2 using triaxial accelerometers (UKK RM-42, UKK

Terveyspalvelut Oy). Participants were instructed to attach the accelerometer to the right side of the waist with an elastic belt for seven consecutive days during waking hours, excluding sick days. They were further instructed to remove the accelerometer at bedtime and during showering, saunas, and swimming. Accelerometer data collected between 6 a.m. and 10 p.m. were included for analysis. Nonwear time was determined as a mean amplitude deviation (MAD) of the acceleration below 0.02*g* for 60-min periods. An accelerometer recording time of at least 10 hr per day, which is a recommended criterion, was considered acceptable (Migueles et al., 2017). Valid accelerometer data for at least two weekdays (on average 4.2 weekdays) and one weekend day (on average 1.9 weekend days) was an inclusion criterion, as this has been shown to provide an acceptable (62%) level of reliability (Penpraze et al., 2006).

MATLAB software was used for the accelerometer data analysis. Accelerometer data (100 Hz) were classified according to MAD based on nonoverlapping epochs of 5-s periods. The MAD is considered suitable for analyzing PA intensity for children (Aittasalo et al., 2015; Gao et al., 2019). Moreover, MAD cut-points in the analysis were under 29 for SB, 29 for LPA, 338 for MPA, and 604 for VPA (Aittasalo et al., 2015). The sum of the time spent engaged in LPA, MPA, and VPA constitutes the LVPA.

Gender, Age, Body Mass Index, and Time Between Measurements

Parents reported the child's gender (options: girl or boy) and date of birth by completing a questionnaire at T1. The exact age of each child was calculated using the date of birth and the test date. BMI-for-age was calculated using weight (seca 877, seca GmbH & Co. KG.) and height (HM200P, Charder Electronic Co., Ltd.) measured directly to the nearest decimal. BMI *SD* scores were calculated according to Finnish children's national standards (Saari et al., 2011). The time between baseline and follow-up measurements (T1–T2) was calculated as the difference between measurement dates in T1 and T2.

Data Analyses

The predictive effect of total FMS score and of LMS and OCS scores on time spent engaged in PA of varied intensities was investigated using two-level regression analyses (Hox et al., 2010) due to data clustering. The two-level hierarchical data structure included the participants (first level) nested within the schools (second level). Individual-level predictive variables in T1 were measured in childcare centers, which is why school level predictive variables were not used in the longitudinal analysis. Participants were nested in 52 schools (on average, 5.3 students per school, range 1–23) in T2.

The predictor variables for the analyses were total FMS score or LMS and OCS scores. In addition to the main effects of age and gender, interactions between total FMS score, LMS, and OCS with gender (total FMS score-by-gender, LMS-by-gender interaction, OCS-by-gender interaction) and age (total FMS score-by-age, LMS-by-age interaction, OCS-by-age interaction) also were used as predictor variables. Interactions were used to analyze gender and age differences in the models. If interactions were statistically significant, more detailed analyses were performed. Otherwise, the interactions were removed from the analysis, and only the main effects were reported. BMI *SD* scores were used as a covariate. All these variables were measured at baseline (T1). Also, the time between measurements (T1–T2, mean 3.2 years, range 2.39–4.55 years) was used as a covariate in the analysis due to the considerable variability between participants. The outcome variables LVPA, LPA, MPA, MVPA, VPA, and SB were measured, on average, 3 years later (T2).

Descriptive statistics and analyses were performed using SPSS (version 28) software. Differences between the means for girls and for boys were tested with the Mann–Whitney *U* test. The statistical significance level was set at $p < .05$ for all analyses. All outcome variables were tested for normality, and VPA was Box-Cox power transformed due to skewness. Standardized values of the variables were used in the analyses.

The two-level regression analyses were executed by linear mixed model using restricted maximum likelihood estimation and Satterthwaite approximation. If school level was not statistically significant in the two-level regression analysis, a linear regression analysis was performed.

Results

The descriptive statistics of the study population are presented in Table 1. Gender differences were found in the total FMS scores ($p = .037$), LMS scores, OCS scores, and PA intensities ($p < .001$). Girls obtained higher LMS scores, and they engaged in more LPA. Correspondingly, boys obtained higher total FMS and OCS scores and engaged in more MPA, MVPA, and VPA.

The school level, according to the interclass correlation of the null model, explained 8.0% ($p = .040$) of the variance for LVPA, 11.4% ($p = .020$) for LPA, 13.3% ($p = .014$) for MPA, 13.8% ($p = .010$) for MVPA, and 12.3% ($p = .004$) for VPA. School level results were not statistically significant for SB (interclass correlation = .041, $p = .224$); a linear regression analysis was performed for SB.

The interaction of total FMS score with gender was statistically significant ($\beta = -0.177$, $p = .044$) only in the pathway from total FMS score to LPA. Thus, the analyses were performed separately with both genders as a reference group (coded 0). Therefore, the main effects of the total FMS score could be obtained for both genders. Despite this, the main effect of the total FMS score did not statistically significantly predict LPA (girls: $\beta = 0.060$, $p = .443$; boys: $\beta = -0.117$, $p = .087$; see Table 2). Gender and its interactions are reported in Table 2 with girls as the reference group (girls = 0). For boys, the estimates for gender and its interactions were the same, except negative values changed to positive. Interactions of total FMS score, LMS score, and OCS score with gender or age were not statistically significant ($p = .117$–$.856$) regarding time spent engaged in other levels of PA intensity. Thus, only the results of the main effects are reported. Results for the pathways from total FMS score to LVPA, MPA, MVPA, and VPA are presented in Table 3, and results on the association between LMS and OCS with the same PA intensities are conveyed in Table 4. The SB results are presented in Tables 5 and 6.

Table 1 Descriptive Statistics

Variable	*M*	*SD*	Gender differences (*p*)
Age (years)	5.60	1.05	.484
Girls	5.57	1.03	
Boys	5.62	1.08	
Body mass index SDS	0.19	1.05	.443
Girls	0.22	1.13	
Boys	0.16	0.96	
T1–T2 (years)	3.22	0.37	.935
Girls	3.22	0.35	
Boys	3.23	0.39	
Total FMS score (0–100 points)	54.94	13.85	**.037**
Girls	53.75	12.57	
Boys	56.22	15.03	
Locomotor skills (0–46 points)	28.95	7.33	**<.001**
Girls	30.23	6.88	
Boys	27.57	7.57	
Object control skills (0–54 points)	26.00	8.71	**<.001**
Girls	23.52	7.59	
Boys	28.65	9.06	
Light-to-vigorous PA (min/day)	452.10	60.74	.993
Girls	452.19	60.25	
Boys	452.01	61.41	
Light PA (min/day)	282.44	44.55	**<.001**
Girls	293.45	42.25	
Boys	270.66	44.03	
Moderate PA (min/day)	156.18	36.01	**<.001**
Girls	147.23	33.44	
Boys	165.76	36.27	
Moderate-to-vigorous PA (min/day)	169.66	41.89	**<.001**
Girls	158.74	38.62	
Boys	181.35	42.18	
Vigorous PA (min/day)	13.48	10.50	**<.001**
Girls	11.51	9.50	
Boys	15.59	11.11	
Sedentary behavior (min/day)	334.02	59.22	.482
Girls	336.24	60.52	
Boys	331.65	57.84	

Note. *p* values of gender differences under .05 are shown in bold. SDS = standard deviation score; T1–T2 = time between baseline (T1) and follow-up (T2) measurements; FMS = fundamental movement skills; PA = physical activity.

Table 2 Results of Pathway From Total FMS Score to Light Physical Activity

	Light physical activity		
Variables	**Estimate**	***SE***	***p***
Total FMS score			
Girls	0.061	0.078	.434
Boys	–0.117	0.068	.087
Total FMS score × Gender[a]	–0.178	0.088	**.043**
Gender[b]	–0.479	0.087	**<.001**
Age	–0.252	0.059	**<.001**
T1–T2	–0.164	0.049	**.001**
Body mass index SDS	–0.016	0.044	.721
$R^2 = .115$			

Note. Statistically significant (*p* value under .05) longitudinal relationships are shown in bold. FMS = fundamental movement skills; T1–T2 = time between baseline (T1) and follow-up (T2) measurements; SDS = standard deviation scores.
[a]Interaction is reported with girls as the reference group. [b]Gender is reported with girls as the reference group.

The pathways from total FMS score to MPA (β = 0.177, $p = .003$) and VPA (β = 0.201, $p < .001$), separately, and to MVPA (β = 0.203, $p < .001$) were statistically significant. Of the skill domains, LMS scores predicted PA intensities similarly to the total FMS scores. LMS predicted, with statistical significance, MPA (β = 0.140, $p = .014$), VPA (β = 0.156, $p = .008$), and MVPA (β = 0.164, $p = .004$) and, inversely, SB (β = –0.116, $p = .042$). The pathways from OCS to PA intensities were not statistically significant (p = .291–.991).

The main effects of baseline age and gender predicted time spent engaged in PA of various intensities 3 years later. Time spent engaged in PA at different intensities decreased (β = –0.419 to –0.170, p = .001–.004) with age, except with respect to LVPA (β = 0.001 to 0.039, p = .703–.987). On the other hand, SB increased statistically significantly with age (β = –0.398 to 0.408, $p < .001$). Gender was a statistically significant predictor of time spent engaged in PA of varied intensities (β = –0.477 to 0.559, $p < .001$) except LVPA (β = 0.001 to 0.039, p = .703–.987) and SB (β = –0.139 to –0.079, p = .168–.372). In addition, BMI *SD* scores predicted a greater degree of SB (β = 0.095 to 0.099, p = .027–.034). T1–T2 was a statistically significant covariate and predicted a lower amount of LVPA (β = –0.196, $p < .001$), LPA (β = –0.162, $p = .002$), and MVPA (β = –0.116 to –0.115, p = .033–.034) and a higher rate of SB (β = 0.176, $p < .001$).

The two-level regression models for total FMS score explained overall 7.8%, 11.5%, 11.4%, 11.8%, and 5.1% of the variability in LVPA, LPA, MPA, MVPA, and VPA, respectively. Results were similar in the model of skill domains, LMS, and OCS, which explained overall 7.9%, 10.3%, 11.2%, 11.8%, and 5.1% of the variability in LVPA, LPA, MPA, MVPA, and VPA, respectively. The linear regression model for total FMS score explained 14.3%, and the model for the LMS and OCS domains explained 14.4% of the variability in SB.

Table 3 Results of Two-Level Regression Analysis for Models of Pathways From Total FMS Score to PA Intensities

	Model 1			Model 2			Model 3			Model 4		
	Light-to-vigorous PA			Moderate PA			Moderate-to-vigorous PA			Vigorous PA		
Variable	Estimate	*SE*	*p*	Estimate	*SE*	*p*	Estimate	*SE*	*p*	Estimate	*SE*	*p*
Total FMS score	0.112	0.059	.057	0.177	0.058	**.003**	0.203	0.058	**<.001**	0.201	0.060	**<.001**
Gender	0.001	0.089	.987	0.489	0.088	**<.001**	0.502	0.087	**<.001**	0.312	0.090	**<.001**
Age	–0.419	0.059	**<.001**	–0.328	0.060	**<.001**	–0.323	0.060	**<.001**	–0.179	0.062	**.004**
T1–T2	–0.196	0.046	**<.001**	–0.116	0.054	**.033**	–0.124	0.054	**.023**	–0.102	0.055	.067
Body mass index SDS	–0.042	0.044	.340	–0.036	0.044	.412	–0.044	0.043	.311	–0.047	0.045	.298
R^2	.078			.114			.118			.051		

Note. Statistically significant (*p* value under .05) longitudinal relationships are shown in bold. PA = physical activity; FMS = fundamental movement skills; T1–T2 = time between baseline (T1) and follow-up (T2) measurements; SDS = standard deviation scores.

Table 4 Results of Two-Level Regression Analysis for Models of Pathways From Locomotor Skills and Object Control Skills to PA Intensities

	Model 1			Model 2			Model 3			Model 4			Model 5		
	Light-to-vigorous PA			Light PA			Moderate PA			Moderate-to-vigorous PA			Vigorous PA		
Variable	Estimate	*SE*	*p*	Estimate	*SE*	*p*	Estimate	*SE*	*p*	Estimate	*SE*	*p*	Estimate	*SE*	*p*
Locomotor skills	0.096	0.057	.092	–0.022	0.057	.701	0.140	0.057	**.014**	0.164	0.057	**.004**	0.156	0.059	**.008**
Object control skills	0.029	0.065	.651	–0.030	0.064	.645	0.059	0.065	.362	0.065	0.064	.310	0.070	0.067	.291
Gender	0.039	0.101	.703	–0.476	0.100	**<.001**	0.536	0.100	**<.001**	0.559	0.099	**<.001**	0.363	0.103	**<.001**
Age	–0.412	0.059	**<.001**	–0.249	0.060	**<.001**	–0.320	0.061	**<.001**	–0.314	0.060	**<.001**	–0.170	0.062	**.006**
T1–T2	–0.196	0.046	**<.001**	–0.166	0.049	**<.001**	–0.115	0.054	**.034**	–0.123	0.054	**.024**	–0.101	0.055	.069
Body mass index SDS	–0.040	0.045	.369	–0.015	0.044	.740	–0.032	0.044	.459	–0.040	0.044	.359	–0.043	0.045	.339
R^2	.079			.103			.112			.118			.051		

Note. Statistically significant (*p* value under .05) longitudinal relationships are shown in bold. PA = physical activity; T1–T2 = time between baseline (T1) and follow-up (T2) measurements; SDS = standard deviation scores.

