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Evaluating the developmental trajectories of fundamental movement skills across late childhood and adolescence

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Abstract

The association between physical inactivity and many non-communicable diseases is now well established. Physical activity is a complex and multidimensional behaviour, with proficiency in fundamental movement skills (FMS) recognised as a key correlate of increased physical activity levels, as well as being positively associated with further health outcomes. As children transition into adolescence, the mechanisms determining physical activity levels appear to become less understood. Therefore, the overarching aim of this thesis was to investigate the development of FMS, and their association with psychological, behavioural, and cognitive factors, in late childhood and adolescence.

Study 1 examined the role of sex in moderating the association of FMS and health and behavioural outcomes in late childhood. The results highlighted the sex-specific development and role of FMS in children transitioning into secondary-level education, and who therefore represent a crucial developmental stage. Subsequently, Study 2 investigated the influence of biological maturation and other moderators on specific performance characteristics of FMS. Given the importance of ensuring validity in the assessment of FMS, Study 2 revealed the risks associated with using a single assessment method, especially in pre-pubertal children. The level of agreement between assessment methods (process- and product-oriented) was highest in post-pubertal children and, as such, practitioners can be more confident when adopting a single assessment approach in this group. Study 3 aimed to identify the association of skill competence, sex, and increasing maturity with the energy expenditure (EE) associated with performing FMS, highlighting the potential health-enhancing benefits associated with achieving proficiency in FMS. From an interventional perspective, the findings of Study 3 reinforce the contribution of FMS towards both direct (i.e. associated EE) and indirect health-enhancing benefits (i.e. physical activity, weight status, health-related fitness).

There is a vast array of evidence pertaining to the association between motor competence and cognitive and social-emotional outcomes in childhood, yet many studies have approached this relationship in isolation. To guide future research, Study 4 presented a conceptual model where underpinning mechanisms of the relationship between motor competence and cognitive and social-emotional outcomes are hypothesised. Moreover, Study 4 synthesised current evidence relating to the influence of FMS on cognitive and social-emotional outcomes, which was subsequently explored in Study 5. In Study 5 the moderated association of FMS and aspects of academic attainment in adolescence were investigated, revealing a key association between object control skills and academic attainment. The results of this study advocate that FMS should remain a key strategic aim in adolescent physical activity interventions and should be integrated within curriculum design as a mechanism for improving academic attainment.

Overall, this thesis demonstrates the continued importance of FMS to a range of health-related and cognitive outcomes during adolescence. Recognising that children are now consistently beginning secondary-level education without proficiency in FMS warrants increased attention is directed towards gaining a better understanding of how we can intervene and approach the development of FMS in a supportive environment.

Publications and Conference Proceedings

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Declarations and statements

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed. [redacted]

Date............26/05/2022..

This thesis is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by footnotes giving explicit references. A bibliography is appended.

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Abbreviations

α	alpha
APHV	Age at peak height velocity
β	Standardised regression weight
BMI	Body Mass Index
BMI z-scores	Measure of relative body mass adjusted for child age and sex with use of reference data
BOTMP	Bruininks-Oseretsky Test of Motor Proficiency
BOT-2	Bruininks-Oseretsky Test of Motor Proficiency, Second Edition
CAMSA	Canadian Agility Movement Skill Assessment
CA	Chronological Age
CFI	Comparative fit index
CI	Confidence Interval
CM	Centimetre
CMIN/DF	Chi-square statistic/Degrees of Freedom
CNS	Central nervous system
CRF	Cardiorespiratory fitness
CY-PSPP	Children and Youth Physical Self-Perception Profile
EE	Energy expenditure
FMS	Fundamental movement skills
Ft	Foot
GFI	Goodness of fit index
GSGA	Get skilled, Get active protocol
HRF	Heath-related fitness
Hz	Hertz
ICC	Intraclass correlation coefficients
IMU	Inertial measurement unit
K	Cohen's kappa coefficient
Kg	Kilograms
KTK	Körperkoordinationtest für kinder
$m \cdot s^{-1}$	Metre pre second
MABC	Movement Assessment Battery for Children
MABC-2	Movement Assessment Battery for Children – Version 2

MET	Metabolic equivalent
Min(s)	Minute(s)
Ml	Milliliters
mL O2 min^{-1}	Milliliters of oxygen per minute
MVPA	Moderate- to vigorous-intensity physical activity
N	Number
p	Level of significance
P-close	P of close fit
PE	Physical education
PHV	Peak height velocity
r	Coefficient of correlation
R^2	Coefficient of determination; statistical measure that represents the proportion of the variance for a dependent variable that is explained by an independent variable
RMR	Resting metabolic rate
SA	Skeletal age
SD	Standard deviation
SE	Standard error
Secs	Seconds
SEM	Structural equation modeling
SES	Socioeconomic status
SA	Skeletal age
SD	Standard deviation
TGMD	Test of Gross Motor Skill and Development
TGMD - 2/3	Test of Gross Motor Skill and Development – version 2/3
TLI	Tucker-Lewis index
UK	United Kingdom
V_E	Ventilation
$VC0_2$	Carbon dioxide output
$\dot{V}O_2$ ($l \cdot min^{-1}$)	Milliliters per minute per kilogram
VPA	Vigorous-intensity physical activity
W	Watts
W/kg	Watts per kilogram
Yrs	Years

YCPA	Youth compendium of physical activity

1.0 Introduction

1.1 Rationale and Background

Physical inactivity is an on-going health pandemic, accounting for 6% of deaths globally, and deemed the fourth leading risk factor for global mortality (Katzmarzyk et al., 2021; World Health Organization, 2010). Physical inactivity is defined as a failure to reach age-specific physical activity guidelines and is identified as a contributing factor to increasing levels of obesity, diabetes, cardiovascular disease and metabolic syndrome (World Health Organization, 2018). Conversely, for young people (5-18 years), accruing recommended levels of physical activity is positively associated with physiological, psychological, and psychosocial health (Department of Health and Social Care, 2019). Despite being a public health priority, just 51% of boys and 43% of girls are sufficiently active (Sport England, 2019). Furthermore, from late childhood there is an observed decline in physical activity levels that becomes more pronounced with increasing age (Farooq et al., 2018; Telama et al., 2014). To reverse current trends, it is suggested that physical activity is considered from a holistic perspective as it represents a complex behaviour that occurs in many contexts and is influenced both directly and indirectly by physical, social, and environmental determinants (Malina et al., 2016). Specifically, practitioners are encouraged to understand the movement competencies that underpin youth physical activity and those factors that may underpin the motivation of children to sustain physical activity behaviours (Brian, Getchell, True, De Meester, & Stodden, 2020).

Fundamental movement skills (FMS) are identified as a 'mediator' and determinant of physical activity (Baron & Kenny, 1986; Lubans et al., 2010). Additionally, FMS have been shown to be positively associated with health-related fitness, cognitive development and psychological well-being (Cattuzzo et al., 2016; Lubans et al., 2010; Robinson et al., 2015; Van Der Fels., 2015). FMS principally comprise of object control skills (i.e. throw, kick, strike), locomotor skills (run, hop, jump) and balancing skills, with their underlying importance to physical activity having been asserted in several health behavioural change models (Clark & Metcalfe, 2002; Robinson et al., 2015; Seefeldt, 1980; Stodden et al., 2008; Welk, 1999). Stodden and colleagues (2008) proposed a conceptual model to outline the developmental associations of FMS and selected health-related outcomes. Stodden et al. (2008) hypothesised that as children age, poor movement competence becomes increasingly associated with negative self-perception, declining physical activity levels and a heightened risk of obesity. Conversely, children proficient in FMS are proposed to be more physically active, have a higher perception of their own fundamental movement skill competence, and have a more positive health-related fitness profile (Robinson et al., 2015; Stodden et al., 2008). For children especially, the role of FMS in promoting positive trajectories of health has been confirmed in systematic reviews and meta-analyses (Barnett et al., 2021; Lubans et al., 2010; Morgan et al., 2013; Robinson et al., 2015; Utesch, Bardid, Büsch, & Strauss, 2019).

In childhood, biological (sex, body mass index [BMI]) and demographic (age, socioeconomic status [SES], cultural background) determinants of FMS have been identified (Barnett, Lai, et al., 2016a). Boys consistently demonstrate higher proficiency in object control skills, although there is indeterminate evidence for sex-related differences in locomotor skills (Barnett, van Beurden, Morgan, Brooks, & Beard, 2010; Spessato, Gabbard, Valentini, & Rudisill, 2013; Valentini, Logan, et al., 2016). Irrespective of sex, a reciprocal relationship between obesity and poor fundamental movement skill competence exits, specifically for locomotor skills (Barnett et al., 2021; D'Hondt et al., 2014; Okely, Booth, & Chey, 2004). Prior to adolescence, increasing age has also been shown to be directly associated with fundamental movement skill proficiency (Barnett et al., 2016a). In early childhood, this relationship is likely influenced through biological maturation and an increasing interaction with environmental constraints and age-appropriate practice (Barnett et al., 2016a; Ng & Button, 2019; Robinson et al., 2015). Whilst there is an expectation that children should be proficient in all FMS by late childhood, children are increasingly transitioning into adolescence without mastering these foundational skills (Hardy, King, Farrell, Macniven, & Howlett, 2010; O' Brien, Belton, & Issartel, 2016a). This evidence, together with continuing socio-cultural and environmental changes that promote sedentary behaviours (i.e. increases in passive transport, screen-time preference), highlight that a more comprehensive understanding of the role of FMS during adolescence is necessary (Archer & Blair, 2012; McGrane et al., 2018).

The onset of adolescence is a transitional period during which children experience physical, biological and behavioural changes, in addition to altering social roles

(Cumming et al., 2012). The biological process of maturation, which is the progress of specific biological systems towards a mature state, underpins the adaptions that occur in physical stature, athletic performance and fitness during adolescence (Cumming et al., 2012; Malina, Bouchard, & Bar-Or, 2004). The influence of biological maturation is also evident in the maturity-related variance found in different components of physical activity (i.e. fitness, energy expenditure [EE], sport participation; Cumming et al., 2012). Although there is a growing body of evidence addressing a maturational influence on physical activity behaviour, few studies have focused on identifying a similar influence on the underpinning constructs of physical activity, such as FMS (Cumming, Standage, Gillison, & Malina, 2008; Sherar, Cumming, Eisenmann, Baxter-Jones, & Malina, 2010). This is despite the maturational influence on physical activity likely being constrained through mediating and moderating factors (i.e. FMS, self-perception, physical appearance) rather than a direct biological effect (Cumming et al., 2012). The transition from childhood to adolescence is aligned with a shift in physical activity behaviours, where there is a gradual change from activities that are characterised by exploration and fun towards those focused more specifically on competition and success (Basterfield et al., 2015). As such, for children transitioning into adolescence, perceived and actual fundamental movement skill competence could be considered even more influential to a sustained engagement in physical activity, especially sport-related activities.

To date, studies investigating the influence of FMS on health-related outcomes during adolescence have largely reported on sex-specific patterns in those of a similar chronological age (CA; Lester et al., 2017; O' Brien, Belton, & Issartel, 2016b). This reliance on CA has confounded interpretation of the developmental trajectories of FMS, and also the association of FMS with health-related outcomes. It is proposed that the influence of biological maturity on FMS may occur through direct (physical and functional characteristics) and indirect (self-perception, motivation) mechanisms (Cumming et al., 2012). Yet, there exists little evidence examining the direct influence of biological maturation on FMS. Moreover, few studies have examined an indirect influence on constructs relating to self-efficacy, despite these constructs considered crucial to the association of FMS and physical activity. Irrespective of sex, the onset of maturation is associated with an elevated outcome performance in physical abilities (i.e. speed, strength, power) that are accepted underpinning components of fundamental movement skill execution (Lloyd et al., 2015; Malina et al., 2004). Additionally, the age at peak height velocity (PHV), which typically occurs 2 years earlier in girls, is speculated as a period where sensorimotor function regressions may occur, influenced by a marked growth spurt (Quatman-Yates, Quatman, Meszaros, Paterno, & Hewett, 2012). Given this, establishing the maturity-related influence on FMS and the association of FMS with health-related outcomes provides opportunity to increase the validity of assessing FMS in adolescent populations. It also provides practitioners with greater insight in how to effectively intervene at these ages.

Along with identifying the role of FMS as a predictor of physical activity engagement, it is also important to gain an understanding of the influence of skill proficiency in the quantitative accumulation of physical activity. Recently, fundamental movement skill proficiency has been shown to be a key influence on the associated EE of specific activities (Sacko, Brazendale, Sacko, McIver, Brian, & Stodden, 2018; Sacko, Nesbitt, et al., 2019b). Recognising this proficiency-related influence on physical activity is important not only for the validity of physical activity measurement, but also as a potential mechanism for promoting further health-related benefits (i.e. health-related fitness [HRF]). In supporting an association between a higher skill competence and a greater associated EE, the findings of Sacko et al. (2019b) emphasise the underpinning influence of fundamental movement skill development (Sacko et al., 2019b). Despite this, there is a need to establish how this association develops with increasing age and maturity, and also across a wider range of discrete skill performance. In adults, a higher skill proficiency has been found to lessen the associated energy cost of many movements, yet, in children the reverse of this is often true, with children suggested to freeze available degrees of freedom (Pfeiffer et al., 2018; Stodden, Langendorfer, Fleisig, & Andrews, 2006a, 2006b). Furthermore, physiological changes associated with maturation have been shown to influence absolute EE, especially in boys (Harrell et al., 2005). As such, more work is needed to ascertain the interaction between maturity and fundamental movement skill competence on the associated EE of skill execution common to many sports and physical activities.

Whilst the importance of FMS to many behavioural and psychological outcomes is firmly established, there still remains a paucity of evidence identifying the association of FMS and cognitive development, especially in adolescence. Recently, a growing body of research has proposed that the qualitative characteristics of physical activity (i.e. visual perceptual skills, cognitive stimulus) may provide the key underpinning mechanism for the association between physical activity and aspects of cognitive development (Pesce et al., 2016; Tomporowski & Pesce, 2019). Given this, the extent to which FMS influence cognitive development, including academic attainment is now being increasingly investigated (Gu, Zhang, Lun Alan Chu, Zhang, & Thomas Thomas, 2019; Haapala, 2013; Van Der Fels et al., 2019). Behavioural and neurobiological similarities between fundamental movement skill performance and aspects of cognitive performance (i.e. executive functions) would support the existence of this association (Van Der Fels et al., 2019). However, there remains a lack of evidence pertaining to how this association develops in youth, with the sex-specific trajectories of cognitive maturation showing increasing sexual dimorphisms during adolescence (Farooqi et al., 2019). Moreover, the influence of biological maturation occurs at different points in childhood to the changes associated with cognitive maturity, and thus it is crucial to identify how this interaction influences the association between FMS and cognitive development. From an academic perspective, there is conflicting evidence as to whether the associations between those cognitive functions most associated with FMS (i.e. executive functions) and academic attainment become more domain-specific in adolescence (Donati, Meaburn, & Dumontheil, 2019). However, to date, few studies have attempted to analyse this and explore the association of FMS and specific academic performances. Establishing this could promote a more widespread use of FMS and cognitively stimulating physical activity as a means of enhancing academic attainment within school-based interventions.

1.2 Problem Statement

Whilst there now exists consistent support for the long-term importance of fundamental movement skill proficiency for physical activity and a range of health-related outcomes in childhood, few studies have built on this evidence in adolescence. To progress the current understanding of the role of FMS during adolescence, explorative studies that investigate the moderating role of biological maturation and perceived sports competence on the development and influence of FMS are warranted.

1.3 Thesis aims

The overarching aim of this thesis was to investigate the influence of growth and maturation on the development of FMS in late childhood and adolescence. Furthermore, this thesis aimed to investigate potential moderators of the association of FMS with specific health-related indicators during this transitional period of development.

Study one:

Guided by the Stodden et al. (2008) conceptual framework, the aim of Study 1 was to use path analysis to investigate the influence of sex on the associations of FMS, perceived sports competence, time spent in vigorous-intensity physical activity, time spent sedentary and BMI z-score in late childhood.

Study two:

The aim of Study 2 was to investigate the maturity-related influence on process- and product-oriented fundamental movement skill competence. Secondly, the aim was to investigate the association of fundamental movement skill competence and perceived sports competence with increasing maturity.

Study three:

The aim of Study 3 was to investigate whether the energy expenditure associated with performing a group of discrete FMS is influenced by skill competence, biological maturity, and sex.

Study four:

The aim of Study 4 was to systematically synthesise current longitudinal evidence pertaining to the relationship of FMS and cognitive and social-emotional outcomes in youth. Furthermore, a conceptual model was developed that provides a wider framework through which the position of motor competence can be evaluated, recognising the dynamic interactions and associations underpinning its role.

Study five:

The aim of Study 5 was to examine the association of FMS with academic attainment in adolescence, and to ascertain whether this association is moderated by perceived sports competence, sex, weight status and/or maturational status.

1.4 Definition of key terms

Fundamental movement skills (FMS): Throughout this thesis the term ‘fundamental movement skills’ will be used to provide a general definition of gross motor skills, deemed the ‘building blocks’ of more complex movements, and that include object control skills, locomotor skills and balance skills (Gallahue, Ozmun, & Goodway, 2012). Within the literature a variety of terms have been used to conceptualise these skills (i.e. motor competence, fundamental movement skills, gross motor skills), creating ambiguity. For this thesis, the term FMS was believed to align most strongly with the facets of motor competence primarily investigated (Logan, Ross, Chee, Stodden, & Robinson, 2018).

Childhood: The term childhood will be used during this thesis to describe those children who are approximately between 3-10 years of age, and as such are yet to commence with secondary-level school education.

Adolescence: Across this thesis adolescence will align with World Health Organisation definition (World Health Organization, 2020) and whilst a definitive age range will not be stipulated, for the most part it will begin with the onset of physiologically normal puberty, and therefore include an approximated age-range of 10-19 years.

Youth: Throughout this thesis the term ‘youth’ will be used as a generalised term to describe the developmental period combining childhood and adolescence.

2.0 Literature Review

2.1 Theoretical approaches to motor development

Motor development has been defined as “the changes in motor behaviour over the lifespan and the process(es) which underlie these changes” (Clark & Whitall, 1989, p.194). Theoretical perspectives of motor development have attempted to explain how, and why, changes in motor behaviour occur, along with the factors that underlie these behavioural changes (Ulrich, 2007). Whilst there exist distinct periods of scientific enquiry, theorists have strived to identify the products (i.e. what development is occurring and at what stage) and/or the underlying mechanisms (i.e. environmental, biological) that control and influence development (Gallahue et al., 2019).

The dynamical systems perspective, along with several similarly aligned approaches, such as the ecological approach and constraints-based approach, emphasises the importance of interactions to motor development (Whitall, Schott, et al., 2020). Newell referred to these interactions as “constraints” and categorised them as being organismic, environmental and task oriented (Newell, 1984; 1986; Gallahue et al., 2019). Accordingly, from this perspective, movement development occurs primarily through the interaction of constraints (internal and external to the person). Moreover, movement development is nonlinear and discontinuous, and is underpinned, and an outcome of, the processes of perception, cognition and decision-making that emerge during constant performer-environment interactions (Davids, Araújo, Vilar, Renshaw, & Pinder, 2013; Gallahue et al., 2019).

In contrast to a dynamical systems approach, an information-processing perspective emphasises the role of the central nervous system (CNS), with the maturation of this system engendering new movement behaviours (Whitall, Schott, et al., 2020). Motor development is proposed to exist in a sequential linear pattern, with movement information stored for future application (Colombo-Dougovito, 2017). The information-processing perspective can be labelled a top-down approach, with the schema or trace within the brain providing the foundation to the movement (Fitts and Posner, 1967; Rudd et al., 2021). Conversely, a dynamical systems perspective is a bottom-up approach, with environmental and behavioural factors acting as the primary stimulus for movement development (Rudd et al., 2021). Indeed, the top-down approach adopted by information-processing theorists is refuted by many who claim that the CNS alone cannot control movement output (Whitall, Schott, et al., 2020).

More recently, three principle approaches to motor development have emerged; the developmental systems approach, the developmental motor neuroscience approach and the developmental health approach (Whitall, Bardid, et al., 2020). The developmental systems approach, which has similar underpinnings to the dynamical systems approach, emphasises the interaction of the motor system with physiological and cognitive systems in forming a more global approach to motor development (Whitall, Bardid, et al., 2020). Motor development provides opportunity to expand perceptual-cognitive capabilities and promotes wider behavioural development through interactions between biological and environmental characteristics (Gabbard, 2009). The developmental motor neuroscience approach analyses the relationship at a neural level (Morita, Asada, & Naito, 2016). Through the use of advancing technologies such as functional near-infrared spectroscopy, researchers have been able to investigate the neuroplasticity of the brain and analyse the direct relationship between movement performance and brain activity (Whitall, Bardid, et al., 2020). Lastly, the developmental health approach considers the role of motor development from an interdisciplinary perspective, highlighting the relationship of motor competence (i.e. fundamental movement skills [FMS]) to health-related outcomes (Whitall, Bardid, et al., 2020). This approach has been prompted by a need to identify the determinants of increasing inactivity and sedentary levels in children (Barnett et al., 2016a; Barnett et al., 2021; Cairney, Dudley, Kwan, Bulten, & Kriellaars, 2019).

To provide a framework through which to understand the discontinuous process of motor development, Gallahue and colleagues (2019) presented a heuristic model that conceptualised both the descriptive products (hourglass) and explanatory processes (inverted triangle) pertinent to motor development (*Figure 1*). Within the model, the respective influence of hereditary and environmental factors is represented by sand entering a hourglass, with the hereditary quantity fixed and the environmental quantity uncapped. Although on a general level the model appears rigid and structured (i.e. stages and phases), rather than being definitive, it reflects the anticipated developmental differences appropriate for childhood (Gallahue et al., 2019). An inverted triangle represents the constraints that influence movement development;

highlighting the importance of practice, instruction, along with the physical and mechanical requirements specific to the task (Gallahue et al., 2019). The model of Gallahue and Ozmun (2006) shares a number of similarities with the earlier 'Mountain of motor development' model presented by Clark and Metcalfe (2002). Akin to the Gallahue and Ozmun (2006) model, Clark and Metcalfe (2002) emphasise the importance of biological and environmental factors, with the 'mountain range' (i.e. individual skill proficiencies) reflecting the variance in skill-specific proficiency (Gallahue et al., 2019). Taken together, both models draw attention to the non-linear development of motor skills, and emphasise the overarching influence of biological and environmental factors to motor development (Gallahue et al., 2019).

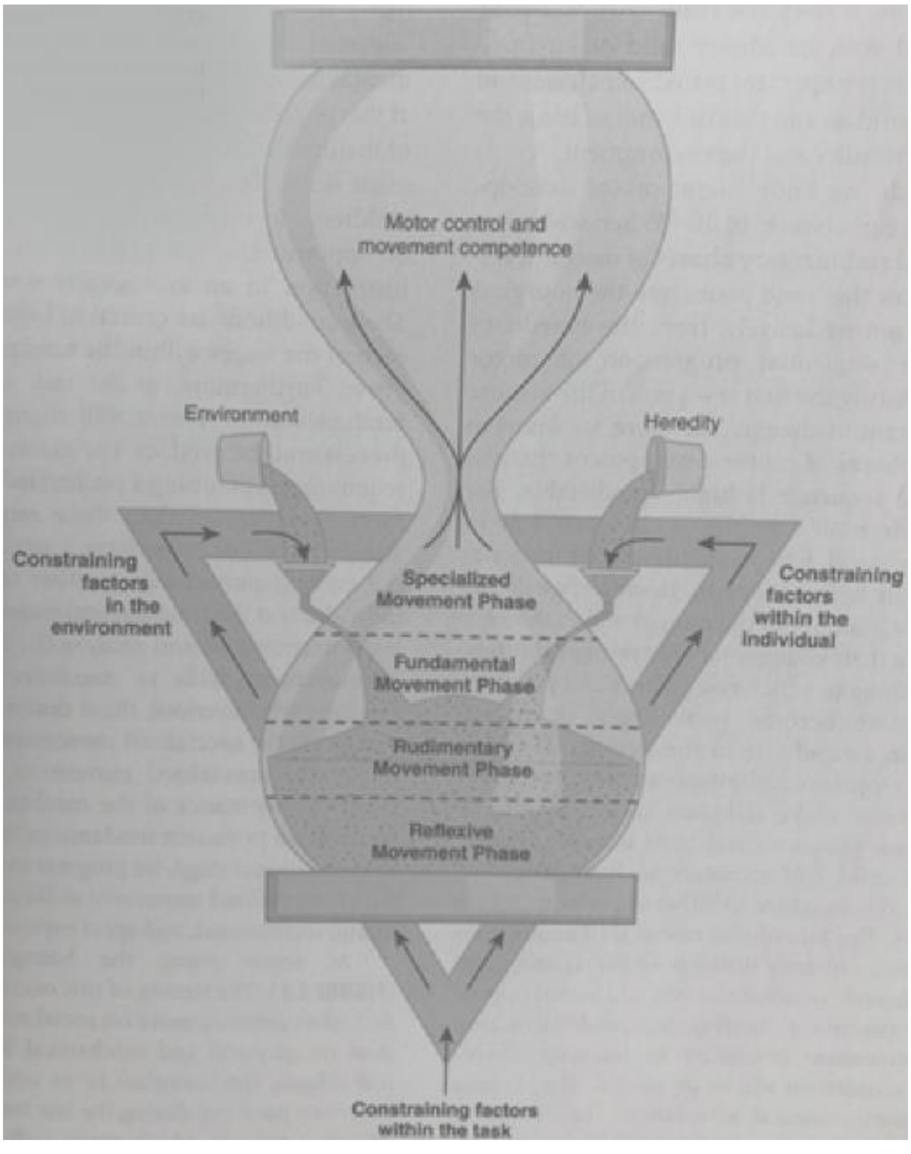


Figure 1. Gallahue's triangulated hourglass: A life span Process/Product Model of Motor Development (Gallahue et al., 2019)

2.2 Fundamental movement skills

FMS are proposed as a range of ontogenetic motor skills, considered to provide the foundation to the development of more complex movements associated with physical and sporting activity (Barnett et al., 2016a; Stodden et al., 2008). FMS are routinely classified into three categories; locomotion (i.e. run, hop, jump), object control (i.e. throw, kick, strike) and stability (i.e. balancing; Barnett, Stodden, et al., 2016b). Clark and Metcalfe (2002) refer to these gross motor skills as the 'base camp' to motor development, providing a platform from which children can transfer to a variety of sport-related activity (Gallahue et al., 2019). In a conceptual model, Seefeldt (1980) proposed that proficiency in FMS is necessary to successfully participate in those physical activities that promote the development of 'transitional' skills (i.e. small-sided games, jump-rope) and sport-specific skills. Few studies have explicitly investigated this hypothesis, although De Meester and colleagues (2018) found that of those children in their study that were in the lowest 25 percentile for fundamental movement skill competency, < 12% met moderate-to-vigorous physical activity (MVPA) guidelines. However, despite some agreement that a form of proficiency barrier does exist, there remains contention on how it is defined and measured (Brian et al., 2020).

The developmental trajectory of FMS is greatly influenced by prior movement experiences, informed practice, and environmental affordances (Newell, 2012; Ng & Button, 2019). FMS comprise of discrete skill executions that are underpinned by salient neuromuscular and kinetic attributes, and that have a broad applicability to seemingly unrelated physical activities, such as swimming and bicycle riding (Barnett et al., 2016a). Thus, the assessment of FMS can offer valuable insight into wider indicators of health across the lifespan (Hulteen, Morgan, Barnett, Stodden, & Lubans, 2018).

Biological (age, sex), behavioural (physical activity, organised sport participation), and cognitive (academic attainment, executive functions) correlates of FMS have all been identified to varying levels of significance (Barnett et al., 2016a; Barnett et al., 2021; Spessato et al. 2013). Distinct developmental patterns do exist, with locomotor skills developing at an earlier stage than object control skills in childhood due to an already maintained exposure, whereas a spike in object control skill competence is commonly observed from mid-childhood (Valentini, Zanell, & Webster, 2016). In childhood, age has been identified as a positive correlate to the constructs of object control and locomotor competence (Barnett, Hinkley, Okely, & Salmon, 2013; Barnett, van Beurden, Morgan, Brooks, & Beard, 2010; Spessato et al., 2013). However, similar to other components of fitness, fundamental movement skill competence is age-related rather than age-determined, and as such is strongly aligned to inter-individual growth-related differences and a range of additional constraining factors (i.e. environmental, social; Gallahue et al., 2012; O' Brien et al., 2016a). Nevertheless, guidelines propose that proficiency across all FMS is achievable prior to adolescence (O' Brien et al., 2016a). Given that an age-related decline in physical activity is apparent during adolescence (especially in girls), this is particularly pertinent, as opportunities to develop fundamental movement skill competence in a supportive context become limited at these ages (Hallal et al., 2012; Nader, Bradley, Houts, McRitchie, & O' Brien, 2008).

In childhood, sex differences in fundamental movement skill competence are suggested to be more greatly influenced by sociocultural rather than biological influences (Spessato et al., 2013). There is consensus within the literature that boys perform better in object control skills and that these advantages track into adolescence (Bardid et al., 2016; Barnett et al., 2010; O' Brien et al., 2016a; Spessato et al., 2013). In contrast, evidence of a similar sex influence on locomotor competence is less compelling with an absence of consistent sex-specific competency development (Barnett et al., 2010; Barnett et al., 2016a). Encouragement to participate in gender stereotyped forms of physical activity and sport may underpin these developmental sex-related patterns (Slykerman, Ridgers, Stevenson, & Barnett, 2016). Girls, in particular, may refrain from participation in organised physical activity if they have a low skill competence and/or if they perceive themselves to be less competent than their peers (Okely, Booth, & Patterson, 2001). Personal barriers towards active-leisure time from family and the community may also consolidate between-sex differences in fundamental movement skill competence (Spessato et al., 2013). However, when FMS are assessed at a behavioural component level, there are no clear between-sex differences for those components that children find most difficult to master (Duncan et al., 2020). For example, irrespective of sex, children find the follow-through actions of FMS (e.g. thrusting forcefully downwards in the horizontal jump) the most difficult to achieve, and it is these components that may limit progression to sport-specific movements (Duncan et al., 2020).

Although more pronounced with increasing age, evidence has shown weight status to be a predictor of fundamental movement skill competence, with an inverse relationship found between fundamental movement skill competence and weight status (D'Hondt et al., 2011; Barnett et al., 2016a; Barnett et al., 2021; Okely et al., 2004; Robinson et al., 2015). This inverse relationship is particularly evident for locomotor skills, not least, given that their execution requires functional movement and the controlling of body mass (Barnett et al., 2016a). The performance deficit apparent in obese children is proposed to be associated with negative self-concept, and also biomechanical factors that may promote insufficient movement patterns (Barnett et al., 2013; Cliff et al., 2012; D'Hondt, Deforche, De Bourdeaudhuij, & Lenoir, 2009). The interaction between weight status and FMS has been identified as dynamic and reciprocal, with obesity being both a product and a causal mechanism (Stodden et al., 2008). A recent systematic review (Barnett et al., 2021) concluded that obesity in early childhood can negatively influence the development of FMS throughout childhood, although there remains insufficient evidence to prove the reverse. At pubertal age the evidence remains inconsistent, with this likely reflecting the limitation of using BMI as an indicator of weight status (Robinson et al., 2015). Indeed, the decrease in association between FMS and BMI has been found to occur earlier in girls and to be more dramatic in boys (Lopes, Maia, Rodrigues, & Malina, 2012). Also, the association is more pronounced in object control skills, with these patterns all reflecting an alignment to the sex-specific influence of maturational development (Cattuzzo et al., 2016; Lopes, Stodden, Bianchi, Maia, & Rodrigues, 2012).

Ecological models have been applied to provide a framework from which to assess the importance of the additional factors (i.e. family characteristics, socioeconomic status [SES]) that may predispose, reinforce or enhance health behaviour (i.e. FMS; Welk, 1999). Given the association between physical activity and FMS, many of the identified factors have been investigated across both constructs (Barnett et al., 2013; Barnett et al., 2016a; Tyler et al., 2020). Parental physical activity levels, parental perceptions of their child's skill competence, and moreover, the SES of the family have all been highlighted as predictors of fundamental movement skill competence

(Cools et al., 2011; O'Neill et al., 2014; Playford et al., 2017). Burns and colleagues, (2017) reported a proficiency level in FMS of only 17% in a school where pupils were receiving financial assistance, and was thus indicative of a lower SES. Acknowledging the importance of an *opportunity-rich* environment in the development of FMS, it is hypothesised that socially disadvantaged children may not be immersed consistently in situations conducive to stimulating movement development (Adams et al., 2018; Zeng et al., 2019). However, despite being identified as a correlate in earlier childhood, evidence pertaining to the influence of SES as children move towards adolescence remains inconclusive (Barnett et al., 2016a). Tyler et al. (2020) adapted the Youth Physical Activity Promotion Model (Welk, 1999) to provide additional insight into the influencing factors upon physical competence (endogenous variable). The Tyler et al. (2020) model consolidated and built upon the results of existing research, specifically emphasising the importance of enabling factors (i.e. physical activity facilities, sport participation) to fundamental movement skill development.

2.2.1. FMS competence in late childhood and adolescence: Current evidence

Given that from a developmental perspective, proficiency across all FMS is achievable by late childhood (Gallahue et al., 2019), there has, until recently, been a dearth of literature analysing competence in proceeding years (Barnett et al., 2021; Robinson et al., 2015). Across the systematic reviews of Logan et al. (2015), Barnett et al. (2016a), and Utesch et al. (2019) only nine of the included studies presented data from adolescent samples. However, of the available studies, evidence suggests that many children are transitioning into adolescence lacking the necessary competence to successfully engage in physical activity and sport-related opportunities (Lester et al., 2017; O' Brien et al., 2016b). Moreover, secular decreases have been found in isolated FMS at these ages (Hardy, Barnett, Espinel, & Okely, 2013). Indeed, despite age-related improvements in FMS, when assessed against age-specific norms, there is a widening gap with increasing age, with this apparent for process- and product-oriented assessment outcomes (Ré et al., 2018).