Table 5 Results of Linear Regression Analysis for Pathway From Total FMS Score to Sedentary Behavior

Variable	Estimate	*SE*	*p*
Total FMS score	−0.107	0.059	.070
Gender	−0.079	0.089	.372
Age	0.408	0.059	**<.001**
T1–T2	0.176	0.045	**<.001**
Body mass index SDS	0.099	0.044	**.027**
$R^2 = .152$, adjusted $R^2 = .143$			
$F(5, 435) = 15.631$, $p < .001$, SEE = 0.926			

Note. Statistically significant (*p* value under .05) longitudinal relationships are shown in bold. FMS = fundamental movement skills; T1–T2 = time between baseline (T1) and follow-up (T2) measurements; SDS = standard deviation scores; SEE = standard error of the estimate.

Table 6 Results of Linear Regression Analysis for Pathway From Locomotor Skills and Object Control Skills to Sedentary Behavior

Variable	Estimate	*SE*	*p*
Locomotor skills	−0.116	0.057	**.042**
Object control skills	−0.001	0.065	.991
Gender	−0.139	0.101	.168
Age	0.398	0.059	**<.001**
T1–T2	0.176	0.045	**<.001**
Body mass index SDS	0.095	0.045	**.034**
$R^2 = .155$, adjusted $R^2 = .144$			
$F(6, 434) = 13.302$, $p < .001$, SEE = 0.925			

Note. Statistically significant (*p* value under .05) longitudinal relationships are shown in bold. T1–T2 = time between baseline (T1) and follow-up (T2) measurements; SDS = standard deviation scores; SEE = standard error of the estimate.

Discussion

This study was designed to investigate how total FMS score, and the LMS and OCS domains in children 3–8 years old predicted time spent engaged in PA at different intensities 3 years later. The results showed that higher total FMS scores and, especially, higher LMS scores predicted more time spent engaged in MPA, VPA, and MVPA. In addition, higher LMS scores inversely predicted SB, while OCS scores did not statistically significantly predict PA of varied intensities. In this study, no age or gender differences were uncovered in the longitudinal relationships between FMS and PA based on interactions, excluding the pathway from FMS to LPA. The results of this study indicate that higher LMS scores, especially, may predict more engagement in MVPA and less SB over time. However, most of the variance in PA remains unexplained; furthermore, other variables also play a significant role in time spent engaged in PA at varying intensities.

As noted, the relationships between FMS or skill domains and PA intensities do not seem straightforward (Barnett, Lai, et al., 2016). The findings of this research support our hypotheses and are consistent with existing theoretical frameworks and models. FMS level may be an underlying variable influencing PA (Brian et al., 2020; Hulteen et al., 2018; Robinson et al., 2015; Seefeldt, 1980; Stodden et al., 2008). However, the longitudinal relationship appears tenuous, as previous studies have shown (Barnett et al., 2021; Duncan et al., 2021; Gu, 2016; Gu et al., 2018; Lima et al., 2017), and the results are indeterminate because some studies have not demonstrated a statistically significant longitudinal association between these variables (Barnett et al., 2021; Bürgi et al., 2011; Foulkes et al. 2021; Melby et al., 2021; Nilsen et al., 2020; Schmutz et al., 2020). An individual's current FMS level has been proposed as having a stronger relationship with PA than the previous FMS level (Nilsen et al., 2020), as FMS are known to develop (Barnett, Lai, et al., 2016), and PA is known to decrease with age (Farooq et al., 2020; Lounassalo et al., 2019). Some studies (Gu, 2016; Gu et al., 2018), including the current investigation, have not been able to consider current FMS or PA levels. At the same time, a statistically significant longitudinal pathway from PA to FMS has been evidenced (Estevan et al., 2022; Lima et al., 2017; Nilsen et al., 2020; Reyes et al., 2019).

The use of skill domains and various PA intensities in analyses may provide more detailed information on the longitudinal pathway from FMS to PA, as earlier studies have suggested (Barnett, Lai, et al., 2016; Barnett, Salmon, & Hesketh, 2016; Jones et al., 2020; Xin et al., 2020). The use of skill domains also enables consideration of the influence of other variables, such as BMI (Barnett, Lai, et al., 2016) and gender (Zheng et al., 2022), that may be related to LMS and OCS in various ways. Additionally, the results of this study are consistent with previous longitudinal research findings regarding relationships between PA and both LMS and OCS (Barnett et al., 2021; Duncan et al., 2021; Gu, 2016) using PA measured by accelerometer. These studies have demonstrated a longitudinal pathway from LMS to various PA intensities, including SB, but not for the pathway from OCS to PA, findings that mirror those of this study. This result is partially inconsistent with those of other studies (Foulkes et al., 2021; Nilsen et al., 2020), based on which no statistically significant longitudinal pathways were reported, even from LMS to varying PA intensities.

Although OCS has been suggested as being associated with many games that involve MVPA (Barnett et al., 2009; Cohen et al., 2014), some activities can be too competitive, making them less enjoyable for children (Allender et al., 2006). This may further diminish the significance of the path from OCS to MVPA. While OCS have been linked to MVPA, particularly during school breaks (Cohen et al., 2014), time spent outside of school hours, such as during journeys between home and school, may be tied to a greater amount of MVPA (Rainham et al., 2012). The importance of LMS in the context of PA, including SB, may increase, and the significance of OCS may decrease when examining PA throughout the day. Over 80% of Finnish primary school children actively travel (e.g., walking or biking) to and from school (Turunen et al., 2023, p. 79), which may emphasize the positive relationship from LMS to MVPA and the inverse association with SB uncovered in this study. Also, Cohen et al. (2014) found that LMS were statistically significant predictors of total and after-school MVPA but not for MVPA during school breaks.

In addition to active travel to and from school, the most common physical activities Finnish children engage in during their free time are football, skating, ice hockey, skiing, swimming, cycling, and frisbee golf, depending on the time of year (Martin et al., 2023, p. 18). Some of these activities require OCS; however, LMS is necessary for all of them. This further emphasizes the importance of LMS, as many common exercises and daily activities are performed using LMS.

Instead of the statistically insignificant results of interactions with age or gender and FMS or skill domain score in this study and previous studies (Nilsen et al., 2020; Schmutz et al., 2020), the main effects of age and gender on PA appear significant in childhood (Cooper et al., 2015). Also in this study, the standardized coefficients of age and gender are generally higher than the standardized coefficients of FMS or skill domains. Schmutz et al. (2018) stated that gender and age are the most important nonmodifiable individual-level variables related to PA levels. Boys engaged in more higher intensity PA (Brazo-Sayavera et al., 2021; Ricardo et al., 2022) and exhibited lower degrees of SB (Brazo-Sayavera et al., 2021; Prince et al., 2020) than girls, while the amount of PA decreases with age, as has been observed in previous studies (Cooper et al., 2015; Farooq et al., 2020; Lounassalo et al., 2019). SB seems to increase with age from childhood to adolescence (Rubín et al., 2022). When many biological, psychological, sociocultural, and environmental variables affect PA (Li & Moosbrugger, 2021) in addition to the main effect of age and gender, the share of total FMS score or skill domains remains small.

Comparison of the relationships found between FMS and PA in prior research results is complicated by the variability of the target group (e.g., age, gender), the difference in the measurements of FMS and PA, and variations in the follow-up periods (Barnett et al., 2021; Jones et al., 2020; Xin et al., 2020). The baseline ages of participants ranged from 2 to 7 years, follow-up periods spanned from 9 months to 7 years, and six tests were used to measure FMS in studies investigating the longitudinal pathways from FMS or skill domains to PA beginning in early childhood (Bürgi et al., 2011; Duncan et al., 2021; Foulkes et al., 2021; Gu, 2016; Gu et al., 2018; Lima et al., 2017; Melby et al., 2021; Nilsen et al., 2020; Schmutz et al., 2020). Moreover, process- and product-oriented measures of FMS are not interchangeable because they assess different aspects of FMS (Palmer et al., 2021). However, both process- (Duncan et al., 2021; Foulkes et al., 2021; Gu, 2016; Gu et al., 2018; Nilsen et al., 2020; Schmutz et al., 2020) and product-oriented (Bürgi et al., 2011; Lima et al., 2017; Melby et al., 2021; Schmutz et al., 2020) measurements of FMS or skill domains seem to produce contradictory results. In addition, Nilsen et al. (2020) evaluated LMS and OCS levels using the TGMD-3, like in the current study; nevertheless, the results were contradictory.

The strength of this study was in examining longitudinal data on young children in early childhood, with an average 3-year follow-up, and the use of two-level regression analysis as a statistical method. In addition, we used total FMS score, skill domains, and PA intensities to explore more specifically the pathway from FMS to PA. Also, the interaction between total FMS score, LMS level, and OCS level with gender and age were used as predictor variables to obtain a more accurate picture.

However, this study also has its limitations. One major limitation is that PA was not assessed at T1. Also, despite the use of high-quality measures in assessing accelerometer-based PA, these measures have their own challenges. For instance, they do not account for water activities, as the device must be removed before entering the water. Moreover, measuring PA over two weekdays and one weekend day may not provide an accurate representation of habitual PA. Another noted limitation of accelerometers is their inability to accurately measure the quality, context, and type of PA (Barnett, Salmon, & Hesketh, 2016). The dropout factor constitutes a final limitation of the current study, as some of the participants at T1 did not participate in the follow-up phase of the research at T2. However, this is a rather frequent phenomenon in longitudinal studies that are based on voluntary participation (Hogan et al., 2004). To conclude, the lacking data were missing completely at random. In total, 675 children provided consent to combine data from T1 and T2, prohibiting the comparison of the analyzed sample ($n = 441$) with the Skilled Kids study sample ($n = 1{,}238$).

More studies are needed in the future that examine the longitudinal relationship between FMS and PA from early childhood to adolescence and beyond, with comparable measures if possible. Moreover, future longitudinal studies should examine different reciprocal aspects of the relationship between FMS and PA with the same study population at multiple time points, which makes the growth curve analysis method possible. The use of skill domains and PA intensities, including SB, in future studies can provide a more detailed picture of this relationship. Also, by comparing process- and product-oriented measurements, a more detailed relationship between FMS and PA can be obtained.

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II

BIDIRECTIONAL RELATIONSHIP OVER TIME BETWEEN BODY MASS INDEX AND FUNDAMENTAL MOVEMENT SKILL DOMAINS MEASURED BY A PROCESS-ORIENTED METHOD IN CHILDHOOD: A 3-YEAR LONGITUDINAL STUDY

by

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Bidirectional Relationship Over Time Between Body Mass Index and Fundamental Movement Skill Domains Measured by a Process-Oriented Method in Childhood: A 3-Year Longitudinal Study

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The worldwide increase in childhood overweight and obesity underscores the need to study variables like fundamental movement skill (FMS) levels from early childhood. This study investigated the bidirectional longitudinal relationship between body mass index (BMI) and process-oriented FMSs, including locomotor skills and object control skills in 675 Finnish children, aged 3–8 years at baseline (50.5% female, mean age 5.5 years) over 3 years. Standardized BMI-for-age *SD* scores (BMI SDS *z*-scores) followed Finnish national standards. The FMS assessment comprised four subtests from the Test of Gross Motor Development, third edition. Age-adjusted standardized residuals of FMS or skill domains and BMI SDS *z*-scores were used in a two-level, cross-classified, cross-lagged regression analysis, accounting for gender, and baseline value of the dependent variables. The results showed no statistically significant longitudinal relationship between BMI and FMS or its skill domains for either gender in either direction. This suggests that BMI and process-oriented FMS, encompassing locomotor skill and object control skill, develop independently, possibly influenced by unexplored variables. These findings contradict earlier results based on product-oriented measurements, which may include a physical capacity component. The

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outcomes further underscore the importance of monitoring weight status from early childhood, given its significant association with later-life weight conditions.

Keywords: children, early childhood, motor development

Childhood overweight and obesity have emerged as significant global issues due to their high prevalence (NCD Risk Factor Collaboration, 2017). The World Health Organization (2021) characterizes overweight and obesity as "abnormal or excessive fat accumulation that may impair health." The body mass index (BMI) serves as a practical method for identifying children who are overweight and obese, although the BMI does not directly measure body fat levels (Martin-Calvo et al., 2016).

Evidence shows a strong longitudinal relationship between obesity in childhood and adulthood, starting in early childhood (Rooney et al., 2011) with children aged 8 years or younger (UNICEF, 2022). Thus, understanding the factors underlying overweight and obesity in childhood is important. Fundamental movement skills (FMSs), which represent the performance level of foundational mechanisms (neural, muscular, biomechanical, and perceptual) that drive gross motor movements (Goodway et al., 2019), are considered to share an inverse bidirectional relationship with overweight and obesity during childhood (Robinson et al., 2015). Hence, improved FMSs may help prevent the conditions of obesity and being overweight through physical activity, while a higher weight status might be associated with poorer FMSs, especially for tasks requiring manipulation of total body mass (Robinson et al., 2015). A systematic review (Barnett et al., 2021) supports this inverse bidirectional relationship between weight status and FMS level in childhood.

Evidence suggests that BMI may differentially affect the multiple FMS domains, such as locomotor skills (LMSs) and object control skills (OCSs; Barnett et al., 2016). A higher BMI can impact LMSs due to movement against gravity, while the relationship between BMI and OCSs, which are more static, remains unclear (Okely et al., 2004). According to the same systematic review, higher BMI or body fat levels negatively affect LMSs, but a reverse pathway from LMS level to weight status and relationships between OCS level and weight status is indeterminate because longitudinal research is limited (Barnett et al., 2021). Therefore, more longitudinal studies focusing on these skill domains are needed.

FMS can be measured using different metrics and approaches (Hulteen et al., 2020) such as process- or product-oriented metrics. Process-oriented tests assess the quality of movement through specific performance criteria, focusing on patterns and techniques, whereas product-oriented tests measure outcomes such as speed, distance, height, or the number of repetitions without considering the method of execution (Williams & Monsma, 2006). These measures correlate to some extent, ranging from low to moderate (Ré et al., 2018), and evaluate different aspects of FMS (Palmer et al., 2021; Ré et al., 2018).

To our knowledge, ours is the first study to investigate the bidirectional longitudinal relationship that BMI has with FMS level or, separately, with LMS and OCS levels, measured via a process-oriented approach from early childhood. Previous studies (D'Hondt et al., 2014; Lima et al., 2019) have investigated the bidirectional longitudinal relationship between FMSs, measured via the product-oriented Körperkoordinationstest für Kinder assessment, and BMI (D'Hondt et al., 2014) or body fatness (Lima et al., 2019) from early childhood. Both studies (D'Hondt et al., 2014; Lima et al., 2019) reported significant inverse bidirectional longitudinal relationships between FMS and both BMI and body fatness, respectively.

However, it is crucial to report research findings on the bidirectional longitudinal relationship of FMS and BMI using process-oriented measures as well because this approach may potentially offer a more accurate picture of the longitudinal relationship between FMS and BMI. Few studies have examined the longitudinal relationship from process-oriented FMSs or skill domains to weight status (Duncan et al., 2021; Foulkes et al., 2021; Vlahov et al., 2014) or the reverse (Lopes et al., 2020) starting in early childhood, and the findings of those studies have been inconsistent. The process-oriented Test of Gross Motor Development, second edition (TGMD-2), was used in these studies. While Duncan et al. (2021) and Vlahov et al. (2014) identified inverse relationships between FMS and BMI or body fatness, Foulkes et al. (2021) and Lopes et al. (2020) found no significant relationship between FMS, LMS, or OCS and an individual's likelihood of becoming overweight or obese.

The partially contradictory findings and limited prior research highlight the need for additional research into the bidirectional longitudinal relationship between weight status and both FMS levels and skill levels in the composite domains separately, particularly from the perspective of process-oriented methods of measuring FMS. The present study examined this relationship using standardized BMI-for-age SD scores (BMI SDS *z*-scores) and process-oriented age-residualized FMS levels starting from early childhood in Finnish children aged 3–8 years at baseline over a 3-year follow-up period. Additionally, the study considered the relationships between BMI SDS *z*-scores and age-residualized skill domains—that is, LMS and OCS—as distinct relationships that may exist (Barnett et al., 2016; Okely et al., 2004). Drawing on existing theory (Robinson et al., 2015) and previous systematic reviews (Barnett et al., 2021), we hypothesize a bidirectional relationship between BMI and FMSs over time. Specifically, we expect that higher baseline BMI levels will predict lower FMSs at follow-up, while proficient baseline FMSs will predict lower subsequent BMI levels. This bidirectional influence suggests that elevated BMI in early childhood may impact development of FMSs negatively in later childhood and, conversely, that proficient FMSs in early childhood may be associated with a reduction in BMI 3 years later. In particular, we anticipate a negative bidirectional relationship between BMI and LMS, as the literature has indicated (Barnett et al., 2016; D'Hondt et al., 2014; Lima et al., 2019; Okely et al., 2004). Given that FMS development exhibits gender differences (Barnett et al., 2016) and that BMI may also be influenced by gender (Shah et al., 2020), our analysis specifically investigated gender differences by examining the interactions between gender and FMS or skill domains, and between gender and BMI.

Materials and Methods

The longitudinal data used in this study were collected at two measurement points from 950 Finnish children who participated in the geographical cluster-randomized Skilled Kids study (2015–2016) and for whom comprehensive data were available on the main study variables (parental support for child physical activity and outdoor time) of the follow-up research, referred to as the Active Family study (2018–2020). Of these 950 children, 675 participated in the measurements approximately 3 years later (mean = 3.23 years, range = 2.39–4.55 years), and these 675 ultimately were included in the study. From a bias perspective, the rate of loss to follow-up (29%) was considered acceptable (Kristman et al., 2004), and the missing data were found to be missing completely at random (Little's MCAR test chi-square = 118.773, degrees of freedom = 141, $p = .913$), considering all model-involved variables. Participants were nested within 36 childcare centers and 97 schools.

Before data collection was initiated, participants' parents provided written informed consent for their own and their children's voluntary participation in the study and for data merging. The Ethics Committee of the University of Jyväskylä granted ethical approval for the baseline on October 30, 2015, and for the follow-up on June 28, 2018.

Measurements

Gender, Age, and BMI

Parents provided their children's gender (options: girl or boy) and birth date in the baseline questionnaire. The exact ages of the children at both the baseline and follow-up points were calculated by comparing the birth date to the date of the assessment.

Body mass (seca 877, seca GmbH and Co. KG) and height (HM 200P, Charder Electronic Co., Ltd.) were measured directly to the nearest decimal, with children lightly dressed and barefoot. BMI SDSs and BMI categories were calculated based on Finnish national standards (Saari et al., 2011). The BMI SDS values were subsequently converted to *z*-scores (BMI SDS *z*-scores) that were standardized separately for boys and girls, reflecting gender-specific differences in interpreting the scores. For comparison in the descriptive statistics, International Obesity Task Force BMI categories (Cole & Lobstein, 2012) were assigned using a classifier (Sanchez-Delgado et al., n.d.).

FMSs and Skill Domains

The FMS score (maximum 28 points) was derived from the sum of the following four subtests from the process-oriented TGMD-3: two LMS subtests (skip, 0–6 points, and one-legged hop, 0–8 points; maximum 14 points) and two OCS subtests (overhand throw, 0–8 points, and one-handed stationary dribble, 0–6 points; maximum 14 points; Ulrich, 2019). These subtests were selected from those that best represented the skill domains (Wagner et al., 2016). Each subtest was performed twice and qualitatively evaluated by a trained observer using specific performance criteria (Ulrich, 2019).

The TGMD-3 is designed for children aged 3–11 years old (Ulrich, 2019). Both the inter- and intrarater reliability of the TGMD-3 were >0.9, and the test–retest reliability exceeded 0.8. Moreover, the internal consistency of the TGMD-3 ranged from acceptable to excellent (Cronbach's alpha .7–.9; Rey et al., 2020). The intraclass correlation coefficients (ICCs = .730–.757) for consistency between different research teams were viewed as fair for the FMS scores, LMS scores, and OCS scores measured using the TGMD-3. However, the agreement ICCs

(.363–.478) were viewed as poor. Therefore, this variability suggests that comparisons between studies or research groups employing the TGMD-3 may not always be reliable (Hulteen et al., 2023). In this study, the same research group performed the TGMD-3 measurements at baseline and at follow-up.

As FMSs are related to age (Barnett et al., 2016), age-adjusted FMS, LMS, and OCS standardized residuals (FMSzre, LMSzre, and OCSzre, respectively) were employed to address the strong correlation between the scores and age (baseline: .460–.602; follow-up: .309–.397; Wurm & Fisicaro, 2014) and to eliminate the influence of varying durations between measurements and different ages (Duncan et al., 2021) at baseline and follow-up. Standardized residuals at baseline were used as predictors, while residuals at follow-up were used as dependent variables. This adjustment allowed for an interpretation of how participants deviated from average FMS, LMS, or OCS scores for their age, with positive residuals indicating performance above the age-predicted value and negative residuals indicating performance below the expected level.

Data Analyses

We employed two-level, cross-classified models (Finch & Bolin, 2017) to analyze the data due to the clustered nature of the data, as participants (Level 1) were cross-classified (Level 2) by 36 childcare centers (on average, 18.1 participants, range 5–35) and 97 schools (on average, 6.9 participants, range 1–31). Only predictors at the individual level (Level 1) were measured and incorporated into the analyses.

Cross-lagged models (Kearney, 2017) were used in the two-level, cross-classified analysis to investigate the bidirectional relationship between BMI SDS *z*-scores and FMSzre. The following models were implemented: (a) an intercept-only model for outcomes (FMSzre and BMI SDS *z*-scores at follow-up) with no predictors to verify the appropriateness of multilevel analysis; (b) a model that included individual-level predictors (FMSzre and BMI SDS *z*-scores at baseline) along with interactions of FMSzre × Gender and BMI SDS *z*-scores × Gender at baseline; and (c) separate models for girls and boys with individual-level predictors (FMSzre and BMI SDS *z*-scores at baseline), executed if the interaction between the baseline FMSzre and gender, or between baseline BMI SDS *z*-scores and gender was a statistically significant predictor in the previous model. To account for the multilevel structure of the data, all variables were allowed to correlate at the between levels. The same models were executed with two skill domains, LMSzre and OCSzre, individually serving as predictors and outcome variables instead of using FMSzre. All predictors were grand mean centered (Finch & Bolin, 2017) in the analyses.

The models were implemented using a Bayesian analysis with algorithms of an iterative Markov chain Monte Carlo method (using the algorithm: GIBBS[PX1], point estimate—median, two parallel Markov chain Monte Carlo chains, maximum 50,000 iterations). Bayesian approaches utilize a distribution of values. Prior distributions (mean 0, variance ∞) were selected with the aim of obtaining parameter estimates based on the observed data. Convergence of the posterior distribution was confirmed by potential scale reduction coefficients (below 1.05) and trace plots. Autocorrelation plots were employed to examine an acceptable level of autocorrelation (Finch & Bolin, 2017).

The standardization of BMI SDS and the residualization of FMS, LMS, and OCS, along with the descriptive statistical analysis, were performed using SPSS (version 28, IBM) software. Two-level cross-classified, cross-lagged models, and correlations between variables within models, were conducted using Mplus (version 8.8, Muthén & Muthén). The statistical significance level was set at a probability of <.05 for all analyses. Credibility intervals (C.I.) for the Bayesian cross-classified models were interpreted similarly to confidence intervals (CI) in frequentist models (Finch & Bolin, 2017).

The model fit was evaluated using the posterior predictive probability value (PPP) and the 95% CI for the difference between observed and replicated chi-square values. The PPP values near .5 suggested an optimal model fit, and a 95% CI that included zero indicated a fitting model (Finch & Bolin, 2017).

Results

Descriptive Statistics

Descriptive statistics at baseline and follow-up are displayed in Table 1. Statistically significant differences between girls and boys were observed in LMS and OCS at both baseline and follow-up ($p < .001$). Gender differences in FMS were statistically significant only at follow-up ($p = .002$). The baseline data included measurements from two girls ages 2.97 years. This age is marginally below the validated age threshold of 3 years for the TGMD-3.

For comparison, the distribution of the participants' weight statuses according to Finnish BMI-for-age references with five categories (Saari et al., 2011) and International Obesity Task Force references with eight categories (Cole & Lobstein, 2012; Sanchez-Delgado et al., n.d.), classified as underweight, normal weight, overweight, obesity, and total overweight and obesity, is presented in the Supplementary Table S1 (available online). The distributions of the participants' weight statuses, particularly the proportions of girls and boys, appear to differ between the Finnish and International Obesity Task Force references, as noted in previous research (Saari et al., 2011). However, the proportion of overweight and obese girls (18.0%–18.6%) and boys (27.1%–29.7%) in this study aligns closely with the proportion of overweight and obese Finnish children of the same age (girls: 16.0%–19.0%, boys: 27.0%–30.0%) that was reported in Finnish references (Jääskeläinen et al., 2021).