A consistent evidence base exists highlighting the low level of proficiency attained in many FMS in late childhood. Assessing the four core FMS (running, jumping, throwing and catching) emphasised by The National Curriculum for PE in England (Department for Education, 2013), Duncan and colleagues (2020) found only 25% of children aged nine years to be competent across all four FMS. In an Irish cohort, Kelly et al. (2019) found evidence of poor fundamental movement skill competence in primary-school aged children, with the percentage of those labelled as poor[1] ranging from 78% in the two-handed strike to 19.1% in the slide. Behan and colleagues (2019) investigated the maturation of FMS across primary-school ages and found further evidence of poor competence, specifically in locomotor and object control skills. In the same study, Behan et al. (2019) found a plateau from age ten in locomotor and balance skills competence, with a decline in overall fundamental movement skill competence between 11-12 years (Behan et al., 2019). Similar patterns have been reported in studies worldwide, although comparisons are limited as many European countries favour product-oriented methodologies (i.e. Körperkoordinationtest für kinder [KTK]) rather than the more commonly adopted process-oriented assessments (Bardid, Huyben, et al., 2016).

Although less extensive, studies assessing FMS in adolescent populations have found a plateauing in competency levels at these ages. O' Brien and colleagues (2016a) assessed fundamental movement skill competence in post-primary school aged children (12-13 years) and identified that irrespective of sex, only 11% of their sample achieved mastery or near mastery across all FMS. Similarly, Lester et al. (2017) found a large number of their cohort (14.4 ± 1.0 years) to be deficient in FMS and functional movement (i.e. squat, lunge) competence. Furthermore, the study of Lester et al. (2017) found a decrease in competence in three core FMS (overhand throw, horizontal and vertical jump) across three academic years in their adolescent sample. These findings add to further cross-sectional studies that have identified adolescent movement competence as an increasing area for concern (Farmer et al., 2018; Philpott et al., 2020). Using the product-oriented KTK assessment, Lopes and colleagues, (2013) found none of their early adolescent sample displayed 'good' motor competence[2], and less than half (48.8%) achieved a normal level[3]. Indeed, the motor competence levels in this study were found to be lower than many studies using the same instrument in younger children (Graf et al., 2004; Lopes et al., 2013; Vandorpe

[1] Poor mastery was defined as the incorrect performance/absence of more than one performance criteria over two trials.
[2] The sum of the standardised scores for the four items provided the motor quotient. Using the motor quotient children were then categorised as having good MC (115 ⩽ motor quotient ⩽ 130).
[3] The sum of the standardised scores for the four items provided the motor quotient. Using the motor quotient children were then categorised as having normal MC (86 ⩽ motor quotient ⩽ 115).

et al., 2012). To build on the collective evidence presented in these studies it is important future studies include the appropriate controls such as biological maturation, and ensure the results are not being constrained by a 'ceiling effect'.

When between-sex fundamental movement skill patterns are explored across late childhood and adolescence, it is apparent that the evidence remains relatively stable. Similar to childhood, boys consistently display a higher proficiency across all object control skills (Barnett et al., 2010; Slykerman, Ridgers, Stevenson, & Barnett, 2016). In British children (9-10 years), McWhannell et al. (2018) found boys to be significantly more competent across object control skills, when analysed individually and as a construct ($p < 0.05$). Further studies have provided evidence on the comparatively poor competence of girls in object control skills (Barnett et al., 2010; O' Brien et al., 2016a). Specifically, the study of O' Brien et al. (2016a) found that 60% of boys achieved mastery level in the overhand throw, in contrast to only 27% of girls. In their longitudinal study, Barnett et al. (2010) found girls to be significantly less competent in object control skills in both childhood (10 years) and adolescence (16 years), and despite a similar improvement percentage irrespective of sex, less than 50% of girls achieved near mastery/mastery at 16 years. In contrast, Coppens et al. (2019) using latent growth curve analysis, found girls to display less progress compared to boys, despite a comparable competence at baseline. However, these between-sex differences only became established at timepoint 3, and may therefore be associated to the earlier influence of maturity (i.e. an increased fat-mass) in girls (Coppens et al., 2019).

Whilst sex has been shown as a strong predictor of object control competence, evidence pertaining to the association between sex and locomotor skills during late childhood and adolescence remains equivocal. A number of cross-sectional studies have found no between-sex differences in locomotor competence, with these sharing agreement with further longitudinal evidence (Barnett et al., 2010; Behan, Belton, Peers, O'Connor, & Issartel, 2019; McWhannell et al., 2018; O' Brien et al., 2016a; Slykerman et al., 2016). Conversely, some studies have reported on a higher competence of girls in locomotor skills (Barnett et al., 2009b; Bolger, Bolger, Neill, et al., 2018; Cliff et al., 2012; Kelly et al., 2019). Cumulatively, evidence supporting sex-related differences may highlight the wide-ranging influence of psycho-social and environmental factors, such as cultural norms and expectations, that can moderate the aforementioned findings (Barnett et al., 2016a; McWhannell et al., 2018). In many UK and Australian studies girls have been found to display a higher locomotor skill competence than boys, and it is suggested that this is aligned to a greater participation of girls in sports and physical activities directly influenced by these skills (i.e. dance, gymnastics, track; Slykerman et al., 2016). For adolescent boys, physical activity is viewed as an opportunity to compete and win amongst their peers, as such it is arguably object control skills that are more prominent and are a greater determinant of success in their sport-participation (i.e. soccer, rugby, cricket; Rose, Larkin, Parker, & Hands, 2015). This explanation strengthens the argument that sex differences, along with being biologically induced, are also influenced by environmental and cultural factors.

When FMS in late childhood are considered from a movement outcome perspective (product-oriented), similar developmental trajectories to process-oriented competence have been found (i.e. a higher performance level in boys, and an age-related increase irrespective of sex; Beunen & Malina., 2005; Watanabe, Mutoh, & Yamamoto, 2001). In their sample (six-nine years), Hulteen, True, & Pfeiffer (2019) found age-related increases in four FMS when assessed using process-and product-oriented protocols (aside from a small decrease in overhand throw score at the ages of seven-eight years). However, in adolescence, marked differences are evident in the developmental trajectories associated with process- and product-oriented competence. For example, there is some evidence that process-oriented competence may decrease during this period (Hardy et al., 2013). In contrast, product-oriented performance, likely influenced by maturational development, has shown distinct increases in many skills (Lloyd & Oliver, 2012). In boys, especially, these increases in product-oriented performance are aligned to the maturity-related increases in height and muscle mass that are conducive to an elevated performance in movements underpinned by strength and power (Philippaerts et al., 2006). Specifically, absolute strength and maturity have been proposed as predictors of run, jump and throw performance in adolescent boys (Pichardo et al., 2019).

Taken together, the current evidence has confirmed that many children in late childhood are demonstrating insufficient competence across a range of FMS, and this is occurring irrespective of sex (Lester et al., 2017; O’ Brien et al., 2016a). Moreover, there is growing evidence that trajectories of poor fundamental movement skill competence continue into adolescence, with little indication of positive linear change. Proposed explanations for these competency patterns include; the influence of obesogenic environments, the associated decrease in physical activity, and the greater influence of autonomy (Malina et al., 2016). In addition, in countries such as the UK, the lack of qualified PE teachers during primary-school education has been presented as a further factor in children not transitioning into secondary-level education with the expected levels of movement proficiency (Philpott et al., 2020). However, a valid interpretation of fundamental movement skill competence at these ages is still limited by methodological inconsistencies and the conclusions offered on the back of these. Therefore, further evidence is warranted to better understand the factors influencing FMS during the transition into adolescence, and to identify how best to accurately report on their assessment.

2.3 Physical literacy

Physical literacy has been conceptualised as “the motivation, confidence, physical competence, knowledge and understanding to value and take responsibility for engagement in physical activities for life” (Whitehead, 2019: page 8). Despite this, physical literacy is an evolving concept, with much inconsistency remaining in how it is defined and operationalised (Edwards et al., 2017). Programmes will often be presented as physical literacy focused despite being specific to FMS. Indeed, physical literacy moves beyond the physical domain (i.e., FMS) to include affective and cognitive attributes, deemed comparably influential to lifelong physical activity (Shearer et al., 2021). Whilst FMS have a key role within physical literacy programmes, FMS do not represent the only pathway for children to achieve adequate levels of physical activity (Edwards et al., 2018). As such, physically literate children are those that have the motivation, confidence and physical competence to engage in physical activities and sports across a range of different settings (PHE Canada, 2014). To promote and nurture all three domains requires an understanding of the philosophical underpinning of physical literacy and the subsequent adoption of an appropriately aligned pedagogical approach (Belton et al., 2022).

The integration of physical literacy within school curriculums and youth sport has gained momentum in recent years, with stakeholders becoming increasingly aware of the failings associated with delivering a reductionist approach to PE (Rudd et al., 2021). To promote the development of physical literacy, a key goal for practitioners is the delivery of an enriched physical activity experience. Although different pedagogical approaches exist, non-linear pedagogy, underpinned by an ecological dynamics rationale, has been suggested as an effective approach for facilitating quality physical activity (Rudd et al., 2021). Ecological dynamics considers learners as complex and dynamic systems that co-adapt with objects and other learners in an evolving environment (Roberts et al., 2018). Therefore, non-linear pedagogy aims to align the affordances offered by the teaching context to the movement capabilities of the child, with this achieved through the manipulation of specific constraints (i.e., game rules, space, equipment; Rudd et al., 2020). Such an approach is in contrast to the structured environments aligned with linear pedagogy and instead affords the child a heightened level of choice and autonomy, that in turn can promote autonomous motivation (Rudd et al., 2020). Moreover, there is not an explicit focus on achieving proficiency in closed-setting, isolated movements, but instead presenting affordances that require the learner to discover and elicit effective movement solutions (Roberts et al., 2018).

Experimental studies have presented some support for the integration of physical literacy approaches within the school context, although the strength of evidence is limited by too few studies investigating all of the multifaceted aspects of the concept (Liu and Chen, 2020). The findings of Belton and colleagues (2019) showed the efficacy of a 24 month whole-school approach that targeted the key components of physical literacy promotion. The intervention aimed to develop physical literacy through fun, motivational and engaging lessons, as well as establishing active role models for the pupils. Yet, despite encouraging outcomes relating to total physical activity levels, outcome measures specific to physical literacy (i.e., self-efficacy and motivation) were not investigated. Mandigo et al. (2019) did include outcomes specific to physical literacy in their study, which included an eight week Teaching Games for Understanding (TGfU) approach. TGfU delivery typically incorporates sampling, representation, exaggeration and tactical complexity as the four pedagogical principles (Mandigo et al., 2019). The TGfU intervention led to significant improvements in 10 of 12 measured physical literacy outcomes. Similarly encouraging findings have been found in community sport settings, where children have participated in programmes guided by the underlying components of physical literacy (Warner et al., 2021). Akin to FMS, physical literacy is also positively associated with wider health-related outcomes such as social-emotional health and cognitive development (Fortnum et al. 2018; Gu et al., 2019).

Given the multidimensional attributes of physical literacy (i.e., physical, cognitive and affective domains) it is important that these are all considered and included in the assessment of physical literacy. Yet, there is tension and a lack of consensus in how best to approach the assessment of physical literacy, with specific approaches associated to the interpretation of physical literacy by particular stakeholders (i.e., PHE Canada; Jurbala, 2015). A common critique is that assessments such as the TGMD-3 are commonly used despite only assessing the domain of physical competence (Robinson and Randall, 2016). This is supported in the systematic review of Edwards et al. (2018) who found certain elements of physical literacy being prioritised, often influenced by the perspective of the user. The Canadian Assessment of Physical Literacy (CAPL) has been proposed as a valid and comprehensive assessment of physical literacy (Longmuir et al., 2015). Individuals are assessed across four domains (physical competence, knowledge and understanding, motivation and confidence and daily behaviour) with domain and overall physical literacy scores interpreted in percentile groupings (Longmuir et al., 2018). However, the fidelity of the CAPL to the concept of physical literacy has been highlighted as a contentious point, as the body is viewed as an object where performance is judged against a predetermined scale (Robinson and Randall, 2017). Whitehead (2019) proposed that rather than assessing progress against such an attainment scale, it is more important to chart an individual's journey. A predetermined scale also goes against the monist principles that underpin the concept of physical literacy and that embrace the mind, body and environment as inseparable (Merleau-Ponty, 1996).

2.3.1 A whole systems approach

Aligned to the development of physical literacy is a whole systems perspective to motor competence, whereby motor skills are considered as part of a complex structure, where they are embodied with cognitive and social-emotional skills (Cheung et al., 2021). The whole system refers to the sub-systems within the body (i.e., muscles, limb segments), cognitive sub-systems (i.e., synaptic connections) and characteristics of the environment, with the synergy of these sub-sections promoting whole system adaptions (Chow et al., 2016; Davids et al., 2003; Rudd et al., 2020). The synergy of these sub-sections is underpinned by the overlapping of the neural networks in the CNS for motor, cognitive and social-emotional development, with this subsequently activated by the interaction of a child with their environment (Cheung, Shen, & Meadan, 2022; Thelen, 2000). As such, a movement solution emerges from the self-organising that occurs at this sub-section level (Raja and Anderson, 2019). The stimulation of these motor, cognitive and social-emotional domains always occurs in harmony and is dependent on the motor and cognitive demands that a specific context is demanding (Cheung, Shen, & Meadan, 2022).

The construct of embodiment refers to movement, thoughts and capabilities as inseparable, and, therefore, focuses on their holistic development (Robinson et al., 2016). Indeed, supporting evidence for the simultaneous development of motor, cognitive and social-emotional skills has been demonstrated in typically and atypically developing children (Asonitou et al., 2010; Cheung et al., 2020; Cheung, Shen, & Meadan, 2022; Hellendoorn et al., 2015). Cheung et al. (2020) found children with disabilities to demonstrate significant gaps in motor, cognitive and social-emotional skills, with these gaps maintained longitudinally. Similarly, the aligned developmental trajectories of motor and cognitive behaviours, notably motor competence and executive functions provide further support for the whole systems perspective (Van der Fels et al., 2015). Approaching physical literacy and FMS from a whole systems perspective challenges the prior assumption that the body is separate from the mind and consequently advocates for this to influence assessment and pedagogy (Lucas, Claxton and Webster, 2010).

From an application perspective, a whole systems approach advocates physical activity interventions that are cognitively enriched and that stimulate motor, cognitive and social-emotional skills (Pesce et al., 2016). Ecological dynamics and notably a non-linear pedagogical approach are considered aligned to a whole systems approach as both identify the key role of environmental characteristics on the development of physical literacy and FMS (Rudd et al., 2020). In contrast to approaching the development and assessment of FMS as isolated skills in closed settings, a whole systems approach advocates for the integration of executive functions in targeting the identification of movement solutions in the face of changing constraints (Pesce, Stodden and Lakes, 2021). It is contended that an emphasis on performing a movement in a closed setting, to an optimal template, is detached from the contexts in which children develop and execute these skills (i.e., sport, unstructured physical activity; Rudd et al., 2020).

2.4 FMS within a health-enhancing model

There is substantial empirical evidence supporting the positive association of FMS and health-related physiological, psychological and behavioural adaptions (Cattuzzo et al., 2016; Lubans, Morgan, Cliff, Barnett, & Okely, 2010; Tompsett, Sanders, Taylor, & Cobley, 2017; Utesch, Bardid, Büsch, & Strauss, 2019). Much recent research assessing the influence of FMS on health-related outcomes has been guided by the Stodden et al. (2008) developmental model (*Figure 2*). Conceptually, the Stodden et al. (2008) model emphasises FMS as a key mechanism in promoting either positive, or negative, trajectories of health in youth. The reciprocal association between FMS and physical activity is central to the model, and is proposed to be mediated through a child's perceived fundamental movement skill competence and health-related fitness (HRF; Robinson et al., 2015; Stodden et al., 2008). As children age, both perceived competence and HRF are considered increasingly important to physical activity and weight status (Robinson et al., 2015).

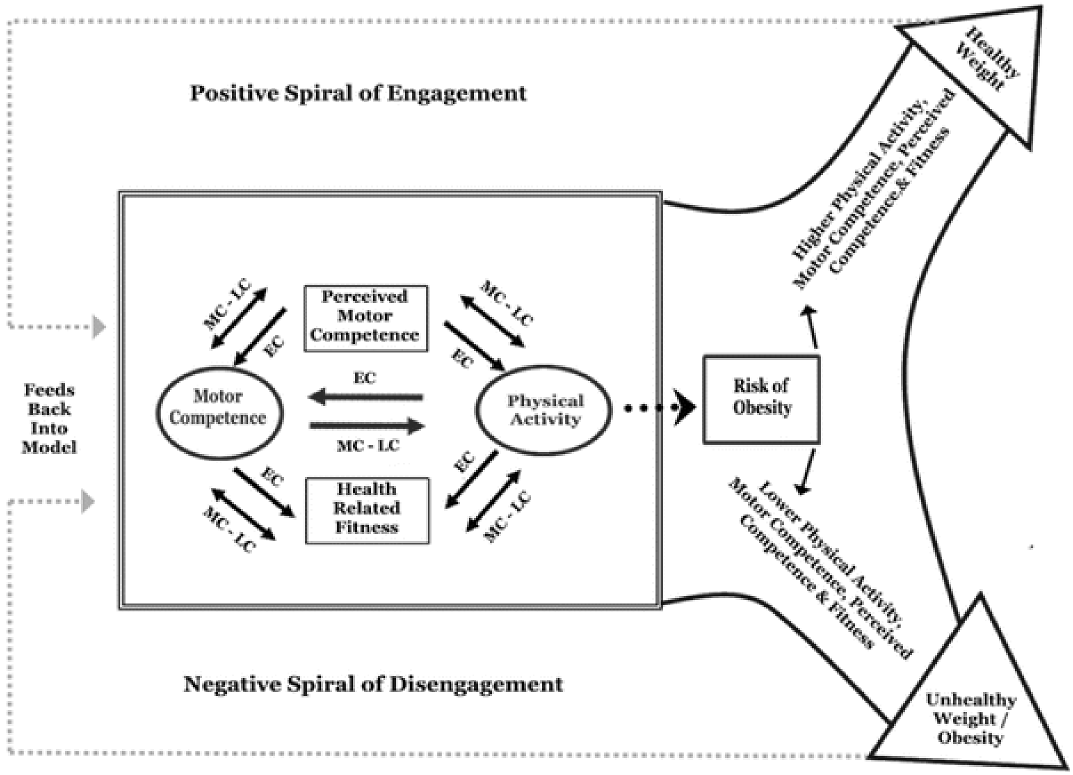


Figure 2. Developmental model proposed by Stodden et al. (2008) hypothesising developmental relationships between motor competence, health-related physical fitness, perceived motor competence, physical activity, and risk of obesity

The 'dynamic' component within the model authored by Stodden and colleagues (2008) implies that in early childhood, when there is a lower cognitive maturity, it is largely physical activity that drives fundamental movement skill development. It is proposed that a growing exposure to physical activity, especially within different contexts, promotes neuromotor development (Stodden et al., 2008; Xin et al., 2020). Evidence supporting the influence of physical activity on FMS in this direction remains weak (Barnett et al., 2021; Xin et al., 2020), although a longitudinal relationship between diversity of physical activity participation and later fundamental movement skill competence has been reported (Melby et al., 2021). From an ecological perspective, it is suggested that this inconsistent evidence reflects the influence of additional factors such as parental influence, home environment and structured PE opportunities (Xin et al., 2020). The complexity of measuring physical activity may also contribute to the indeterminate evidence (Barnett et al., 2020). In the years proceeding early-childhood, increasing cognitive capacity is thought to enable a more accurate perception of fundamental movement skill competence relative to peers.

Given this, from late childhood onwards, FMS are proposed to have a crucial role in outcomes associated with HRF, physical activity, and, subsequently, weight status (Lai et al., 2014; Stodden et al., 2008). Stodden and colleagues (2008) hypothesise that FMS synergistically interact with the aspects of health identified within their model, promoting either a positive spiral of engagement or, conversely, a negative spiral of disengagement with physical activity (Stodden et al., 2008).

Robinson and collegues (2015) critically reviewed empirical evidence pertaining to the Stodden et al. (2008) hypotheses. Notably, the authors concluded that whilst there is evidence for the direct influence of FMS on aspects of health (i.e. physical activity, HRF), supporting evidence for the indirect associations, such as the influence of FMS on physical activity through HRF, remains limited. More recently, Barnett et al. (2021) have suggested there is a bias in the evidence relating to the paths within the Stodden et al. (2008) model, where there has been a tendency towards reporting on solely positive associations. As such, Barnett and colleagues (2021) concluded that sufficient longitudinal evidence only exists for distinct paths within the model (i.e. the negative association between weight status and FMS), with indeterminate evidence apparent for many remaining paths, including the model in its entirety.

Although accruing review evidence has synthesised the influence of FMS across childhood, the lack of comparable research directed towards the continued influence of FMS in adolescence has made a similar synthesis of evidence at these ages challenging (Robinson et al., 2015). Adolescence is a transitional period, defined by inter-individual variance in physical and psychological development (Sherar, Cumming, Eisenmann, Baxter-Jones, & Malina, 2010). Furthermore, it is a period where there is a reduced biological drive to be physically active and where sport participation becomes increasingly underpinned by competition (Malina et al., 2016). As such, greater insight is needed to confirm whether the underpinning role of FMS upon health-related outcomes during adolescence is similar to that which is evident in childhood, and if the association with outcomes such as self-perception and cognition is maintained during this period.

2.4.1. FMS and physical activity

The role of FMS as a prerequisite for physical activity is the underpinning construct of numerous motor development theories (Logan, Kipling Webster, Getchell, Pfeiffer,

& Robinson, 2015). As evidenced in several systematic reviews, there has been strong agreement that a linear association between FMS and physical activity is apparent in youth (Holfelder & Schott, 2014; Logan, Kipling Webster, Getchell, Pfeiffer, & Robinson, 2015; Lubans et al., 2010). However, the review of Barnett and colleagues (2021) advises caution, and in reviewing all longitudinal study analyses (i.e. significant and non-significant results), the authors contend that there is weak evidence at a domain and composite level for this relationship. Moreover, whilst a linear association between FMS and physical activity has consistently been reported, the factors that moderate this association are less well elucidated, at least in part because of the heterogeneity in the methodological approaches used for physical activity and fundamental movement skill measurement. Indeed, the inconsistent evidence may be attributable to the type of fundamental movement skill assessment used (i.e. process or product-oriented) and the specific FMS assessed (i.e. locomotor or object control skills; Khodaverdi, Bahram, Stodden, & Kazemnejad, 2016; Logan et al., 2015). The potential influence of sex and age as moderators of this relationship has also been highlighted in existing evidence (Barnett, Lubans, Timperio, Salmon, & Ridgers, 2017; Okely, Booth, & Patterson, 2001; Slykerman, Ridgers, Stevenson, & Barnett, 2016). When approaching the association of FMS and physical activity in adolescence it is important to consider the role of additional moderating factors, including the inter-individual and sex-specific variance associated with biological maturation (Malina et al., 2016). In adolescence, the influence of maturity may lessen the role of chronological age, and instead promote an increased interaction with environmental and psychosocial variables that include self-efficacy and level of social support (Garcia et al., 2016; Laird, Fawkner, & Niven, 2018).

Whilst it may be expected that the influence of FMS on physical activity would increase during childhood and subsequently into adolescence, there is not the strength of evidence to support this (Barnett et al., 2021; Robinson et al., 2015). Logan et al. (2015) found the association between FMS and physical activity to range from low (r = 0.24 to 0.38, R^2 = 6–14%) to moderate (r = 0.44 to 0.55, R^2 = 19–30%) in mid-late childhood, and for this to then remain consistent across adolescence. Again, this may reflect the methodological inconsistencies associated with some studies, and also an increasing influence of additional factors (i.e. self-perception, HRF). The longitudinal studies of Barnett et al. (2009a) and Lopes et al. (2019) support the developmental trajectory hypothesis between FMS and physical activity (Stodden et al., 2008). However, both of the aforementioned studies used FMS as the sole predictor, so identifying a reciprocal relationship was not achievable. To address this, further studies have investigated the reciprocal relationship by using FMS and physical activity as predictor variables. In a seven year longitudinal study (6.8 ± 0.4 years), Lima et al. (2017) found evidence of a reciprocal relationship at baseline (vigorous-intensity physical activity [VPA] → FMS; $\beta = 0.18$; 95% CI: 0.10, 0.26; FMS → VPA; $\beta = 0.14$; 95% CI: 0.08, 0.21). However, only locomotor skill competence was selected as an indicator of FMS in this study (Lima et al., 2017). A further longitudinal study found evidence of a reciprocal relationship in adolescent boys, but not girls (Jaakkola & Washington, 2013). Additional cross-sectional support has been provided by Barnett et al. (2011) who found a reciprocal association between object control skills and physical activity; although locomotor skills were only associated with physical activity when locomotor skills were considered as the outcome. Taken together, the current evidence remains indeterminate and highlights the importance of assessing the relationship between FMS and physical activity relative to sex and at a construct-level.

Although analysis of the relationship between FMS and total physical activity can provide important insight into the health-related influence of FMS, considering physical activity as solely a product of time spent in MVPA may obscure some of the nuances of this relationship. Justification for approaching the FMS-physical activity relationship more explicitly can be found in physical activity guidelines that now recognise the importance of specific physical activity characteristics (i.e. activity type, skill underpinning; Department of Health and Social Care, 2019). Given this, more recent research has attempted to identify the association of FMS with specific intensities, modalities and contexts of physical activity (Lopes, Santos, Pereira, & Lopes, 2012; Adank et al., 2018). Webster et al. (2019) observed FMS to become more influential during VPA than MVPA. It was proposed that this is likely attributable to VPA being more indicative of sport-related participation where FMS are more relevant to successful participation. Additionally, it may indicate that MVPA is comprised mostly of moderate-intensity physical activity (MPA). Similar patterns to the aforementioned studies were found in an earlier longitudinal study where children were assessed at three time points over seven years. FMS were found to be directly associated with VPA ($\beta VPA = 0.08$; 95% CI: 0.02–0.15), but not MVPA ($\beta MVPA =$

0.06; 95% CI: –0.01 to 0.13; Lima et al., 2017). A further consideration for those studies measuring physical activity objectively (i.e. accelerometer) is whether the positioning of the accelerometer offers enough sensitivity to capture the execution of discrete-skill performances that are likely a crucial indicator of the influence of FMS (Barnett et al., 2021; Duncan et al., 2019).

As children are now spending more time sedentary (Bucksch et al., 2016; Hallal et al., 2012), studies have examined the potential role of FMS as a mechanism to reduce time spent sedentary (Adank et al., 2018; Van Kann, Adank, van Dijk, Remmers, & Vos, 2019). Adank et al. (2018) found the inverse association between fundamental movement skill competence and time spent sedentary to be stronger than the association between FMS and MVPA. Congruent with these findings, the longitudinal study of Duncan et al. (2021) also found FMS in pre-school children to have a greater influence on time spent sedentary than levels of physical activity, when assessed a year later, with this relationship not analysed specific to sex. A limitation of the study of Adank et al. (2018) was that the assessment of sedentary behaviour was restricted to weekdays, and as such these levels were likely heavily influenced by the overarching governance of the school setting. It would also be beneficial if further studies assessed the role of perceived competence in the association between FMS and time spent sedentary. A more recent study (Martins, Clark, Bandeira, Mota, & Duncan, 2020) presented initial evidence for the role of FMS in influencing adherence to 24 hour movement guidelines. Although the results were inconsistent, object control skills were found to have the greatest influence, with a negative association with sedentary screen time found to strengthen with age (Martins et al., 2020).

Despite a growing evidence base, the comparability and validity of studies assessing the relationship of FMS and physical activity is limited by the use of a myriad of approaches for physical activity measurement (i.e. questionnaire, pedometer, accelerometer). Understanding of the relationship is further constrained by the concurrent use of process-oriented (technique), product-oriented (outcome) and circuit-based approaches to fundamental movement skill assessment, along with a range of competency markers being analysed (i.e. standardised score, construct-specific score, normailsed percentile). Whilst it may be assumed that product-oriented competence would demonstrate a stronger association with physical activity, as a combined outcome of practice opportunity and maturational development, existing evidence reveals little variance between process- or product-oriented approaches (Holfelder & Schott, 2014; Lima et al., 2017; Lopes, Rodrigues, Maia, & Malina, 2011). An additional consideration is whether FMS are analysed at a composite level, or as is more prevalent, separated into distinct constructs (i.e. object control skills and locomotor skills). In boys, evidence suggests that object control skills are a stronger predictor of physical activity (Barnett et al., 2011; Logan et al., 2015; Miller, Eather, Duncan, & Lubans, 2019). Furthermore, object control skills are more ontogenetic, meaning there is often a more influential and measurable disparity in competence levels (Hulteen et al., 2019). In girls, whilst less consistent, studies have found locomotor skills to be a strong predictor, likely due to a greater alignment to the activities girls are more likely to engage in (Cliff, Okely, Smith, & McKeen, 2009; Logan et al., 2015).

2.4.2. FMS and self-perception

From middle childhood, domains of physical self-concept, such as perceived fundamental movement skill competence are proposed to have an increasingly crucial role in influencing health-related behaviours (Stodden et al., 2008). Recent studies have provided insight into the role of perceived competence, identifying that for some children it is a stronger predictor of physical activity than actual fundamental movement skill competence (Bardid, De Meester, et al., 2016; Bolger, Bolger, O'Neill, et al., 2018; De Meester, Maes, et al., 2016a). From a broader perspective, positive self-perception has been shown to be a central determinant of physical activity, especially in adolescence (Babic et al., 2014; Robinson et al., 2015). Perceived fundamental movement competence, perceived sports competence and perceived athletic competence are used interchangeably to describe the underlying construct of physical self-concept, with this signifying a child's personal perception of their fundamental movement skill competence (De Meester et al., 2020; Estevan & Barnett, 2018). These terms along with physical self-concept are closely related to self-efficacy, which reflects the confidence and beliefs that an individual has of successfully performing certain tasks (Bandurra, 1997). It is proposed that self-perceived fundamental movement skill competence/perceived sports competence, in addition to actual fundamental movement skill competence, strongly influence the willingness and motivation of children to engage in physical activity (Pesce, Masci, Marchetti, Vannozzi, & Schmidt, 2017). Although there exists some support for the influence of perceived fundamental movement skill competence on self-determined motivation for sport participation, physical activity and participation in PE settings (De Meester et al., 2016a; Estevan et al., 2020), evidence pertaining to the association between actual FMS and perceived competence remains indeterminate (Barnett et al., 2021).

The influence of perceived competence on health-enhancing outcomes has been found to differ with age, sex, and fundamental movement skill construct (Barnett et al., 2008a; Bolger, Bolger, O'Neill, et al., 2018; Jason Moran, Drury, Venetsanou, Clark, & Fernandes, 2018). The lack of agreement could relate to the interchangeable use of terms and assessment methods chosen to analyse perceived competence (Estevan & Barnett, 2018). However, despite these methodological inconsistencies, there is some support for the developmental hypothesis of Stodden et al. (2008). In late childhood, perceived competence has been found to be a stronger predictor of MVPA than actual fundamental movement skill competence (Chan, Ha, Ng, & Lubans, 2019). In contrast, in young children (four-eight years) there is limited evidence supporting an assertive influence of perceived competence on physical activity (Barnett et al., 2015b; Slykerman, Ridgers, Stevenson, & Barnett, 2016). It is suggested that at younger ages children generally have a high perception of self-competence, irrespective of actual fundamental movement skill competence. This is supported in the literature with high mean scores and small standard deviations evident (Barnett et al., 2015a; Slykerman et al., 2016). However, the results may also reflect the difficulty of observing distinct associations between perceived competence and physical activity in childhood, as the findings may be constrained by the more homogeneous and higher physical activity levels, relative to children in late childhood and adolescence, and also the contexts in which physical activity occurs (i.e. a greater participation in free-play; Barnett et al., 2015b; Slykerman et al., 2016).

To gain a greater understanding of the dynamic relationship between perceived and actual fundamental movement skill competence, studies have investigated the level of agreement between these competencies (Moran et al., 2018; Schmidt, Valkanover, & Conzelmann, 2013). In childhood, non-veridicality has been found to exist between actual and perceived fundamental movement skill competence (Moran, Drury, Venetsanou, Clark, & Fernandes, 2018), although this discord has been contested in some studies where a strong association between perceived and actual fundamental movement skill competence has been found (Duncan, Jones, O' Brien, Barnett, & Eyre, 2018; Barnett et al., 2015a). The inconsistent evidence is highlighted in the systematic review and meta-analysis of De Meester et al. (2020) where age was not found to be a significant moderator of the association between actual and perceived FMS. This absence of a significant finding is purported to be influenced by a lack of studies in adolescents and young adults, and the failure of many studies to include potential cofounders such as biological maturation and sex in their analyses (De Meester et al., 2020). More recently, analysis of the association between actual and perceived fundamental movement skill competence has shifted from a variable centered to a person-centered approach (Bardid, De Meester, et al., 2016; Pesce et al., 2017). That is, whilst a variable approach can provide an overall picture of a relationship, a person-centered approach can identify specific groups of relationships that may demonstrate divergence (i.e. those with high perceived competence but low actual competence; Bardid, De Meester, et al., 2016). Adopting a person-centered approach, Bardid, and collegues (2016) found that 47% of children (age = 8.8 ± 0.7 years) had divergence between actual and perceived fundamental movement skill competence, with those children overestimating their actual fundamental movement skill competence rather than underestimating (Bardid, De Meester, et al., 2016).

Although the moderating role of sex on perceived fundamental movement skill competence has not been widely researched, boys are reported to have a higher self-perception of their competence, irrespective of actual competence level (Duncan et al., 2018; Noordstar, van der Net, Jak, Helders, & Jongmans, 2016; Pesce et al., 2017). Furthermore, girls are more likely to underestimate their actual competence, specifically in relation to object control skills (Pesce et al., 2017). This may highlight a need to prescribe sex-specific interventions to ensure girls have the necessary competence in FMS to promote enjoyment and a desire to remain actively engaged in structured sports and physical activity (Pesce et al., 2017). Recent evidence in an adolescent sample has provided additional support for a sex-related influence, with perceived physical competence found to moderate the fundamental movement skill - physical activity relationship in girls, but not boys (Jaakkola et al., 2019). Yet, as with age, when the evidence is summarised, sex is not found to be a significant moderator of the association between actual and perceived fundamental movement skill competence (De Meester et al., 2020). Authors do cite several methodological inconsistencies that may contribute to the failure of sex to be considered as a moderator, including some studies presenting sex-standardised scores and further studies using sex-specific versions of a self-perception assessment (De Meester et al., 2020).