Table 2 indicated to a strong correlation between baseline and follow-up BMI SDS *z*-scores ($r = .774–.775$, $p < .001$) but showed no relationship between BMI SDS *z*-scores and FMSzre, or between BMI SDS *z*-scores and age-residualized skill domains. Likewise, within-variable correlations between baseline and follow-up were statistically significant for FMSzre, LMSzre, and OCSzre ($r = .281–.390$, $p \leq .001$).

The results of the intercept-only model indicated that FMSzre, LMSzre, and OCSzre and the BMI SDS *z*-scores exhibited statistically significant variations (Table 3) across childcare centers (1.9%–6.0%, $p < .001$) and schools (1.0%–5.2%, $p < .001$). The statistical significance of the between-level variances suggests that multilevel analytical techniques were warranted.

Table 1 Descriptive Statistics for Age, TGMD-3-Based FMSs (Maximum: 28 Points), LMSs (Maximum: 14 Points), OCSs (Maximum: 14 Points), and Finnish National Standards-Based BMI *SD* Scores at Baseline and Follow-Up ($N = 675$)

	N	*M*	*SD*	Minimum	Maximum	Gender differences (*p*)
Age at baseline	675	5.53	1.09	2.97[a]	7.80	.303
Girls	341	5.48	1.10	2.97	7.29	
Boys	334	5.58	1.08	3.10	7.80	
Age at follow-up	674	8.76	1.08	6.33	11.44	.316
Girls	341	8.72	1.08	6.72	11.44	
Boys	333	8.80	1.09	6.33	11.28	
FMS at baseline	596	12.2	5.4	0	27	.439
Girls	299	12.3	4.9	0	24	
Boys	297	12.0	5.8	0	27	
FMS at follow-up	643	17.2	5.0	0	28	**.002**
Girls	328	16.7	4.3	5	27	
Boys	315	17.8	5.5	0	28	
LMS at baseline	602	7.0	3.5	0	14	**<.001**
Girls	304	7.7	3.3	0	14	
Boys	298	6.4	3.5	0	14	
LMS at follow-up	645	8.9	2.9	0	14	**<.001**
Girls	330	9.5	2.5	2	14	
Boys	315	8.3	3.2	0	14	
OCS at baseline	604	5.1	3.1	0	14	**<.001**
Girls	302	4.6	2.6	0	12	
Boys	302	5.7	3.3	0	14	
OCS at follow-up	648	8.3	3.3	0	14	**<.001**
Girls	329	7.2	2.8	0	14	
Boys	319	9.4	3.3	0	14	
BMI SDS at baseline	621	0.18	1.05	−4.55	3.24	.325
Girls	311	0.21	1.13	−4.55	3.24	
Boys	310	0.14	0.95	−3.37	2.47	
BMI SDS at follow-up	641	0.22	0.99	−3.43	3.22	.580
Girls	328	0.25	1.02	−3.01	3.22	
Boys	313	0.19	0.96	−3.43	2.51	

Note. p values of gender differences under .05 are shown in bold. LMS = locomotor skill level; OCS = object control skill level; FMS = fundamental movement skill level; BMI SDS = body mass index *SD* score; TGMD-3 = Test of Gross Motor Development, third edition.
[a]The baseline data include measurements from two girls ages 2.97 years.

Table 2 Correlations Within Models: Standardized BMI SDS Scores and Age-Residualized FMSs and Skill Domain Levels at Baseline and Follow-Up

	BMI SDS z-scores		FMSzre	
	Baseline	Follow-up	Baseline	Follow-up
BMI SDS *z*-scores at baseline	1			
BMI SDS *z*-scores at follow-up	0.774[a]	1		
FMSzre at baseline	–0.032	–0.035	1	
FMSzre at follow-up	0.002	0.002	0.390[a]	1

	BMI SDS z-scores		LMSzre		OCSzre	
	Baseline	Follow-up	Baseline	Follow-up	Baseline	Follow-up
BMI SDS *z*-scores at baseline	1					
BMI SDS *z*-scores at follow-up	0.775[a]	1				
LMSzre at baseline	–0.061	–0.058	1			
LMSzre at follow-up	–0.028	–0.036	0.299[a]	1		
OCSzre at baseline	0.019	0.010	0.113[a]	0.219[a]	1	
OCSzre at follow-up	0.032	0.035	0.099[a]	0.189[a]	0.281[a]	1

Note. BMI SDS = body mass index *SD* score; FMSzre = age-residualized fundamental movement skill level; LMSzre = age-residualized locomotor skill level; OCSzre = age-residualized object control skill level.

[a]Correlation is significant at the .05 level (two-tailed).

Bidirectional Longitudinal Relationship Between Standardized BMI-for-Age *SD* Score and Age-Residualized FMSs

Table 4 displays the outcomes of individual-level predictors in the bidirectional relationship between BMI SDS *z*-scores and FMSzre. An interaction between baseline FMSzre and gender significantly predicted both BMI SDS *z*-scores ($\beta = -0.076$, $p = .006$) and FMSzre ($\beta = 0.142$, $p < .001$) at follow-up. However, the final models (Table 5) revealed no statistically significant bidirectional longitudinal relationship between BMI SDS *z*-scores and FMSzre for either

Table 3 Variation in Standardized BMI SDS Score, and Age-Residualized FMS, LMS, and OCS Levels Across Childcare Centers and Schools According to Intercept-Only Models

	Intercept-only models (*N* = 649, 36 childcare centers and 94 schools)				
Variance	BMI SDS z-scores	FMSzre	BMI SDS z-score	LMSzre	OCSzre
$\sigma_{childcarecenter}$ (ICC)	0.019* (.019)	0.061* (.060)	0.021* (.021)	0.041* (.040)	0.026* (.026)
σ_{school} (ICC)	0.019* (.019)	0.023* (.023)	0.027* (.027)	0.009* (.009)	0.053* (.052)

Note. BMI SDS = body mass index *SD* score; FMSzre = age-residualized fundamental movement skill level; LMSzre = age-residualized locomotor skill level; OCSzre = age-residualized object control skill level; ICC = intraclass correlation coefficient.
*Significant at $p < .05$.

Table 4 Results of the Analysis of the Bidirectional Longitudinal Relationship Between Standardized BMI SDS Scores and Age-Residualized FMS Level, Including Gender and Interactions as Predictors

	Outcomes at follow-up (*N* = 673, 36 childcare centers and 97 schools)	
Individual-level predictors at baseline	BMI SDS z-scores (95% C.I.)	FMSzre (95% C.I.)
BMI SDS *z*-cores	0.774* [0.739, 0.805]	0.011 [–0.065 to 0.087]
FMSzre	–0.005 [–0.059 to 0.050]	0.379* [0.303, 0.449]
Gender	–0.005 [–0.058 to 0.047]	0.153* [0.080, 0.225]
FMSzre × Gender	–0.076* [–0.130 to – 0.022]	0.142* [0.064, 0.218]
BMI SDS *z*-scores × Gender	0.006 [–0.048 to 0.058]	0.057 [–0.021 to 0.133]
Within-level R^2	.606* [.553, .655]	.206* [.146, .269]

Note. C.I. = credibility interval; BMI SDS = body mass index *SD* score; FMSzre = age-residualized fundamental movement skill level.
*Significant at $p < .05$.

Table 5 Results of the Analysis of the Bidirectional Longitudinal Relationship Between the Standardized BMI SDS Score and Age-Residualized FMS Levels in Girls and Boys

Individual-level predictors at baseline	Outcomes at follow-up			
	Girls (n = 340, 36 childcare centers and 76 schools)		Boys (n = 332, 36 childcare centers and 76 schools)	
	BMI SDS *z*-scores (95% C.I.)	FMSzre (95% C.I.)	BMI SDS *z*-scores (95% C.I.)	FMSzre (95% C.I.)
BMI SDS *z*-scores	0.757* [0.700, 0.805]	–0.056 [–0.175, 0.066]	0.780* [0.727, 0.824]	0.037 [–0.066, 0.140]
FMSzre	0.063 [–0.018, 0.145]	0.262* [0.142, 0.376]	–0.079 [–0.158, 0.001]	0.516* [0.417, 0.603]
Within-level R^2	.573* [.492, .647]	.077* [.026, .152]	.614* [.536, .683]	.271* [.179, .369]

Note. C.I. = credibility interval; BMI SDS = body mass index *SD* score; FMSzre = age-residualized fundamental movement skill level.
*Significant at $p < .05$.

gender. Instead, baseline BMI SDS *z*-scores and FMSzre significantly predicted their follow-up values. The model accounted for 57.3%–61.4% of BMI SDS *z*-scores variance and 7.7%–27.1% of FMSzre variance.

Final models for girls and boys were fitted to the data according to the PPP-value (girls: 0.345, boys: 0.340) and a 95% CI for the difference between the observed and the replicated chi-square values (girls: [–20.490, 34.403], boys: [–21.652, 35.113]).

Bidirectional Longitudinal Relationship Between Standardized BMI-for-Age *SD* Scores and Age-Residualized Skill Domains

The findings on the bidirectional relationship between BMI SDS *z*-scores and age-residualized skill domains mirrored the findings presented previously related to BMI SDS *z*-scores and FMSzre. The interactions between age-residualized skill domains and gender (Table 6) predicted at least one of the dependent variables ($\beta = -0.079$ to 0.096, $p = .004$–.020), leading to separate analyses for each gender (Table 7). However, no significant relationship was found between BMI SDS

Table 6 Results of the Analysis of the Bidirectional Longitudinal Relationship Between the Standardized BMI SDS Score and Age-Residualized Skill Domains, Including Gender and Interactions as Predictors

	Outcomes at follow-up (*N* = 673, 36 childcare centers and 97 schools)		
Individual-level predictors at baseline	BMI SDS z-scores (95% C.I.)	LMSzre (95% C.I.)	OCSzre (95% C.I.)
BMI SDS *z*-scores	0.771* [0.735, 0.803]	–0.029 [–0.106, 0.046]	0.041 [–0.031, 0.114]
LMSzre	–0.015 [–0.071, 0.043]	0.223* [0.144, 0.301]	0.174* [0.100, 0.253]
OCSzre	0.004 [–0.051, 0.060]	0.205* [0.123, 0.288]	0.165* [0.086, 0.246]
Gender	–0.010 [–0.067, 0.049]	–0.185* [–0.262, –0.106]	0.389* [0.314, 0.462]
LMSzre × Gender	–0.079* [–0.131, –0.025]	0.035 [–0.046, 0.112]	0.049 [–0.025, 0.125]
OCSzre × Gender	–0.015 [–0.072, 0.040]	0.084* [0.003, 0.163]	0.096* [0.016, 0.173]
BMI SDS *z*-score × Gender	0.004 [–0.049, 0.055]	0.060 [–0.018, 0.139]	0.023 [–0.053, 0.096]
Within-level R^2	.608* [.557, .655]	.176* [.122, .236]	.242* [.180, .304]

Note. C.I. = credibility interval; BMI SDS = body mass index *SD* score; LMSzre = age-residualized locomotor skills; OCSzre = age-residualized object control skills.
*Significant at $p < .05$.

Table 7 Results of the Analysis of the Bidirectional Longitudinal Relationship Between the Standardized BMI SDS Score and Two Age-Residualized Skill Domains (LMSs and OCSs) in Girls and Boys

	Outcomes at follow-up					
	Girls (n = 340, 36 childcare centers, 76 schools)			Boys (n = 332, 36 childcare centers, 76 schools)		
Individual-level predictors at baseline	BMI SDS *z*-scores (95% C.I.)	LMSzre (95% C.I.)	OCSzre (95% C.I.)	BMI SDS *z*-scores (95% C.I.)	LMSzre (95% C.I.)	OCSzre (95% C.I.)
BMI SDS *z*-scores	0.756* [0.700, 0.804]	−0.090 [−0.208, 0.032]	0.002 [−0.116, 0.120]	0.776* [0.722, 0.820]	−0.013 [−0.124, 0.097]	0.060 [−0.049, 0.167]
LMSzre	0.064 [−0.017, 0.145]	0.219* [0.097, 0.336]	0.158* [0.034, 0.273]	−0.079 [−0.160, 0.002]	0.229* [0.113, 0.337]	0.212* [0.096, 0.321]
OCSzre	0.019 [−0.062 to 0.099]	0.121 [−0.002, 0.240]	0.070 [−0.055, 0.189]	−0.018 [−0.098, 0.061]	0.315* [0.201, 0.421]	0.299* [0.186, 0.409]
Within-level R^2	.573* [.493, .646]	.088* [.033, .164]	.040* [.008, .095]	.616* [.537, .683]	.188* [.108, .278]	.173* [.096, .262]

Note. C.I. = credibility interval; BMI SDS = body mass index *SD* score; LMSzre = age-residualized locomotor skills; OCSzre = age-residualized object control skills.
*Significant at $p < .05$.

z-scores and the age-residualized skill domains for either gender. Instead, baseline BMI SDS *z*-scores and LMSzre significantly predicted their follow-up values, while OCSzre at baseline significantly predicted its follow-up only for boys. The model explained 57.3%–61.6% of BMI SDS *z*-scores variability and 4.0%–18.8% for LMSzre and OCSzre.

The final models for girls and boys fitted to the data according to PPP-value (girls: .201, boys: .198) and 95% CI for the difference between the observed and the replicated chi-square values (girls: [–23.945, 58.084], boys: [–22.426, 59.732]).

Discussion

The present study was intended to investigate the bidirectional longitudinal relationship between BMI SDS *z*-scores and FMSzre, also considering two skill domains—LMSzre and OCSzre—separately, measured by a process-oriented assessment in Finnish children over a 3-year follow-up period, starting from early childhood. The final models revealed no statistically significant bidirectional longitudinal relationship between BMI SDS *z*-scores and FMSzre for either girls or boys, in either direction. Investigating the skill domains separately did not change the results. The lack of a statistically significant longitudinal relationship may suggest that BMI and process-oriented FMS, including the skill domains, develop independently of each other in both girls and boys, and may further suggest that other variables influence their development. Another possibility is that the bidirectional longitudinal relationship does not appear yet in early childhood (Barnett et al., 2021; Robinson et al., 2015). Also, the cultural variations (Adeyemi-Walker et al., 2018; Barnett et al., 2021; Cordovil et al., 2022; Jeong et al., 2023; Robinson et al., 2015) and different methods of measuring and interpreting FMS (Hulteen et al., 2020; Palmer et al., 2021) or weight status (Cheng et al., 2016; Saari et al., 2011; Vlahov et al., 2014) may have affected study results.

The findings of this research do not support the hypothesis of an inverse bidirectional relationship between weight status and FMS described by the theoretical framework (Robinson et al., 2015) or reflected in the findings of a published systematic review (Barnett et al., 2021). Contrary to some evidence from the review (Barnett et al., 2021) suggesting a bidirectional longitudinal relationship between skill domains and weight status, the current study did not find such an association. Furthermore, despite previous research (Okely et al., 2004) suggesting that LMSs might be more influential than OCSs for body movement against gravity, this study did not observe a significant differential impact of LMS and OCS on weight status.

One explanation for the results of this study may be the process-oriented manner in which FMS was measured. The process-oriented test focuses on the quality of movement, including movement patterns and execution methods, through observation of children's body positioning and motion engagement (Williams & Monsma, 2006). In addition, the performance of a process-oriented subtest takes a short time and does not require high levels of physical capacity, whereas product-oriented measures may contain more overlap with the physical capacity component of fitness tests (Utesch et al., 2019), typically involving quantitative information of movement, such as speed, repetitions, height, and length (Williams & Monsma, 2006). For instance, the physical capacity component of FMS has been found to be significant in the relationship between FMS and executive functions (Malambo et al., 2022).

We propose that the physical capacity component of FMS might be the primary reason for the bidirectional longitudinal relationship between BMI and FMS, as measured in a product-oriented manner, which may explain the findings of this study. In addition, prior studies substantiate this conclusion regarding the relationship between the physical capacity element of FMS and BMI or body fatness. Earlier bidirectional longitudinal studies (D'Hondt et al., 2014; Lima et al., 2019) that started in early childhood and employed the product-oriented Körperkoordinationstest für Kinder measure identified an inverse relationship between Körperkoordinationstest für Kinder results and BMI (D'Hondt et al., 2014) or body fatness (Lima et al., 2019).

On the other hand, studies (Duncan et al., 2021; Foulkes et al., 2021; Lopes et al., 2020; Vlahov et al., 2014) that investigated only one direction pathway and used the process-oriented TGMD-2 measure reported partly conflicting results. Foulkes et al. (2021) and Lopes et al. (2020) supported the results of this study, as they found no relationship from FMS, LMS, or OCS to BMI (Foulkes et al., 2021) or a reverse path (Lopes et al., 2020). In contrast, Duncan et al. (2021) showed that baseline LMS subtests, such as jumps and slides, predicted BMI, while Vlahov et al. (2014) found that FMS, LMS, and OCS had a significant relationship to body fatness. However, these studies did not consider baseline BMI (Duncan et al., 2021) or body fatness (Vlahov et al., 2014) as predictive variables, which means that change or development in variables was overlooked, which may have affected the results of the analysis. Nevertheless, the results of this study and of previous studies (Rooney et al., 2011; Simmonds et al., 2016) have demonstrated that baseline BMI is a strong predictor for follow-up BMI.

In addition, previous studies have supported an inverse relationship between weight status and the physical capacity component as measured by physical fitness tests, even in early childhood (Ortega et al., 2013; Silva-Santos et al., 2017). Enhanced physical fitness might increase calorie expenditure, for instance, through an increase in muscle mass (Ortega et al., 2013). The relationship between weight status and physical fitness, or product-oriented FMS, may occur in a similar way, considering the similarities of the tests (Robinson et al., 2015; Utesch et al., 2019). Furthermore, the terminology is often used interchangeably across studies (Utesch et al., 2019). For example, jumping sideways and the standing long jump are considered part of FMS in some studies (D'Hondt et al., 2014; Lima et al., 2019), while in others, the same tests are classified as components of physical fitness (Ruedl et al., 2022). However, notably, conflicting results exist regarding the relationship between BMI and physical fitness (Lopes et al., 2020).

Reliable comparisons of results between studies appear to be challenging due to factors such as different measurement methods and variations in study samples. Weight-measuring methods vary, ranging from body fat assessments (Jeong et al., 2023) to different methods of calculating BMI (Meyers et al., 2013). Additionally, there is a wide range of metrics used by researchers to determine FMS in childhood (Hulteen et al., 2020). Comparing results from different measurement methods is challenging, and even using the same test does not always guarantee reliable comparisons. For example, results from the TGMD-3 can vary between different research teams (Hulteen et al., 2023), and the TGMD-2 and TGMD-3 do not align completely in terms of subtests and scoring, with a particularly notable difference observed in the OCS between the tests (Field et al., 2020). Furthermore, when considering cultural variations and different study populations (e.g., age, sex, ethnicity, and number of overweight or obese children), comparing results becomes even more complex (Adeyemi-Walker et al., 2018; Jeong et al., 2023).

The strength of this research lies in its analysis of longitudinal data gathered from children in their early childhood over an average 3-year period and in its use of a two-level, cross-classified, cross-lagged regression analysis as a statistical method, considering the impacts of childcare centers and schools. We also adopted a process-oriented approach to measure FMS, and we analyzed skill domains separately to explore more precisely the bidirectional longitudinal relationship between BMI and FMS. Furthermore, we used BMI-for-age, which considers age (Saari et al., 2011), and age-residualized FMS, LMS, and OCS, as well as the interaction between FMS, LMS, OCS, and gender, as predictor variables to ensure a more detailed depiction.

Nonetheless, this study did have certain limitations. The first limitation is that FMS levels were based only on the results of four subtests of TGMD-3; thus, LMS and OCS levels were each based on two subtests. This may give a limited picture of skill levels, even though the subtests were selected from among those found to best describe the skill domains (Wagner et al., 2016). Additionally, the potential ceiling effect of TGMD-3 might have influenced the results (Ulrich, 2019). The cultural characteristics and homogeneity of the Finnish sample, especially in terms of BMI, compared with other international studies, could also impact the findings.

More studies are needed in the future that examine the bidirectional longitudinal relationship between FMS and BMI from early childhood to adolescence and beyond. It is also crucial to consider that this relationship may vary between individuals of normal weight and those who are obese (Cheng et al., 2016). Gathering data from the same study population at multiple time points would make the growth curve analysis method also possible. Future research should also aim to compare the bidirectional longitudinal relationship between weight status and FMS, measured using both process- and product-oriented methods. This could enhance our understanding of the relationships between these variables, even though both process- and product-oriented measures of FMS are recommended (Williams & Monsma, 2006).

The results of this study highlight the importance of considering multiple levels of influence when examining the predictors of BMI. They also emphasize that individual differences alone may not fully explain the variation, and variables related to childcare centers and schools should also be considered. A more holistic picture of a bidirectional relationship between BMI and FMS may also require including the influence of the family (Rooney et al., 2011; Scott-Sheldon et al., 2020).

Perspective

The current study suggests that a bidirectional longitudinal relationship between BMI and FMSs or individual skill domains may relate more to the physical capacity component of FMS than the qualitative information gleaned from the process-oriented way of measuring FMS. Thus, we recommend considering the influence of the childcare center, school, and family (Rooney et al., 2011; Scott-Sheldon et al., 2020) in the prevention and treatment of obesity and being overweight, in addition to the individual characteristics of children. Overall, the results of this and a previous study (Rooney et al., 2011) highlight the importance of paying attention to weight status in early childhood because it has a strong association with weight status later in life.

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III

PROCESS- AND PRODUCT-ORIENTED FUNDAMENTAL MOVEMENT SKILLS IN EARLY CHILDHOOD AS PREDICTORS OF LATER HEALTH-RELATED FITNESS

by

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Process- and Product-Oriented Fundamental Movement Skills in Early Childhood as Predictors of Later Health-Related Fitness

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ABSTRACT

KASANEN, M., A. SÄÄKSLAHTI, D. NIEMISTÖ, A. TOLVANEN, N.-M. LUUKKAINEN, E. MEKLIN, and A. LAUKKANEN. Process- and Product-Oriented Fundamental Movement Skills in Early Childhood as Predictors of Later Health-Related Fitness. *Med. Sci. Sports Exerc.*, Vol. 56, No. 9, pp. 1722–1731, 2024. **Introduction:** The skill domains of fundamental movement skills (FMS), emphasizing gross motor movements, including locomotor skills (LMS) and object control skills (OCS), along with process- and product-oriented measures of FMS, may predict cardiorespiratory fitness (CRF) and muscular fitness (MF) differently. This study investigates the longitudinal relationship from early childhood FMS, focusing on process-oriented LMS and OCS and product-oriented FMS, to CRF and MF in late childhood. **Methods:** The study involved 441 Finnish children (49.9% female; mean age at baseline, 5.5 yr) over a 6-yr period. FMS was evaluated using the Test of Gross Motor Development, third version, for process-oriented LMS and OCS, and the Körperkoordinationstest Für Kinder (KTK) was used to evaluate the product-oriented FMS. CRF was assessed through the total number of laps completed in the 20-m shuttle run test, whereas MF was measured via repetitions of curl-ups and push-ups. Employing a two-level cross-classified regression analysis and Cholesky decomposition, this study aimed to determine the contributions of product-oriented KTK and process-oriented LMS and OCS. Adjustments for variations in age, measurement intervals, and maturation were achieved through residualization. In addition, gender and body mass index were incorporated as covariates in the analysis. **Results:** The analysis revealed that process-oriented LMS (CRF: $\Delta R^2 = 0.016$; MF: $\Delta R^2 = 0.014$) significantly predicted later health-related fitness, whereas OCS did not. However, KTK exhibited a better ability to predict both CRF (ΔR^2 = 0.092) and MF (ΔR^2 = 0.032), overshadowing process-oriented measures. **Conclusions:** In conclusion, the findings suggest that KTK, which potentially encompasses a broader spectrum of fitness elements along with FMS, more effectively predicts health-related fitness components than process-oriented FMS. **Key Words:** CARDIORESPIRATORY FITNESS, LONGITUDINAL STUDY, MOTOR COMPETENCE, MUSCULAR FITNESS

Health-related fitness components, as defined by Caspersen et al. (1), include cardiorespiratory fitness (CRF) and muscular fitness (MF), which are linked to various health indicators such as cardiovascular disease risk factors, skeletal health, and psychosocial health during childhood, adolescence, and later life stages (2–6). In general, studies have shown a decline in CRF (7,8) and MF (8) among children and adolescents in numerous countries in recent decades. According to Caspersen et al. (1), CRF refers to the ability of the circulatory and respiratory systems to supply fuel and oxygen to muscles during sustained physical activity and to remove fatigue products thereafter. MF involves the capacity of different muscle groups to exert external force through repeated or consecutive efforts (1).

According to Robinson et al. (9), fundamental movement skills (FMS), which encompass the performance level of neural, muscular, biomechanical, and perceptual mechanisms in gross motor movements (10), promote positive CRF and MF trajectories in children and adolescents. The development of FMS primarily occurs in early childhood (10) and generally in children 8 yr or younger (11). Research findings suggest that FMS remain relatively stable and consistent with age during childhood (12,13), underscoring the importance of exploring their development early on.