From late childhood, perceived competence has been found to align more strongly with actual competence (McGrane, Belton, Fairclough, Powell, & Issartel, 2017). When analysed specific to fundamental movement skill construct, object control skills have been observed as a predictor of perceived object control competence ($R^2 = 0.38$), whilst in the same study a similar association between actual and perceived locomotor skills was not found (Rogers, Barnett, & Lander, 2018). As previously acknowledged, this may reflect competence-related differences in object control skills being far more observable than for locomotor skills when measured using process-oriented approaches. It could also relate to object control skills being more influential upon sport participation than locomotor skills (Pesce et al., 2017).

It is purported that in adolescence, the sub-domains of physical self-concept (perceived sports competence, fitness, strength, body appearance) become more relevant than in childhood, as they more strongly align to the characteristics of competition and performance that underpin much physical activity and sport participation at these ages (Estevan & Barnett, 2018). At younger ages, perceived fundamental movement skill competence and specific aspects of perceived fundamental movement skill competence (i.e. perceived locomotor skill competence) can be considered the broader concept, as from a developmental perspective children are less able to perceive performance and success in relation to sport participation (Estevan & Barnett, 2018). Moreover, for children, sports competence is arguably less relevant and instead it is the self-perception of their ability to perform FMS that is of greater importance as this allows for a more enjoyable experience in the activities they are participating in (De Meester et al., 2020). In adolescence, the association has been found to be stronger in those studies where the instruments used are less aligned, such as when TGMD-2 score is compared to perceived sports competence (De Meester et al., 2020). As such, a stronger indication of perceived competence in adolescents may be found by assessing their perceived sports perception, as this is the social context in which FMS will be performed and compared relative to peers (De Meester et al., 2020).

2.4.3. FMS and weight status

Within the conceptual model of Stodden et al. (2008), sustaining a healthy weight status is presented as a central outcome. Fundamental movement skill proficiency is hypothesised to be both a predictor and a consequence of weight status, with this association mediated through an interaction with physical activity and self-perception (Robinson et al., 2015; Stodden et al., 2008). Numerous studies have provided supportive longitudinal evidence for a reciprocal inverse association between fundamental movement skill competence and weight status (Barnett et al., 2021; Cattuzzo et al., 2016; Lubans et al., 2010; Robinson et al., 2015). Specifically, D'Hondt and collegues (2014) found lower fundamental movement skill competence in children aged 5-13 years at baseline predicted an increase in BMI at follow-up (2 years). Conversely, a higher BMI at baseline was longitudinally associated with a lower performance on the KTK motor competence assessment. In addition, there is consistent evidence for obesity being a predictor of lower fundamental movement skill competence (Bryant, James, Birch, & Duncan, 2014; Cheng et al., 2016) and for the role of FMS in predicting future weight status (Antunes et al., 2016; Lima et al., 2017).

The inverse association between fundamental movement skill competence and weight status is suggested to be underpinned by behavioural and biomechanical determinants (Hills, Hennig, Byrne, & Steele, 2002; Morrison, Cairney, Eisenmann, Pfeiffer, & Gould, 2018). Competence-related differences between obese and normal weight children are more prominent in locomotor skills compared with object control skills (Barnett et al., 2016; Bryant et al., 2014; Okely et al., 2004). Specifically, the negative influence of an elevated BMI is most evident in tasks that require dynamic strength, explosiveness, and the propulsion of the whole body (D'Hondt et al., 2011). Whilst these biomechanical mechanisms provide some basis for the marked differences in fundamental movement skill competence between obese and normal weight children, less is known as to the specific causes. That is, are the differences solely an outcome of attempting to move more body mass in the respective performances, or are they related to a less competent technique, a consequence of less physical activity and sport participation (Riddiford-Harland, Steele, & Baur, 2006). More recent support for the inverse association between weight status and locomotor skills has been provided in the systematic review of Barnett and colleagues (2021), with the authors proposing that excess body weight in early childhood will likely restrict the development of FMS throughout proceeding years. Childhood obesity is likely to synergistically interact with both actual and perceived fundamental movement skill competence by limiting the ability and the willingness of children to participate in many activities (Duncan, Stanley, & Wright, 2013).

Although studies have shown the inverse association between FMS and weight status to become more pronounced with age during childhood, in adolescence the findings are far less consistent (D'Hondt et al., 2014, 2011; Malina et al., 2016). In some adolescent samples similar patterns to childhood have been found (Hardy, King, Farrell, Macniven, & Howlett, 2010; O' Brien, Belton, & Issartel, 2016a), although there has been insufficient evidence of an inverse association to be present in others (Lopes, Stodden, Bianchi, Maia, & Rodrigues, 2012; Okely et al., 2004). The studies of Lopes et al. (2012) and Okely et al. (2004) both found a decrease in the inverse association between weight status and FMS from early adolescence onwards. Lopes et al. (2012) suggest this is likely explained by the onset of maturity, which is characterised by accelerated growth patterns and marked increases in muscle mass. As such, BMI may be less reflective of excess fatness, specifically in boys (Malina, Bouchard, & Bar-Or, 2004). Nevill and colleagues (2021) highlight the limitations of using BMI as a proxy of obesity in adolescence. The authors found that with percent body fatness not controlled for, the between-sex developmental trajectories of BMI remained similar, but with percent body fatness controlled for, considerable age-by-sex differences became evident. The inverse association between weight status and FMS may be further weakened in the performance of specific product-oriented assessments (i.e. overhand throw velocity), where advanced maturity may have an inverse influence on BMI but a positive influence on performance potential (Lopes et al., 2012; Malina et al., 2004). In girls, the earlier decrease in association between poor fundamental movement skill competence and increased weight status may provide support for a maturational effect, as girls are known to have an earlier maturity onset than boys (Lopes, Maia, et al., 2012). Taken together, these studies highlight the importance of controlling for the potential influence of biological age in study designs that include child and adolescent samples.

2.4.4. FMS and health-related fitness (HRF)

Health-related fitness is considered to fulfil an important mediating role in the association between FMS and physical activity (Cattuzzo et al., 2016; Stodden et al., 2008). In this context, HRF is a generic term used to identify the multifaceted markers of cardiorespiratory and musculoskeletal fitness, but can also include flexibility and measurements of body weight status (Cattuzzo et al., 2016). Akin to physical activity, Stodden and colleagues (2008) propose the association between FMS and HRF to strengthen with age, as children proficient in FMS will likely persist in high intensity sports and physical activities that are conducive to fitness development. Moreover, to achieve proficiency, many FMS require repeated practice, which, with advancing age, often occurs within sport-related contexts that promote a positive fitness profile (Utesch et al., 2019).

A recent systematic review has concluded that whilst strong evidence exists for the FMS-HRF path, there is insufficient evidence for the reverse (Barnett et al., 2021). There has also been disagreement as to the relative importance of independent skill constructs (object control, locomotor or stability skills) to HRF. Irrespective of sex, Luz and collegues (2017) found locomotor skills and stability skills to be the strongest predictor of HRF ($0.51 < r < 0.97$), and, in contrast to the Stodden et al. (2008) hypothesis, found this to remain stable with increasing age (7-14 years). However, the results may have been influenced by the authors selecting a fundamental movement skill assessment that was more applicable to measuring motor fitness, and also the failure of the study to consider the influence of biological maturation. The results from the Luz et al. (2017) study differed from Barnett et al. (2008b) who, after adjusting for sex, found object control skills to be the stronger predictor of future cardiorespiratory fitness ($p = 0.012$). Barnett et al. (2008b) suggest that this may reflect the greater reliance upon these skills in organised sport and school PE lessons. Overall, when analysing at a domain-level, Barnett and colleagues (2021) conclude that presently a consistent relationship is only apparent for locomotor skills.

A reciprocal relationship between FMS and aspects of HRF is to be expected as they are reliant on similar underpinning movement patterns (i.e. stabilisation of body segments, inter- and intra-muscular coordination and control; Cattuzzo et al., 2016). The direct association between FMS and HRF is driven through two principle pathways (Cattuzzo et al., 2016). Firstly, FMS promote engagement in activities conducive to fitness development (i.e. organised sport), and secondly, they have a direct influence on the neuromuscular control that is a prerequisite of multi-joint movements (Utesch et al., 2019). These parallels are especially pertinent in many of the product-oriented assessment protocols (i.e. Movement Assessment Battery for Children - Version 2 [MABC-2], KTK), where there is an evident overlap with fitness measures (i.e. broad jump distance; Utesch et al., 2019). Support for the mediating role of HRF in the relationship of FMS and physical activity, as hypothesised by Stodden and colleagues (2008), has only been provided in a single study (Khodaverdi et al., 2016). Khodaverdi et al. (2016) found aerobic fitness to be the sole HRF component to mediate the association between locomotor skills and physical activity, when assessed in girls (Khodaverdi et al., 2016). The widespread applicability of the findings is however limited by the narrow age-range (eight-nine years), the inclusion of only aerobic fitness in the mediation model, and the subjective measurement of physical activity using a questionnaire. Future research should endeavor to analyse the effect on physical activity via additional indirect pathways (i.e. object control, muscular fitness) and analyse the moderating influence of sex, age, and biological maturation. In addition, there is initial evidence that suggests that acute HRF benefits could be associated with performing FMS competently (Sacko et al., 2019b) and as such this could offer further justification for prioritising the development of FMS in health-related interventions in youth.

2.5 FMS and metabolic expenditure

Despite the direct and indirect importance of FMS to physical activity and sport participation, little evidence exists identifying the influence of developmental factors (i.e. age, maturation, skill competence) on the metabolic expenditure associated with performing FMS. Given the diverse nature of physical activity in youth, and the strong underpinning of FMS to many of the common activities engaged in, understanding the associated energy expenditure (EE) of FMS is important to informing physical activity interventions (Butte et al., 2018; Sacko et al., 2019b). Moreover, investigating the influence of factors such as skill proficiency to the associated EE of FMS offers opportunity to gain additional insight into the relationship between FMS and HRF.

Quantifying EE in youth is complex, as a range of physical and physiological characteristics such as age, sex and body composition contribute to variance in metabolic rates (McMurray et al., 2015). For example, in comparison to adolescents, children have a higher resting metabolic rate (RMR) per unit of body mass, along with a suggested lower economy of movement (McMurray et al., 2015).

The Youth Compendium of Physical Activity (YCPA) provides an overview of the age-related metabolic equivalent (MET) intensities for respective physical activity types, and these normative values provide the basis for achieving daily recommendations (Butte et al., 2018). The respective physical activity classifications in youth differ from adults, reflecting the lower EE per unit of body mass for children completing the same activity (moderate intensity = 4.0 METs, vigorous intensity = ≥ 7.0 METs in children, in comparison to moderate intensity = 3.0 METs, vigorous intensity = ≥ 6.0 METs in adults; Butte et al., 2018). Moreover, during childhood and adolescence there are physiological and competency related changes that influence the energy costs of specific physical activities (Butte et al., 2018). It is hypothesised that as children age they become more proficient in their movement patterns and this lessens the associated energy costs (Butte et al., 2018). However, whilst age-related increases in fundamental movement skill competence are consistent in pre-pubertal children, for many, fundamental movement skill competence remains poor in adolescence, and in some instances competence has been observed to regress (Hardy et al., 2013; Lester et al., 2017). Moreover, for specific FMS, higher proficiency has been found to be associated with a higher EE (Sacko et al., 2019b).

Significant kinematic differences have been found in many FMS. In the overhand throw there are stark differences between competent and non-competent children, with these aligning strongly with their respective developmental levels (Stodden et al., 2006a). In children displaying a high level of proficiency, there is an increased energy generation and transfer, achieved through a more optimal interaction of underpinning kinematic mechanisms (Stodden et al., 2006b). For example, in highly skilled throwers, a forward step with the ipsilateral foot, allows for the pelvis and upper torso to open and rotate, promoting an increased transfer through the kinetic chain (Stodden et al., 2006b). In contrast, non-competent throwers display little trunk rotation and an ipsilateral step is often deficient (Eather et al., 2018; Stodden et al., 2006b). Similar differences have been found in the kick, with those efficient in kicking displaying multi-joint coordination across the whole body, with the most significant differences found at the hip and knee (Shan & Westerhoff, 2005). This full body control is absent in less competent kickers, where the focus is specific to the leg movement (Shan & Westerhoff, 2005). Bernstein (1967) identified coordinated movement as “the process of mastering redundant degrees of freedom,” while defining coordination as “the organization of the control of the motor apparatus” (Bernstein, 1967, p.127). From this perspective, it is proposed that a novice mover will restrict the considerable degrees of freedom associated with a movement, so to enable performance of the task (Bernstein, 1967; Vereijken, Emmerik, Whiting, & Newell, 1992). The ideas of Bernstein (1967) are clearly evident in the majority of FMS when assessing competent and non-competent performances. For example, in locomotor skills the freezing of degrees of freedom have been identified (i.e. in the horizontal jump, non-competent children will restrict the influence of the arm swing on the jump; Jarvis et al., 2018).

Sacko and colleagues (Sacko et al., 2018; Sacko et al., 2019b) have recently provided insight into sex-related differences in the metabolic expenditure associated with object projection skills (kicking, throwing, strike) in children (seven-nine years) and adults. In adults, men were found to yield a significantly higher metabolic expenditure ($p < 0.001$) across three interval schedules (6 seconds, 12 seconds, 30 seconds) of repeated object projection performance (Sacko et al., 2018). Men also displayed a greater increase in METs ($p < 0.001$) across the progressively shorter interval schedules (Sacko et al., 2018). In children, boys displayed a higher metabolic expenditure when performing object projection skills across the same interval schedules, and again, the differences between intervals was more pronounced in boys (Sacko et al., 2019b). Additionally, in children, higher product-oriented skill competence was found to be significantly associated with an increased metabolic expenditure (Sacko et al., 2019b). Collectively, these studies provide initial evidence of the moderating roles of sex and skill competence on acute differences in the metabolic expenditure of FMS. However, no studies have yet investigated whether a moderating influence exits for the associated EE of individual FMS.

Current studies have further highlighted the importance of accurately assessing the associated EE of different movements and activities (Arvidsson et al., 2019; Duncan et al., 2019). These studies have investigated the optimal processing of inertial measurement unit (IMU) data and positioning of the IMU on the body, in an attempt to provide an accurate measurement of activity intensity (Arvidsson et al., 2019). To achieve this, the level of agreement between IMU position and associated data cut-points with metabolic expenditure has been analysed (Duncan et al., 2019). Given this, continued investigation into the influence of skill competence, along with that of further developmental factors is needed to establish validity for the relationship between IMU data and associated EE measurement.

2.6 Fundamental movement skill assessment

Despite accumulating evidence identifying FMS as a predictor of multiple health outcomes (Barnett et al., 2021; Holfelder & Schott, 2014; Logan et al., 2015; Lubans et al., 2010), there is still contention as to the specific skills that constitute FMS (Barnett et al., 2016b; Ng & Button, 2019; Rudd et al., 2015). The lack of agreement is reflected in how these skills are conceptualised and measured (Logan et al., 2018). Specifically, fundamental movement skill assessments may adhere to a criterion- or norm-referenced scoring approach (i.e. scored against test items, or reported in relation to a specific population), and measure either product- or process-oriented fundamental movement skill competence. Indeed, there exists no *gold standard* assessment for fundamental movement skill competence (Bardid, Vannozzi, Logan, Hardy, & Barnett, 2018), with the review of Logan et al. (2018) identifying 14 validated protocols. Underpinning this variance in assessment protocols are a group of specific underlying factors (i.e. population characteristics, administrative properties and psychometric quality; Bardid et al., 2018).

Current fundamental movement skill assessments primarily adhere to two distinct methodologies: process- and product-oriented assessment. A process-oriented assessment (e.g. TGMD, Get skilled: Get Active [GSGA]) focuses on the behavioural component of the skill and the qualitative movement pattern, for example, both hands reaching above the head in the horizontal jump (Haywood & Getchell, 2014). In contrast, a product-oriented approach (e.g. KTK, Bruininks–Oseretsky Test of Motor Proficiency) emphasises the executed outcome of a skill (i.e. jump distance; Logan et al., 2018). Whilst product-oriented assessments can be implemented in the absence of trained practitioners and are less time-consuming, the use of this approach in isolation has been contested (Logan, Barnett, Goodway, & Stodden, 2017). In contrast to process-oriented approaches, product-oriented assessments lack the sensitivity to identify specific movement weaknesses and technical components that are not optimally developed (Hulteen et al., 2019). An additional factor limiting the utility of product-oriented assessment is that performance gradients of those of the same chronological age may be more strongly influenced by maturity-related development (i.e. increased muscle mass) rather than discrete differences in technical competence (Radnor et al., 2018). The level of agreement between process- and product-oriented methodologies has been found to be age- and skill-specific (Logan et al., 2017). For example, in a comparison of the TGMD-2 (process-oriented) and MABC (product-oriented) protocols, the total performance correlation was low (r = 0.23), with variance in the level of agreement evident when analysed specific to construct: locomotor skills (r = 0.17), object control skills (r = 0.32; Valentini et al., 2015). Akin to the findings of Valentini et al. (2015), Hulteen and colleagues (2019) also reported a higher correlation between assessment approaches in the object control skill construct. Furthermore, when comparing age group performance (4-5, 7-8, 10-11 years), a decrease in agreement between process- and product-oriented performance for the hop has been found as children age (r = 0.65 - 0.25), whilst an increase in agreement has been found for the overhand throw (r = 0.30 - 0.62; Logan et al., 2017). The complex kinematic underpinning of the overhand throw, and the more pronounced performance disparity when compared to locomotor skills may support this stronger alignment between process- and product-oriented methodologies with increasing age (Hulteen et al., 2019; Stodden et al., 2006a).

The TGMD protocol is principally a process-oriented assessment, with the inclusion of a few product-oriented components (i.e. underarm throw to 15ft, completion of four consecutive hops; Ulrich, 2020; Webster & Ulrich, 2017). The TGMD is a widely utilised protocol; 64% of studies identified in a recent systematic review administered a version of the TGMD (Logan et al., 2018). In assessing FMS, the TGMD affords practitioners the opportunity to follow a norm- or criterion-referenced approach, with this governed by the identified assessment objectives (Cools, Martelaer, Samaey, & Andries, 2009; Ulrich, 2000). Whilst a criterion-referenced approach assesses performance against a set standard, the norm-referenced approach provides comparison to a representative sample and as such requires similar sample characteristics between the assessed and normative samples (Webster & Ulrich, 2017). The TGMD-2 consists of 12 motor-skills (see Appendices VII, VIII), organised into two subsets (locomotor skills and object control skills), with each skill including three-five performance criteria that represent the appropriate movement pattern of the skill. The TGMD-2 has demonstrated strong test-retest reliability, ranging from good-to-excellent in children aged 3-10 years ($0.84 < r < 0.96$; Ulrich, 2000). The assessment has also demonstrated reliability in different cultural contexts (Kim, Han, & Park, 2014; Valentini, Zanella, & Webster, 2017) and is considered a valid assessment of FMS in adolescents (Issartel et al., 2017). Though the skills comprising the TGMD models are deemed 'sport-specific', the emphasis of the assessment is on the underlying attributes of each skill, such as dynamic balance and inter- and intramuscular coordination, with these considered crucial to engagement in a broad range of health-enhancing activities (Barnett et al., 2016b).

The TGMD-3 (see Appendices VII, VIII) has been introduced to accommodate changes in the normative population and to establish a higher psychometric quality than its predecessor the TGMD-2 (Mohammadi, Bahram, Khalaji, Ulrich, & Ghadiri, 2019). Amendments to the previous protocol include: the removal of the underhand roll and leap, and the addition of the underhand throw, one-handed strike and skip, along with increasing the required number of repetitions from three to four in those skills requiring repetitive actions (Ulrich, 2020). The amendment to the skill inclusion is aimed at strengthening the wider cultural appropriateness of the protocol and subsequently improving the wider validity of the protocol in comparison to the TGMD-2 (Valentini et al., 2017). Alongside displaying high inter- and intra-reliability (Mohammadi et al., 2019; Valentini, Zanell, et al., 2016; Wagner & Ulrich, 2017), the TGMD-3 has been shown to demonstrate content and construct validity (Allen, Bredero, Van Damme, Ulrich, & Simons, 2017; Valentini et al., 2017; Webster & Ulrich, 2020). From a research perspective, the TGMD-3 provides an assessment that can be applied in a practical setting, that can identify skill-specific, construct-specific (object control skill and locomotor skills) and composite level fundamental movement skill competence, and also demonstrates developmental validity (Valentini, Zanell, et al., 2016).

Akin to the TGMD protocol, the Get Skilled: Get Active (GSGA) protocol is an assessment of process-oriented competence (Department of Education and Training, 2000). The GSGA assesses technical components for each of the 12 included FMS. Given that the GSGA resource assesses movement criteria in greater depth to the TGMD models, it is proposed to provide a more valid tool with which to identify skill mastery, specifically in adolescents (Logan et al., 2017). A consideration when implementing the TGMD-3 model with older children is that specific skills may display a ceiling effect (i.e. run, skip; Webster & Ulrich, 2017). However, recent research has highlighted that competence levels have been found to plateau from late childhood and in some instances have shown an observed decrease in adolescence (Hardy et al., 2013; O' Brien et al., 2016b). Similar to the TGMD, the GSGA resource has displayed adequate interrater reliability in child (K = 0.61) and adolescent (K = 0.70) samples, although some skills have been identified as problematic (i.e. hop; Barnett et al., 2009b; Department of Education and Training, 2000). Indeed, the heightened number of technical components for movements has limited the reliability of the protocol, and as such, alterations to the scoring criteria have been suggested to improve agreement (Barnett et al., 2009b).

As a standalone methodology within a research setting, process-oriented approaches require trained observers, video collection, and post-priori analyses (Bisi, Pacini Panebianco, Polman, & Stagni, 2017). Despite their widespread adoption, undertaking subjective analysis presents issues relating to the interpretation of criterion execution (Rintala, Sääkslahti, & Iivonen, 2017). Barnett and colleagues (2014) observed that whilst interrater reliability was strong for overall object control (ICC = 0.93), when specific skill components were analysed, problematic areas were evident in a number of skills (i.e. overhand throw, catch, kick). In an earlier study, with more assessors (10 raters in total), the interrater reliability was markedly lower (K = 0.70), again, this became more apparent at an individual skill level i.e. hop (K = 0.31; Barnett et al., 2009b). Disagreement has also been found at the component level, with inter-rater reliability low for the reaching above the head component of the horizontal jump (K = 0.21) and the preferred hand in the two-handed strike (K = 0.07; Rintala et al., 2017). Additional inconsistencies exist relating to how competence is formulated. Specifically, in studies where individual components are presented as a summed score, there is a risk of missing key salient descriptors in the movement (Jarvis et al., 2018).

Ward and colleagues (2020) found high reliability between teacher and trained observer scoring at the performance level, but found inconsistencies at the criterion level. Their study highlighted that agreement at the performance level (i.e. 2/4 for the overhand throw) can mask competence-related differences, as a subsequent assessor may record two different components from the four as present; Ward et al., 2020). Notwithstanding these limitations, the TGMD-3 protocol can be considered an appropriate and valid assessment protocol for use across a range of participant characteristics.

More recently, circuit-based approaches, combining elements of process- and product-oriented assessment, have been developed as a means of assessing the wider, multidimensional concept of 'physical competence' (Whitehead, 2010). The Canadian Agility and Movement Skill Assessment (CAMSA; Longmuir et al., 2017) and the Dragon Challenge (Tyler, Foweather, Mackintosh, & Stratton, 2018) are examples of assessments that follow a circuit-based approach. These assessments emphasise the dynamic combination of fundamental and complex movement patterns, in contrast to examining skill performance in isolation. Such assessments also introduce greater constraints to the execution of movement skills, aligning more strongly with an interactionist approach. A critique of the CAMSA and Dragon Challenge is that both emphasise the speed of completion, which may inadvertently promote non-optimal technical performance, especially at younger ages. Furthermore, the age-related validity of these assessments is markedly restricted in comparison to the aforementioned process-oriented protocols.

2.7 Biological maturation: Assessment and Implications

Biological maturation describes the progress towards a mature state, and involves processes occurring within bodily tissues, organs and systems (Malina, Rogol, Cumming, Silva, & Figueiredo, 2015). Whereas growth refers to the quantifiable increase in size of isolated parts of the body (or, indeed, the body as a whole), maturation is specific to the progress of the biological system (Malina, 2004). Indeed, in contrast to CA, which is a linear progression from the date of birth to a measured time point, biological maturation is non-linear, with significant inter-individual and inter-system variance in the magnitude, onset and tempo (Lloyd, Oliver, Faigenbaum, Myer, & De Ste Croix, 2014; Malina, Bouchard, & Bar-Or, 2004). Malina and collegues (2004) report that variance in the biological age of children with a similar CA can be as high as four to five years. Common approaches to measuring or estimating maturity utilise skeletal, sexual or somatic markers and provide an insight into maturity status (i.e. skeletal age) or timing (i.e. age at peak height velocity [APHV]; Lloyd et al., 2014).

Despite the three main approaches to maturity measurement (skeletal, somatic, and sexual) being inter-related and demonstrating acceptable agreement (i.e. a correlation coefficient of 0.83 between skeletal age offset and peak height velocity offset [PHV]), they are specific to distinct underlying cellular activities (Malina, 2014b; Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). Skeletal age is considered the *gold standard* approach to maturity assessment and can identify progress from birth to a mature state (Mirwald et al., 2002). Furthermore, skeletal age offers a precise indicator of the maturation of an important biological system (Beunen, Rogol, & Malina, 2006). The most cited skeletal age methods (Greulich-Pyle method [Greulich & Pyle, 1959], the Tanner-Whitehouse method [Carty, 2002] and the Fels method [Chumela, Roche, & Thissen, 1989]) all focus on the degree of ossification within the bones of the hand-wrist. A skeletal age output only presents a measure of maturation aligning to the reference sample of the selected method and each skeletal age procedure has specific limitations (Beunen et al., 2006). For example, the Tanner-Whitehouse-3 method uses the beginning of epiphysial fusion as the indication of a mature state and as such may encourage a greater classification of children as mature in comparison to other skeletal age procedures (Freitas et al., 2016). There are also more general considerations that restrict the applicability of skeletal age procedures, including a requirement for qualified staff and ethical concerns over radiation exposure, although notably this is widely accepted to be minimal (0.001 millisievert; Malina et al., 2015).

The development of secondary sex characteristics provides an indication of pubertal status and sexual maturity (Malina et al., 2004). The Tanner stages criteria is the preferred protocol for assessing pubertal status and is commonly undertaken through a self-assessment (Tanner, 1962). The Tanner stage criteria classifies a systemised group of pubertal events into five developmental stages, progressing from the immature state (Stage 1) to mature state (Stage 5). For females, this is breast development, for males, it is the development of external genitalia, as well as also including the development of pubic hair, irrespective of sex (Faria, Franceschini, Peluzio, Sant’Ana, & Priore, 2013; Tanner, 1962). In addition to the ethical considerations of undertaking such an invasive protocol, the reliability of self-assessment is an important concern, especially in male subjects (Campisi et al., 2020; Malina, Silva, Figueiredo, Carling, & Beunen, 2012). The conflicting results between clinical assessment and self-assessment have highlighted the potential influence of cultural norms, notions of self-image, and methodological considerations when participants are performing self-assessment (Faria et al., 2013; Hergenroeder, Hill, Wong, Sangi-Haghpeykar, & Taylor, 1999). Furthermore, the assessment of secondary sex characteristics has been misused as a continuous variable and this may limit the validity of the measurement, as children could potentially be at opposite ends of the same development scale (Baxter-Jones, Eisenmann, & Sherar, 2005). Misuse of this measurement is also seen when studies align boys and girls, often with an assumption that identical secondary sex characteristics are being measured, despite these not being directly comparable (i.e. a boy at Stage 3 for genital development is not necessarily of the same biological age as a girl that is at Stage 3 for breast development; Baxter-Jones et al., 2005).

APHV provides an approach to assessing somatic maturation and refers to the estimated CA at which the maximum rate of growth in height will occur (Malina et al., 2015). In boys, APHV typically occurs at 14 years, whilst in girls it is approximately two years prior (Malina et al., 2004). Identifying the age at which a child reaches PHV requires longitudinal assessment (annually or semiannually) and can only be identified retrospectively, therefore limiting its applicability within many research settings (Lloyd et al., 2014). The APHV prediction equation presented by Mirwald and colleagues (2002) provides a non-invasive approach to calculating PHV in instances where longitudinal measurement is not possible. The APHV equation is a sex-specific equation that incorporates CA, height, sitting height, estimated leg length and weight to predict a maturity offset (Malina et al., 2015), with maturity offset being defined as the years prior to, or post, PHV (Mirwald et al., 2002). Predicted APHV can then be established by summing the maturity offset with CA (Fransen et al., 2018). For example, an offset value of (-1.0) would indicate that the participant was one year from PHV (at time of testing). As a field-based approach, the predicted PHV equation provides a validated alternative to more invasive methodologies (i.e. skeletal age assessment, Tanner assessment; Mirwald, Baxter-Jones, Bailey, & Beunen, 2002)). The APHV equation has also demonstrated an acceptable standard error for both girls (0.57 years) and boys (0.59 years) one year either side of PHV (Mirwald et al., 2002). Acknowledging this measurement error, it is suggested that the equation should primarily be applied for sex-specific classifications (i.e. pre-PHV, post-PHV) rather than as a continuous measurement of maturity (Mirwald et al., 2002). Despite the widespread use of the predicted PHV equation as an indicator of maturity status, the validation studies of Malina & Kozieł (2014) raised concerns. A noted limitation was that the further children are from PHV, the less valid the predicted PHV data becomes, and similarly, the validity is also influenced by those who are early or late maturing (Malina & Kozieł, 2014).

An additional non-invasive approach to somatic maturity assessment is the prediction of adult stature achieved at a given age (Beunen, Rogers, Woynarowska, & Malina, 1997). Differences in the percentage stature attained for those of the same CA reflects variation in maturational development and identifies children as either early, on-time or late maturing (Beunen et al., 1997). In sport development systems, prediction of adult stature can be used with children of similar stature to identify those that are genetically predisposed to be tall and those that are early maturing (Lloyd et al., 2014). Indeed, equations incorporating mid-parental height (i.e. Khamis-Roche protocol) have removed the requirement of including SA measurement when predicting adult stature (Malina, Dompier, Powell, Barron, & Moore, 2007). Predicted adult stature methods typically demonstrate standard errors of between three-five cm and have also been validated against SA measurement with a 62% concordance (Lloyd et al., 2014; Malina et al., 2007). A limitation of adopting a predicted adult stature approach is that it fails to offer insight into the timing or tempo of maturation (Lloyd et al., 2014). However, longitudinal PHV data has been used to align the onset of the adolescent growth spurt with the respective predicted adult stature (i.e. 88%-89%), and, similarly, the predicted adult stature at which adolescents would return to pre-PHV growth velocities (95%-96%; Cumming, Lloyd, Oliver, Eisenmann, & Malina, 2017).

The influence of biological maturation on physical fitness characteristics has been extensively reported in the literature, especially in boys (Malina et al., 2011; Malina et al., 2015; Matthys et al., 2012). The onset of APHV is associated with concomitant sex-related rises in power, strength and speed-related performance, underpinned by physiological adaptions that occur with increasing biological age (Malina et al., 2004). Radnor et al. (2018) highlighted the structural (fiber type, muscle size) and neuromuscular (motor unit recruitment, co-contraction) adaptations that occur naturally due to biological maturation that likely underpin these performance improvements. For boys, maturity-related alterations have been shown to be largely beneficial to physical performance. Indeed, in youth sport, a selection bias during the period of PHV towards early maturing males has been consistently observed (Malina et al., 2015; Philippaerts et al., 2006). Philippaerts and collegues (2006) found PHV to coincide with definitive increases in anaerobic capacity, speed, agility, and explosive strength, noting that for many of these tasks, improvements remained post-PHV. Furthermore, larger training induced improvements in some parameters (i.e. sprint performance) have been found in pubertal and post-pubertal individuals compared to those that are pre-pubertal (Moran, Sandercock, Rumpf, & Parry, 2017). Yet, similar evidence relating to a maturity-related training response in aerobic fitness has not been consistently reported, with the existence of a 'maturational threshold', prior to which children achieve little training response being refuted (Armstrong & McNarry, 2016).

For girls, the influence of increasing maturity on physical fitness is less defined, and is suggested to be specific to defined fitness characteristics (Malina et al., 2004). Dissimilar to boys, biological maturation sees a marked increase in fat mass in girls and this is reported to negatively influence functional capacities (Bitar, Vernet, Coudert, & Vermorel, 2000). In contrast to boys, this period of rapid skeletal growth and increasing fat mass is not coupled with similar increases in muscle mass and skeletal tissue (Malina et al., 2004). Therefore, the period of PHV in girls is often characterised by neuromuscular imbalances and a heightened injury risk (Hewett, Myer, & Ford, 2004). Quatman et al. (2006) suggest that the neuromuscular 'spurt' evident in boys is absent during the same period in girls. Given this, performance advantages associated with biological maturation in girls have, for the most part, been limited to strength-based tasks, and specifically those involving the upper body (Myburgh, Cumming, Silva, Cooke, & Malina, 2016), with negligible maturity-related differences in speed and agility performance (Cumming et al., 2017). This was previously found by Freitas et al. (2014) who found no performance related differences between girls who were pre- and post-menarche, except in hand-grip strength. Within sport, an over-representation of early and on-time maturing female athletes is evident in most sports (basketball, swimming, tennis) during childhood and early adolescence, whilst the opposite is true for sports such as gymnastics and dance (Baxter-Jones, Thompson, & Malina, 2002).