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Systematic reviews support the longitudinal relationship from FMS to both CRF and MF (14–16). However, the nature of this relationship varies when the skill domains of FMS (10) —namely, locomotor skills (LMS), such as running, jumping, and hopping; and object control skills (OCS), such as throwing, catching, kicking, striking, and dribbling—are examined separately, with some results being indeterminate (14). Notably, a short-term longitudinal study by Chen et al. (12) suggests that LMS may be a stronger predictor of fitness outcomes than OCS in early childhood, although other findings have highlighted OCS as a predictor (17), particularly from middle childhood to adolescence (18).

The performance of FMS, CRF, and MF, based on neuromuscular control and coordination (e.g., effective coordination patterns in complex multijoint movements; stabilization of body segments; isometric, concentric, and eccentric force generation), potentially increases participation in physical activities, although they are theoretically distinct constructs (15,16). Furthermore, there is a content overlap between assessments. The measurements of FMS, CRF, and MF are closely linked (15,16). This overlap is evident in the use of similar metrics for measuring FMS, CRF, and MF, which often involves goal-directed movements requiring similar abilities (9,15,16). Closely linked backgrounds and similar measurements have led to the interchangeable use of terminology (16) and metrics across studies (15). For instance, tasks such as jumping sideways and the standing long jump are categorized as FMS in some research (19,20) but as part of fitness components in others (21).

FMS assessments may also extensively include components of CRF and MF (15,16), depending on their approach. Process- and product-oriented measures assess different aspects of FMS (22). Process-oriented tests primarily focus on qualitative movement aspects, such as the movement patterns and technique involved, based on specific skill performance criteria, while product-oriented tests, which more frequently include parts of CRF and MF, emphasize quantitative outcomes, such as speed, distance, height, or repetition of tasks (23). For instance, the Test of Gross Motor Development, third version (TGMD-3), is a process-oriented assessment by which tasks, such as running, are scored based on detailed performance criteria (0 points if the criterion is absent, and 1 point if the criterion is fulfilled). For example, the four quality criteria to measure running skills are as follows: 1) arms move in opposition to legs, with elbows bent; 2) a brief period where both feet are off the surface; 3) narrow foot placement landing on the heel or toes rather than flat-footed; and 4) the nonsupport leg is bent approximately 90 degrees, bringing the foot close to the buttocks (24). In contrast, the Körperkoordinationstest Für Kinder (KTK) assessment exemplifies a product-oriented measure, where performance on tasks such as jumping sideways is scored based on quantitative outcomes, specifically with respect to jumping sideways, the number of sideways jumps completed in 15 s (25). Notably, these two types of measures, despite their low to moderate correlation (26), are not interchangeable (22). Moreover, the similarity between FMS measures, especially those that are product oriented, and CRF and MF may significantly influence their longitudinal relationship.

This study aims to investigate the longitudinal relationship between FMS, with a focus on gross motor movements, and both CRF and MF from early to late childhood. We concentrate on the skill domains of LMS and OCS, evaluated using the process-oriented method of the TGMD-3 (24). In addition, we compared the longitudinal relationship from the perspectives of both process- and product-oriented measurements, employing the LMS and OCS of TGMD-3 and the total scores from the KTK (25). Our hypotheses are twofold: first, that LMS will be a more significant predictor of CRF and MF than OCS (12), and second, that product-oriented FMS measures will demonstrate a stronger longitudinal relationship with CRF and MF than process-oriented FMS. These hypotheses are based on existing research indicating that both LMS (12) and product-oriented measures (9) require physical attributes that are akin to those needed in CRF and MF tests. Given the relative stability of CRF and MF during childhood (12,13), it is anticipated that product-oriented FMS tests measuring similar abilities and characteristics will likely predict more robust CRF and MF.

MATERIALS AND METHODS

This study utilized longitudinal data from 950 Finnish children, aged 3 to 8 yr, who participated in the geographically cluster-randomized Skilled Kids study (2015 to 2016) (27), with comprehensive data available on the main study variables, namely, parental support for child physical activity and child outdoor time, of the follow-up research referred to as the Skills, Support and Physical Activity—TAITURIT study (2021 to 2023) (28). Of the original 950 participants, 443 agreed to grant permission and participated in the follow-up measurements approximately 6 yr later (M = 6.14 yr, range = 5.24 to 7.45 yr, SD = 0.52 yr). However, two participants who were under 3 yr of age at baseline were excluded from the analysis because of the validated age range for TGMD-3. All 441 participants, representing 46.4% of the initial cohort, were included in the analysis. The data were determined to be missing completely at random (Little's test for missing completely at random = 86.672, df = 69, P = 0.074), taking into account all variables involved in the model. Participants were originally clustered within 37 childcare centers at baseline and later within 80 schools at the follow-up stage.

Written informed consent was obtained from the participants and their parents before data collection commenced. This consent authorized the voluntary participation in the study and granted permission for data integration and the analysis of health information. The study received ethical approval from the Ethics Committee of the University of Jyväskylä, with baseline study approval granted on October 30, 2015, and follow-up study approval on May 21, 2021.

Measurements

Age, gender, anthropometric measures, and maturation. In the baseline questionnaire, parents reported their

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children's gender (options: girl or boy) and birth date. The exact ages of the children at the time of both the baseline and follow-up assessments were determined by comparing their birth dates with their respective assessment dates. Children's body mass and height were accurately measured to the nearest decimal using seca 877 flat scale (seca GmbH & Co. KG, Hamburg, Germany) and HM 200P portable stadiometer (Charder Electronic Co., Ltd., Taichung City, Taiwan, ROC), respectively, while the children were lightly dressed and barefoot. Body mass index (BMI)-for-age standard deviation scores (BMI SDS) were computed using Finnish national standards (29). These scores were then standardized into BMI SDS *z*-scores, with distinct calculations for boys and girls to account for gender-specific differences in interpreting BMI SDS values.

The children's sitting height, along with the chair height, was measured using the portable stadiometer (HM 200P, Charder Electronic Co., Ltd.), similarly to the way stature was measured. The sitting height was calculated by subtracting the chair height from the measured sitting height. Leg length was then determined by subtracting the sitting height from the overall stature. Maturation offset for both genders was calculated using age, weight, height, sitting height, and leg length, based on the equations provided by Mirwald et al. (30). These equations offer a practical and reliable method (model for boys: $R^2 = 0.92$, SEE = 0.49; model for girls: $R^2 = 0.91$, SEE = 0.50) for assessing maturation noninvasively, utilizing the concept of maximum growth during adolescence, known as peak height velocity (PHV). The maturation offset, measured in years from PHV, indicates the stage of maturation, where a negative maturity offset indicates pre-PHV and a positive offset indicates post-PHV (30).

FMS measured by process- and product-oriented methods. In this study, FMS was assessed in a process-oriented manner using TGMD-3 (24), whereas KTK (25) was employed for measuring FMS in a product-oriented manner at baseline. The tests were conducted on two separate days. On the first day of measurement, children aged 5 to 7 yr (mean age, 6.14 yr; range, 5.03 to 7.44 yr) underwent KTK measurements, which are suitable for children aged 5 to 14 yr (25). On the second measurement day, TGMD-3 was administered to children over 3 yr of age (mean age, 5.51 yr; range, 3.03 to 7.44 yr) because TGMD-3 was designed for children aged 3 to 11 yr (24). The same research group performed all tests.

TGMD-3 (24) is highly recommended for FMS testing because of its feasibility and robust psychometric properties, which include high inter-rater reliability (over 70 % of measurements exceed 0.9), intra-rater reliability (approximately 85% of measurements exceeding 0.9), internal consistency (Cronbach's alpha values ranging from 0.7 to 0.9), and test–retest reliability (over 0.8) (31). For the current study, inter-rater reliability was established as good (interclass correlation: 0.88; 95% confidence interval (CI), 0.85 to 0.92) based on the performance of 167 children before baseline data collection (32). Findings from a previous study (33) indicate that comparing TGMD-3 results between studies may present challenges, as indicated by the fair (0.730 to 0.757) intraclass correlation coefficients (ICCs) and the poor (0.363 to 0.478) agreement ICCs.

TGMD-3 comprises six subtests for LMS and seven for OCS. The LMS subtests are running (0 to 8 points), galloping (0 to 8), hopping (0 to 8), skipping (0 to 6), horizontal jumping (0 to 8), and sliding (0 to 8). The OCS subtests include two-hand striking of a stationary ball (0 to 10 points), one-hand forehand strike (0 to 8), one-hand stationary dribble (0 to 6), two-hand catching (0 to 6), kicking a stationary ball (0 to 8), overhand throwing (0 to 8), and underhand throwing (0 to 8). Scores for LMS and OCS were out of a maximum of 46 and 54 points, respectively. Each skill is evaluated based on three to five performance criteria, varying by skill (24). A trained observer scores each performance based on these criteria, with 1 point awarded for meeting each criterion (1 point = performs correctly, 0 = does not perform correctly). Children first perform a practice trial for each subtest and then complete each subtest twice. The sum of the scores from these two trials constitutes the total score for each skill (24).

Product-oriented KTK (25) has evolved into a highly regarded, user-friendly, and standardized assessment tool for FMS, known as motor coordination (34). KTK showcases high reliability in various aspects. It achieves an inter-rater reliability above 0.85, indicating strong agreement among different raters and an impressive intra-rater reliability with an interclass correlation of 0.97, ensuring consistent evaluations. The test–retest reliability is also high, exceeding 0.85, with no significant differences found between the initial test and the retest, affirming the KTK's reliability over time (35).

KTK includes four subtests: 1) walking backward on balance beams of decreasing widths (maximum, 72 points), 2) hopping for height on one foot (maximum, 78 points), 3) jumping sideways from side to side for 15 s (total correct jumps in two trials), and 4) moving sideways with wooden plates as quickly as possible for 20 s (total points in two trials) (25).

Cardiorespiratory fitness. CRF was assessed using the 20-m shuttle run test, as described by Léger and Lambert (36). This test is a recognized and reliable method for evaluating the CRF of children (37,38). It begins with a beep signal, prompting children to run 20 m until they hear the next beep, signaling the start of a new lap. The initial running speed was set at 8.5 km/h and increased by approximately 0.5 km/h every minute. The test result was determined by the total number of laps completed in sync with the beep signals (36).

Muscular fitness. In this study, MF was evaluated using curl-ups and push-ups. Curl-ups (39), which assess the endurance of abdominal muscles, are known to have acceptable measurement properties. Participants began the curl-ups lying down, with their heads, straight arms, and soles of the feet touching the mat and with knees bent at 100 degrees. Fingertips were placed at one edge of a marked 8-cm wide tape. During the exercise, participants started in a supine position and raised their upper bodies from the mat until their fingertips touched the opposite edge of the tape. This motion ensured engagement of their abdominal muscles, while their heads returned to the starting position on the mat after each repetition.

The test involved performing as many correctly executed curl-ups as possible, synchronized with an audio tape, with the maximum score of 75 repetitions (39).

The push-up test (39), a reliable measure of upper-body muscle strength for children (39,40), was also used. In the push-up test, boys started with their weight on their toes and girls on their knees, both with straight arms positioned next to the shoulders and fingers pointing forward. The body remained straight, and the face was positioned downward. From this starting position, participants lowered themselves until their upper arms were horizontal and then pushed up to full arm extension, returning to the starting position to complete one push-up. The result was based on the number of correctly performed push-ups within 60 s (39).

Data Analysis

To account for age-related differences in FMS scores (41) and health-related fitness components (42,43), as well as for the individually varying durations between baseline and follow-up measurement points, scores for KTK, TGMD-3 LMS, and TGMD-3 OCS, along with CRF and MF, were adjusted based on the children's ages at the measurement point. This process involved creating standardized residuals from regression models, with age serving as the predictor for all dependent variables—specifically, TGMD-3 LMS, TGMD-3 OCS, KTK scores, CRF, and MF. Subsequently, the scores for CRF and MF, already adjusted for age via regression analysis, underwent further refinement. In this next stage, regression models were utilized once more, this time with the maturation offset as a predictor. This maturation offset, individually calculated for each participant according to the equations provided by Mirwald et al. (30), allowed for adjustments that considered the specific impacts of maturation, in addition to age, on CRF and MF scores.

These adjustments allowed for the interpretation of how participants' FMS scores, adjusted for age, deviated from the average for their age, and how their CRF and MF, adjusted for both age and maturity, deviated from the average for these variables. Positive residuals indicated performance above the age-predicted value, whereas negative residuals suggested performance below the expected level. The age-residualized CRF and MF were then further interpreted in relation to the maturation offset, where negative residuals indicated performance below the maturation-predicted level, and positive residuals indicated performance above the expected level. Age-adjusted KTK (KTK_{adj}), TGMD-3 LMS (LMS_{adj}), and TGMD-3 OCS (OCS_{adj}) were used as predictors, along with gender (coded as girls 0, boys 1), and BMI SDS *z*-scores, and age maturation-adjusted CRF (CRF_{adj}) and MF (MF_{adj}) were used as outcome variables. Residualizing provided values that took into account varying ages, durations between measurements, and maturation offset.