Although there is supportive evidence of a maturity-related influence on much athletic performance, a similar influence on the underpinning movement patterns (i.e. FMS, along with wider aspects of motor competence) has not been comprehensively investigated. Freitas et al. (2016) found skeletal age to have a negligible influence on FMS and coordination when scored using a process-oriented criterion. Skeletal age on its own, or interacting with stature, only explained 0-9% of total variance in FMS and coordination (Freitas et al., 2016). However, the age range in this study was limited to children aged 7-10 years, and therefore likely did not include the marked physiological adaptions associated with APHV. A similar study in adolescents (11-14 years) also found a low maturational influence on motor competence, although it was found to be higher in boys (9%) than girls (1%; Freitas et al., 2016). When assessing FMS such as the jump and overhand throw using a product-oriented approach, a positive association with increasing maturity has been found (Lloyd et al., 2015). Specifically, Lloyd and collegues (2015) found maturity to be a primary predictor of squat jump performance (adjusted R^2 = 46%) and also provided initial evidence of a similar maturational influence on functional movement. In the same study, the lack of performance differences between two pre-PHV groups (under 11 and under 13 years) was speculated to be a potential outcome of 'adolescent awkwardness' (Lloyd et al., 2015). Such a period of awkwardness may relate to some sensorimotor mechanisms still being immature at the onset of PHV (Quatman-Yates, Quatman, Meszaros, Paterno, & Hewett, 2012). Moreover, the dramatic growth associated with maturation may cause regressions in some sensorimotor mechanisms as the body moves through an adjustment period (Quatman-Yates et al., 2012). In addition, divergent sex-specific biomechanical profiles have been observed, with girls especially, displaying regressions in some movements (i.e. jumping) following maturity-related changes to the skeletal system and position of center of mass (Holden, Boreham, & Delahunt, 2016).

2.8 A Biobehavioural perspective of FMS

Existing systematic reviews and meta-analyses have provided supportive evidence for the influence of FMS upon selected health behaviours and outcomes (Barnett et al., 2016a; Lubans et al., 2010; Robinson et al., 2015). Aside from sex, there is a dearth of empirical research that has investigated the contribution of other biological factors to the development of FMS. Within physical activity research it is proposed that sex-related changes associated with biological maturation, such as physical appearance and functional capacity, influence physical activity engagement (Smart et al., 2012). Although evidence pertaining to a direct influence of maturation on FMS and physical activity remains indeterminate, it is important to consider the proposed indirect influence, underpinned by the interaction of biological (maturation, growth) and behavioural (perceptions, values) factors (Luz et al., 2018; Malina et al., 2016).

Central to a biobehavioural approach is emphasising physical activity as a medium for enjoyment, learning, and social interactions among youth (Malina et al., 2016). This is in contrast to physical activity being approached as principally an accumulation of frequency, duration, and intensities. Similar to physical activity, the development and performance of FMS occur within cultural and social contexts, that change greatly during adolescence. Influenced in part by a greater cognitive maturity; self-perception and further psychosocial factors become increasingly important as children transition into adolescence (Malina et al., 2016). The physical changes associated with advancing maturity, especially in girls, have been found to influence domains of self-perception (i.e. body attractiveness, physical condition; Cumming et al., 2011). In girls, the onset of maturation, which occurs earlier than in boys, is associated with increases in height, weight, and absolute and proportional fat mass (Cumming, Sherar, Esliger, Riddoch, & Malina, 2014). As such, these somatic changes are reported to negatively influence movement competence (i.e. fundamental movement skill competence) and participation in sport, driving the inter-individual differences found within these constructs (Luz et al., 2018). In contrast, early maturing boys are suggested to display a more positive physical self-concept and body image (Cumming et al., 2012). However, many studies investigating this maturity-related influence in boys have been centered around athlete-focused groups (Malina et al., 2015). Studies investigating a similar maturity-related influence on recreational sport and physical activity, in more representative samples, have provided inconclusive evidence (Moore et al., 2020).

These potential inter-individual differences may have important implications on the validity of data when analysing adolescent populations, especially when reporting relative to CA. Additionally, it may highlight a need to consider the influence of maturity-related development on perceived competence in late childhood and adolescence.

Exploring how biobehavioural interactions influence fundamental movement skill competence may provide additional insight into the factors most crucial to promoting health-related development. For example, it is proposed that the influence of maturation may be lessened in cultures where participation in organised sport is positively encouraged and highly valued (irrespective of sex) across adolescence (Malina et al., 2016). Moreover, the meanings and values attached to FMS and physical activity likely vary with sex and culture, so that attaining competence in FMS maybe pursued by some and not others (Luz et al., 2018). It is further postulated that the reduced drive to be physically active during adolescence may have biological underpinnings, influenced by neuromuscular maturation and that this may explain the earlier reduction in physical activity levels evident in girls (Malina et al., 2016). When physical activity levels are reported as years from PHV rather than CA, little evidence of between-sex differences remain (Sherar, Esliger, Baxter-Jones, & Tremblay, 2007). It is, therefore, important to assess the trajectories of the subcomponents of physical activity as a function of these developmental processes (Cumming et al., 2012).

Adopting a biobehavioural approach may be considered especially relevant given the increasing number of children reaching adolescence without proficiency in all FMS (O' Brien et al., 2016b). Seefeldt's conception of a proficiency barrier proposed that children who fail to reach a proficient level of fundamental movement skill competence are likely to have difficulty in successfully participating in transitional skills (i.e. jump rope, throw-and-catch volleyball) and later sport-specific activities (Seefeldt, 1980). Whilst the original conception of the proficiency barrier was placed between early childhood and middle childhood to adulthood, recent evidence suggests few children are moving through the transitional period of skill development prior to adolescence (Bolger et al., 2020; O' Brien et al., 2016a). Brian et al. (2020) contend that along with having a negative influence on mastering FMS, a proficiency barrier may also have an aligned negative influence on self-concept and weight status. From a constraints perspective, children who enter adolescence poorly competent across many FMS are unlikely to receive the continued exposure to context-specific and developmentally appropriate practice and will often spend less time participating in free-play (Brian et al., 2020). Crucially in adolescence, competence in FMS has been shown to influence a wider group of self-perceptions (i.e. social competence, behavioural conduct), with these found to mediate the association between FMS and identity health (Timler, McIntyre, Rose, & Hands, 2019). Although the study of Timler et al. (2019) did not control for maturation it did highlight the wider influence of FMS on social, cognitive, and behavioural domains during adolescence that demand further investigation.

3.0 General Methodology

This chapter provides an overview of the methods employed throughout this thesis. Specific detail relating to recruitment, sample size, and statistical analyses is described within each chapter, whilst additional information is provided in the appendices (i.e. participant information sheets, consent forms, fundamental movement skill assessment criteria).

3.1 Ethical Approval

Ethical approval for **Chapter four** was obtained from the Liverpool John Moores University Research Ethics Committee (application reference # 10/ECL/039 and 8.56). Ethical approval for **Chapters five, six and eight** was obtained from the Swansea University College of Engineering Research Ethics and Governance Committee (PG/2018-065; PG/2019-010; PG/2019-039, respectively). The Declaration of Helsinki were adhered to throughout all research conducted in this thesis.

3.2 Recruitment

Participants in all studies were school-aged children (6-16 years). All children who participated were free from any physical or neurological conditions (i.e. dyspraxia). For each individual study, an introductory email was distributed to schools outlining the objectives of the research. Following Headteacher authorisation and consent, the research team leader(s) and the relevant teacher(s) discussed the most efficient process for data collection. Where feasible, a formal presentation was then completed during an assembly, outlining the research project to potential participants, and providing an opportunity for all children and staff to have any outstanding questions answered. Overall, eleven secondary schools and a single primary school were approached to participate, with subsequent study presentations made to four secondary schools and the primary school. The greatest barrier to participation for schools were school timetable restrictions, staffing capacity and a lack of available facilities.

Due to the categorisation of participants as a vulnerable population, special considerations were adhered to in the recruitment of participants. All parents or guardians of prospective participants were sent an information sheet and were required to complete a parental consent form and pre-screening health questionnaire (see

Appendix I). All prospective participants were provided with an age-appropriate information sheet (see Appendices IV, VI, VII) and participant assent in paper form (see Appendices IV, VI, VII), with all forms completed and collected prior to data collection. Upon receipt of the required consent, assent and pre-screening health form, children were provided with an anonymous participant identification number. This identification number was used for all assessments, worksheets, and data collection in all studies.

3.3 Pilot work underpinning study development

Following ethics approval from the Swansea University College of Engineering Research Ethics and Governance Committee, pilot studies were conducted for the studies in **Chapter five and Chapter six**. The pilot studies were conducted to identify methodological limitations and to familiarise the research group with the respective equipment and assessment protocols. Specifically**, Chapter five** utilised an interval protocol to assess the repeated performance of isolated fundamental movement skill performances. Previous studies that have analysed the associated energy expenditure (EE) of fundamental movement skills (FMS) have assessed multiple FMS in combination (i.e. throw, kick and catch) to lessen the injury risk associated with the repeated execution of a single movement (Duncan et al., 2019; Sacko et al., 2018). As the objective of **Chapter five** was to investigate the EE of individual FMS, an interval approach was trialed, reviewed and then implemented as a method by which a valid assessment could be achieved whilst avoiding a heightened injury risk. A further objective of the pilot studies was to assess the validity of using an iPad (Apple iPad, Apple Inc, 2019) to record the performance of FMS for subsequent analysis by a trained researcher(s). Some previous studies have opted to use high-definition cameras with a capacity to record at a higher frames per second (Bardid et al., 2018; Duncan et al., 2018). Although a high-definition camera may offer a preferred approach, the use of two iPad’s permitted each fundamental movement skill assessment session to be time-aligned with device-based measurement units that were worn on multiple body positions across the studies.

3.4 Instruments and procedures

3.4.1 Test of Gross Motor Development – Version 3

The Test of Gross Motor Development - Version 3 (TGMD-3) assesses thirteen isolated FMS, classified as either locomotor (n=6) or object control (n=7) skills (Ulrich, 2020). The TGMD-3 is primarily a process-oriented assessment that grades the presence or absence of specific qualitative movement criteria (see Appendices VII, VIII). A participant can obtain a maximum raw score of 46 (locomotor skills construct), 54 (object control skills construct) and 100 (overall gross motor skill score). Respectively, the average alpha coefficient was 0.85 for the locomotor subtest, 0.88 for the ball skills subtest and 0.92 for the composite score (Garn & Webster, 2021). To improve the validity of the TGMD-3 as an assessment of the FMS most influential to physical activity and sport participation, the skills included have recently been updated from the previous model (Test of Gross Motor Development - Version 2 [TGMD-2]). Amongst the changes, the object control skills construct was re-labelled to the more familiar term of ball skills, and, within this construct, the forehand strike and underhand throw were added, and the underhand roll removed. Furthermore, the leap was replaced with the skip in the locomotor skill construct, with these aforementioned changes aimed at more strongly reflecting FMS across a wider range of cultures (Field, Esposito Bosma, & Temple, 2020; Ulrich, 2017). Additional changes are also evident in the terminology used to identify specific movement patterns, and in the removal of assessed components that were deemed non-essential to a proficient fundamental movement skill execution (Field et al., 2020).

Prior to assessing TGMD-3 performance, a demonstration was given by a trained member of the research team, following which the participant was provided with a single practice opportunity. The participants then performed each skill twice, with no prompting or feedback. If at any point the participant executed an incorrect skill (i.e. an overhand throw instead of an underhand throw), the research team provided a further verbal description of the skill and asked the participant to repeat their effort. Trials were recorded from frontal and sagittal planes (Apple iPad, Apple Inc, 2019). In **Chapter five**, the participants completed a total of 15 FMS, of which the additional skills (underhand roll, skip) were from the TGMD-2 protocol. This provided opportunity to record data for children across both protocols, as at the time of beginning data collection the TGMD-3 had not been validated or completed in research projects involving children of similar ages. Short rest-periods were incorporated following each skill performance to ensure a fatigue-related effect did not influence the results. The assessment layout (see Appendix XI) was designed to permit sessions to be conducted in the sports hall of the participating school or in the biomechanics laboratory at the Applied Sports, Technology, Exercise and Medicine Research Centre, Swansea University.

3.4.2 Assessment agreement

Of the fundamental movement skill assessments included within the initial pilot study for **Chapter five**, inter-rater reliability was excellent (ICC = 0.92: 95% CI 0.87 - 0.98), as was test re-test reliability (ICC = 0.94: 95% CI 0.91- 0.97). To assess re-test reliability observer assessment was completed seven- and fourteen-days post pilot testing. For **Chapters five, six and eight** inter- and intra-rater reliability were completed for 10% of all fundamental movement skill assessments in the studies, in accord with Duncan et al. (2018).

3.4.3 Indirect Calorimetry

For **Chapter six**, the EE associated with isolated fundamental movement skill performance was measured using indirect calorimetry. Gas exchange variables were measured for all participants on a breath-by-breath basis using a mobile gas analyser (MetaMax Cortex 3B CORTEX Biophysik GmbH, Germany). Several studies have investigated the validity, and subsequently supported the use of, the MetaMax Cortex 3B against comparable portable analysers (e.g. Oxycon Pro) and across a range of metabolic intensities (Macfarlane & Wong, 2012; Perkins, Pivarnik, & Green, 2004; Vogler, Rice, & Gore, 2010). Macfarlane and Wong (2012) observed the relative percentage technical error of minute ventilation (V_E), oxygen uptake ($\dot{V}O_2$) and carbon dioxide output (VCO_2) to typically be less than 2% across low, medium and high metabolic rate field trials.

Participants were requested to arrive at the laboratory at least two hours post prandial and were asked to avoid caffeine and strenuous exercise in the 24 hours prior to their visit. The MetaMax Cortex 3B is attached on the upper body via a harness, with volume measured using a bidirectional turbine (Macfarlane & Wong, 2012). The additional weight of the equipment did not exceed 850 g. Prior to each assessment session, the analyser was turned on for at least 20 minutes and then calibrated. Unit calibration was completed with gases of known concentration and then verified against ambient air. Likewise, the turbine volume transducer was calibrated using a 3-L syringe (Hans Rudolph, Kansas City, MO, USA). Resting metabolic rate (RMR) was measured for each participant, with the participant lying in a supine position for 15 minutes. During the assessed skill performances, continuous breath-by-breath analysis was undertaken to provide a measure of EE. Each fundamental movement skill was performed using an intermittent protocol involving six bouts of 30 seconds continuous performance interspersed by 15-seconds rest intervals. Following the final performance interval of each fundamental movement skill, participants had a three-minutes seated rest to allow $\dot{V}O_2$ to return to the baseline value prior to the next skill performance. Upon the completion of the assessment, participants observed an additional three-minute seated rest and were then given the opportunity to undertake a cool-down. The recorded oxygen consumption $\dot{V}O_2$ ($l \cdot min^{-1}$) from the entirety of the assessment (~ 1 hour) was separated for each of the five isolated skill performances (overhand throw, slide, strike, hop, kick). To calculate the metabolic EE associated with each skill, the mean $\dot{V}O_2$ between 10 and 25 seconds of bouts two-five was averaged (*Figure 3*). This was completed for absolute $\dot{V}O_2$ ($l \cdot min^{-1}$) and also allometrically scaled ($\dot{V}O_2 \cdot kg^{-0.75} \cdot min^{-1}$).

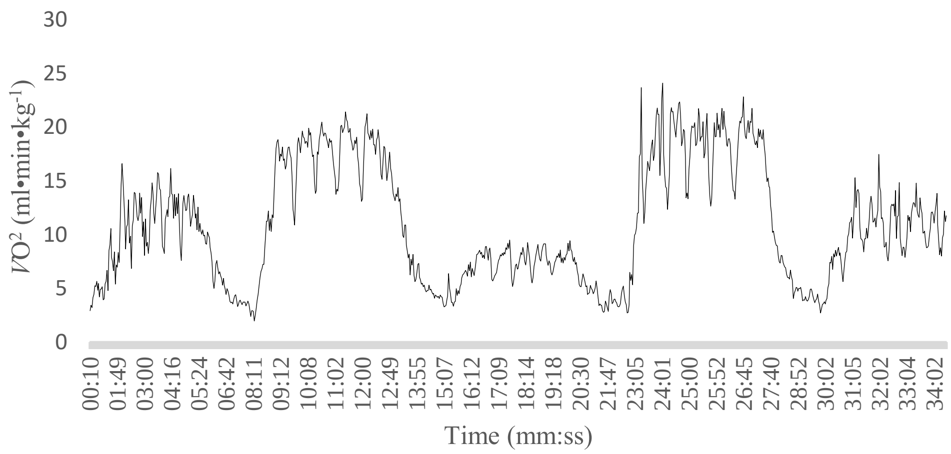


Figure 3. Breath-by-breath analysis $\dot{V}O2$ (ml•min•kg-1) results of a participant performing the 5 FMS (Kick, Slide, Strike, Hop, Throw) in an interval approach (30 seconds x 6, 15 seconds rest, 3 minutes seated rest in between each fundamental movement skill)

3.4.4 The Children and Youth Physical Self-Perception Profile (CY-PSPP)

The CY-PSPP is a scale consisting of 36 questions which are scored using a four-point Likert scale. In the CY-PSPP model, questions are grouped into six distinct constructs (six questions per construct) in a hierarchical arrangement that include all those mechanisms relating to physical self-perception that may go on to influence global self-esteem. Global self-esteem is at the apex of the model (*Figure 4*), thought to be directly influenced by physical self-worth, which is underpinned by a further four sub-domains (sports competence, body attractiveness, physical strength, physical condition; Fox and Corbin, 1989). Each sub-domain has been previously observed to provide a sensitive and reliable measure, irrespective of sex, with internal consistency values for the sports competence sub-domain ranging from $\alpha = 0.60$ to 0.90 (Fox, 1989). Congruent with the findings of Fox and Corbin (1989), along with more recent studies (Barnett et al., 2011; Barnett et al., 2008a), the sports competence sub-domain in the studies contained within this thesis, demonstrated acceptable reliability (**Chapter four**; $\alpha = 0.65$; **Chapter five**; $\alpha = 0.73$; **Chapter six** $\alpha = 0.76$).

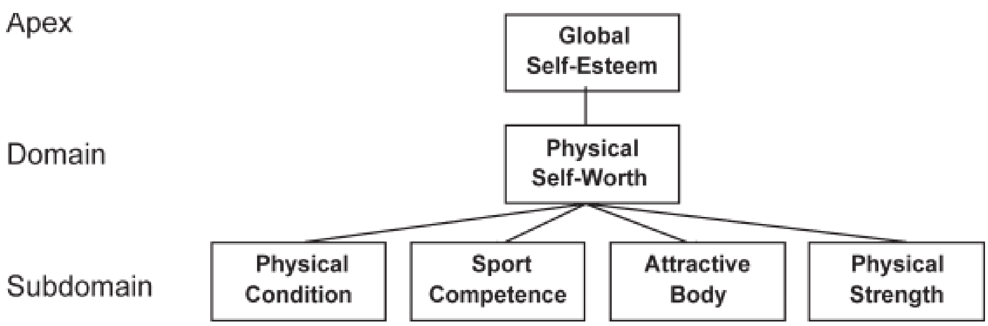


Figure 4. Hierarchical structure of physical self (Fox & Corbin, 1989)

Participants were given an overview of the CY-PSPP by a member of the research team prior to giving them privacy to complete the questionnaire. The items are arranged in a structured alternative format, the construct scores are then presented as the mean of the summed score for the six related questions. Each item has a scoring range of 1 (low self-perception) to 4 (high self-perception). For example, an item would state ‘Some kids wish they could be a lot better at sports’ BUT ‘Other kids feel that they are good enough at sports’, a child would select the statement that is most accurate to themselves and then select either ‘really true of me’ or ‘kind of true of me’. A score of 1 (low self-perception) would be aligned to ‘some kids wish they could be a lot better at sports’ being really true for them, whereas a score of 4 (high self-perception) would be aligned to ‘other kids feel that they are good enough at sports’ being really true for them (Fox and Corbin (1989). As such, the cumulative score for the sports competence sub-domain could range from 6-24. Whilst only the sports competence sub-domain was utilised in **Chapters four, five, six and eight**, the CY-PSPP was completed in its entirety.

3.4.5 Standing Stature

Stature was measured using a portable stadiometer to the nearest 0.001m (Seca 213 portable stadiometer, Hamburg, Germany). Participants were asked to remove footwear and stand up-right, with heels positioned against base and head level.

3.4.6 Sitting Stature

Participants’ sitting stature was measured using a portable stadiometer to the nearest 0.001m (Seca 213 portable stadiometer, Hamburg, Germany), with the base positioned on a raised surface to allow participants to remain as tall as possible and have their legs supported, with knees at right angles. The head was positioned in the Frankfort plane position, and the distance from the base to the top of the skull was then recorded (Norton, 2019).

3.4.7 Body Mass

Participant body mass was recorded to the nearest 0.1kg, following the removal of outer clothing and footwear. This was then used to provide a measure of Body Mass Index (BMI), where BMI = body mass (kg)/stature^2. To acknowledge the variability associated with age- and growth-related patterns in children, BMI z-scores were used in all analyses (Cole, Freeman, & Preece, 1995). The z-score provides an indication of how far away from a referenced dataset a participant is, and this is presented as a multiple of the population standard deviation (Sedgwick, 2014).

3.4.8 Biological Maturation

In **Chapters five, six and eight** where biological maturation was assessed, the predictive equation of Mirwald and collegues (2002) was chosen as a non-invasive method which can provide an accurate indication of a child's years from peak height velocity [PHV]. The sex-specific equations (Equations 1 and 2) provides a maturity offset that has been validated with standard error of estimates of 0.57 and 0.59 years for boys and girls, respectively. The equation has also demonstrated acceptable agreement with the assessment of skeletal age (r = 0.83; Mirwald et al., 2002). In **Chapter five**, participants were separated into three sex-specific maturational groups based on estimated years from PHV: pre-pubertal (more than 1 year pre-PHV), pubertal (-1 to +1 year from PHV) and post-pubertal (more than 1 year following PHV).

Maturity Offset (Boys) = -9.236 + (0.0002708*(leg length*sitting stature)) - (0.001663*(age*leg length)) + (0.007216*(age*sitting stature))+ (0.02292*(mass/stature*100)

Equation 1

Maturity Offset (Girls) = -9.376 + (0.0001882*(leg length*sitting stature)) + (0.0022*(age*leg length)) + (0.005841*(age*sitting stature)) - (0.002658*(age*mass))
+ (0.07693*(mass/stature))

Equation 2

Thesis Map

	Study		Outcomes
1.	Sex-related differences in the association of fundamental movement skills and health and behavioural outcomes in children	***Aim***	To evaluate the sex-related influence on fundamental movement skill competence in late childhood, and to identify if this subsequently influences the association of FMS with health and behavioural outcomes.
		Key findings	
2.	The Influence of Biological Maturation on performance characteristics of the overhand throw and horizontal jump in youth	***Aim***	
		Key findings	
3.	The importance of skill competence as a as a key predictor of the energy expenditure associated with performing fundamental movement skills	***Aim***	
		Key findings	
4.	The influence of motor competence on broader aspects of health: a systematic review of the longitudinal associations between motor competence and cognitive and social-emotional outcomes	***Aim***	
		Key findings	
5.	Potential moderators of the association between fundamental movement skills and academic attainment in adolescence	***Aim***	
		Key findings	

4.0 Study One

4.1 Sex-related differences in the association of fundamental movement skills and health and behavioural outcomes in children

* This chapter is a published manuscript:
Phillip J. Hill, Melitta A. McNarry, Leanne Lester, Lawrence Foweather, Lynne M. Boddy, Stuart J. Fairclough, and Kelly A. Mackintosh. (2021). Sex-Related Differences in the Association of Fundamental Movement Skills and Health and Behavioral Outcomes in Children. *Journal of Motor Learning and Development, Nov 21*(Epub ahead of print)
https://doi.org/10.1123/jmld.2020-0066

4.2 Introduction

Fundamental movement skills (FMS), that include object control and locomotor skills, are referred to as foundational 'building-block movements' and are proposed to provide a crucial underpinning to the development of more complex movement patterns (Gallahue et al., 2012). Object control skills refer to FMS that allow for the manipulation and controlling of objects, such as throwing and catching, whilst locomotor skills consist of those FMS associated with the propulsion and navigation of individuals through space, such as running and hopping (Gallahue et al., 2012). FMS are primarily ontogenetic; competence is influenced through dynamic interactions with the environment, coupled with biological and psychological constraints that change over time (Robinson et al., 2015). Along with being associated with health and behavioural outcomes, FMS are identified as a precursor to physical activity, and more recently, time spent sedentary (Adank et al., 2018; Robinson et al., 2015). Current physical activity guidelines state that children and young people aged 5-18 years should engage in an average of at least 60 minutes moderate-to-vigorous physical activity (MVPA) per day across the week, and minimise time spent sedentary (Department of Health and Social Care, 2019). Despite this, few children accrue the required levels of physical activity, with less than 25% of school-aged children meeting recommended guidelines (National Health Service, 2019). Furthermore, sedentary behaviour, attributable in part to reductions in active play, organised sport, and a concomitant rise in exposure to screen devices, has been highlighted as an independent risk factor for many non-communicable diseases (Saunders, Chaput, & Tremblay, 2014).

Typically developing children have the potential to be proficient in many FMS by six years (Gallahue et al., 2012). However, the literature has shown that proficiency remains low, with the standardised fundamental movement skill levels of children aged 6-10 years deemed “below average”, and less than half of all children aged 9-15 years proficient across all FMS (Bolger et al., 2020; Hardy et al., 2013). Sex-specific differences also exist, with boys consistently reported as being more proficient in object control skills, though evidence relating to locomotor skills remains equivocal (Barnett et al., 2016a). Such sex-specific differences in fundamental movement skill competence likely reflect the influence of environmental and socio-cultural factors, such as the level of family support and encouragement. These factors are proposed to underpin physical activity and sport participation choice, with boys often engaging in activities requiring a high object control skill competence, such as rugby, football and basketball, and girls often engaging in activities underpinned by locomotor skill competence, such as gymnastics and dance (Barnett, Hinkley, Okely, & Salmon, 2013; Slykerman, Ridgers, Stevenson, & Barnett, 2016).

Stodden and colleagues (2008) proposed a conceptual model that represented the inter-dependence of the developmental trajectories of FMS, physical activity and parameters of health. The narrative review of Robinson and colleagues (2015) alongside more recent meta-analyses (Barnett et al., 2016a; Utesch et al., 2019) have supported the direct and, to a lesser degree, indirect, associations of FMS and the parameters included within the Stodden et al. (2008) model. From mid-childhood, the association between FMS and physical activity is hypothesised to become increasingly reciprocal, with FMS a driver for sustained engagement in a variety of physical activities that subsequently promote perceived competence, physical fitness and a healthy weight status (Stodden et al., 2008). Whilst a positive association between perceived and actual competence has been identified as a key predictor of health benefits (De Meester et al., 2016b), high perceived competence, irrespective of actual competence, may induce similarly favourable outcomes (De Meester et al., 2016a). The model further proposes that poor competence in FMS, coupled with low self-perception, is a precursor to a negative spiral of disengagement, expressed through a higher risk of being physically inactive and obese (Stodden et al., 2008).

Evidence suggests that the role of FMS may differ according to age, sex and the specific health parameters of interest (Barnett, Morgan, Van Beurden, Ball, & Lubans, 2011; Luz, Cordovil, Almeida, & Rodrigues, 2017). The developmental influences on the associations between FMS and health and behavioural outcomes are emphasised in the Stodden et al. (2008) model. Increasing age has been found to positively moderate the relationship between FMS and physical fitness (Utesch et al., 2019). In addition, competence in object control skills, rather than locomotor skills, has been found to be more strongly associated with physical activity (Barnett et al., 2011), whilst a stronger association between FMS and physical activity has been observed in girls (Jarvis et al., 2018). Given the role of perceived competence within the Stodden et al. (2008) model, further evidence is required to identify whether its association with additional outcomes is moderated by sex and fundamental movement skill construct (Barnett et al., 2008a; Khodaverdi, Bahram, Stodden, & Kazemnejad, 2016). Previous studies have reached little consensus on which skills are most strongly associated with perceived competence (Khodaverdi et al., 2016; Barnett, Ridgers, & Salmon, 2015a).

Although the association between FMS and MVPA has been consistently reported (Robinson et al., 2015), further research is needed to better understand the association between FMS and specific intensities and characteristics of physical activity (Lima et al., 2017). Time spent in vigorous physical activity (VPA) has been shown to provide enhanced benefits in comparison to light- and moderate-intensity physical activity across a range of cardiometabolic, cognitive and fitness indicators (Carson et al., 2014; Poitras et al., 2016). VPA is also proposed to be more strongly associated with participation in sport than lower intensities of physical activity (Kokko et al., 2019; Pfeiffer et al., 2006). Children can accrue high levels of MVPA from free-play, where proficiency in FMS may be less critical to engagement (Lubans et al., 2010) and therefore the influence of FMS may become more evident in VPA. Conversely, a reciprocal association between FMS and time spent sedentary may exist, fostered by the same confounders that promote inactivity (i.e. weight status, perceived competence, and sex). Sedentary behaviour has been found to track from childhood into adolescence, and an inverse influence of time spent sedentary on wider parameters, such as academic attainment, has also been identified (Biddle, Pearson, Ross, & Braithwaite, 2010; Haapala et al., 2017). As such, understanding the role of FMS as a mechanism through which to reduce time spent sedentary is warranted. Few studies have investigated the sex-related influence of FMS on these characteristics of physical activity and sedentary time, with an absence of available evidence pertaining to how these associations may be moderated by sex and additional parameters of health.

Guided by the Stodden et al. (2008) conceptual framework, the aim of this study was to use path analysis to investigate the influence of sex on the associations between FMS, perceived sports competence, time spent in VPA, time spent sedentary and BMI z-score in late childhood. It was hypothesised that for girls, locomotor skill competence, and for boys, object control skill competence, would be associated with time spent in VPA. In addition, irrespective of sex, perceived sports competence would have an important mediating role on the association of fundamental movement skill constructs with VPA and time spent sedentary.

4.3 Methods

4.3.1 Participants

Following written informed parental consent and child assent, 190 (110 girls; 80 boys) children from school year 6 (10.6 ± 0.3 years), recruited from 16 primary (elementary) schools within the Borough of Wigan, England, participated in this study. School year 6 represents the final year of primary education prior to the transition to secondary education, and as such is a key developmental stage for children where they have the potential to have mastered FMS. All children were invited to participate and were only excluded if they had any functional impairment that precluded regular physical activity participation. Home postcodes were used to generate Indices of multiple deprivation (IMD) scores for each participant and these along with the percentage of children per school eligible for free school meals were used to define school-level socio-economic status (SES). Within each neighbourhood management area, one high and one low SES school were randomly selected to take part to ensure acceptable representation. Participant data has been combined from one cross-sectional study (n = 46) and baseline sub-sample data from one cluster randomised controlled trial (n = 144; Fairclough, Boddy, Mackintosh, Valencia-Peris, & Ramirez-Rico, 2015; Fairclough et al., 2013). Ethical approval was obtained from the Liverpool John Moores University Research Ethics Committee (application references 8.56 and 10/ECL/039, respectively). Ethical principles of the Declaration of Helsinki were adhered to throughout this research.

4.3.2 Anthropometric measures

All anthropometric measurements were conducted by a trained researcher. Standing and sitting stature were measured to the nearest 0.1cm using a stadiometer (Seca, Bodycare, Birmingham, UK). Body mass were measured to the nearest 0.1kg using calibrated scales (Seca, Bodycare, Birmingham, UK). BMI was calculated as body mass (kg) divided by height squared (m^2) and subsequently standardised using BMI z-scores. Biological maturity was assessed using a predictive equation (Mirwald et al., 2002), which estimates the years from or post peak height velocity and has been validated with standard error of estimates of 0.57 and 0.59 years for boys and girls, respectively (Mirwald et al., 2002).

4.3.3 Instruments

The Children and Youth Physical Self-Perception Profile (CY-PSPP; Whitehead, 1995) was used to determine self-perceived competence. The CY-PSPP consists of four sub-domains (sports competence, physical condition, body attractiveness, and physical strength) positioned underneath a domain (self-worth) and global domain (global self-esteem). Each sub-domain comprises of six individual questions rated on a four-point Likert scale in a structured alternative format. For each question, the participant is initially presented with two statements from which they must select the one most identifiable to themselves and then select either ‘sort of true’ or ‘very true’. Akin to previous studies, the CY-PSPP was completed in full, with the sub-scale for sports competence analysed as the measure of perceived sports competence (Barnett et al., 2011, 2008; De Meester et al., 2016b). Each sub-domain has been previously shown to provide a sensitive and reliable measure, irrespective of sex (Fox, 1989), and in the current study, the perceived sports competence sub-domain demonstrated acceptable internal consistency ($\alpha = 0.65$).

Three locomotor (sprint, hop and vertical jump) and three object control (catch, kick, overarm throw) skills were assessed using the Get skilled, Get active protocol (Department of Education and Training, 2000). These FMS are identified as core curriculum movement skills and underpin the specialised movements that are desirable for organised sport participation (Department for Education, 2013). Children were given a verbal description and a demonstration of each skill. Each fundamental movement skill has six individual grading components that relate to a specific technical characteristic of the movement skill. FMS were completed five times, if the individual grading component was checked as being present on four out of five trials, then the child was marked as possessing that specific technical characteristic of the movement skill. The summed score of the trials was used to provide an overall score for object control and locomotor skills. Following the assessment session, video analysis of each performance was completed by two trained assessors who scored a separate sub-sample of children. Inter-rater reliability was established prior to data collection (Kappa = 0.77; 90% CI: 0.71 to 0.83).

Physical activity was objectively assessed using an ActiGraph GT1M accelerometer (ActiGraph, LLC, Pensacola, Florida) worn on the right hip for seven consecutive days measuring at 5 second epochs. Evenson et al. (2008) cut-points were used to determine physical activity intensity. These cut-points have been shown to have acceptable classification accuracy for physical activity and inactivity in children and adolescents (Trost, Loprinzi, Moore, & Pfeiffer, 2011). Non-wear time was defined as 20 minutes of consecutive zero counts (Catellier et al., 2005). To classify wear-time and sleep-time, children completed a log sheet to record any periods during which the accelerometer was removed for sleep and additional activities (i.e. contact sport, showering). These log sheets were checked and initialed by parents at the end of each day. A minimum daily wear-time of 540 minutes on at least two weekdays and 480 minutes on a weekend day was required to be included in the analyses. These inclusion criteria have previously shown acceptable reliability in similarly aged children (Fairclough et al., 2015; Mattocks et al., 2008). From the initial sample, 20 participants were omitted from the analyses (incomplete FMS and physical activity data), leaving a sample of 170 children (10.6 ± 0.3 years; 98 girls).

4.3.4 Statistical analysis

Data were analysed using IBM SPSS and AMOS for Windows, Version 25 [IBM SPSS Statistics Inc., Chicago, IL, USA]. All descriptive results are presented as means ± standard deviation (SD), with Student t-test for independent samples used to analyse between-sex differences. Path analysis was conducted to determine direct and indirect associations between FMS (object control and locomotor skill competence), perceived sports competence, VPA, sedentary time and BMI z-score. Bootstrapping for indirect effects was based on 2,000 bootstrap samples, and confidence intervals were set as 95% (MacKinnon, Lockwood, & Williams, 2004). Path coefficients and correlations were reported as standardised estimates. Statistically significant criterion for all paths was set at $p < 0.05$. The hypothesised model was tested initially to ensure its viability. Global model fit was assessed using Chi-square statistic/Degrees of Freedom (CMIN/DF), Comparative fit index (CFI), Goodness of fit index (GFI), Root mean square error of approximation (RMSEA), and p of Close Fit (P-Close). Multi-group analysis was used to examine the moderating role of sex. This was performed by testing a constrained model (paths constrained to be equal for both sexes) and comparing this against an unconstrained model (i.e. sex-specific). A chi-squared difference test was then used to determine whether the models differed significantly by sex.

4.4 Results

Descriptive statistics are provided in Table 1. Results indicated no significant sex differences in fundamental movement skill constructs, BMI z-score, and perceived sports competence. However, boys were significantly more competent in the throw ($p < 0.05$), and accrued significantly more time in VPA ($p < 0.01$) and significantly less time sedentary ($p < 0.05$). The overall model demonstrated excellent global model fit (CMIN/DF = 1.418; CFI = 0.989; GFI = 0.989; RMSEA = 0.050; P-Close = 0.416). Maturity was removed as a covariate from the initial model because it did not have a significant effect. The multi-group analysis showed that the structural model was significantly different between girls and boys (X^2 (17) = 20.9, p = 0.023).

Table 1. *Participant characteristics (mean ± SD)*

Variables	**Boys (*N* = 72)**	**Girls (*N* = 98)**	**All (*N* = 170)**
Age (years)	10.6 ± 0.3	10.7 ± 0.3	10.6 ± 0.3
Height (cm)	143.1 ± 7.6	144.7±8.2	144.0 ± 8.0
Body mass (kg)	36.3 ± 7.9	38.3 ± 9.5	37.4 ± 8.9
BMI (kg·m^{-2})	17.6 ± 2.6	18.3 ± 3.8	18.0 ± 3.4
BMI z-score	0.12 ± 1.28	0.06 ± 1.32	0.09 ± 1.30
Maturity offset (years)	-3.1 ± 0.4	-1.3 ± 0.6	-2.0 ± 1.1
Catch (0-6)	4.8 ± 1.6	4.8 ± 1.5	4.8 ± 1.5
Throw (0-6)	3.6 ± 1.8	2.8 ± 1.7*	3.2 ± 1.8
Kick (0-6)	3.1 ± 1.6	2.8 ± 1.5	2.9 ± 1.5
Sprint (0-6)	3.0 ± 1.1	2.7 ± 1.2	2.9 ± 1.2
Vertical jump (0-6)	4.2 ± 0.9	4.1 ± 0.9	4.1 ± 0.9
Hop (0-6)	4.1 ± 0.9	3.9 ± 0.9	4.0 ± 0.9
Object control skills (0-18)	11.5 ± 4.1	10.5 ± 3.6	10.9 ± 3.8
Object control skills (range)	3-18	4-18	3-18
Locomotor skills (0-18)	11.3 ± 1.9	10.7 ± 2.2	11.0 ± 2.1
Locomotor skills (range)	7-16	7-17	7-17
Perceived sports competence	16.1 ± 3.4	15.6 ± 3.0	15.8 ± 3.2
VPA (min/day)	22.8 ± 6.8	17.4 ± 6.4**	19.7 ± 7.1
Sedentary time (min/day)	563.5 ± 63.9	579.0 ± 56*	572.4 ± 59.8

Means ± SD. BMI = Body mass index, APHV = Predicted age at peak height velocity, VPA = Vigorous physical activity
* Significant difference between boys and girls ($p < 0.05$)
** Significant difference between boys and girls ($p < 0.01$)

For girls (*Figure 5*), locomotor skill competence had a direct association with VPA ($\beta = 0.18$, $p = 0.03$). Additionally, perceived sports competence was found to have a direct association with time spent sedentary ($\beta = -0.29$, $p = 0.002$) and BMI z-score ($\beta = -0.23$, $p = 0.01$). A further direct association was found between time spent in VPA and BMI z-score ($\beta = -0.37$, $p < 0.001$).

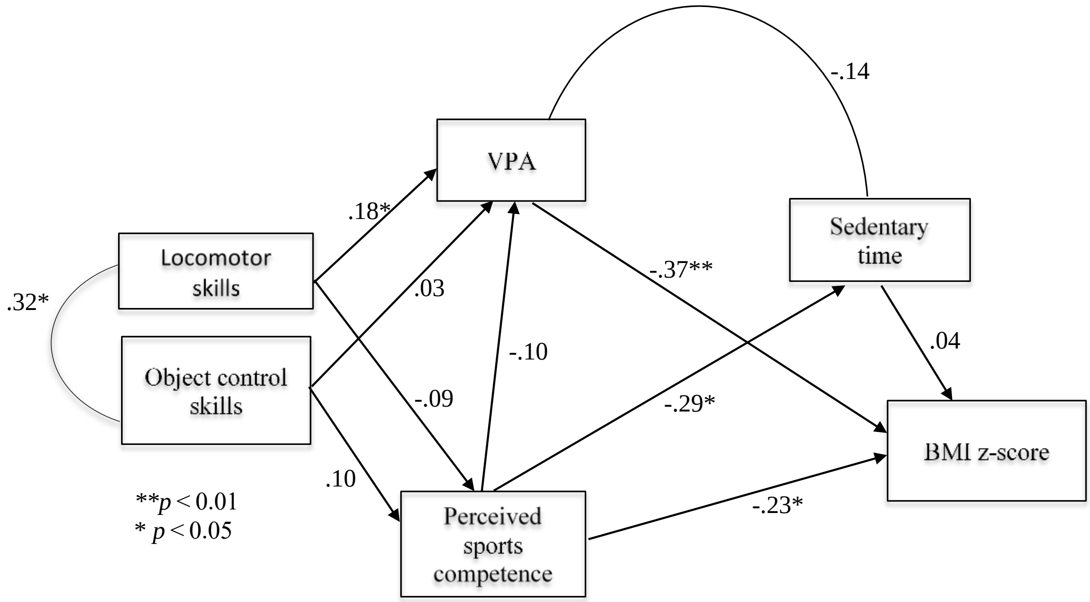


*Figure 5. Structural equation model of FMS (locomotor skills and object control skills) and their influence on perceived sports competence, VPA (vigorous-intensity physical activity), sedentary time, and BMI z-score in girls, with standardised beta coefficients (*p < 0.05; **p < 0.01)*

For boys (*Figure 6*), a direct association between object control skill competence and perceived sports competence was observed ($\beta = 0.39$, $p < 0.001$) and an indirect association was found between object control skills competence and time spent sedentary ($\beta = -0.19$, $p < 0.001$), mediated by perceived sports competence. In contrast, locomotor skill competence was negatively associated with perceived sports competence ($\beta = -0.28$, $p = 0.01$). Perceived sports competence was found to have a direct association with time spent sedentary ($\beta = -0.48$, $p < 0.001$). Additionally, time spent in VPA was found to be directly associated with BMI z-score ($\beta = -0.25$, $p = 0.03$).

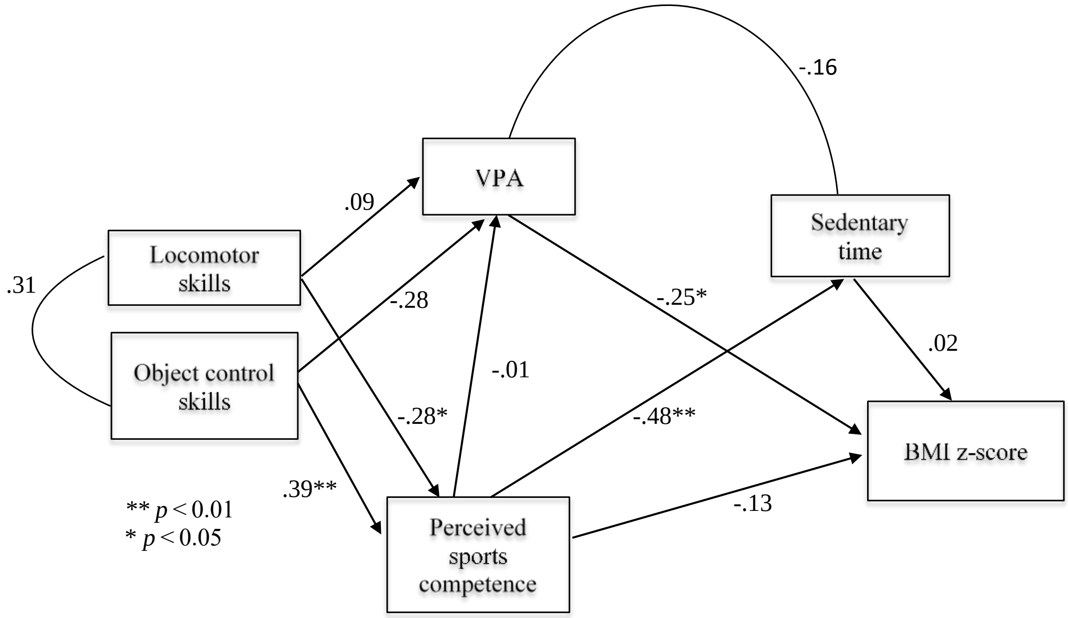


Figure 6. Structural equation model of FMS (locomotor skills and object control skills) and their influence on perceived sports competence, VPA (vigorous-intensity physical activity), sedentary time, and BMI z-score in boys, with standardised beta coefficients ($p < 0.05$; **$p < 0.01$)*

4.5 Discussion

This study sought to explore whether sex moderates the association between FMS, perceived sports competence, time spent in VPA, sedentary time and BMI z-score during late childhood. Overall, the results provide evidence of the moderating role of sex on the association of FMS and selected health and behavioural outcomes, during late childhood. For boys, object control skill competence was directly associated with perceived sports competence and had an indirect association with time spent sedentary. For girls, only a direct association between locomotor skill competence and VPA was found. These results suggest that the underpinning factors most influential to the developmental health trajectories of children may differ with sex.

The present study failed to provide support to previous research that has found marked sex differences in fundamental movement skill competence (Barnett et al., 2010; Bolger et al., 2018a). Although no significant sex differences in the object control and locomotor skill constructs were found, boys were significantly more competent in the overhand throw. The higher competence of boys in the overhand throw, may suggest that cultural and environmental constraints, such as stronger parental support and increased practice opportunities, nurture the development of this skill performance to a greater extent in boys (Barnett et al., 2016a). Research has consistently found boys in late childhood to be more competent in object control skills, whilst evidence of differences in locomotor skills remains equivocal (Barnett et al., 2010; Hardy et al., 2013). The higher competence of boys in the overhand throw, coupled with spending more time in VPA, may indicate a greater participation in sport-related activity, and fewer opportunities and/or less support for girls to develop these skills in similar contexts (Barnett et al., 2016a).

Interestingly, the present study found only object control skill competence to be positively associated with perceived sports competence, which was only significant for boys. The results concur with the majority of previous studies finding object control competence as the only significant predictor of perceived sports competence (Barnett et al., 2016a; Robinson et al., 2015). Proficiency in object control skills has a greater influence in many of the sports boys commonly participate in (i.e. rugby, tennis, football; Barnett et al., 2011). Boys will likely align their perceived sports competence to object control skills, as these are deemed more important to their activity choices. For boys in the current study, locomotor skills were found to be negatively associated with perceived sports competence. Although unexpected, these results may indicate a lack of alignment between actual and perceived competence with regards to locomotor skills and may also reflect that locomotor skill competence is less important for perceptions of sports competence.

As previous studies have found FMS to be positively associated with MVPA, we expected a similar influence to be evident with VPA and that this association would be mediated through perceived sports competence. VPA was selected as an independent indicator of physical activity as it has been shown to have additional health benefits, beyond those of MVPA (Carson et al., 2014; Poitras et al., 2016). Whilst our study did not provide support for an indirect association between FMS and BMI z-score, for either sex, the models for girls and boys did identify VPA as a predictor of BMI z-score. This is an important finding as this provides further evidence of the importance of VPA for achieving health-enhancing benefits (Carson et al., 2014). It was hypothesised that FMS would be more influential to activities incorporating VPA (i.e. sport participation). However, although a direct association between locomotor skills and VPA was observed for girls, object control skills were not associated with VPA, irrespective of sex. Similarly, an indirect association between FMS and VPA, through perceived sports competence, was not evident. It is possible that children at this age are still achieving a large proportion of VPA through active play, where actual and perceived fundamental movement skill competence has less influence on engagement. Additionally, sport participation in late childhood is still underpinned by development and enjoyment, with less emphasis on performance indicators (Barnett, Vazou, et al., 2016c; Malina, Cumming, & Silva, 2016). For girls. the direct association between locomotor skills and VPA may reflect the greater direct importance to the physical activity and sport-related choices of many girls at these ages (i.e. track, gymnastics; Barnett et al., 2016c). The lack of association between perceived sports competence and time spent in VPA particularly in early maturing girls may suggest that other barriers, such as physical self-perception, motivation, and societal context, exert a greater influence on time spent in VPA in comparison to perceived sports competence (Malina et al., 2016).

To our knowledge, this is the first study to use path analysis to assess both the direct and indirect association between FMS and sedentary time specific to sex. Advancing previous research, which has focused largely on the influence of FMS on physical activity levels (Robinson et al., 2015), the present study found perceived sports competence to have a crucial association with time spent sedentary. Irrespective of physical activity levels, sedentary time has been identified as an independent construct associated with acute and chronic health consequences (Saunders et al., 2014). Yet, in line with studies that have observed the influence of self-perception on physical inactivity (Barnett et al., 2011, 2008; Robinson et al., 2015), the present results show that, whilst independent, there are similarities in the underpinning attributes associated with sedentary time and physical inactivity. Perceived competence has previously been suggested to be as important as actual competence in predicting physical inactivity (Robinson et al., 2015). Advancing this, the present results found perceived sports competence to be strongly associated with sedentary time. Along with fundamental movement skill competence, it can be postulated that psychosocial factors (i.e. low perceived competence, lack of enjoyment) are associated with sedentary behaviours in children, especially during weekdays where leisure-time is more finite (Hardy, Ding, Peralta, Mihrshahi, & Merom, 2018). This association between FMS, self-perception, and sedentary time may become amplified in adolescents with greater autonomy and where the biological drive to be physically active is less (Malina et al., 2016).

Whilst there are numerous strengths associated with the present study, such as using device-measured physical activity and using a validated fundamental movement skill assessment, it is important to acknowledge the limitations. As a cross-sectional study, causal inferences were not possible, and it is therefore important that future studies seek to identify bidirectional associations. The hypothesised directionality of the data in the current study was based on the conceptual model of Stodden et al. (2008). In addition, the questions used to analyse perceived sports competence (i.e. some kids do very well at all kinds of sports, but other kids don't feel they are good when it comes to sport) were not specific to the assessed FMS. Similarly, the use of accelerometers to measure sedentary time has been challenged, although 100 counts·min^{-1}, as used in the current study, has been identified as a valid measure of youth sedentary time (Kim, Lee, Peters, Gaesser, & Welk, 2014). Future research should also look to incorporate a fitness measurement, such as peak oxygen uptake, to provide analysis of all parameters within the Stodden et al. (2008) model.

4.6 Conclusion

The findings from the current study extend previous research by identifying sex-related differences in the influence of FMS upon health and behavioural outcomes. Specifically, for boys in late childhood, object control skills appear more important to a positive trajectory of health than their female counterparts. In contrast, for girls, it is locomotor skills that may have a greater association with health and behavioural outcomes. Importantly, this study highlights the crucial role of perceived competence in predicting time spent sedentary, irrespective of sex. These results support the adoption of a more holistic pedagogical approach that seeks to understand and enhance a child's perceived competence along with FMS. Furthermore, this study emphasises the importance of adopting this form of approach during childhood to provide children with a strong movement profile and a motivation from which they can embrace a physically active lifestyle during adolescence.

Thesis Map

	Study		Outcomes
1.	Sex-related differences in the association of fundamental movement skills and health and behavioural outcomes in children	***Aim***	To evaluate the sex-related influence on FMS competence during late childhood, and to identify if this subsequently influences the association of FMS with further health-related benefits.
		Key findings	For boys, object control skill competence had a direct association with perceived sports competence and an indirect association with sedentary time (through perceived sports competence). For girls, locomotor skills were found to predict VPA. Irrespective of sex, perceived sports competence was associated with sedentary time. The study supports a holistic approach to health-related interventions and highlights a key association of perceived sports competence and the time children spend sedentary.
2.	The influence of biological maturation on performance characteristics of the overhand throw and horizontal jump in youth	***Aim***	To identify the influence of sex and biological maturity on performance characteristics of the horizontal jump and overhand throw, and to investigate the association of these FMS with perceived sports competence.
		Key findings	
3.	The importance of skill competence as a as a key predictor of the energy expenditure associated with performing fundamental movement skills	***Aim***	
		Key findings	
4.	The influence of motor competence on broader aspects of health: a systematic review of the longitudinal associations between motor competence and cognitive and social-emotional outcomes	***Aim***	
		Key findings	
5.	Potential moderators of the association between fundamental movement skills and academic attainment in adolescence	***Aim***	
		Key findings	

5.0 Study two

5.1 The influence of biological maturation on performance characteristics of the overhand throw and horizontal jump in youth

5.2 Introduction

Fundamental movement skills (FMS) are proposed as key components in the promotion of health-enhancing behaviours during childhood and adolescence (Barnett et al., 2016a; Robinson et al., 2015; Stodden et al., 2008). Systematic reviews have identified, biological (sex, age), behavioural (physical activity and organised sport participation), environmental (playground formation, toys at home) and psychological (perceived competence, self-esteem) correlates of FMS (Barnett et al., 2016a; Robinson et al., 2015). From a developmental perspective, it is assumed that most children will be proficient in performing all FMS by late childhood (9-11 years; Gallahue, Ozmun, & Goodway, 2012; O' Brien, Belton, & Issartel, 2016a). As such, the majority of research in this field has focused on pre-adolescent children and the developmental trajectories of FMS relative to chronological age (Robinson et al., 2015). There is, however, growing evidence that children are reaching adolescence non-proficient in many FMS (McGrane et al., 2017; O' Brien et al., 2016a).

FMS are basic observable movement patterns (i.e. jumping, throwing, kicking) that are a component of the multidimensional concept of 'movement competence' (Rudd et al., 2016). FMS are typically classified as either locomotor, object control or balance skills and are suggested to become increasingly integral to physical activity and sport participation with advancing age (Haywood & Getchell, 2009). Given the absence of a *gold standard* assessment, either a process- or product-oriented assessment protocol are predominantly used in the measurement of FMS (Bardid et al., 2018). Process-oriented assessments (i.e. Test of Gross Motor Development [TGMD], Get Skilled Get Active; Department of Education and Training, 2000; Ulrich, 2020) emphasise the technical movement pattern and provide a qualitative movement description of a skill (Bardid et al., 2018; Wagner & Ulrich, 2017). Despite similar methodological underpinnings, individual process-oriented protocols differ in the skills assessed, the criteria chosen to discriminate developmental sequences, and whether scoring is performed real-time or using video analysis (Logan et al., 2017). In contrast, product-oriented assessments (i.e. Bruininks-Oseretsky Test of Motor Proficiency, Movement Assessment Battery for Children) measure the outcome of a movement, such as in terms of throw or kick velocity (Bardid et al., 2018). Crucially, the predictive validity of fundamental movement skill competence on health outcomes is likely influenced by how these skills are conceptualised (Logan et al., 2017). In childhood, the association between process- and product-oriented fundamental movement skill performance has been found to range from moderate to strong (*r* range = 0.26 – 0.88), with the strength of correlations suggested to be age- and skill-specific (Logan et al., 2017). For locomotor skills, the agreement between process- and product-oriented assessments has been identified as weak (Hulteen et al., 2019). This may reflect the less discernible differences in locomotor skill performance across a range of competency levels, in comparison to object control skill performance, where competency-related differences appear more observable (Hulteen et al., 2019).

Understanding the developmental trajectories of FMS from late childhood onwards requires consideration of the potential influencing role of biological maturation on both process- and product-oriented competence (Logan et al., 2017). Biological maturation is the key developmental event during adolescence and refers to the progress towards a mature state, independent of chronological age (Beunen et al., 2006). In pre-pubertal children, fundamental movement skill competence has been observed to be positively correlated with age (Spessato et al., 2013; Valentini, Logan, et al., 2016), yet, in adolescence, an inverse relationship between increasing age and proficiency in specific FMS has been reported (Jaakkola & Washington, 2013). It is known that biological maturation, specifically the period of peak height velocity (PHV), is associated with physiological adaptions that influence components of physical performance (Lloyd & Oliver, 2012). The onset of PHV is positively correlated with increases in strength, power and sprint speed, with this especially apparent in boys (Malina et al., 2004). Nonetheless, the evidence on ‘technical’ movement patterns across PHV, remains equivocal; there is no clear consensus on whether the ‘adolescent growth spurt’ is similarly influential to technical competence (Quatman-Yates et al., 2012). Moreover, despite being conducive to a superior physical performance in many motor tasks, the physical changes associated with advancing maturation for boys (increased muscle mass, widening of shoulders) and girls (widening of hips, increased proportional fat mass) have a contrasting psychobehavioural influence on exercise behaviour (Cumming et al., 2012; Malina et al., 2004). Irrespective of sex, maturity-associated changes in body size are considered to directly influence dimensions of physical activity (i.e. FMS, health-related fitness), whilst indirectly influencing these same dimensions through mechanisms such as physical self-concept, body image and self-esteem (Cumming et al., 2012).

As adolescents have the cognitive maturity to more accurately assess their fundamental movement skill competence than children, perceived competence and self-perception are proposed to become more strongly aligned to actual fundamental movement skill competence than in early childhood (Stodden et al., 2008). However, studies investigating the association between FMS and perceived competence in adolescence have predominantly focused on process-oriented performance (McGrane, Powell, Belton, & Issartel, 2018; Rogers et al., 2018). In younger children, performance in both product- and process-oriented assessments has been positively associated with perceived skill competence (Duncan et al., 2018). Establishing whether a similar association exists in adolescence has not yet been widely examined (Logan et al., 2017).

Therefore, the aim of the current study was to assess the association of biological maturity, chronological age, sex and perceived sports competence with process- and product-oriented performance of FMS. Furthermore, the study sought to assess the importance of technical competence to outcome performance across three maturational groups.

5.3 Methods

5.3.1 Participants: Following informed parental consent and child assent, 140 school-aged children (12.8 ± 1.9 years; 70 girls) from three primary schools and one secondary school (South Wales, UK) participated in the study. Ethics approval was granted by Swansea University College of Engineering Research Ethics Committee (2019-010).

5.3.2 Anthropometry: All anthropometric measurements were undertaken by trained researchers (PH and MM), with participants asked to wear light clothing and to remove shoes prior to measurements. Standing and sitting stature were measured to the nearest 0.1 cm with a portable stadiometer (Seca 213, Seca Ltd, Birmingham, UK), with body mass measured to the nearest 0.1 kg using portable calibrated scales (Seca 899, Seca Ltd, Birmingham, UK). Biological maturity status was assessed using the predictive equation of Mirwald and collegues (2002). Participants were classified into three sex-specific maturity groups based on estimated years from PHV: pre-PHV (> 1 year prior to PHV), circa-PHV (-1 to 1 year from PHV) and post-PHV (> 1 year following PHV).

5.3.3 Process-oriented FMS assessment: Technical-skill competence in the overhand throw and horizontal jump was assessed using the TGMD-3 (Ulrich, 2020), which is a validated and norm-referenced assessment for fundamental movement skill competence in children and adolescents (Issartel et al., 2017; Valentini, Zanell, et al., 2016). Prior to skill performance, each participant completed a dynamic warm-up, were provided with a single demonstration of the skill, and then had the opportunity for a single practice effort. The participant performed each skill twice, with each effort being graded against the four respective qualitative assessment components (Ulrich, 2017). The four components were awarded based on the presence (scored 1) or absence (scored 0) of the specific component. The summed scores of each trial (0-4) were then combined to provide a total skill score (0-8). Skill performance was video recorded using an iPad (3rd generation; Apple Inc., Cupertino, CA, USA), with post-priori analysis conducted by two trained researchers (PH and MM). As previously adopted by Duncan and colleagues (2018), inter-rater reliability of summed scores was conducted on 10%, randomly selected, of participants, using Intra Class Correlations (ICC = 0.91).

5.3.4 Product-oriented FMS assessment: Each participant performed two maximal effort overhand throws and horizontal jumps interspersed with a 30-second recovery; the mean score for each skill was used for analysis. For the overhand throw, ball velocity ($m \cdot s^{-1}$) was measured with a radar gun (Stalker Pro II, Stalker Radar, TX, USA). Take-off kinetics of the horizontal jump were recorded using a portable force platform (Kistler, model number 92866AA, Kistler Instruments Ltd., Farnborough, United Kingdom) operating at 1,000 Hz, and were analysed using Bioware software V.5.3. (Kistler, Switzerland). A sample length of five seconds was chosen for each jump effort. Prior to each jump, participants were asked to remain stationary on the force platform, with bodyweight calculated as the mean vertical ground reaction force across one second at this point. The data measured were absolute peak power expressed in Watts (W) and relative peak power expressed in $W{\cdot}kg^{-1}$.

5.3.5 Perceived sports competence: Perceived skill competence was assessed using the Children and Youth Physical Self-Perception Profile (CY-PSPP; Whitehead, 1995), as a validated instrument to assess constructs of physical self-concept (physical conditioning, sports competence, body attractiveness, strength, physical self-worth and self-esteem). Each construct is assessed with six items, with the response for each item scored on a four-point Likert scale; these scores are then averaged to provide a mean score for the construct. In accord with previous research, the sports competence construct was utilised to provide a measure of perceived competence in FMS (Barnett et al., 2011; Barnett et al., 2008b; Rogers et al., 2018).

5.3.6 Statistical Analyses:

Data analyses were conducted using IBM SPPS, version 26 [IBM SPSS Statistics Inc., Chicago, IL, USA] and STATA Version 16.1 [College Station, TX: StataCorp LLC], with significance level set at $p < 0.05$. Descriptive statistics were calculated for all variables. Homogeneity of variance was assessed using Levene's statistic, with differences between maturity-offset groups assessed using Kruskal–Wallis testing with post hoc tests. Spearman's Rho correlations were conducted to assess the maturity-related correlations between process- and product-oriented fundamental movement skill competence, along with the association of these performance measures with perceived sports competence. Separate linear mixed models were used to examine the influence of identified characteristics (sex, age, maturity offset, perceived sports competence) with each individual aspects of fundamental movement skill competence. Fundamental movement skill competence (overhand throw and horizontal jump) were included as outcome variables, with individual participants as a random factor, and age, sex, maturity-offset classification, and maturity-offset by age interaction as fixed factors.

Table 2. *Participant characteristics (mean ± SD)*

Variables	Girls (n = 70)			Boys (n = 70)		
	Pre-PHV	**Circa-PHV**	**Post-PHV**	**Pre-PHV**	**Circa-PHV**	**Post-PHV**
Age (years)	10.6 ± 0.6	11.6 ± 0.7[a]	14.4 ± 0.7[a,b]	11.3 ± 1.2	13.9 ± 1.1[a]	15.3 ± 0.5[a,b]
Height (cm)	137.9 ± 4.6	153.6 ± 7.8[a]	160.6 ± 3.9[a,b]	147.4 ± 8.6	166.5 ± 6.2[a]	176.8 ± 5.5[a,b]
Weight (kg)	32.1 ± 5.0	50.2 ± 13.7[a]	53.4 ± 6.5[a]	42.9 ± 12.4	60.9 ± 10.4[a]	68.3 ± 13.2[a]
BMI (kg·m^{-2})	16.9 ± 2.4	21.2 ± 5.7[a]	20.7 ± 2.8[a]	19.5 ± 4.2	22.0 ± 3.5	21.9 ± 3.6
Maturity offset (years)	-1.7 ± 0.4	-0.07 ± 0.7[a]	1.8 ± 0.4[a,b]	-2.4 ± 0.8	0.01 ± 0.6[a]	1.5 ± 0.5[a,b]
Overhand throw (m·s^{-1})	8.3 ± 1.7	9.2 ± 1.9	12.2 ± 1.[a,b]	11.6 ± 2.8	16.7 ± 3.7[a]	17.5 ± 4.5[a]
Overhand throw (TGMD-3)	1.5	1.7	1.8	5.5	5.9	7.0
Horizontal jump (W)	1,043.7 ± 116.7	1,775.9 ± 490.1[a]	2,005.8 ± 444.8[a]	1,481.7 ± 383.3	2,569.7 ± 628.7[a]	3,035.3 ± 607.9[a,b]
Horizontal jump (W·kg^{-1})	33.2 ± 5.6	35.4 ± 3.1	37.5 ± 7.0[a]	35.1 ± 5.3	42.4 ± 8.5[a]	44.9 ± 7.7[a]
Horizontal jump (TGMD-3)	5.0	5.7	5.5	5.3	6.6	5.5

PHV = peak height velocity; BMI = body mass index; cm = centimeter; m·s^{-1} = meters per second; kg = kilogram; TGMD-3 = test of gross motor development version 3; W = Watt; W·kg^{-1} = Watts per kilogram.
[a] Significantly different to Pre-PHV group ($p < 0.05$); [b] Significantly different to Circa-PHV group ($p < 0.05$)

5.4 Results

Descriptive statistics are summarised in Table 2. Irrespective of sex, agreement between process- and product-oriented performance (Table 3) was found to be strongest in post-PHV participants. Additionally, a higher level of agreement was found between the performance assessments (process- and product-oriented) for boys. In boys, the single significant association between a fundamental movement skill and perceived sports competence was found in pre-PHV children in the process-oriented performance of the overhand throw. For girls, horizontal jump performance was most strongly correlated to perceived sports competence, with the association between product-oriented performance and perceived sports competence only significant for those classified as post-PHV (Table 4).

Table 3. *Spearman's Rho correlations between process- and product-oriented competence*

	Maturity offset classification		
Variables	**Pre-PHV**	**Circa-PHV**	**Post-PHV**
Product-oriented	**Process-oriented (TGMD-3)**		
Girls			
Overhand throw ($m \cdot s^{-1}$)	0.00	-0.12	0.64**
Horizontal Jump (W)	0.37	0.07	0.43*
Horizontal Jump ($W \cdot kg^{-1}$)	0.28	-0.04	0.45*
Boys			
Overhand throw ($m \cdot s^{-1}$)	0.45*	0.06	0.68**
Horizontal Jump (W)	0.33	0.41*	0.58**
Horizontal Jump ($W \cdot kg^{-1}$)	-0.13	0.33	0.29

TGMD-3 = Test of Gross Motor Development-3; PHV = Predicted age at peak height; $m \cdot s^{-1}$ = meters per second velocity; W = Watt, $W \cdot kg^{-1}$ = Watts per kilogram.
*$p < 0.05$ **$p < 0.01$

Table 4. *Spearman's Rho correlations between perceived sports competence and fundamental movement skills performance characteristics*

	Maturity offset Classification		
Variables	**Pre-PHV**	**Circa-PHV**	**Post-PHV**
		Perceived sports competence	
Boys			
Process-oriented			
Overhand throw (TGMD-3)	0.43*	0.34	-0.11
Horizontal jump (TGMD-3)	0.27	0.14	0.21
Product-oriented			
Overhand throw ($m \cdot s^{-1}$)	-0.08	0.36	0.16
Horizontal jump ($W \cdot kg^{-1}$)	0.11	-0.08	0.02
Horizontal jump (W)	-0.09	-0.15	0.13
Girls			
Process-oriented			
Overhand throw (TGMD-3)	-0.15	-0.09	0.22
Horizontal jump (TGMD-3)	0.17	0.35	0.37
Product-oriented			
Overhand throw ($m \cdot s^{-1}$)	-0.13	0.15	0.14
Horizontal jump ($W \cdot kg^{-1}$)	0.35	0.09	0.41*
Horizontal jump (W)	0.08	0.16	0.51*

PHV = peak height velocity; TGMD-3 = Test of Gross Motor Development-3; $m \cdot s^{-1}$ = meters per second; W = Watt; $W \cdot kg^{-1}$ = Watts per kilogram.
*$p < 0.05$

For the overhand throw, a main effect of sex was found, with boys demonstrating a higher technical competence (β = 4.14; p = ≤ 0.001), however, no significant maturity-related or age-related main effects were found. For overhand throw velocity, boys outperformed girls (β = 3.44; p = ≤ 0.001), and there was a main effect of age (β = 1.23; p = 0.002). There was no effect of maturity (when controlled for age) on throw velocity.

For horizontal jump performance, a significant main effect of maturity was found for relative peak power ($W \cdot kg^{-1}$) with planned contrasts demonstrating that this difference was between pre- and post-PHV groups (β = 3.32; p = 0.04). In contrast, no main effect of age, sex or perceived sports competence was found for relative ($W \cdot kg^{-1}$) horizontal jump performance. With regard to absolute peak power (W) in the horizontal jump, there was a significant sex difference (β = 542.11; $p < 0.001$), although no main effect of age was found. However, there was a significant main effect of maturity on absolute peak power (W) in the horizontal jump, with planned contrasts revealing that the difference was between the pre- and post-PHV groups (β = 307.96; p = 0.01). For the process-oriented assessment of the horizontal jump, age (β = 0.60; p = 0.03) and perceived sports competence (β = 0.13; p = 0.003) were found to significantly influence performance, with no significant main effect of sex.