A two-level cross-classified regression analysis (44) was utilized in this analysis of clustered data. Participants comprised level 1, with cross-classified childcare centers (n = 37; average, 12 participants; range, 1 to 22) and schools (n = 80; average, 5.6 participants; range, 1 to 22), constituting level 2. In the two-level analysis, only individual-level (level 1) predictors were included.

Intercept-only models and models including level 1 predictors were executed using Bayesian analysis (an iterative Markov chain Monte Carlo method: GIBBS[PX1], point estimate —median, two parallel chains, 18,000 to 110,000 iterations; burn-in: half of the iterations; and thinning rate = 1) for each outcome variable. To account for the multilevel structure of the data, all variables were allowed to correlate at the between levels in the current analyses (44). Predictors including models were performed only for covariates (model 1), and after that, separately (models 2 to 4) and simultaneously (models 5 to 6), including predictors such as KTK_{adj}, LMS_{adj}, and OCS_{adj} with covariates like BMI SDS *z*-scores and gender.

Because fundamental movement scores are correlated with each other, we also performed a hierarchical fixed-order regression analysis using the Cholesky decomposition approach (45) with the observed predictors and dependent variables. This approach allowed us to dissect the independent effects of each FMS measurement score on the outcome variables, revealing the additional variance in the outcomes that is explained by each specific FMS predictor beyond what is already accounted for by other predictors in the model. Cholesky decomposition provides insights into how R^2 increases when adding a specific FMS predictor to the model and is particularly useful for understanding the unique contribution of each predictor in a model, especially when these predictors are correlated (45).

In our analysis, one FMS measurement score (e.g., KTK_{adj}) was included after controlling for the other two FMS measurement scores (e.g., LMS_{adj} and OCS_{adj}) and covariates. In addition, we applied the Cholesky decomposition approach to analyze the interrelationship between LMS_{adj} and OCS_{adj}, providing further insights into their unique contributions when considered together. Therefore, two specific models focusing on LMS_{adj} and OCS_{adj} were executed, followed by three additional models incorporating LMS_{adj}, OCS_{adj}, and KTK_{adj}. In these models, each FMS measurement score was added after controlling for the other FMS measurements and covariates.

The level of statistical significance was set at a probability of less than 0.05, and credibility intervals in the models were interpreted similarly to CI in frequentist models. All models were executed using Bayesian approaches that utilized a distribution of values (prior distribution: mean, 0; variance, ∞), with the aim of obtaining parameter estimates based on the observed data, and all predictors were grand mean centered in the analysis (44). Potential scale reduction (PSR) coefficients below 1.1 and trace plots were used to assess the convergence of the posterior distribution. An acceptable level of autocorrelation was confirmed with autocorrelation plots (46). The posterior predictive probability value (PPP; values near 0.5 that suggested optimal model fit) and the 95% CI (including zero that indicated a fitting model) for the difference between the observed and replicated chi-square values were used to evaluate model fit (44).

Descriptive statistics and residualizing of age- and maturation-related variables were performed using IBM SPSS Statistics version 28 software (IBM, Armonk, NY). Both the correlation coefficients by the Bayesian approach and the two-level cross-classified models, including the Cholesky decomposition analysis, were implemented using Mplus version 8.8. (Muthén & Muthén, Los Angeles, CA). The research project of the Skills, Support, and Physical Activity—TAITURIT study is not yet completed; the data will be available at a later date. Until then, the data of this study are available upon request from the corresponding researcher. The codes of analysis are presented in Supplemental Digital Content 1, http://links.lww.com/MSS/D8, and 2, http://links.lww.com/MSS/D9.

RESULTS

Descriptive statistics and gender differences for the variables included in the model before residualization were examined (Table 1). The estimation of the correlation coefficients of model-included variables at the individual level, using the Bayesian approach, is presented in Table 2.

The results from the intercept-only models indicated that multilevel analytic techniques were warranted. Variations in CRF_{adj} and MF_{adj} were found to be statistically significant across individuals (77.2% to 82.9%, $P < 0.001$), childcare centers (8.8% to 10.2%, $P < 0.001$), and schools (6.7% to 13.9%, $P < 0.001$), as indicated in Table 3.

The two-level cross-classified regression analysis (Table 4) revealed that all FMS measurements, namely, LMS_{adj} (model 2), OCS_{adj} (model 3), and KTK_{adj} (model 4), predicted CRF_{adj} and MF_{adj} statistically significantly when included separately in the model. However, in a model where both LMS_{adj} and OCS_{adj} were included (model 5), only LMS_{adj} emerged as a statistically significant predictor, whereas OCS_{adj} did not significantly predict either outcome variable. In a model that included KTK_{adj} alongside LMS_{adj} and OCS_{adj} (model 6), only KTK_{adj} was a statistically significant predictor of CRF_{adj} and MF_{adj}. Gender and BMI SDS *z*-scores, as covariates, significantly predicted CRF_{adj} in all models except model 3, where gender was not a statistically significant predictor. BMI SDS *z*-scores did not significantly predict MF_{adj} in any model containing an adjusted FMS score, showing statistical significance only in the model where gender and BMI SDS *z*-scores were the sole predictors. In contrast, gender consistently emerged as a significant predictor of MF_{adj} across all models.

TABLE 1. Descriptive statistics and gender differences for variables before residualization.

	N	Mean	SD	Min	Max	Gender Differences (*P*)
Baseline						
Age	440	5.51	1.08	3.03	7.44	0.429
Girls	218	5.47	1.12	3.10	7.29	
Boys	222	5.55	1.08	3.03	7.44	
TGMD-3 LMS[a]	393	28.3	7.8	6	46	**0.002**
Girls	193	29.5	7.3	6	45	
Boys	200	27.1	8.0	6	46	
TGMD-3 OCS	394	25.9	8.8	4	49	**<0.001**
Girls	194	23.4	8.0	4	44	
Boys	200	28.4	8.8	5	49	
KTK	183	107.3	34.2	27	189	0.257
Girls	88	109.9	31.4	49	182	
Boys	95	104.8	36.6	27	189	
BMI SDS	410	0.17	1.04	−3.41	3.13	0.815
Girls	201	0.19	1.10	−3.41	3.13	
Boys	209	0.16	0.98	−3.29	2.50	
Follow-up						
Age	440	11.65	0.91	9.06	13.33	0.333
Girls	218	11.60	0.93	9.06	13.33	
Boys	222	11.70	0.89	9.55	13.28	
BMI SDS	424	0.14	1.05	−6.37	2.46	0.493
Girls	212	0.17	1.12	−6.37	2.46	
Boys	212	0.12	0.99	−2.33	2.34	
Maturity	417	−2.46	0.74	−4.35	0.17	0.320
Girls	210	−2.44	0.72	−4.35	−0.79	
Boys	207	−2.48	0.76	−3.96	0.17	
CRF	323	33.1	15.7	5	81	**0.002**
Girls	157	30.0	13.2	6	64	
Boys	166	36.1	17.2	5	81	
MF[b]	401	57.4	29.1	0	127	**0.007**
Girls	203	61.3	26.5	4	127	
Boys	198	53.3	31.1	0	110	

[a]Only one participant reached maximum points in the TGMD-3 LMS.
[b]In push-up test, boys started with their weight on their toes and girls on their knees.

TABLE 2. Estimation of correlation coefficients for model-included variables at the within-level using the Bayesian approach.

	1	2	3	4	5	6	7
1. Gender	1						
2. BMI SDS *z*-scores	0.008	1					
3. TGMD-3 LMS_{adj}	−0.210*	−0.118*	1				
4. TGMD-3 OCS_{adj}	0.349*	−0.026	0.314*	1			
5. KTK_{adj}	−0.135	−0.215*	0.503*	0.371*	1		
6. CRF_{adj}	0.161*	−0.240*	0.161*	0.191*	0.357*	1	
7. MF_{adj}	−0.170*	−0.107	0.212*	0.095*	0.288*	0.498*	1

*Correlation is significant at the 0.05 level.
BMI SDS *z*-score, BMI standard deviation scores standardized separately for girls and boys; CRF_{adj}, CRF adjusted by age and maturity; KTK_{adj}, KTK adjusted by age; LMS_{adj}, LMS adjusted by age; MF_{adj}, MF adjusted by age and maturity; OCS_{adj}, OCS adjusted by age.

The results of the Cholesky decomposition analysis (Table 5) indicate that LMS_{adj} was a statistically significant predictor of both CRF_{adj} and MF_{adj} when OCS_{adj} and covariates were controlled. LMS_{adj} uniquely contributed to CRF_{adj} ($\Delta R^2 = 0.016$) and MF_{adj} ($\Delta R^2 = 0.014$). However, when KTK_{adj} was added to the models, it emerged as the only statistically significant predictor of CRF_{adj} and MF_{adj}, even when other predictors and covariates were controlled. Although all FMS variables were correlated, KTK_{adj} demonstrated a specific independent effect, contributing uniquely to CRF_{adj} ($\Delta R^2 = 0.092$) and MF_{adj} ($\Delta R^2 = 0.032$).

The models fit the data (Tables 4 and 5) according to PPP values and the 95% CI. PSR coefficients were acceptable, and trace plots graphically represented the convergence across the chains when the curves were centered at a consistent value along the *y*-axis.

DISCUSSION

This study investigated the longitudinal relationship from early childhood process-oriented FMS, focused on gross

TABLE 3. Variation in age- and maturity-residualized cardiorespiratory and MF across individuals, childcare centers, and schools based on intercept-only models.

	Intercept Only Models (*N* = 398, 37 Childcare Centers, 77 Schools)	
Variance	CRF_{adj}	MF_{adj}
$\sigma_{individual}$ (ICC)	0.899* (0.772)	0.886* (0.829)
$\sigma_{childcarecenter}$ (ICC)	0.103* (0.088)	0.110* (0.102)
σ_{school} (ICC)	0.162* (0.139)	0.072* (0.067)

*Significant at least $P < 0.05$.
CRF_{adj}, CRF adjusted by age and maturity; ICC, intraclass correlation coefficient; MF_{adj}, MF adjusted by age and maturity.

TABLE 4. Results of two-level cross-classified regression analysis (models 1 to 6) predicting age- and maturity-adjusted CRF and MF using age-adjusted FMS and covariates.

		Outcome Variables (N = 441, 37 Childcare Centers, 80 Schools)				Model Fit Information		
Models	**Individual Level Predictors**	**CRF_{adj}**	**95% C.I.**	**MF_{adj}**	**95% C.I.**	**PPP**	**95% CI**	**PSR**
Model 1	Gender	0.173*	0.060 to 0.280	−0.164*	−0.265 to −0.058			
	BMI SDS z-score	−0.244*	−0.347 to −0.134	−0.112*	−0.215 to −0.006			
R^2 within level		0.092*	0.039 to 0.163	0.042*	0.011 to 0.093	0.346	−20.850 to 34.588	1.007
Model 2	Gender	0.203*	0.088 to 0.312	−0.136*	−0.238 to −0.029			
	BMI SDS z-score	−0.222*	−0.325 to −0.113	−0.091	−0.194 to 0.014			
	TGMD-3 LMS_{adj}	0.179*	0.056 to 0.294	0.167*	0.057 to 0.274			
R^2 within level		0.123*	0.059 to 0.202	0.073*	0.029 to 0.134	0.276	−23.565 to 46.899	1.010
Model 3	Gender	0.122	−0.002 to 0.241	−0.221*	−0.325 to −0.110			
	BMI SDS z-score	−0.235*	−0.341 to −0.126	−0.101	−0.204 to 0.003			
	TGMD-3 OCS_{adj}	0.140*	0.014 to 0.263	0.163*	0.050 to 0.275			
R^2 within level		0.111*	0.051 to 0.186	0.067*	0.026 to 0.126	0.287	−23.762 to 44.440	1.008
Model 4	Gender[a]	0.211*	0.092 to 0.324	−0.126*	−0.232 to −0.017			
	BMI SDS z-score	−0.183*	−0.292 to −0.068	−0.061	−0.166 to 0.049			
	KTK_{adj}	0.358*	0.199 to 0.491	0.309*	0.158 to 0.444			
R^2 within level		0.215*	0.114 to 0.332	0.136*	0.058 to 0.238	0.277	−22.833 to 45.258	1.008
Model 5	Gender[a]	0.172*	0.040 to 0.300	−0.180*	−0.293 to −0.065			
	BMI SDS z-score	−0.220*	−0.324 to −0.111	−0.088	−0.191 to 0.016			
	TGMD-3 LMS_{adj}	0.149*	0.012 to 0.279	0.125*	0.003 to 0.241			
	TGMD-3 OCS_{adj}	0.071	−0.070 to 0.213	0.108	−0.016 to 0.234			
R^2 within level		0.129*	0.065 to 0.208	0.084	0.036 to 0.149	0.204	−22.268 to 58.429	1.006
Model 6	Gender[a]	0.225*	0.089 to 0.356	−0.145*	−0.266 to −0.023			
	BMI SDS z-score	−0.167*	−0.278 to −0.053	−0.056	−0.166 to 0.054			
	TGMD-3 LMS_{adj}	0.021	−0.139 to 0.175	0.056	−0.087 to 0.196			
	TGMD-3 OCS_{adj}	−0.029	−0.180 to 0.122	0.053	−0.087 to 0.189			
	KTK_{adj}	0.354*	0.147 to 0.531	0.209*	0.012 to 0.396			
R^2 within level		0.213*	0.118 to 0.325	0.121*	0.057 to 0.208	0.135	−18.928 to 75.310	1.011