5.5 Discussion

The aim of the current study was to investigate whether a maturational influence exists on process- and product-oriented performance of the overhand throw and horizontal jump, as well as to identify the role of chronological age, sex and perceived sports competence on the performance of these FMS. Whilst evidence of a maturity-related influence was found for the product-oriented performance of both measurements of the horizontal jump, a similar influence on overhand throw velocity and the technical competency in both FMS was not evident.

Akin to previous studies (Barnett et al., 2016a; Hardy et al., 2013; McWhannell et al., 2018), boys demonstrated higher competency in the overhand throw, regardless of whether it was assessed using a process- or product-oriented assessment. Indeed, sex was significantly associated with process-oriented performance in the overhand throw, with boys scoring higher than girls, irrespective of maturity. Moreover, girls demonstrated poor competency in the overhand throw across all maturity classifications. The higher competence of boys in throwing, as well as in additional object control skills, has been consistently reported in the literature (Barnett et al., 2016a; Barnett et al., 2015a; Slykerman et al., 2016). Given that the present study included participants who were post-PHV, it provides evidence of the tracking of poor movement competence observed at younger ages in girls (Behan et al., 2019). Whilst a biological influence has been proposed as a contributing factor, these between-sex findings likely reflect the sociological and cultural influences (i.e. lack of opportunity and encouragement to participate in associated sport) that impede the development of these FMS in girls (Barnett et al., 2016a). Although the overhand throw was included as the only object control skill in the current study, a strong correlation between all object control skills has been previously identified (Eather et al., 2018). These findings may therefore highlight a wider issue concerning the development of object control skills in school-aged girls (Kelly et al., 2019), with girls potentially leaving school displaying poor competency in core curriculum movement skills (Department for Education, 2013; Duncan et al., 2020).

In the current study it was expected that an increase in overhand throw velocity would be associated with greater maturational development. However, although age and sex were found to influence performance, a main effect of maturity on overhand throw velocity was not evident. The overhand throw is a skill where absolute strength is likely more important to outcome performance as it involves little propulsion of a child’s body mass (Pichardo et al., 2019). The lack of difference between the circa- and post-PHV children in the current study may indicate that strength gains were already manifest in the circa-PHV group and, as such, there were no identifiable differences to those in the post-PHV group. As highlighted by Stodden and colleagues (2006a; 2006b), the overhand throw is a complex movement pattern, requiring the explicit interaction of specific kinematic variables to optimise energy transfer. It can therefore be postulated that a dynamic throw that utilises the full interaction of these kinematic variables is required to be influenced by maturity-related changes.

In contrast to the overhand throw, there were no between-sex differences for process-oriented horizontal jump competence, though age was found to be a significant predictor of technical competence. This is in partial agreement with previous studies, with little evidence identifying sex as a consistent predictor of technical competence in locomotor skills (Barnett et al., 2016a; Slykerman et al., 2016). It is suggested that this reflects the less ontogenetic development of locomotor skills when compared to object control skills, but also an earlier and maintained exposure, including within many activities commonly favoured by girls (i.e. gymnastics, dance, athletics; Barnett et al., 2010; Cliff et al., 2012; Slykerman et al., 2016). Although not significant, a small decrease in TGMD score was found between the circa- and post-PHV groups, regardless of sex. It is plausible that this is associated with indirect factors (i.e. reduced physical activity levels, lower motivation), however, it may provide some evidence of a maturity-related regression in performance, relating to the marked changes in limb length during the period of PHV (Myburgh, Cumming, Silva, Cooke, & Malina, 2016).

The current study identified that boys achieved a higher absolute peak power in the horizontal jump, although these differences were not significant when peak power was reported relative to body mass. However, a maturity-related influence was found for absolute and relative peak power performance, with the influence greater for absolute than relative horizontal jump performance. These results provide some support to previous evidence that has shown a more pronounced maturational influence when jump performance has been analysed without controlling for body mass (Pichardo et al., 2019). In the current study, a more significant association of relative jump performance with process-oriented competence than was evident for absolute peak power jump performance may highlight the more crucial role of relative strength to performance levels in jump performance and additional movement competencies (i.e. sprinting; Pichardo et al., 2019).

In contrast to previous studies (Hulteen et al., 2019; Logan et al., 2017), the agreement between process- and product oriented competence was strongest in the post-PHV group and was significant for both FMS. Importantly, previous studies had not controlled for the influence of biological maturation (Hulteen et al., 2019; Logan et al., 2017). Also, the use of a radar gun (overhand throw) and force platform (horizontal jump) in the current study may have allowed for a heightened level of differentiation between competent and non-competent performance, and as such may have more accurately aligned outcome performance to technical competence. When comparing the correlations between FMS (process- and product-oriented) and perceived sports competence in the current study, the correlations were found to be weak. It has been proposed that the alignment between actual and perceived competence will strengthen with increasing age (Stodden et al., 2008), although evidence in support of this has been inconsistent (Bardid, De Meester, et al., 2016; De Meester et al., 2016a). In boys, as expected, a stronger correlation between perceived and actual competence was found in the overhand throw than in the horizontal jump, although this association was not significant across any of the maturity-offset classifications. In girls, product-oriented performance in the horizontal jump was found to be significantly associated with perceived sports competence. This is congruent with previous evidence that has suggested that girls view locomotor skills to be more influential to their wider skill competence (Slykerman et al., 2016). Overall, the present results extend the evidence relating to the inconsistent association between perceived and actual competence that has been found to exist in youth (Moran et al., 2018). As such, this highlights that continued work is needed to understand how children build their self-perception of fundamental movement skill/sports competence, and why for some a lack of competence in FMS may act as a barrier to engagement and in others no such influence is apparent (Malina et al., 2016).

The current study had numerous strengths, not least investigating the age-controlled maturational influence on specific aspects of FMS and aligning these performances to a measure of self-perception. Nonetheless, it is important to acknowledge associated limitations of the study. First, the validity of the maturity-offset predictive equation has been shown to decrease with increasing age from PHV (Mirwald et al., 2002). It is also pertinent to note that a maturity by sex interaction was not analysed, which may provide additional insight into the developmental trajectories of FMS. Given that the current study only analysed performance in two FMS, caution is advised in making more global assertions. Finally, both sport involvement and the motivation of the participants to perform to their maximal level were not measured in the current study, which may have influenced some of the performance levels observed across the study.

5.6 Conclusion

In conclusion, these results highlight the importance of controlling for a maturity-related influence when using a product-oriented approach to fundamental movement skill assessment. The current study also indicates that a reliance on a single assessment method may limit the validity of results, especially in younger children. In post-PHV adolescents the level of agreement between process- and product-orientated outcomes was higher, suggesting that practitioners can be more confident in adopting either assessment approach in isolation. However, for pre- and circa-PHV children, practitioners should seek to utilise a circuit-based approach to fundamental movement skill assessment that captures both aspects of competence measurement. Of importance, irrespective of sex, no group achieved process-oriented competence mastery in either skill. This is concerning as children are transitioning through adolescence without proficiency in FMS, in a period where physical activity levels are known to decline and where sport participation becomes more skill-oriented and competitive.

Thesis Map

	Study		Outcomes
1.	Sex-related differences in the association of fundamental movement skills and health and behavioural outcomes in children	***Aim***	To evaluate the sex-related influence on FMS competence during late childhood, and to identify if this subsequently influences the association of FMS with further health-related benefits.
		Key findings	For boys, object control skill competence had a direct association with perceived sports competence and an indirect association with sedentary time (through perceived sports competence). For girls, although locomotor skills were found to predict VPA Irrespective of sex, perceived sports competence was associated with sedentary time. The study supports a holistic approach to health-related interventions and highlights a key association of perceived sports competence and the time children spend sedentary.
2.	The influence of biological maturation on performance characteristics of the overhand throw and horizontal jump in youth	***Aim***	To identify the influence of sex and biological maturity on performance characteristics of the horizontal jump and overhand throw, and to investigate the association of these FMS with perceived sports competence.
		Key findings	Irrespective of sex, agreement between technical and outcome performance characteristics was strongest in the post-PHV group. Perceived sports competence was most strongly associated with product-oriented horizontal jump performance in the post-PHV group for girls. A maturational influence was only found for product-oriented horizontal jump performance, with this between the pre- and post-PHV groups.
3.	The importance of skill competence as a key predictor of the energy expenditure associated with performing fundamental movement skills	***Aim***	To evaluate the influence of biological and developmental characteristics, along with skill competence on the energy expenditure associated with the performance of isolated FMS
		Key findings	
4.	The influence of motor competence on broader aspects of health: a systematic review of the longitudinal associations between motor competence and cognitive and social-emotional outcomes	***Aim***	
		Key findings	
5.	Potential moderators of the association between fundamental movement skills and academic attainment in adolescence	***Aim***	
		Key findings	

6.0 Study 3

6.1 The importance of skill competence as a key predictor of the energy expenditure associated with performing fundamental movement skills

6.2 Introduction

The health-enhancing benefits associated with regular physical activity are now well-established (Janssen & Leblanc, 2010; Poitras et al., 2016). In youth, physical activity has been shown to be positively associated with weight status, cognitive health-indicators, and cardiometabolic risk factors, with these associations strengthening with age (Corder et al., 2019; Poitras et al., 2016). However, despite the well-recognised health benefits, there is a continuing rise in physical inactivity in many countries (Lobstein et al., 2015; Tremblay, Carson, & Chaput, 2016), with children becoming increasingly inactive as they transition into adolescence (Andersen, Mota, & Di Pietro, 2016; Farooq et al., 2018). A growing body of evidence has identified a reciprocal association between fundamental movement skills (FMS) and physical activity, with high physical activity levels typically associated with higher proficiency in these skills (Lubans et al., 2010; Robinson et al., 2015). In light of this, FMS are now considered a central tenant to physical activity promotion and intervention in young people.

FMS are classified as basic movement patterns – such as throwing, striking, and jumping – that provide the foundation to more advanced movements that underpin physical activity and sport-related participation (Gallahue & Ozmun, 2002). Fundamental movement skill competence is age-related rather than age-determined, with development considered to be non-linear and an outcome of multiple dependent factors (Gallahue & Ozmun, 2002; Ulrich, 2007). Specifically, along with age, proficiency in these skills has been found to be directly associated with sex, weight status and social-ecological correlates (Barnett et al., 2016a, 2019; Hardy, King, Farrell, Macniven, & Howlett, 2010). In many object control skills, boys consistently display advanced performance characteristics (i.e. qualitative technical components) and performance outcomes (i.e. speed, power) in comparison to their female counterparts (Barnett et al., 2010; Gromeier, Koester, & Schack, 2017; Kokštejn, Musálek, & Tufano, 2017). Prior to puberty, these differences are proposed to be strongly influenced by sociocultural factors, which promote a greater exposure of boys to activities emphasising the integration of these specific skills (Spessato et al., 2013). In contrast, sex-related differences in locomotor competence are more equivocal, although the performance outcomes of some locomotor skills (i.e. jump and sprint) have been found to display a maturity-associated variance that is more exaggerated in boys (Malina, Bouchard, & Bar-Or, 2004; Malina, Rogol, Cumming, Coelho E Silva, & Figueiredo, 2015). Taken together, the aforementioned correlates contribute to the significant inter-individual differences that exist in the developmental trajectories of FMS in young people (Barnett et al., 2016b; Valentini et al., 2015, 2016).

Given FMS are inherent components of physical activity participation in young people (Gallahue & Ozmun, 2002), understanding the associated energy expenditure (EE) of performing these movements is crucial to the establishment of normative EE values for many physical activities and sports (Sacko, Nesbitt, et al., 2019a). Moreover, understanding the influence of mediators (e.g. sex and age) on the associated EE of FMS can ensure appropriate physical activity interventions for children and provide clinicians with a greater understanding of health outcomes (Harrell et al., 2005). The physical and physiological changes that occur across childhood and adolescence emphasise the importance of normalising EE for body mass. For example, absolute EE has been shown to increase with age as a function of body mass, whilst the energy cost of some movement patterns has been shown to decrease with age relative to body mass, proposed to be aligned with more efficient movement (McMurray et al., 2015; Pfeiffer et al., 2018; Rowland, 2005). Furthermore, puberty-related differences in absolute EE are suggested to exist as an outcome of increased muscles mass, especially in boys (Harrell et al., 2005). Sacko and colleagues (2018;2019a; 2019b) addressed the dearth of literature relating to the energy costs of discrete skill performance by analysing the associated EE for object projection skills in children and adults. In children, the performance of those with a higher skill competence (ball speeds) was found to be associated with acute increases in energy expenditure, a proposed outcome of the greater neuromuscular demand (Stodden et al., 2006a, 2006b). The energy cost associated with performing specified types of physical activity has been previously aligned to economy of movement, and moreover has been found to display maturity-related variance (Harrell et al., 2005; McMurray et al., 2015). Conversely, for the overhand throw, younger children and those with low competence have been found to display kinematic ‘constraints’ (i.e. trunk rotation, step action, humerus action), that limit the transfer and generation of energy during the movement (Stodden et al., 2006b).

Whilst recent studies offer much needed insight into the associated EE of FMS (Duncan et al., 2019; Sacko et al., 2018; Sacko et al., 2019b), they are specific to the performance of children and adults. Adolescence, as previously highlighted, is a hugely transitional period, yet few studies have analysed how inter-individual characteristics may influence the EE associated with FMS. Therefore, the purpose of the present study was to investigate whether fundamental movement skill competence had a significant influence on the associated EE of individual FMS. A secondary aim was to identify the further influence of sex, age and increasing maturity on the EE associated with performing FMS.

6.3 Methods

6.3.1 Participants

A total of 27 healthy Caucasian youth (14 girls; 12.0 ± 2.2 years., 13 boys; 12.2 ± 2.4 years) participated in the study. Parental/guardian consent and participant assent were obtained for all children prior to participation. Each participant was assessed at the Applied Sports Technology, Exercise and Medicine Research Centre, Swansea University. The study, and all procedures were approved by Swansea University College of Engineering Research Ethics and Governance Committee and were conducted in accordance with the Declaration of Helsinki (ref: PG/2019-039).

6.3.2 Study protocol

Participants' stature and sitting height were measured to the nearest 0.1 cm using a portable stadiometer (Holtain Stadiometer, Holtain Ltd). Body mass was recorded to the nearest 0.1 kg using electronic scales (SECA, Seca Instruments, Ltd, Hamburg, Germany). Body mass index (BMI) was calculated (body mass (kg) / stature^2 (m^2)) to provide an estimate of participant weight status. All anthropometric measurements were conducted by a trained researcher, with children wearing light clothes and with shoes removed. Biological maturity status was determined using the non-invasive predictive equation of Mirwald and colleagues (2002). This sex-specific equation uses anthropometric measurements to predict years from peak height velocity, with a reported standard error estimate of 0.57 (girls) and 0.59 (boys) years (Mirwald et al., 2002).

Oxygen uptake ($\dot{V}O_2$) was measured breath-by-breath using a mobile gas analyser (MetaMax 3B; Cortex Biophysik, Leipzig, Germany), calibrated according to manufacturer instructions at the beginning of each session. Specifically, the gas analyser was calibrated using standardised gases and the turbine volume transducer calibrated prior to each participant using a 3-L syringe (Hans Rudolph, Kansas City, MO, USA). During the protocol, the gas analyser was worn on a harness, with the additional weight of the equipment not exceeding 850g.

Participants performed five FMS in total (overhand throw, one-handed strike, kick, hop, slide), selected from and subsequently assessed using the Test of Gross Motor Development - version 3 (TGMD-3; Ulrich, 2020). The TGMD-3 is a process-oriented assessment of FMS with established validity (Temple & Foley, 2016) that assesses skills from two primary constructs: object control and locomotor skills. Each individual skill performance is assessed on specific technique-related components. In the current study, individual FMS were scored (0-4) based on the presence or absence of each technical component. Prior to the protocol, all participants performed a warm-up and were provided with the opportunity to practice and familiarise themselves with all skills. They were then instructed to perform each skill to the best of their ability for the duration of the assessment protocol. Each fundamental movement skill was performed using an intermittent protocol involving six bouts of 30 seconds continuous performance interspersed by 15 second rest intervals. Following the completion of the final performance interval of each fundamental movement skill, participants had a three-minute seated rest to allow $\dot{V}O_2$ to return to the baseline value prior to the next skill performance. To limit the risk of potential bias from order effects a randomised design was selected. To reduce the risk of injury a skill from the same fundamental movement skill construct (object control or locomotor) was never performed consecutively.

Each skill was video recorded from frontal and sagittal planes (Apple Ipad, Apple Inc, 2019) to allow subsequent analysis to be performed by two trained assessors.

6.3.3 Data Analyses

Descriptive statistics (mean, M; standard deviation, SD) were calculated for anthropometric measures, fundamental movement skill competence (individual and construct), and EE, presented as absolute $\dot{V}O_2$ ($l \cdot min^{-1}$) and allometrically scaled ($\dot{V}O_2 \cdot kg^{-0.75} \cdot min^{-1}$), with this exponent chosen a priori. Unadjusted t-tests and the Mann-Whitney U-test were used to assess between-sex differences in anthropometrical measures and fundamental movement skill competence levels. To calculate the mean EE associated with each skill performance, the mean $\dot{V}O_2$ between 10 and 25 seconds of interval bouts 2-5 was averaged. All statistical analyses were performed using Stata, version 16.1 (StataCorp, College Station, TX, USA), with significance level set at $p < 0.05$. Separate linear mixed models were performed with the associated $\dot{V}O_2$ ($l \cdot min^{-1}$) and $\dot{V}O_{2ALLOM}$ as the outcome variables. Within each model, individual participants were included as random effects, and FMS skill, FMS competence, maturity offset, age, sex, and BMI z-score as fixed effects. Interaction terms were examined to assess the effect modification of skill competence level and associated EE for each individual fundamental movement skill, and also the sex-specific effect of increasing maturity on associated EE.

6.4 Results

Table 5 presents demographic information and fundamental movement skill competence scores (TGMD-3). As shown, there were no significant anthropometrical differences according to sex. A significantly higher skill competence level was found in boys for the overhand throw and the object control skills construct. Sex-specific and group mean values for $\dot{V}O_2$ ($l \cdot min^{-1}$) and $\dot{V}O_{2ALLOM}$ are presented in Table 6.

In the linear mixed models, with $\dot{V}O_2$ ($l \cdot min^{-1}$) as the outcome measure, there were no significant differences between each fundamental movement skill and their associated EE. Akin to $\dot{V}O_{2ALLOM}$, a significant interaction was found between a higher skill competence level in the kick and $\dot{V}O_2$ ($l \cdot min^{-1}$) ($\beta = 0.10$; $p = 0.02$), and a higher skill competence level in the hop and $\dot{V}O_2$ ($l \cdot min^{-1}$) ($\beta = 0.17$; $p = \leq 0.01$). Along with boys having a higher $\dot{V}O_2$ ($l \cdot min^{-1}$) across all skill performance ($\beta = 0.66$; $p = \leq 0.01$), increasing maturity (sex*maturity interaction) was found to have a significant influence on the associated $\dot{V}O_2$ ($l \cdot min^{-1}$) in boys ($\beta = 0.23$; $p = \leq 0.01$), with this not evident in girls. With $\dot{V}O_{2ALLOM}$ as the outcome measure, the $\dot{V}O_{2ALLOM}$ associated with performing the hop was significantly higher (β = 13.74; p = 0.01) than all other FMS. In addition, for the $\dot{V}O_{2ALLOM}$, a significant interaction was found between a higher skill competence level and $\dot{V}O_{2ALLOM}$ in the kick (β = 4.68; p = 0.01), hop (β = 7.86; p = ≤ 0.01) and slide (β = 10.24; p = 0.01). Whilst boys had a higher $\dot{V}O_{2ALLOM}$ during fundamental movement skill performance (β = 13.06; p = 0.03), no maturity-related or age association were found.

Table 5. *Participant characteristics (mean ± SD)*

Variables	**Boys (*N* =**	**Girls (*N* = 16)**	**All (*N* = 29)**
Age (years)	12.2 ± 2.4	12.0 ± 2.2	12.2 ± 2.2
Height (cm)	156.2 ± 16.5	148.5 ± 11.1	152.0 ± 14.1
Weight (kg)	52.3 ± 22	42.5 ± 11.7	46.9 ± 17.5
BMI ($kg \cdot m^{-2}$)	20.6 ± 5.0	19.2 ± 5.2	19.9 ± 5.1
Maturity offset (years)	-0.9 ± 1.7	-0.7 ± 1.0	-0.8 ± 1.3
One handed strike (0-4)	2.9 ± 0.8	2.5 ± 0.9	2.7 ± 0.9
Overhand throw (0-4)	2.5 ± 1.5	0.9 ± 1.2*	1.6 ± 1.6
Kick (0-4)	3.3 ± 0.6	2.8 ± 1.1	3.0 ± 0.9
Slide (0-4)	3.8 ± 0.4	3.9 ± 0.3	3.8 ± 0.3
Hop (0-4)	2.8 ± 0.5	2.3 ± 0.9	2.5 ± 0.8
Object control (0-12)	8.8 ± 2.0	6.2 ± 2.3*	7.4 ± 2.5
Locomotor competence (0-8)	6.6 ± 0.8	6.2 ± 1.1	6.4 ± 1.0

Means ± SD. BMI = Body mass index.
* Significant difference between boys and girls ($p < 0.05$)

Table 6. *Descriptive statistics for $\dot{V}O2$ (l·min−1) and $\dot{V}O2ALLOM$*

	$\dot{V}O_2$ (l·min^{-1})				$\dot{V}O_{2ALLOM}$			
	Boys		**Girls**		**Boys**		**Girls**	
FMS	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**
Overhand throw	0.9 ± 0.5*	0.3 – 1.9	0.6 ± 0.2	0.3 – 1.0	45.4 ± 18.4	18.3 – 71.7	36.4 ± 11.8	21.7– 64.3
Kick	1.2 ± 0.6	0.4 – 2.6	0.8 ± 0.2	0.4 – 1.2	58.1 ± 17.9	25.0 – 84.6	50.6 ± 12.9	30.8 – 76.3
Two-handed strike	0.8 ± 0.4	0.2 – 1.4	0.5 ± 0.2	0.3 – 0.9	40.5 ± 16.7	14.5 – 68.8	35.6 ± 9.2	18.6 – 52.3
Hop	1.7 ± 0.8*	1.0 – 3.6	1.1 ± 0.4	0.6 – 1.9	84.4 ± 21.7	51.9 – 121.3	68.9 ± 21.1	43.7 – 101.0
Slide	1.4 ± 0.5*	0.9 – 2.4	1.0 ± 0.4	0.5 – 1.6	71.23 ± 16.8	44.8 – 95.4	65.2 ± 21.1	37.6 – 91.4
Object control	0.9± 0.5	0.2 – 0.6	0.6 ± 0.2	0.4 – 0.8	45.9 ± 17.7	20.3 – 73.1	39.2 ± 11.8	25.4 – 62.4
Locomotor	1.5 ± 0.7*	0.6 – 3.0	1.0 ± 0.4	0.5 – 1.7	75.2 ± 19.7	48.4 – 108.3	65.9 ± 20.9	42.6 – 95.5

Note. FMS = Fundamental movement skills. $\dot{V}O_{2ALLOM} = \dot{V}O_2 \cdot kg^{-0.75} \cdot min^{-1}$
* Significant difference between boys and girls ($p < 0.05$)

6.5 Discussion

This study examined the role of biological and competence-related factors on the associated EE of fundamental movement skill performance. In analysing individual FMS, the current study sought to extend prior research that has observed inter-individual variance in the EE associated with performance of these skills in combination (Duncan et al., 2019; Sacko et al., 2018; Sacko et al., 2019b). The results of the present study further emphasise the influence of skill competence on the EE associated with fundamental movement skill performance, especially locomotor skills. This association between skill competency level and associated EE may emphasise the importance of targeting the development of FMS, especially in physical activity interventions implemented to reduce obesity.

Congruent with previous studies (Bardid et al., 2016; Barnett et al., 2016a; O' Brien, Belton, & Issartel, 2016; Valentini et al., 2016), sex differences were observed in fundamental movement skill competence, with boys demonstrating a higher competence across all object control skills and these differences significant in the overhand throw and overall object control construct. It is suggested that these sex-related patterns reflect cultural and environmental influences that promote a greater participation of boys in sports underpinned by these skills (i.e. football, baseball, rugby; Barnett et al., 2016a). The present results also indicate that these sex-related differences remain consistent in adolescence, with additional influences (i.e. self-efficacy, social and demographic factors) postulated to consolidate the developmental trends observed in childhood (Malina, Cumming, & Silva, 2016; O' Brien et al., 2016). Aligned with prior studies (Bardid et al., 2016; Slykerman, Ridgers, Stevenson, & Barnett, 2016), locomotor skill competence (i.e. hop and slide) did not differ significantly between sex. This is to be expected as locomotor skills are less ontogenetic than object control skills and have a far wider ranging influence on physical activities and sport participation, irrespective of sex, both in free-play and organised settings (Hulteen, True, & Pfeiffer, 2020). Furthermore, a lot of the boys in the current sample were early maturing and this could have also influenced any between-sex differences.

Results showed the significant influence of skill competence on the EE associated with individual FMS, when EE was analysed as absolute or allometrically scaled EE. It has previously been suggested that in many athletic movement patterns, a lower skill competence is associated with a higher energy expenditure, with this an outcome of increased muscle activation and poorer economy of movement (Malina et al., 2004; McMurray et al., 2015). However, the present study extends the work of Sacko and colleagues (2019b) by identifying competence-related trajectories. In observing the contribution of skill-level to object projection skills, Sacko et al. (2019b) proposed that this likely reflects the greater neuromuscular involvement (i.e. concentric and eccentric muscle activation) associated with a more proficient performance level. Whilst the current study differed from the aforementioned study in utilising a process-oriented approach (i.e. technical competence) to classify skill level, it is plausible that our results are underpinned by similar mechanisms. Indeed, agreement between process and- product-oriented assessment has previously been found (Hulteen et al., 2019). Significant positive associations were evident between skill competence and associated $\dot{V}O_{2ALLOM}$ for the kick, hop, and slide, along with a similar association between skill competence and absolute EE for the kick and hop. These skills are all kinematically complex, and all require a high level of energy generation and transfer when performed competently. For example, in contrast to a proficient performance, poor competency in many FMS is aligned with a visibly more constrained movement, resulting in far lower internal velocities (Stodden et al., 2006a). Furthermore, although the kick is classified as an object control skill, a key feature of poorly competent efforts is the absence of an accelerated and continuous run-up, and it is this that may influence the EE associated with this movement. These findings may offer insight into the consistent relationship found between fundamental movement skill proficiency and weight status (Lopes et al., 2020). If children who are poorly competent are expanding less energy when performing these skills, it is likely that they are not gaining the same health-related benefits of those with a higher skill competency when participating in sport-related activities.

Our findings showed sex to be a significant predictor of the EE (both $\dot{V}O_{2ALLOM}$ and $\dot{V}O_2$ ($l \cdot min^{-1}$)) associated with fundamental movement skill performance. Previous studies have found little evidence of sexual dichotomy in movements similar to those performed in the current study (Pfeiffer et al., 2018; Trost, Drovandi, & Pfeiffer, 2016). However, the higher observed EE in boys in the current study is in agreement with the only previous study that assessed discrete fundamental movement skill performance (Sacko et al., 2019a). In the current study, the higher EE in boys was aligned with a higher competence level across all skills, except the slide. When considering the hop, the performance of many boys was found to be a closer replication of an athletic single leg bound and would be more likely to recruit a greater percentage of muscle mass. In contrast, girls displayed a more constrained hop performance. The higher EE associated with the fundamental movement skill performance in boys could be further associated to a higher perceived competence, and therefore the motivation to perform to their full competence (De Meester et al., 2016a; Duncan, Jones, O'Brien, Barnett, & Eyre, 2018). In boys especially, this has been found to become more apparent in power-based movements as perception relative to peers is suggested to be more aligned with fitness-related outcomes (i.e. throw speed, jump distance; Barnett, Salmon, Timperio, Lubans, & Ridgers, 2017). Furthermore, the boys would likely have a higher muscle mass than the girls given maturity status, and this may also play a role in the EE associated with skill performance.

An age-related influence on the EE associated with FMS was not observed in the current study. Previously in skilled activities (i.e. basketball dribble), $\dot{V}O_{2ALLOM}$ has displayed an age-related trajectory (McMurray et al., 2015), although evidence remains inconsistent (Schuna, Barreira, Hsia, Johnson, & Tudor-Locke, 2016). It is plausible that the influence of age is non-linear and becomes more pronounced in those activities of a higher intensity (Pfeiffer et al., 2018). Indeed, an age-related decrease in EE relative to mass (kcal·kg^{-1}·min^{-1}), together with a higher level of competence may explain a decrease in energy cost of submaximal performance across a range of activities (Butte et al., 2018; Rowland., 2005). The failure of children to achieve proficiency in FMS by late-childhood (O' Brien et al., 2016), and the non-linear developmental patterns in FMS across adolescence may provide additional explanations as to why data relating to the associated EE of FMS remains inconsistent. Whilst age was not found to significantly affect associated EE, a maturity-related influence in boys (but not girls) was found when EE was expressed as absolute $\dot{V}O_2$ (l·min^{-1}). This finding further highlights the limitations of failing to account for growth-related differences when analysing the EE associated with movement in youth. As these skill performances were underpinned by eccentric and concentric muscle activation, it is plausible that, at least in boys, more powerful movements are evident for circa- and post-pubertal participants.

Despite presenting a novel approach to fundamental movement skill energy cost analysis, there were limitations associated with the current study. Specifically, resting metabolic rate was not measured, precluding the identification of inter-individual differences at rest, including the potential influence of cardiovascular fitness. Also, the sample size limits the generalisability of the findings, especially across different ethnicities. Although the current study is novel in analysing the potential maturational influence on the EE associated with FMS, the predictive equation that was used (Mirwald et al., 2002; Sacko et al., 2021) has a measurement error that limits its validity as a continuous variable. Given this, future studies should classify participants relative to maturity-related groups (i.e. pre-pubertal, circa-pubertal, post-pubertal). In addition, relationships dealing with maturity may have been affected by the fact the high number of early maturing boys with this likely to exacerbate differences between the boys and average or late maturing girls. Lastly, whilst the study provides insight into the importance of skill competence on the associated EE of FMS performed in a laboratory setting, future studies should attempt to extend this to assess whether these influences are consistent, or indeed exaggerated, in a free-living setting where additional constraints may become magnified (i.e. self-perception).

6.6 Conclusion

The approach taken to measuring the absolute and allometrically scaled EE associated with FMS in the current study has further extended understanding of the related energy costs of these movements. The present findings showed skill competence to be a significant factor on the EE associated with FMS, and further highlight the potential health-enhancing benefits associated with achieving proficiency in FMS. The findings not only highlight the inter-individual variance that exists when performing these skills but also contributes to extending knowledge on the respective EE associated with those activities most commonly participated in during childhood and adolescence. From an intervention standpoint, the current study reinforces that a focus on fundamental movement skill development can contribute towards direct health outcomes (i.e. associated EE) along with the already established indirect health-enhancing benefits (i.e. physical activity, weight status, health-related fitness).

Thesis map

	Study		Outcomes
1.	Sex-related differences in the association of fundamental movement skills and health and behavioural outcomes in children	***Aim***	To evaluate the sex-related influence on FMS competence during late childhood, and to identify if this subsequently influences the association of FMS with further health-related benefits.
		Key findings	For boys, object control skill competence had a direct association with perceived sports competence and an indirect association with sedentary time, through perceived sports competence. For girls, although locomotor skills were found to predict VPA Irrespective of sex, perceived sports competence was associated with sedentary time. The study supports a holistic approach to health-related interventions and highlights a key association of perceived sports competence and the time children spend sedentary.
2.	The influence of biological maturation on performance characteristics of the overhand throw and horizontal jump in youth	***Aim***	To identify the influence of sex and biological maturity on performance characteristics of the horizontal jump and overhand throw, and to investigate the association of these FMS with perceived sports competence.
		Key findings	Irrespective of sex, agreement between technical and outcome performance characteristics was strongest in the post-PHV group. Perceived sports competence was most strongly associated with product-oriented horizontal jump performance in the post-PHV group for girls. A maturational influence was only found for product-oriented horizontal jump performance, with this between the pre- and post-PHV groups.
3.	The importance of skill competence as a as a key predictor of the energy expenditure associated with performing fundamental movement skills	***Aim***	To evaluate the influence of biological and developmental characteristics, along with skill competence on the energy expenditure associated with the performance of isolated FMS
		Key findings	Boys were found to have a higher associated absolute and relative energy expenditure across all skill performances. A significant sex and maturity interaction was found in boys with absolute $\dot{V}O_2$ ($l \cdot min^{-1}$) as the outcome. For the kick and hop, level of skill competence was found to influence both relative and absolute associated energy expenditure.
4.	The influence of motor competence on broader aspects of health: a systematic review of the longitudinal associations between motor competence and cognitive and social-emotional outcomes	***Aim***	1. To evaluate and summarise evidence pertaining to the longitudinal relationship of motor competence and cognitive and social-emotional outcomes. 2. To present a conceptual model outlining the proposed influence of motor competence on the development of cognitive and social-emotional outcomes during childhood and adolescence.
		Key findings	
5.	Potential moderators of the association between fundamental movement skills and academic attainment in adolescence	***Aim***	
		Key findings	

7.0 Study 4

7.1 The influence of motor competence on broader aspects of health: a systematic review of the longitudinal associations between motor competence and cognitive and social-emotional outcomes

7.2 Introduction

Stodden and colleagues (2008) proposed a conceptual developmental model to illustrate the critical role of motor competence in the development of positive and negative health trajectories during childhood. Motor competence refers to the goal-directed and coordinated motor acts (i.e. running, throwing) that provide the basis for the complex movement patterns required for participation in many sport and physical activity contexts (Gallahue, Ozmun, and Goodway, 2019). Central to the model authored by Stodden et al. (2008) is the synergistic, and increasingly reciprocal, associations between age, motor competence, physical activity, perceived skill competence, health-related fitness, and weight status. The model of Stodden and colleagues (2008) has since been examined to identify those health-enhancing pathways most strongly supported through empirical evidence (Barnett et al., 2021; Robinson et al., 2015). Robinson and colleagues (2015) found consistent evidence for a direct association between motor competence and physical activity, health-related fitness and weight status, although this was based on limited longitudinal research. Subsequently, support for these original pathways has been provided by several systematic reviews and meta-analyses, although these have often focused on a single pathway in the model (Cattuzzo et al., 2016; Figueroa and An, 2017; Tompsett et al., 2017; Utesch et al., 2019). In contrast, whilst the most recent review by Barnett and colleagues (2021) supported the relationship of motor competence with fitness and weight status, they concluded there was insufficient evidence for the physical activity - motor competence path. This review synthesised the longitudinal and experimental evidence since 2015 and adopted a more rigorous approach than some past reviews by considering all analyses in each study rather than only highlighting results in the hypothesised direction. Nonetheless the review of Barnett and colleagues (2021) was still limited as a meta-analysis could not be conducted. The authors suggest that limitations associated to the measurement of physical activity behaviours may be a contributing factor to the lack of supporting evidence for the physical activity - motor competence path (Barnett et al., 2021).

Physical activity that has a strong perceptual-motor underpinning is considered by some to have a key role in the relationship between motor competence and cognitive and social-emotional outcomes (Pesce et al., 2016; Schmidt, Jäger, Egger, Roebers, & Conzelmann, 2015). In this respect, the quality of the motor movement within the physical activity or sport is seen as crucial and not simply the dose and intensity. In agreement with others (Pesce, 2012; Pesce et al., 2019; Tomporowski, McCullick, Pendleton, & Pesce, 2015), Barnett and colleagues (2021) advocate for less emphasis on strictly quantitative approaches to physical activity measurement (i.e. dose-response) in favour of a more holistic assessment that can also capture the contextual and qualitative characteristics (i.e. cognitive engagement, task complexity) of physical activity. In their model, Lubans et al. (2016) proposed neurobiological, psychosocial, and behavioural mechanisms as being responsible for the positive influence of physical activity on cognitive health. Since the model of Lubans and colleagues (2016), studies investigating these mechanisms have moved away from assessing metabolic factors in isolation to assessing the metabolic and motoric demand in synergy (Diamond, 2000; Tomporowski et al., 2015; Van Der Fels et al., 2019).

The developmental relationships between motor competence and health outcomes included within the Stodden et al. (2008) model continue to be important to examine, especially longitudinally. However, a growing evidence base suggests motor competence may have a similarly important role in the development of cognitive and social-emotional outcomes (Haapala et al., 2019; Leisman, Moustafa, & Shafir, 2016; van der Fels et al., 2015). Cognition is an umbrella term that has been defined as the mental processes that contribute to perception, memory, intellect, and action (Donnelly et al., 2016). Social-emotional functioning refers to social-behavioural and mental health outcomes, and includes competencies such as self-regulation, inter-personal skills and externalising behaviours (Sheridan et al., 2019). The Robinson et al. (2015) narrative review presented initial evidence of a positive association between motor competence and aspects of cognitive development and highlighted this as an essential focus of future research. Cognition and social-emotional functioning have a dynamic interdependency and are positively influenced by physiological and behavioural factors (Immordino-Yang, Darling-Hammond, and Krone, 2019).

This review will present a conceptual model outlining the proposed influence of motor competence on the development of cognitive and social-emotional outcomes during childhood and adolescence. The model will also provide a wider framework through which the position of motor competence can be evaluated, recognising the dynamic interactions and associations underpinning its role.

7.2.1 Conceptual model

Although this review only synthesises evidence for the paths within the highlighted grey section of the conceptual model (*Figure 7*), it is important to consider the theoretical rationales underpinning the wider model. Motor competence is positioned as a mediator between physical activity and cognitive and social-emotional health. Within the model, physical activity is the global term that comprises structured and spontaneous physical activity. Structured physical activity refers to a deliberate effort to prepare and support skill acquisition (MacNamara, Collins, and Giblin, 2015), whilst spontaneous physical activity is largely unstructured, freely-chosen and characterised by exploration (Truelove, Vanderloo, and Tucker, 2017). Both physical activity domains are proposed to have a crucial role in eliciting cognitive and social-emotional development, with free-play offering an autonomous child-directed context and structured practice providing a platform whereby children engage in cognitively challenging play and sport (Pesce et al., 2016). The model also hypothesises that the qualitative characteristics of physical activity hold a key role in moderating the association between motor competence and cognitive and social-emotional outcomes. Physical activity that is underpinned by decision making, variability and that is consistently challenging is seen to align with specific cognitive processes (Pesce et al., 2019). Behavioural qualitative factors are similarly highlighted, and may include characteristics relating to the quality of on-task engagement, interaction and exploration (Hastie, Rudisill, and Wadsworth, 2013). Indeed, within the school-setting, low motor competence has been found to be associated with reduced on-task attention, and a withdrawal from those opportunities that promote motor development (Burns, Byun, and Brusseau, 2019).

This review presents a conceptual model (*Figure 7*) that extends previous models that have solely considered an isolated part of the picture, such as the hypothesised moderated relationship of physical activity and mental health outcomes, and the direct and indirect relationship of motor competence with physical activity (Lubans et al., 2016; Stodden et al., 2008). Many of the hypothesised pathways in these more narrowly defined models have been extensively investigated. Instead, this review focuses on the developmental relationship between motor competence and cognitive and social-emotional outcomes and looks to identify the contextual role of physical activity as a key mechanism for these relationships. Longitudinal evidence is focused on to provide insight to cause and effect, and to summarise those studies that have included a contextual intervention within their analyses.

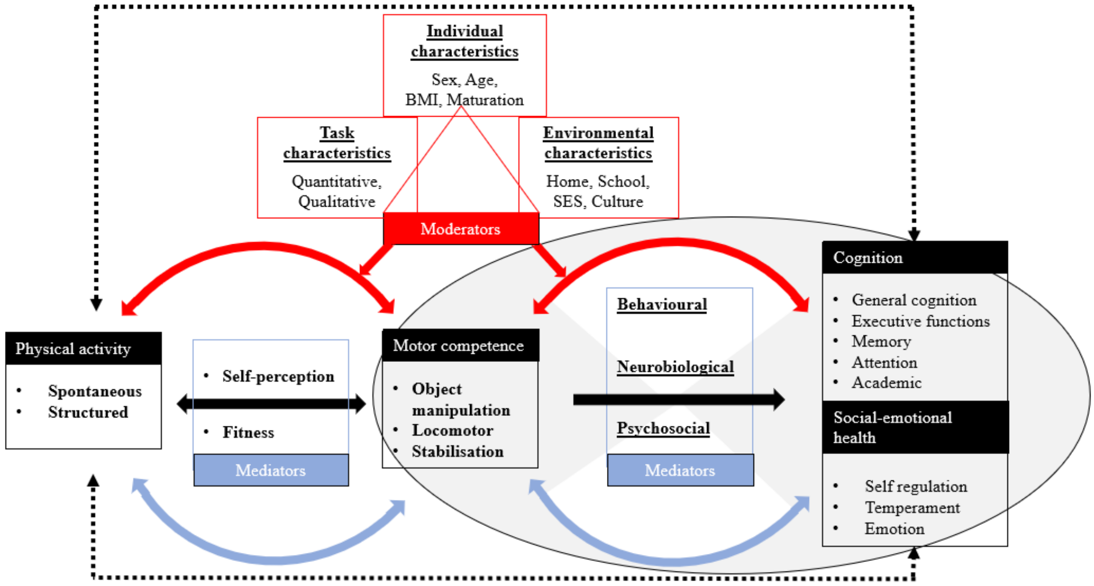


Figure 7. Conceptual model

The model posits that there is strong alignment and interaction between the underlying mechanisms of motor competence and cognitive development, particularly executive functions (Koziol, Budding, and Chidekel, 2012). Consistent with the Lubans et al. (2016) model, the proposed mechanisms that support the influence of motor competence on cognitive and social-emotional outcomes are set as neurobiological, psychosocial and behavioural. Increasingly, the term 'embodied cognition' has been used to outline the connections and overlap between the brain areas responsible for motor competence and cognition (Da Rold, 2018). This notion emphasises the role of sensorimotor experiences in developing cognitive processes (Mavilidi et al., 2018). From a behavioural perspective, it is proposed that motor competence and cognitive processes are inextricably linked, with components of executive functions evident in the execution of gross motor skills. Children proficient in these skills will often engage within contexts such as sport practice and game-play, that are developmentally challenging from a motor and cognitive perspective and further promote cognitive function (i.e. information processing, working memory, executive function; Tomporowski and Pesce, 2019). The cognitive processes used to successfully control and adapt movement in these contexts mirror those of strictly cognitive tasks (Maurer and Roebers, 2019). It is hypothesised that there is a narrow-transfer in the association between motor competence and cognitive function. That is, associations are likely component and domain-specific and are moderated by task, individual and environmental factors.

Importantly, biological maturation is included as a moderator within the model. Biological maturation describes the progress towards a mature state and involves processes occurring within bodily tissues, organs and systems (Malina et al., 2015). With increasing maturity, it is suggested that there exists a sex-specific direct (kinematic) and indirect (psychological and behavioural) influence on aspects of motor competence (Cumming et al., 2012; Malina and Kozieł, 2014b; Sherar et al., 2010). Whilst for boys, puberty is associated with a defined increase in muscle mass that underpins elevated performance levels across a range of fitness parameters, for many girls, a marked increase in proportional fat mass has been found to negatively influence athletic performance and self-efficacy (Cumming et al., 2014; Malina, Bouchard, and Bar-Or, 2004; Sherar et al., 2010). Moreover, puberty-related hormonal changes contribute to a period of heightened social, emotional and cognitive development, with specific cognitive functions coming ‘on-line’ at different stages (Immordino-Yang, Darling-Hammond, and Krone, 2019). As a result of many children entering adolescence with poor motor competence, more research is now being conducted on adolescent populations (Hardy et al., 2013; Lester et al., 2017; O’ Brien et al., 2016b). However, a continued reliance on chronological age to describe and group participants likely confounds interpretation of reported associations and effects, and therefore fails to accurately consider the physiological, cognitive and social development associated with maturation. The potential role of biological maturation and growth in the interand intra-individual variability in motoric development, and the methods that can be adopted to sensitively capture the influence longitudinally are summarised in the 'Michigan State University Motor Performance Study' (Pacewicz and Myers, 2021; Pfeiffer et al., 2021)

In the conceptual model, environmental constraints are proposed as the home, school-setting, socio-economic status (SES) and cultural factors. Within the home, parental social interactions, parental sensitivity, and involvement of parents (quantitatively and qualitatively) are all deemed influential to motor competence, physical activity and cognitive development (Barnett et al., 2016a). In addition, SES can further influence factors associated with the home (i.e. physical context, stimulation, lower parental expectation) along with promoting independent risk factors that include nutritional status and access to organised sport (Hesketh et al., 2017; Pate et al., 2019). Whilst the moderating influence of the school may be multi-faceted, the pedagogical approach to physical education (PE) provides a key tool through which the motor and cognitive development of children can be enhanced (Rudd, O'Callaghan, and Williams, 2019). Implementing non-linear pedagogy, whereby task and environmental constraints are manipulated in a way that encourages the child to successfully develop and execute movement solutions, has been presented as an approach for enriching PE classes, and providing children with greater autonomy, self-regulation and improved decision making (Rudd et al., 2020; Rudd, O'Callaghan, and Williams, 2019).

7.3 Methods

7.3.1 Selection of literature

This systematic review was registered with the International Prospective Register of Systematic Reviews (PROSPERO) and adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement for reporting systematic reviews and meta-analyses. The review protocol can be accessed via: https://www.crd.york.ac.uk/PROSPERO/#recordDetails. In total, five electronic databases (PubMed, Web of Science, Scopus, PsycINFO and SPORTDiscus) were searched for peer-reviewed articles published only in English language, with no date restrictions applied. To formulate the search, search combinations were defined and implemented following discussion by all authors (Table 7).

Table 7. *Search combinations used with each of the five electronic databases (PubMed, Web of Science, Scopus, PsycINFO and SPORTDiscus) to identify potential studies for inclusion.*

Variable	**Search combination**
Motor competence	“motor skill*” OR “movement skill*” OR “motor development” OR “gross motor” OR “motor performan*” OR “Motor Proficien*” OR “motor abilit*” OR “object manipulation” OR “motor coordination” OR “actual competen*” OR “object control” OR “locomotor skill*” OR “motor proficiency” OR “motor competen*” OR “movement competenc*” OR “motor fitness” OR “fundamental movement” OR “fundamental motor” OR “basic movement” OR “manipulative skill*” OR “motor function*” OR “athletic skill*” OR “athletic competen*” OR “skill proficiency” OR “movement pattern” OR “motor fitness” OR “movement assessment”
Children	“child*” OR “adolescen*” OR “student” OR “teen*” OR “youth” OR “pediatric*” OR “paediatric*” OR “pube*” OR “juvenil*” OR “school*” OR “youngster*” OR “preschool*” OR “kindergart*” OR “kid” OR “kids” OR “playgroup*” OR “play-group*” OR “playschool*” OR “prepube*” OR “preadolescen*” OR “junior high*” OR “highschool*” OR “senior high” OR “young people*” OR “young person” OR “minors”
General cognition	“cognit*” OR “cognitive function” OR “cognitive skill*” OR “cognitive abil*” OR “neurocognitiv*” OR “cognitive development” OR “neuro-cognitive” OR “cognitive performance” OR “cognitive control”
Cool executive functions	“executive function*” OR ‘problem solving’ OR “planning” OR “reasoning” OR “fluid intelligence” OR “creativity” OR “working memory” OR “inhibition”

Hot executive functions	“decision making” OR “social cognit*” OR “decision making” OR “social cognition” OR “emotional regulat*” OR “cognitive flexibility”
Memory	“operational memory” OR “visuospatial memory” OR “implicit memory” OR “explicit memory ” OR “declarative memory” OR “semantic memory” OR “episodic memory”
Attention	“selective attention” OR “divided attention” OR “sustained attention” OR “vigilance” OR “attention* orienting”, OR “focusing” OR “executive attention” OR “focus”
Academic	“Academic achievement” OR “academic performance” OR “academic behavior” OR “standardized testing” OR “academic readiness” OR “school readiness” OR “task behavior” OR “classroom behavior”
Social-emotional/self-regulation	“self-regulat*” OR “behavior self-regulat*” OR “self-control” OR “delayed gratification” OR “temperamental control” OR “emotion*” OR “social” OR “social skills” OR “emotional skills” OR “life skills”

* word has been truncated to include different forms of the same word

7.3.2 Eligibility criteria

The eligibility for inclusion of studies was independently assessed by two authors (PH, MM) according to the following criteria:

1. The review was constrained to studies targeting typically developing children and youth (aged 3-18 years). Therefore, studies comprising of populations with known physical or cognitive impairment were not included.
2. Experimental and observational studies were required to have undertaken two or more assessment timepoints and to have measured as a minimum

inclusion criterion: motor competence and a cognitive and social-emotional development measurement at either time point.

3. Guided by the selection criteria presented by Barnett et al. (2016a), motor competence encompassed fundamental movement skills and motor coordination. Any study using a protocol that specifically assessed wider aspects of 'motor fitness' or 'physical fitness' (i.e. strength, flexibility) were excluded. Similarly, any study that specifically targeted fine motor skills was excluded.

4. If motor competence and components of either motor/physical fitness or fine motor skills were analysed and presented as a composite score (i.e. McCarron Assessment of Neuromuscular Development [MAND]; McCarron, 1997), they were excluded. An exception was those studies where gross motor competence analysis was presented independently from fine motor skills.

5. Studies needed to assess a summary score of at least one aspect of motor competence (i.e. object manipulation, locomotor). Within a summary score, at least two skill assessments needed to be included (i.e. for object manipulation - overhand throw, kick).

6. Studies that analysed a single individual skill (i.e. overhand throw) were excluded.

7. Only studies where motor competence was analysed using a validated process-oriented and/or product-oriented approach to motor competence assessment were included, this included any circuit-based approaches (i.e. Dragon Challenge (Tyler et al., 2018), Canadian Agility and Movement Skill Assessment [CAMSA]; Longmuir et al., 2017).

8. The psychometric properties (i.e. construct and content validity) relating to specific motor competence assessments were required to have been supported and presented in peer-reviewed evaluation and/or testing manuals.

9. Studies were included if the cognitive and social-emotional outcome(s) included a standardised test or a measure relating to any of the following: general cognition, executive functions, memory, attention, academic attainment/performance, and/or socio-emotional development.

10. Studies were included if they reported statistical analyses of (potential) changes in cognitive function (general cognition, executive functions, memory,

attention, academic) or indicators of socio-emotional development (self-regulation, temperament, emotion) in relation to motor competence.

11. The review only included studies published in English in peer-reviewed journals, with no date restriction being applied to the search.

All retrieved records were imported into the Rayyan systematic review platform for screening (Rayyan – Intelligent Systematic Review). Following the removal of duplicate studies, individual authors (LB, MAM, KM, PT, LR, CP, NV, PT, NG) were provided the opportunity to search their personal bibliographic libraries to identify additional articles for inclusion. An initial assessment of eligibility on retrieved titles and abstracts was completed independently by two authors (PH and MM). Following this, the same two authors completed a full text screen of all potentially included articles. In instances where agreement on inclusion/exclusion could not be reached (n=17), three additional authors (LB, CP, NV) were consulted to review the article, and each article was discussed until a resolution had been reached.

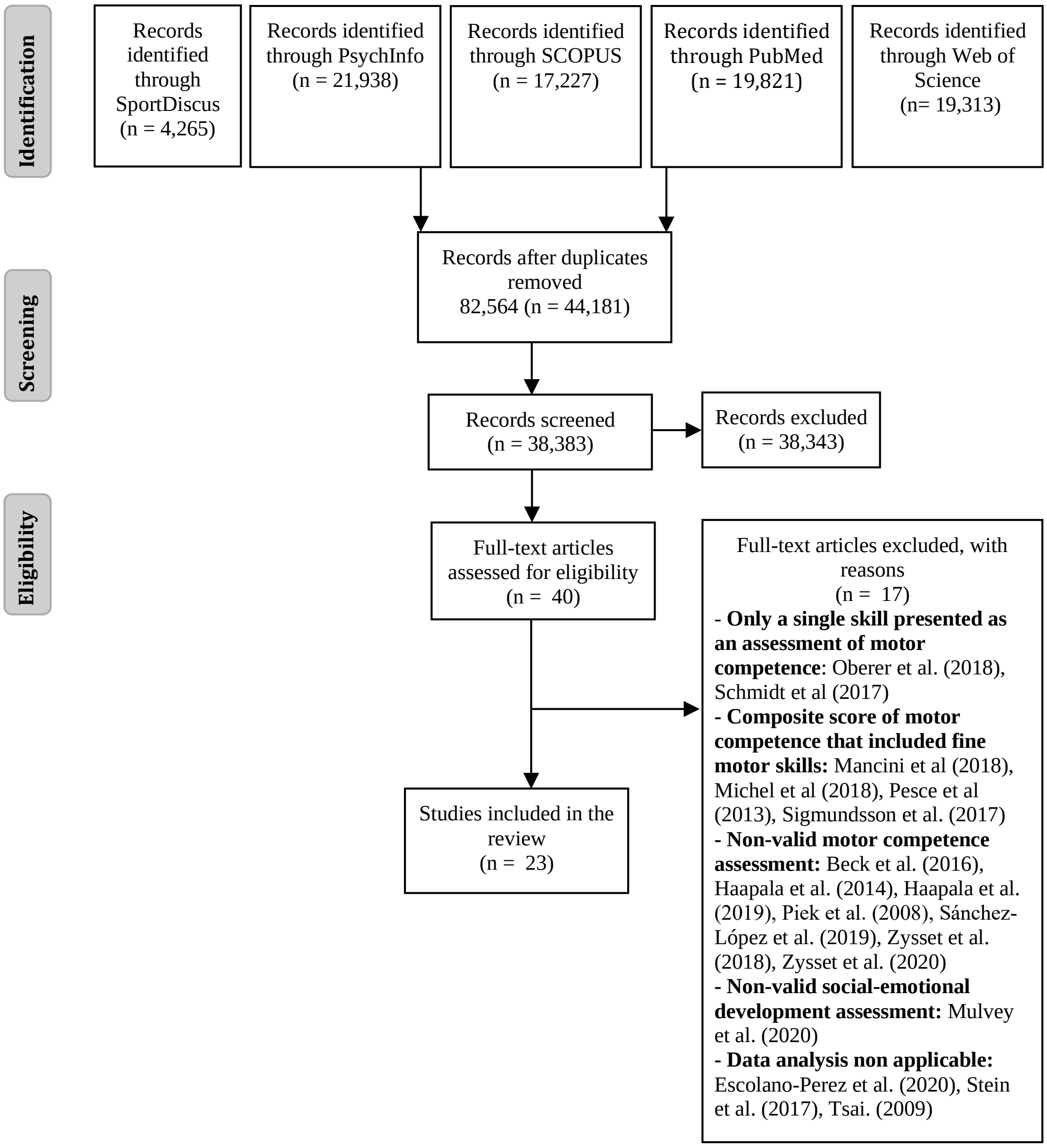


Figure 8. Flow of studies through review process

7.3.3 Data extraction and reliability

Descriptive data for included studies were extracted and uploaded to an excel document. Data extraction was completed by two authors (PH and MM) and verified by three further authors (LB, CP and NV). For all studies, study characteristics (first author, year, sample size, study type, number of timepoints and study length, statistical procedure, mediating and/or moderating variables), participant characteristics (sex, age, country, biological maturity, weight status), motor competence assessment, cognitive and/or social-emotional assessment, and study results were imputed by a single author (PH). In addition, for experimental studies, the intervention content was coded. All extracted data was then reviewed for accuracy (MM).

Risk of bias was assessed for individual studies by two authors (PH and NG). Prior to reviewing included studies, risk of bias was assessed on a subsample of five studies by both authors (PH and NG) to ensure consistency, with any disagreements resolved in a consensus meeting with an additional author (PT). The same two authors (PH and NG) then assessed the study quality of all studies (Table 10). To assess study quality, the criteria established from reviewing the Strengthening the Reporting of Observation Studies in Epidemiology (STROBE) statement (von Elm et al., 2014) were used. Following input from all authors, the criteria were amended to ensure strong applicability to the current review. This approach has been adopted in previous systematic reviews within this field (Barnett et al., 2016a; De Meester et al., 2020; Morgan et al., 2013). The individual criteria were marked as “yes” (a tick), “no” (a cross), “unclear” (?).

7.3.4 Criteria for risk of bias assessment

1. Could the participant selection have introduced bias i.e. were schools or students randomly selected or were other data provided to indicate population representativeness? For experimental studies, was the process of randomisation clearly outlined and adequately completed, including any between-group baseline differences?

2. Of those who consented to the study, did an adequate proportion have complete data for the outcome and all measures relating to this review (i.e. no more than 20 % of data was missing from longitudinal studies ≤ 6 months, and no more than 30 % for a studies ≥ 6 months)?

3. Did the study report the sources and details of motor competence assessment? Were valid measures of motor competence used (validation in same age group published or validation data provided in the manuscript)?

4. Did the study report adequate reliability of motor competence assessment [i.e. intra-class correlation (ICC) (or similar) ≥ 0.60] (Brown, Hume, and Chinapaw 2009) relating to the current study? For studies that used process-oriented motor competence instruments, adequate inter-rater reliability needed to be

reported [i.e. ICC (or similar) ≥ 0.60] in addition to the above validity and reliability measures.

5. Did the selected cognitive and social-emotional assessment provide evidence supporting construct validity (i.e. the extent to which the test provided a measure of the construct of interest)?

6. Did the study use appropriate statistical analysis for the study design?

7. Did the study report the sources and details of assessment of potential correlates?

7.3.5 Interpretation of scientific evidence

The effect size was estimated using the available data provided by the authors in each study (e.g. standardised regression coefficient or unstandardised beta, R^2 for multiple regression, *F*-test, *T*-tests, means, standard deviations, and sample sizes) with two freely effect size calculators (https://www.campbellcollaboration.org/escalc/html/EffectSizeCalculator-SMD22.php; https://www.danielsoper.com/statcalc/calculator.aspx?id=5). If authors reported correlation, Partial η2, and Cohen's *d*, these were recorded as effect size. Conventional guidelines for interpretation of the effect size were used (Portney, 2009; Preacher & Kelley, 2011; Wen & Fan, 2015).

7.4 Summary of Included studies

Following removal of duplicates, the titles and abstracts of 38,383 studies were screened for eligibility (*Figure 8*). Descriptive data (Table 8) for the 23 studies that met the inclusion criteria were extracted by two authors (PH and MM). Of the included studies, 12 (Aadland et al., 2017b; Battaglia et al., 2018; Bedard et al., 2018; Botha and Africa, 2020; Ericsson, 2008; Koutsandréou et al., 2016; Lee et al., 2020b; Mulvey et al., 2018b; De Oliveira et al., 2018; Pesce et al., 2016; Robinson, Palmer, and Bub, 2016; Taunton, Mulvey, & Brian, 2018) used an experimental study design, with the remaining 11 studies (Aadland et al., 2017a; Gu et al., 2018; Jaakkola et al., 2015; Ludyga et al., 2020; MacDonald et al., 2016; Niederer et al., 2011; Osorio-Valencia et al., 2018; Rigoli et al., 2013; Son and Meisels, 2006; Syväoja et al., 2019; de Waal and Pienaar, 2020) using an observational design.

The majority of included studies were conducted in the USA (Gu et al., 2018; Lee et al., 2020; MacDonald et al., 2016; Mulvey et al., 2018; Robinson, Palmer, and Bub, 2016; Son and Meisels, 2006), with two studies conducted in each of the following countries: South Africa (De Waal and Pienaar, 2020; Botha and Africa, 2020), Italy (Battaglia et al., 2018; Pesce et al., 2016), Australia (De Oliveira et al., 2018; Rigoli et al., 2013), Finland (Jaakkola et al., 2015; Syväoja et al., 2019), Norway (Aadland et al., 2017a; Aadland et al., 2017b) and Germany (Koutsandréou et al., 2016; Ludyga et al., 2020). In addition, a single study was conducted in Canada (Bedard et al., 2018), Sweden (Ericsson, 2008), Switzerland (Niederer et al., 2011), and Mexico (Osorio-Valencia et al., 2018).

Pre-school children were recruited to participate in 11 studies (Battaglia et al., 2018; Bedard et al., 2018; De Oliveira et al., 2018; Gu et al., 2018; Macdonald et al., 2016; Mulvey et al., 2018; Niederer et al., 2011; Osorio-Valencia et al., 2018; Robinson et al., 2016; Son & Meisels, 2006; Taunton et al. 2018), pre-adolescent children in 10 of the studies (Aadland et al., 2017a; Aadland et al., 2017b; Botha and Africa, 2020; de Waal & Pienaar, 2020; Ericsson, 2008; Koutsandréou et al., 2016; Lee et al., 2020; Ludyga et al., 2020; Pesce et al., 2016; Rigoli et al., 2013), and only two studies were conducted with adolescent populations at baseline (Jaakkola et al., 2015; Syväoja et al., 2019). Although the studies included within this review were characterised by a range of sample sizes (11-12,583), 65% of included studies had sample sizes >100 participants.

Table 8. *Descriptive information of included observational studies*

Authors	**Country**	**Sample**	**Sex**	**Age (mean ± SD) Baseline**	**Motor competence assessment**	**Motor competence assessment method**	**Cognitive assessment**	**Social-emotional assessment**	**Analysis**	**Study protocol**
Aadland et al. (2017a)	Norway	1,129	541(g), 588(b)	10.2 ± 0.3y	MABC-2	Product-oriented - Object manipulation	Numeracy, reading, English (NDET) inhibition (Stroop colour and word test) cognitive flexibility (Verbal fluency test, trail and making test) working memory (WISC-IV)		SEM (mediation), Linear mixed model	Observational, 7m Object manipulation **(T1)** to academic performance **(T2)** – through executive function **(T2)**
de Waal & Pienaar. (2020)	South Africa	381	200(g), 181(b)	6.9 ± 0.4y	BOT-2	Product-oriented - R and A, strength, and balance	Numeracy, literacy, writing skills (The mastery of basic learning assessment), maths, home language, second language, natural sciences, and technology and life orientation (CAPS intermediate) language, maths (ANA), English, maths (NWPA)		Repeated measure ANOVA, SEM	Observational, 7y R and A, strength, and balance **(T1)** to academic achievement **(T2)** R and A, strength, and balance **(T1)** to academic achievement **(T3)** Academic achievement **(T1)** to R and A, strength, and balance **(T2)** Academic achievement **(T1)** to R and A, strength, and balance **(T3)**
Gu et al. (2018)	USA	141	69(g), 72(b)	5.4 ± 0.5y	PE Metrics	Process-oriented - Locomotor skills, object manipulation	Cognitive functioning (PedsQL™ Cognitive Functioning Scale)	Psychosocial function	Multiple regression, SEM	Observational, 1y (academic) Locomotor skills **(T1)** to Cognitive functioning Scale, psychosocial function **(T2)** Object manipulation **(T1)** to Cognitive functioning Scale, psychosocial function **(T2)**
Jaakkola et al. (2015)	Finland	325	162(g), 162(b)	13.1 ± 0.3y	FMS Test Package	Product-oriented - Leaping, shuttle-run, dribbling	Finnish language, mathematics, and history (academic grades)		SEM (multi-group)	Observational, 34m Leaping, shuttle-run, dribbling **(T1)** to academic performance **(T2)** Leaping, shuttle-run, dribbling **(T1)** to academic performance **(T3)** Leaping, shuttle-run, dribbling **(T2)** to academic performance **(T3)**

										Academic performance **(T1)** to leaping, shuttle-run, dribbling **(T2)** Academic performance **(T2)** to leaping, shuttle-run, dribbling **(T3)**
Ludyga et al. (2020)	Germany	52	25(g), 27(b)	10.3 ± 0.5y	MOBAK-5	Product-oriented - Locomotor skills and object manipulation	Visual working memory (Sternberg task), event-related potentials		SEM (path analysis)	Observational, 9m Motor competence **(T1)** to reaction time **(T2)** Motor competence **(T1)** to iCNV amplitude **(T2)** Motor competence **(T1)** to Cue-P300 **(T2)**
MacDonald et al. (2016)	USA	92	33(g), 59(b)	4.3 ± 0.7y	PDMS-2	Process-oriented - Object manipulation	Attentional flexibility, working memory, inhibitory control (HTKS)	Social behaviour (SSIS-RS)	SEM	Observational, 5m Object manipulation **(T1)** to executive function **(T2)** Object manipulation **(T1)** to externalizing/hyperactivity **(T2)** Object manipulation **(T1)** to cooperation **(T2)** Object manipulation **(T1)** to self-control **(T2)**
Niederer et al. (2011)	Switzerland	245	121(g), 124(b)	5.2 ± 0.6y	Balance beam, Obstacle course	Circuit-based - Agility, balance	Attention performance (KHV-VK), partial working memory performance (IDS)		Mixed linear regression models	Observational, 9m Agility **(T1)** to attention performance, partial working memory performance **(T2)** Balance **(T1)** to attention performance, partial working memory performance **(T2)**
Osorio-Valencia et al. (2018)	Mexico	148	64(g), 84(b)	0-5y	PDMS-2	Process-oriented - Stationary balance, locomotor skills, object manipulation	McCarthy Scales of Children's Abilities (verbal, quantitative, memory)		Linear regression	Observational, 24m Balance **(T1)** to cognitive abilities **(T2)** Locomotor skills **(T1)** to cognitive abilities **(T2)** Object manipulation **(T1)** to cognitive abilities **(T2)**
Rigoli et al. (2013)	Australia	41	27(g), 14(b)	5-11y	MAND	Product-oriented - Gross motor skills	Visual working memory (The One-Back task)		Multi-level mixed effects linear regressions	Observational, 18m Gross motor skills **(T1)** to visual working memory **(T2)** Visual working memory **(T1)** to gross motor skills **(T2)**
Son & Meisels (2006)	USA	12,583	6,241 (g), 6,342 (b)	49-83m (4.1-6.9y)	ESI-R	Product-oriented - Balancing, hopping, skipping, and walking backwards	Item Response Theory based composite scores of reading and mathematics		Hierarchical regression analyses	Observational, 15.8m and 21.5m Gross motor skills **(T1)** to reading **(T2)** Gross motor skills **(T1)** to mathematics **(T2)**

Syväoja et al. (2019)	Finland	954	496(g), 458(b)	12.5 ± 1.3y	5-leaps test, throwing–catching combination test	Product-oriented - Leaping, throwing-catching combination	Overall academic achievement (Grade point average)		SEM, Linear growth curve modelling	Observational, 2m Leaping, throwing-catching combination **(T1)** to academic achievement **(T2)** Leaping, throwing-catching combination **(T2)** to academic achievement **(T3)** Academic achievement **(T1)** to leaping, throwing-catching combination **(T2)** Academic achievement **(T2)** to leaping, throwing-catching combination **(T3)**

BOT-2 Bruininks-Oseretsky Test of Motor Proficiency (Second Edition), *b* boy, *ESI-R.* Early Screening Inventory-Revised, *FMS Test Package* Fundamental Movement Skills Test Package, *g* girl, *HTKS* Head Toes Knees Shoulders, *KHV-VK* Konzentrations-Handlungsverfahren für Vorschulkinder, *MABC-2* Movement Assessment Battery for Children - Second Edition, *m* months, *MAND* McCarron Assessment of Neuromuscular Development, *MOBAK-5* Motoriche BAsisKompetenzen-5, *NDET* Norwegian Directorate for Education and Training, , *PDMS-2* Peabody Developmental Motor Scale (Second Edition), *PedsQL*™ Pediatric Quality of Life Inventory, *R and A* Running speed and agility, *SEM* structural equation model, *T* timepoint, *WISC-IV* Wechsler Intelligence Scale for Children ® - Fourth Edition, *SSIS-RS* Skills Improvement System – Rating Scales, *y* years