[a]Gender coded as girls 0 and boys 1.
*Significant at least $P < 0.05$.
BMI SDS z-score, BMI standard deviation scores standardized separately for girls and boys; C.I., credibility interval; CRF_{adj}, CRF adjusted by age and maturity; KTK_{adj}, KTK adjusted by age; LMS_{adj}, LMS adjusted by age; MF_{adj}, MF adjusted by age and maturity; OCS_{adj}, OCS adjusted by age.

motor movements, in specific skill domains—LMS and OCS—to CRF and MF in late childhood. The study also evaluated the comparative predictive effects of process- and product-oriented FMS measurements on CRF and MF. Employing a two-level cross-classified regression analysis, it was shown that scores for process-oriented FMS—LMS and OCS—measured by TGMD-3, along with scores for product-oriented KTK, independently and significantly predicted both CRF and MF. LMS, when combined with OCS, emerged as a significant predictor, emphasizing its unique influence. However, KTK demonstrated its superior predictive power for both CRF and MF, exceeding that of process-oriented FMS measurements. The results of the current study highlight that, according to Cholesky decomposition analysis, product-oriented KTK uniquely and significantly predicts both CRF and MF, even when controlling for LMS and OCS, as measured in a process-oriented manner by TGMD-3.

Our findings affirm the existence of a longitudinal relationship from FMS to both CRF and MF, as identified in previous theory (9) and reviews (14–16). Previous research (15,16) has noted overlaps in the construct elements of FMS and fitness components, and overlap also may exist between FMS and health-related fitness tests (16). In essence, FMS, CRF, and MF are interconnected both directly via neuromuscular functions and indirectly through increased participation in physical activities (15,16). This dual pathway may explain their longitudinal relationship. The findings of a previous study (15) suggest that FMS and various fitness components develop together. The same test elements are seen in FMS, CRF, and MF tests. MF tests (e.g., push-ups and curl-ups) and CRF tests (e.g., 20-m shuttle run) contain complex movements that need to be learned and require a good deal of FMS (15). On the other hand, FMS tests may assess abilities (e.g., high force and speed) that are usually assessed by fitness tests (9).

However, our results also highlight the significance of the types of FMS measurements used. Similar to previous studies (22,23), our findings highlight the distinct impacts of process-oriented and product-oriented FMS measurement methods, although the discussion has not been related to the longitudinal relationship between FMS and CRF or MF.

TABLE 5. Results of Cholesky decomposition analysis for predicting age- and maturity-adjusted CRF and MF, exploring the unique contributions of age-adjusted FMS while controlling for other predictors and covariates.

	Outcome Variables N = 441, 37 Childcare Centers, 80 Schools				Model Fit Information		
	CRF_{adj}	**95% C.I.**	**MF_{adj}**	**95% C.I.**	**PPP**	**95% CI**	**PSR**
LMS_{adj} controlled by OCS_{adj}	0.126*	0.011 to 0.239	0.117*	0.014 to 0.220	0.219	−22.607 to 59.950	1.094
OCS_{adj} controlled by LMS_{adj}	0.055	−0.067 to 0.172	0.084	−0.024 to 0.189	0.222	−23.618 to 58.402	1.094
LMS_{adj} controlled by OCS_{adj} and KTK_{adj}	0.021	−0.112 to 0.146	0.042	−0.073 to 0.156	0.122	−19.332 to 74.907	1.098
OCS_{adj} controlled by LMS_{adj} and KTK_{adj}	−0.017	−0.139 to 0.105	0.045	−0.064 to 0.152	0.128	−19.767 to 73.381	1.097
KTK_{adj} controlled by LMS_{adj} and OCS_{adj}	0.304*	0.147 to 0.433	0.178*	0.022 to 0.348	0.134	−18.373 to 74.151	1.094

*Significant at least $P < 0.05$.
C.I., credibility interval; CRF_{adj}, CRF adjusted by age and maturity; KTK_{adj}, result of KTK adjusted by age; LMS_{adj}, LMS measured by test of gross motor development and adjusted by age; MF_{adj}, MF adjusted by age and maturity; OCS_{adj}, OCS measured by test of gross motor development and adjusted by age.

The results of the current study demonstrated that when FMS is measured using only the process-oriented method, it exhibits a predictive longitudinal relationship with CRF and MF in childhood. This is supported by previous studies, which have found that process-oriented FMS predicts CRF and/or MF (12,17,18). In our analysis comparing skill domains, FMS measured in a process-oriented way revealed that LMS had an independent R^2 contribution when OCS was controlled, aligning with previous findings (12) that suggest LMS is a stronger predictor of CRF and MF than process-oriented OCS in early childhood. LMS might be more advanced in early childhood, whereas OCS are still developing during this stage of growth. FMS theories suggest that OCS relies on LMS skills (10), and the importance of OCS, when measured in childhood, may become more pronounced during adolescence. This is supported by previous research, which demonstrated that process-oriented OCS (kick, catch, and overhand throw), unlike LMS (hop, side gallop, vertical jump, and sprint run), predicts CRF from middle childhood to adolescence (18). However, conflicting findings indicate that OCS measured by a process-oriented method (TGMD-2) in early childhood is a stronger predictor of CRF and MF in adolescence compared with LMS, although LMS still significantly predicts these outcomes (17).

A key finding of the current study is KTK's unique ability to predict CRF and MF independently of the process-oriented LMS and OCS measures. The longitudinal relationship from product-oriented FMS to CRF or MF has been established in several previous studies that have used only a product-based approach (20,47–50). Furthermore, numerous studies have established a positive longitudinal relationship from specific FMS level groups to CRF or MF (51–56), all utilizing a product-oriented method to measure FMS scores.

Previous studies have recommended utilizing skill domains (10) and employing both process- and product-oriented tests together, emphasizing the differences between the tests (22,26,57), to comprehensively assess FMS in children where the tests complement each other. However, when investigating the longitudinal relationships from FMS to CRF and MF, the distinctions between skill domains and between process- and product-oriented measures may offer possible explanations for findings of the current study.

Comparing the properties of LMS and OCS measured with a process-oriented method revealed that LMS closely aligned with the abilities assessed in fitness tests (12), particularly LMS, rather than with OCS. This alignment suggests the potential for more accurate predictions of fitness outcomes. Within the TGMD-3, LMS subtests, such as running, are integral to CRF tests, whereas hopping and jumping are indicative of MF through lower limb strength (58,59). Despite encompassing LMS similar to those required by fitness tests (12), the product-oriented KTK surpasses the process-oriented LMS in predicting CRF and MF, indicating that LMS alone do not fully explain the independent longitudinal relationship from KTK to CRF and MF. We propose that the KTK, in contrast to the TGMD-3, includes additional elements of fitness testing (e.g., high force, speed, and muscular endurance) (9), thus enhancing its predictive power for CRF and MF. The stable nature of CRF (13) and MF (60) from childhood into adulthood likely underpins the significant relationship observed from KTK to CRF and MF. Although direct comparisons between the KTK and fitness tests for CRF and MF may seem complex, a closer inspection of their required features reveals underlying similarities.

The product-oriented KTK may extensively measure MF (16). Specifically, jumping sideways and hopping for height on one foot (25) require a notable degree of lower limb MF. The ability to create and transfer force in the lower limbs depends on core strength (58), which was measured in this study through an endurance approach using curl-ups. In addition, the results of jump tests are related to the outcomes of push-ups (59), which were also used in this study to determine MF.

Similar components, which may explain a longitudinal relationship, can also be found between KTK and CRF tests. Both the KTK (61) and the 20-m shuttle run test (62) involve for instance balance, rhythm, speed, and agility, particularly through changes in direction. In the 20-m shuttle run test, poorer agility, which affects the ability to quickly change direction or speed, can increase the oxygen cost of running, further challenging performance in CRF assessments (62). The subtests of KTK (25), namely, jumping sideways and moving sideways, can also be seen to measure anaerobic capacity because of the short but intense nature of the tests (63). Similarly, maximal aerobic performance in the 20-m shuttle run test could be affected by anaerobic capacity (64). Anaerobic capacity is crucial in tests like the 20-m shuttle run because it affects the energy supply for maximal short-duration exercises. A lower anaerobic capacity limits the energy available from anaerobic metabolism, which is particularly important in the final stages of the test. This aspect is especially relevant for children in their last laps of the test or for those who are less conditioned and can only complete a few stages (62).

One unifying factor between KTK, CRF, and MF can also be overweight or obesity, which presents challenges for children in tests where body mass must be moved against gravity (15). The presence of overweight children negatively influences KTK performance (65). It is also possible that increased fat mass increases the oxygen cost of running in the 20-m shuttle run test at any given speed relative to the total body mass (66). In addition, an inverse association between MF and increased fat mass has been found in children (67). In contrast, the relationship between FMS measured in a process-oriented way (TGMD-2 or TGMD-3) and overweight or obesity is not as clear cut, and the relationship may only be with LMS (67,68).

The process-oriented TGMD-3 (24) and product-oriented KTK (25) differ in several respects beyond their method of assessment. For example, the TGMD-3 (24) is designed for younger children compared with the KTK (25). In addition, the scoring of TGMD-3 is value limited, posing a potential ceiling effect (24) that can limit significant variability among individuals. In contrast, the KTK (25) has no maximum score limit in the subtests for jumping sideways and moving sideways, except for time constraints, thus potentially capturing a broader range of CRF and MF than the TGMD-3. Given

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these differences, the TGMD-3 may be more suitable for younger children, whereas the KTK may be preferable for older children. However, certain KTK subtests, such as walking backward, might not challenge older children as much (70), leading to less variability in KTK results for such tasks. The distinct target age groups and the potential ceiling effect of TGMD-3 may introduce bias when comparing test results, especially for older children. In this study involving young children aged 3 to 7 yr, no ceiling effect was observed for the TGMD-3 among participants, and the application of standardized residuals for age-adjusted predictors eliminated the influence of age differences and normalized the variable distributions.

The strength of this study lies in its longitudinal approach, beginning in early childhood with a 6-yr follow-up period, and the use of both process- and product-oriented FMS methods, which enabled a comparison between metrics. The application of two-level cross-classified regression analysis accounted for clustered data, and the use of Cholesky decomposition analysis provided a more accurate comparison of FMS metrics. With the selected variables and analysis method, it has been possible to eliminate the influence of clusters, age distribution, individual measurement interval, and maturity from the results.

Despite the insights this study offers, it is not without its limitations. The study data lacked CRF and MF measurements at baseline; consequently, the follow-up numbers did not include comparable FMS measurements. Therefore, these variables could not be included in the analysis to assess the stability of the variables (13,60), which could have provided a more accurate picture of the longitudinal relationship between the variables. We were also unable to compare LMS and OCS measured in a product-oriented way, a comparison that could have further emphasized the differences in the relationship between LMS and OCS. In addition, participant dropout is a limitation of the current study, as some baseline participants did not engage in the follow-up phase. However, dropout is a common challenge in longitudinal studies that rely on voluntary participation (71).

Future research should further examine the longitudinal relationship between FMS and fitness components from early childhood into adolescence and beyond considering the stability of variables (13,60). It is also crucial to consider that this relationship may vary between product-oriented measures of LMS and OCS. Comparing the same skills measured with process- and product-oriented methods (57) can also clarify the longitudinal relationship of FMS with CRF and MF. Future research should also more clearly separate the definitions and tests of FMS and fitness (15,16). Such clarification could significantly enhance our understanding of the relationships between these variables. Gathering comparative data from the same study population at multiple time points would also make the growth curve analysis method possible.

PERSPECTIVE AND CONCLUSIONS

The practical implications of our findings are significant for predicting and enhancing children's CRF and MF, thereby contributing to children's health. Predicting children's CRF and MF in early childhood appears to be better executed using the product-oriented KTK measurement than the process-oriented TGMD-3 metric because our findings indicate that KTK maintains a distinct longitudinal effect on CRF and MF, surpassing the influence of process-oriented FMS measurements. Given that CRF and MF are relatively stable characteristics in childhood (13,60), it is plausible that KTK encompasses a broader range of fitness elements in addition to skills (15,16), thus predicting fitness components more effectively.

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