Table 9. *Descriptive information of included experimental studies*

Authors	Country	Sample	Sex	Age (mean ± SD) Baseline	Intervention	Motor competence assessment	Motor competence assessment method	Cognitive assessment	Social-emotional assessment	Study protocol
Aadland et al. (2017b)	Norway	1,129	541(g), 588(b)	10.2 ± 0.3y	PA educational lesson (3x30min per week), PA breaks during lessons (5mins x 5 days/week), PA homework (10mins x 5 days/week). CG participated in curriculum-prescribed 90 min/week of PE and 45 min/week PA.	MABC-2	Product-oriented - Aiming, catching, shuttle run	Inhibition, cognitive flexibility, working memory (WISC-IV)		Experimental, 10m **T1:** Aiming, catching, shuttle run, inhibition, cognitive flexibility, working memory **T2:** Aiming, catching, shuttle run, inhibition, cognitive flexibility, working memory
Battaglia et al. (2018)	Italy	119	51(g), 68(b)	Con: 4.3 ± 0.7y, Int: 4.8 ± 0.8y	PE delivered 2 hrs/week x 16 weeks, specific aims of developing body awareness, fundamental motor and perceptual-sensory skills. The CG participated in classroom activities for the same amount of time as the IG.	TGMD	Process-oriented - Object manipulation, locomotor skills	Preliteracy skills (PRCR-2/2009)		Experimental, 16w **T1:** Literacy readiness, object manipulation, locomotor skills **T2:** Literacy readiness, object manipulation, locomotor skills
Bedard et al. (2018)	Canada	11	5(g), 6(b)	45.6 ± 7.3m (3.8 ± 0.6y)	The intervention was run 1 h/week x 10 weeks. Each session consisted of 30-min of movement skill instruction, 15-min of free play, and a 15-min interactive reading circle.	PDMS-2	Process-oriented - Gross motor skills	Preliteracy skills (PALS-PK)		Experimental, 10w **T1:** Gross motor skills, preliteracy skills **T2:** Gross motor skills, preliteracy skills **T3:** Gross motor skills, preliteracy skills **T4:** Gross motor skills, preliteracy skills
Botha & Africa. (2020)	South Africa	97	-	6-7y	Focused primarily on perceptual-motor skills and incorporated different letters and shapes into gross motor activities. The experimental group participated in the intervention twice a week for 60 min.	BOT-2	Product-oriented - Upper limb coordination, balance, running speed and agility	Letter knowledge (ESSI reading and spelling tests)		Experimental, 12w **T1:** Upper limb coordination, balance, running speed and agility, letter knowledge **T2:** Upper limb coordination, balance, running speed and agility, letter knowledge

De Oliveira et al. (2018)	Australia	511	254(g), 257(b)	5.4 ± 3.6y	Animal Fun (AF) was implemented for 30 mins/day x 4 days/week for a minimum of 10 weeks. AF focuses on embedding gross and fine motor development and social-emotional development into learning curriculum. CG classes followed normal curriculum.	BOT-2 SF, MABC-2	Product-oriented - Aiming, catching and balance	Intellectual functioning (WPPSI-III)	Experimental, 18m **T1**: Aiming, catching and balance, WPPSI-III **T2:** Aiming, catching and balanc**e** **T3:** Aiming, catching and balance
Ericsson. (2008)	Sweden	251	-	School year 1-3	Intervention groups PE was extended from two to three lessons and different local sports clubs had physical activities for two lessons every week. Intervention group had PA for five lessons per week and also, if needed, one extra lesson of motor training per week. The control group had only the school's ordinary PE for two lessons per week.	MUGI Observation	Process-oriented - Balance/bilateral coordination, hand-eye coordination	Conners' questionnaire (teachers' and parents' conceptions of children's attention ability and impulse control) academic performance	Experimental, 3y **SY1:** Motor observations, reading development, teachers' and parents' conceptions of children's attention ability and impulse control **SY2:** Motor observations, academic performance, teachers' conceptions of children's attention ability and impulse control **SY3:** Motor observations, word and reading test, parents' conceptions of children's attention ability and impulse control
Koutsandréou et al. (2016)	Germany	71	39(g), 32(b)	9.4 ± 0.6y	Randomly assigned to a cardiovascular exercise (CE), a motor exercise (ME), or a control group (CON). Intervention period that involved 10 weeks of an additional after school exercise regimen, which took place three times a week for 45 min.	HGMT	Circuit-based - balance, rhythm, spatiotemporal orientation, and motor adaption to moving objects	Working memory processing (The Letter Digit Span)	Experimental, 10w **T1:** Balance, rhythm, spatiotemporal orientation, and motor adaption to moving objects, working memory processing **T2:** Balance, rhythm, spatiotemporal orientation, and motor adaption to moving objects, working memory processing
Lee et al. (2020)	USA	31	19(g), 12(b)	6.7 ± 1.0y	An 8-week FMS intervention, embedded in an afterschool program three times per week (60 mins each time) in 24 sessions, control group followed a regular afterschool program (e.g. unstructured child free-play, drawing, reading, and/or academic tutoring)	TGMD-2	Process-oriented - Locomotor skills and object manipulation	Cognitive functioning (PedsQL™ (Cognitive Functioning Scale)	Experimental, 8w **T1:** Locomotor skills and object manipulation, cognitive functioning scale **T2:** Locomotor skills and object manipulation, cognitive functioning scale

Mulvey et al. (2018)	USA	107	58(g), 49(b)	5.4 ± 0.8y	Intervention condition participated in the SKIP motor skill intervention twice weekly over 6 weeks for 30 min. Children in the control condition participated in the center's "business as usual" condition 5 days per week for 30 min.	TGMD-2	Process-oriented - Locomotor skills and object manipulation		Behavioural regulation (HTKS task)	Experimental, 6w **T1:** Locomotor skills and object manipulation, behavioural regulation **T2:** Locomotor skills and object manipulation, behavioural regulation
Pesce et al. (2016)	Italy	460	230(g), 230(b)	5-10y	The two experimental interventions differed from one another in that in one the PA games were altered to involve a higher amount of mental engagement and challenge executive functions (cognitively engaging specialist led ceS-led intervention). All children participated in PE for 1 hr once a week, and the intervention duration was 6 months	M-ABC	Product-oriented - Object manipulation, static and dynamic balance	Inhibition and working memory updating (RNG task), attention (CAS)		Experimental, 6m **T1:** Object manipulation, static and dynamic balance, inhibition and working memory updating (RNG task), attention (CAS) **T2:** Object manipulation, static and dynamic balance, inhibition and working memory updating (RNG task), attention (CAS)
Robinson et al. (2016)	USA	113	57(g), 56(b)	51.9 ± 6.5m (4.3 ± 0.5y)	Children were randomly assigned to a CHAMP treatment or control. Children in the CHAMP group replaced their outdoor recess with CHAMP 3 days/week for 5 weeks (15x 40 min sessions). The control condition was the typical movement program. CHAMP looks to enhance motor skills, perceived physical competence, and physical activity	TGMD-2	Process-oriented - Locomotor skill and object manipulation		Self-regulation (The delay of gratification snack task of the Preschool Self-Regulation Assessment)	Experimental, 5w **T1**: Locomotor skills and object manipulation, self-regulation **T2:** Locomotor skills and object manipulation, self-regulation
Taunton et al. (2018)	USA	80	39(g), 41(b)	55.4 ± 7.0m (4.6 ± 0.6y)	Children in the experimental condition participated in the SKIP motor skill intervention twice weekly for 6 weeks for 30 mins during each session (360 mins), and they participated in "business as usual" (i.e. regularly implemented recess) the other 3 days per week throughout the study.	TGMD-2	Process-oriented -Locomotor skills and object manipulation		Surgency, negative affect, and effortful control (CBQ)	Experimental, 6w **T1:** Locomotor skills and object manipulation **T2**: Surgency, negative affect, and effortful Control **T3**: Locomotor skills and object manipulation

b boys, *BOT-2* Bruininks-Oseretsky Test of Motor Proficiency (Second Edition), *BOT-2 SF* Bruininks-Oseretsky Test of Motor Proficiency (Second Edition) short form, *CAS* cognitive assessment system, *CBQ* Children's behaviour questionnaire, *CG* control group, *CHAMP* Children's health activity motor programme, *con* control, *g* girls, *HTKS* Head Toes Knees Shoulders, *Int* intervention, *MABC* Movement Assessment Battery for Children, *MABC-2* Movement Assessment Battery for Children - Second Edition, *mins* minutes, *m* months *PA* physical activity, *PE* physical education, *PDMS-2* Peabody Developmental Motor Scale (Second Edition), *PedsQL*™ Pediatric Quality of Life Inventory, *TGMD-2* Test of Gross Motor Development – Version 2, *RNG* random number generation, *SKIP* Successful Kinesthetic Instruction for Preschoolers, *SY* school year, *T* timepoint, *w* weeks, *WISC-IV* Wechsler Intelligence Scale for Children ® - Fourth Edition, *WPPSI-III* Wechsler Preschool and Primary Scale of Intelligence – Version 3, *y* years

For all included studies, a high rate of agreement (91%) was observed between researchers (NG and PH) on the risk of bias assessment. Within the studies, there were eight individual criteria where initial agreement between authors was not reached. In these instances, the study was further reviewed and a final decision agreed upon with an additional author (PT). Only 48% of included studies were found to have achieved representative sampling and, likewise, only 52% of studies presented an adequate level of data completion for participants. Although the majority of studies included validation data for the motor competence assessment (validation in same age group published or validation data provided in the manuscript) and for the assessment of cognitive and social-emotional development, only 44% of studies reported adequate reliability for the motor competence assessment used in the specific study. In assessing the data analysis of included studies, over 80% of studies were found to use an appropriate approach to data analysis, with 83% of included studies considering covariates.

Table 10. *Methodological quality*

		Study and assessment quality					Data analysis	
Authors	Study Design	1. Representative Sampling	2. Minimal missing data	3. Valid motor competence assessment tool	4. Motor competence assessment reliabilities	5. Cognitive/Socio-emotional assessment validity	6. Appropriate statistical analysis	7. Covariates accounted for
Aadland et al.(a)	Observational	✓	✓	✓	x	✓	✓	✓
Aadland et al.(b)	Experimental	✓	✓	✓	x	✓	✓	✓
Battaglia et al.	Experimental	x	?	?	x	?	✓	✓
Bedard et al.	Experimental	x	✓	✓	x	✓	?	x
Botha & Africa	Experimental	✓	✓	✓	x	✓	?	x
De Oliveira et al.	Experimental	x	x	✓	✓	✓	✓	✓
De Waal & Pienaar	Observational	✓	x	x	x	x	✓	✓
Ericsson.	Experimental	x	?	✓	✓	✓	?	x
Gu et al.	Observational	x	?	✓	✓	✓	✓	✓
Jaakkola et al.	Observational	x	✓	x	x	x	✓	✓
Koutsandreou et al.	Experimental	✓	x	x	x	✓	✓	x
Lee et al.	Experimental	x	✓	✓	✓	✓	✓	x
Ludyga et al.	Observational	x	?	✓	x	✓	✓	✓
MacDonald et al.	Observational	x	✓	✓	✓	✓	✓	✓
Mulvey et al.	Experimental	✓	✓	✓	✓	✓	✓	✓
Niederer al.	Observational	✓	✓	x	✓	✓	✓	✓
Osorio-Valencia et al.	Observational	x	x	✓	x	x	✓	✓
Pesce et al.	Experimental	✓	x	✓	✓	✓	✓	✓
Rigoli et al.	Observational	✓	✓	✓	x	✓	✓	✓
Robinson et al.	Experimental	x	x	✓	✓	x	✓	x

Son & Meisels	Observational	✓	✓	✓	**x**	**?**	✓	✓
Syväoja et al.	Observational	**x**	✓	**x**	**x**	**x**	✓	✓
Taunton et al.	Experimental	✓	**?**	✓	✓	✓	**?**	✓
Totals by risk of bias criteria (23)		**11**	**12**	**17**	**10**	**15**	**19**	**17**

✓ met criteria, **x** did not meet criteria, ? unclear whether it met criteria

7.4.1 Motor competence assessment

For studies that met the inclusion criteria, motor competence was assessed using process-oriented, product-oriented, and circuit-based instruments. A process-oriented assessment was used in 10 studies (Battaglia et al., 2018; Bedard et al., 2018; Ericsson, 2008; Gu et al., 2018; Lee et al., 2020; Macdonald et al., 2016; Mulvey et al., 2018; Osorio-Valencia et al., 2018; Robinson et al., 2016; Taunton et al., 2018), a product-oriented instrument in 11 studies (Aadland et al., 2017a; Aadland et al., 2017b; Botha and Africa, 2020; Jaakkola et al., 2015; Ludyga et al., 2020; De Oliveira et al., 2019; Pesce et al., 2016; Rigoli et al., 2013; Son and Meisels, 2006; Syväoja et al., 2019; de Waal & Pienaar, 2020), with the remaining two studies (Koutsandréou et al., 2016; Niederer et al., 2011) using a circuit-based approach to assessment. The TGMD-2 was the most commonly selected process-oriented assessment (Lee et al., 2020; Mulvey et al., 2018; Robinson et al., 2016; Taunton et al., 2018), with three studies using the PDMS-2 (Bedard et al., 2018; MacDonald et al., 2016; Osorio-Valencia et al., 2018), and further studies using the Test TGM (Battaglia et al., 2018), the MUGI Observation instrument (Ericsson, 2008) and the PE Metrics assessment (Gu et al., 2018). A range of product-oriented instruments were used in the included studies; the MABC-2 (Aadland et al., 2017a; Aadland et al., 2017b; De Oliveira et al., 2019) and BOT-2 (Botha and Africa, 2020; De Oliveira et al., 2018; de Waal & Pienaar, 2020) were both used in three studies each. For the remaining six studies the M-ABC (Pesce et al., 2016), MAND (Rigoli et al., 2013), FMS Test Package (Jaakkola et al., 2015), MOBAK-5 (Ludyga et al., 2020), 5-leaps test and throwing-catching combination test Syväoja et al. (2019), and the ESI-R (Son and Meisels, 2006) were all used in single studies. The two circuit-based approaches to assessment were the Heidelberg Gross Motor Test used in the study of Koutsandréou et al. (2016) and the Balance beam and Obstacle course assessment used in the study of Niederer et al. (2011). In nine studies (Aadland et al., 2017a; Bedard et al., 2018; Ericsson, 2008; Ludyga et al., 2020; Koutsandréou et al., 2016; Mulvey et al., 2018; Rigoli et al., 2013; Son and Meisels, 2006; Syväoja et al., 2019) a composite level outcome of motor competence was analysed, with the remaining studies assessing object control/manipulation skills, locomotor skills, and balance competency, or isolated skills from these constructs.

7.4.2 Cognitive and social-emotional assessment

Cognitive and social-emotional assessment validity was deemed acceptable for 15 (65%) of the included studies within the current review. Only three studies exclusively investigated the relationship of motor competence and aspects of social-emotional development (Mulvey et al., 2018; Robinson et al., 2016; Taunton et al., 2018). In contrast, 20 studies analysed the relationship of motor competence and aspects of cognitive functioning. In the studies that included children of pre-school age, pre-literacy score and intellectual functioning were the assessed outcomes. The studies that included school-aged children assessed the relationship of motor competence and domains of cognitive functioning (i.e. executive functions), academic performance or social-emotional development. The two studies that included adolescent samples, included aspects of academic performance as their assessed outcome.

7.4.3 Exposure characteristics

Of the 11 studies that followed an observational study design, the length of study ranged between two months and seven years, and of these studies, eight included two timepoints, with the remaining studies all having three measurement timepoints (Table 8). The 12 experimental design studies (Table 9) had a study length of between six-weeks to three-years. The intervention designs included individual, environmental and physical activity characteristics. Interventions primarily occurred as part of the school-day and included the promotion of motor competence within a an enriched and developmentally appropriate PE context.

7.4.4 Biological maturity

The majority of studies (> 50%) within the current review focused on pre-pubescent children and therefore biological maturity was not included within the study analyses. Of the eight studies that can be considered to have included pubertal participants during the study duration, the possible confounding influence of pubertal status was only adjusted for in three studies (Aadland et al., 2017a; Aadland et al., 2017b; Syväoja et al., 2019), with a further study assessing pubertal status to ensure all participants were pre-pubescent (Koutsandréou et al., 2016). No studies assessed the influence of biological maturity on the relationship of motor competence and cognitive and social development in the primary analyses.

7.4.5 Observational evidence

As shown in Table 11, there was no clear pattern of evidence supporting the relationship between motor competence and cognitive and social-emotional outcomes, or for the reverse direction of this relationship (cognitive/social-emotional development - motor competence). The majority of eligible analyses assessed the motor competence - cognition/social - emotional development path, with few assessing the reverse path (cognition/social-emotional development - motor competence). Of the observational studies, only the studies of Ludyga et al. (2020), MacDonald et al. (2016) and Son & Meisels (2006) presented evidence supporting the positive influence of motor competence across all of their analyses. The remaining observational studies all found indeterminate, weak evidence, with effect sizes reported as small for all analyses aside from a single study (Jaakkola et al., 2015).

A total of five observational studies assessed the longitudinal influence of motor competence on aspects of academic performance (Aadland et al., 2017a; Jaakkola et al., 2015; Son and Meisels, 2006; Syväoja et al., 2019; de Waal & Pienaar, 2020). Of these studies, the leap skill was found to have a consistent small-moderate positive influence (16/21 analyses), although these analyses were all from a single study (Jaakkola et al., 2015). Two further studies found positive evidence (6/9 analyses) for the influence of composite motor competence on academic performance, with effect sizes ranging from small-large (Son & Meisels, 2006; Syväoja et al., 2019). A similar level of evidence was found for the reverse path (academic performance - motor competence), with two studies finding a positive relationship between academic performance and the leap skill and composite motor competence (Jaakkola et al., 2015; Syväoja et al., 2019). Of the studies that found a positive influence of motor competence on academic performance, all assessed motor competence using a product-oriented assessment and included mid-childhood and adolescent samples (Jaakkola et al., 2015; Son & Meisels, 2006; Syväoja et al., 2019).

Some evidence relating to the positive influence of motor competence on specific and composite level executive functions was presented in eligible studies. Working memory was the most commonly assessed outcome, with balance (4/5 analyses), running speed and agility (1/2 analyses), and composite motor competence (6/8 analyses) all found to have a positive relationship, with effect sizes ranging from small-large (Ludyga et al., 2020; Niederer et al., 2011; Osorio-Valencia et al., 2018). For attention and composite executive functions, the evidence was less supportive, although in a single analysis, object manipulation competence was found to have a moderate influence on composite executive functions (MacDonald et al., 2016). The reverse path (executive functions - motor competence) was only analysed in the study of Rigoli et al. (2013), with 2/4 analyses showing a small positive influence of working memory on later motor competence level.

In relation to cognitive functioning, psychosocial functioning and social behaviour, a positive influence of object manipulation and locomotor skills was found in analyses across two studies (Gu et al., 2018; Macdonald et al., 2016). Specifically, for social behaviour, object manipulation was found to positively influence the outcome in all analyses (6/6). No studies presented eligible analyses investigating the reverse paths for these variables. For the studies that found a positive influence of motor competence on cognitive functioning, psychosocial functioning and social behavioural outcomes, a process-oriented assessment of motor competence was completed.

Table 11. *Analyses and Results (Observational studies)*

	Significant improvement Reported effect sizes	**No significant improvement Any reported effect sizes**	**Summary: significant positive finding**
	Summary of studies classified by cognitive and social-emotional outcome		
	Academic performance		
Catching		Aadland et al. (2017a) *Small* (3/3)	0/3
Aiming		Aadland et al. (2017a) *Small* (3/3)	0/3
Balance		de Waal and Piennar (2020) *Small* (6/6)	0/6
Running speed & agility	Jaakkola et al. (2015) *Small* (1/1)	de Waal and Piennar (2020) (6/6) Jaakkola et al. (2015) *Small* (23/23)	1/30
Leaping	Jaakkola et al. (2015) *Small* (14/24) Jaakkola et al. (2015) *Moderate* (2/24)	Jaakkola et al. (2015) *Small* (8/8)	16/24
Motor competence	Syväoja et al. (2019) (1/10) Son and Meisels (2006) *Small* (2/10) Son and Meisels (2006) *Large* (2/10) Syväoja et al. (2019)* (1/10)	Syväoja et al. (2019) *Small* (4/4)	6/10
	Attention		
Balance		Niederer et al. (2011) *Small* (2/2)	0/2
Running speed & agility	Niederer et al. (2011) *Small* (1/2)	Niederer et al. (2011) *Small* (1/1)	1/2
	Working memory		
Object manipulation		Osorio-Valencia et al. (2018)* (3/3)	0/3
Locomotor skills		Osorio-Valencia et al. (2018)* (3/3)	0/3
Balance	Niederer et al. (2011) *Small* (2/5) Osorio-Valencia et al. (2018)* (2/5)	Osorio-Valencia et al. (2018)* (1/5)	4/5
Running speed & agility	Niederer et al. (2011) *Small* (1/2)	Niederer et al. (2011) *Small* (1/2)	1/2
Motor competence	Ludyga et al. (2020) *Moderate* (4/8) Ludyga et al. (2020) *Large* (2/8)	Rigoli et al. (2013) *Small* (2/2)	6/8
	Executive functions		
Object manipulation	MacDonald et al. (2016) *Moderate* (1/1)		1/1
Catching		Aadland et al. (2017a) *Small* (3/3)	0/3
Aiming		Aadland et al. (2017a) *Small* (3/3)	0/3
	Cognitive functioning		
Object manipulation	Gu et al. (2018) *Small* (1/2)	Gu et al. (2018)* (1/2)	1/2
Locomotor skills	Gu et al. (2018) *Small* (2/2)		2/2
	Psychosocial function		
Object manipulation	Gu et al. (2018) *Small* (1/1)		1/1
Locomotor skills	Gu et al. (2018) *Small* (1/1)		1/1
	Social behaviour		
Object manipulation	MacDonald et al. (2016) *Small* (6/6)		6/6

	Summary of studies classified by motor competence outcome		
	Balance		
Academic performance		de Waal and Piennar (2020) *Small* (6/6)	0/6
	Running speed & agility		
Academic performance		de Waal and Piennar (2020) *Small* 6/14 Jaakkola et al. (2015) *Small* (8/14)	0/14
	Leaping		
Academic performance	Jaakkola et al. (2015) *Small* (5/8)	Jaakkola et al. (2015) *Small* (3/8)	5/8
	Motor competence		
Academic performance	Syväoja et al. (2019) *Small* (1/2)	Syväoja et al. (2019) *Small* (1/2)	1/2
	Motor competence		
Working memory	Rigoli et al. (2013) *Small* (2/4)	Rigoli et al. (2013) *Small* (2/4)	2/4

**ES* effect size could not be calculated due to lack of information

7.4.6 Experimental evidence

The inclusion criteria for the current review permitted studies that assessed parallel gains in motor competence and cognitive and social-emotional development. This type of study design cannot explicitly answer the question of whether changes in motor competence have a causal influence upon outcome variables (and vice-versa). However, these studies do afford insight into the developmental association of variables within an interventional context.

Four experimental studies (Battaglia et al., 2018; Bedard et al., 2018; Botha and Africa, 2020; Ericsson, 2008) assessed the role of an intervention in eliciting positive adaptions in aspects of motor competence and academic performance, with these studies reporting indeterminate evidence and no clear domain specific outcome patterns (small-large effect sizes). Pre-literacy skills were the assessed outcome in three of the studies (Battaglia et al., 2018; Bedard et al., 2018; Botha & Africa, 2020). Of these studies, no significant differences in academic performance between intervention- and control-group at follow-up were found, and only the studies of Battaglia et al. (2018) and Bedard et al. (2018) showed a parallel improvement in motor competence and academic performance across the intervention. The study of Bedard et al. (2018) did not include a control group, and although significant changes were observed in motor competence (process-oriented) and alphabet knowledge and print-concept skills from pre-post intervention, between post and follow-up no significant changes were evident. Battaglia et al. (2018) reported significant between-group (intervention and control) differences in the improvement of object control and locomotor skills, although when gain scores across the four pre-literacy indicators were analysed, no between-group differences were evident. In children aged 6-7 years, Botha & Africa (2020) reported an aligned improvement in bilateral coordination and balance and ESSI reading and spelling, with the strongest correlations found between motor competence (upper-limb coordination and balance) and spelling. Although De Oliveira et al. (2018) found a significant difference in improvement in balance between intervention- and control-group, no moderating effect of intellectual functioning was found at post-intervention or follow-up in pre-school children.

Only one study (Pesce et al., 2016) investigated how a change in motor competence influenced adaptions in executive functions, with four further studies (Aaland et al., 2017b; Ericsson, 2008; De Oliveira et al., 2018; Koutsandreou et al., 2016) all analysing outcomes of motor competence and executive functions in parallel. Using a product-oriented motor competence assessment, Pesce et al. (2016) reported significant post-intervention differences between the intervention and control group in only one of three analysed executive functions. The authors found ball skill competence but not balance to mediate the influence of an enriched PE intervention (directed exploration, task complexity) on inhibitory function, with this mediated path moderated by the level of outdoor-play. Also using the MABC, Aaland et al. (2017b) reported between-group differences (intervention and control) in composite executive functions score but not motor competence at post-intervention, although notably, at a domain level, TMT-B (verbal fluency) was the only executive function with a significant between-group improvement. In the only experimental study to investigate working memory performance, Koutsandreou et al. (2016) reported a higher post-intervention motor competence score in the motor exercise group than the control group, and a higher gain in working memory performance in the motor exercise group than both the control group and a cardiovascular exercise intervention group. In a study that was deemed to have poor methodological quality (Ericsson, 2008), between-group differences (intervention and control) in composite motor competence were apparent post-intervention, although whilst similar differences in attention and impulse control existed at year two follow-up, these were not maintained at year three.

Three experimental studies (Mulvey et al., 2018; Robinson et al., 2016; Taunton et al., 2018) investigated outcomes associated with behavioural regulation and social-emotional outcomes. In pre-school children, an intervention-related improvement in process-oriented motor competence, and a significant difference in post-intervention delay of gratification score between the intervention and control group were reported, with effect sizes ranging from medium-very large (Robinson et al., 2016). However, analyses in this study were only presented in parallel. The studies of Mulvey et al. (2018) and Taunton et al. (2018) both utilised the same intervention programme (SKIP) in a pre-school sample. Mulvey et al. (2018) reported a significant difference between pre-post intervention motor competence in the intervention group, with similar improvements found in behavioural regulation. Taunton et al. (2018) also found increases in process-oriented motor competence following participation in the SKIP intervention, with significant improvement aligned to low levels of negative affect and surgency and high levels of effortful control demonstrated at baseline.

Table 12. *Analyses and Results (Experimental studies)*

	Significant difference between IG and CG	No significant difference between IG and CG	Significant causal improvement Reported effect sizes	No significant causal improvement Reported effect sizes	Significant aligned improvement of motor competence and cognitive/social-emotional outcome Reported effect sizes	No significant aligned improvement of motor competence and cognitive/social-emotional outcome Reported effect sizes
			Academic performance			
Object manipulation		Battaglia et al. (2018)*			Battaglia et al. (2018)*	
Catching						
Aiming						
Upper limb coordination		Botha and Africa (2020)*				Botha and Africa (2020) *Small*
Locomotor skills		Battaglia et al. (2018)*			Battaglia et al. (2018)*	
Balance		Botha and Africa (2020)*				Botha and Africa (2020) *Moderate*
Running speed & agility		Botha and Africa (2020)*				Botha and Africa (2020) *Moderate*
Leaping						
Motor competence		Ericsson (2008) *Medium* Ericsson (2008)*			Bedard et al. (2018) *Small* Bedard et al. (2018) *Large*	Bedard et al. (2018) *Small* Bedard et al. (2018) *Medium*
			Executive functions			

Motor competence	Aadland et al. (2017b)*	Aadland et al. (2017b)*				
	Cognitive functioning					
Object manipulation		Lee et al. (2020)*				Lee et al. (2020)*
Locomotor skills		Lee et al. (2020)*				Lee et al. (2020)*
Motor competence		Lee et al. (2020)*				Lee et al. (2020)*
	Attention					
Ball skills	Pesce et al. (2016) *Large* Pesce et al. (2016) *Moderate*					Pesce et al. (2016) *Large* Pesce et al. (2016) *Moderate*
Balance	Pesce et al. (2016) *Large* Pesce et al. (2016) *Moderate*					Pesce et al. (2016) *Large* Pesce et al. (2016) *Moderate*
Motor competence	Ericsson (2008)*	Ericsson (2008)*				
	Working memory					
Motor competence	Koutsandreou et al. (2016) *Small*	Koutsandreou et al. (2016) *Small*			Koutsandreou et al. (2016) *Large*	Pesce et al. (2016) *Small*
	Inhibition					
Ball skills	Pesce et al. (2016) *Small*		Pesce et al. (2016) *Small*			
Balance	Pesce et al. (2016) *Small*					
	Impulse control					
Motor competence	Ericsson (2008)*	Ericsson (2008)*				
	Behavioural regulation					

Motor competence	Mulvey et al. (2018) *Moderate* Robinson et al. (2016) *Moderate*		Mulvey et al. (2018) *Moderate* Robinson et al. (2016) *Moderate*	
	Summary of studies classified by motor competence outcome			
	Catching			
Intellectual functioning		De Oliveira et al. (2018) *Small*		De Oliveira et al. (2018) *Small*
	Balance			
Intellectual functioning		De Oliveira et al. (2018) *Small*		De Oliveira et al. (2018) *Small*
	Object manipulation			
Temperament	Taunton et al. (2018) *Medium*		Taunton et al. (2018) *Large*	
	Locomotor skills			
Temperament	Taunton et al. (2018) *Large*		Taunton et al. (2018) *Large*	

Note: *ES effect size could not be calculated due to lack of information

7.5 Discussion

7.5.1 Overview of findings

The aim of this systematic review was to evaluate and summarise evidence pertaining to the longitudinal relationship of motor competence and cognitive and social-emotional outcomes. Specifically, the review attempted to establish the role of motor competence as a mechanism through which physical activity may support chronic cognitive and social-emotional adaptions in children and adolescents. Overall, the strength of evidence supporting the positive influence of motor competence on cognitive and social-emotional outcomes was inconsistent and weak, with many studies considered to have poor internal and external validity. Few studies investigated the reverse path of the relationship (cognitive and social emotional development – motor competence), with those studies that did presenting similarly indeterminate evidence. Despite this, there is some evidence regarding the mechanistic paths that may underpin the influence of motor competence on cognitive and social-emotional development. Specifically, there is support for the role of enriched physical activity in mediating the relationship between motor competence and aspects of executive functions (Koutsandréou et al., 2016; Pesce et al., 2016).

7.5.2 Observational evidence

Despite synthesising the findings from the 11 observational studies included in this review, there remains insufficient evidence to support a strong causal relationship between motor competence and cognitive and social-emotional development. Whilst individual studies do provide some indications of a relationship and warrant discussion, the current review highlights key issues that currently contribute to the inconclusive evidence base. Unfortunately, for many of the included studies, the primary analyses were not deemed eligible for this review, as the studies had used a composite measure of motor competence that included fine and gross motor skills. An important aim of this review was to identify which processes are interrelated at a construct (motor competence) and domain-level (cognitive and social-emotional development).

7.5.3 Experimental evidence

The 12 experimental studies that met the inclusion criteria offer some support for the role of motor competence and also cognitively enriched physical activity in promoting positive cognitive and social-emotional adaptions. However, taken together, the evidence provided in these studies remains inconsistent and indeterminate. The lack of methodological alignment between individual studies, and the failure to adequately capture the contextual influence of the intervention, makes it difficult to identify common themes.

7.5.4 Academic performance and intellectual functioning

Nine studies investigated the relationship between motor competence and aspects of academic performance, with less than half of these (n=3) including analyses relating to the reverse path of academic performance - motor competence. For both path directions, the evidence is indeterminate and insufficient, with no consistent domain-specific relationships identified. This agrees with the earlier systematic review of van der Fels and colleagues (2015). In adolescents, the studies of Jaakkola et al. (2015) and Syväoja et al. (2019) failed to present clear evidence of a positive influence of motor competence on subject-specific and overall academic performance, and this was similarly true for analyses relating to the reverse path. Of these two studies, only the study of Jaakkola and colleagues (2015) included domain-specific analyses, with the leaping skill found to be the strongest predictor of academic performance (small-moderate effect sizes), with no evidence of a subject-specific relationship. It is hypothesised that, in adolescence, there is an increased specificity in the cognitive abilities that are associated with individual academic subjects (Donati et al. 2019). For example, it is proposed that the increased complexity of executing object manipulation skills may underpin an enhanced relationship between mathematics and object manipulation skills (Westendorp et al., 2011). Whilst some previous evidence has supported an increasingly domain specific relationship (Lee et al., 2013), this was not supported in the current review. To advance understanding, there is a need for more studies to perform construct-level and subject-specific analyses. It is also important that adolescent studies look to include executive functions (i.e. processing speed, working memory) as moderators, in an attempt to identify the mechanisms through which constructs of motor competence may influence individual subject performance.

As previously noted, much research investigating the relationship between motor competence and academic performance has focused on pre-adolescent samples, specifically pre-school children and children transitioning into school. In pre-adolescent children, only the study of de Waal and Piennar (2020) analysed the relationship in both directions, finding no significant relationship between balance, running and agility and several academic domains. At similar ages, the study of Son & Meisels (2006) did find composite motor competence to have a significant influence on reading and maths performance (small-large effect sizes). However, it is important to consider that in this study, fine motor skills were found to have a stronger influence than motor competence on both of the assessed academic disciplines. A similar finding was presented in the experimental study of Both & Africa (2020) where subsets of fine motor skills were found to have a stronger association than constructs of motor competence on reading and spelling. Acknowledging the role of fine motor skills is important as, in pre-school children especially, visuomotor integration is proposed to have a key influence on many of the academic activities that children participate in, including reading, handwriting and letter-word identification (Cameron et al., 2012,2015; McClelland and Cameron, 2019).

Similar to the observational study evidence, the included experimental studies provide little support for a direct relationship between motor competence and academic performance. In addition, there was no clear pattern highlighting an increased influence of an individual construct of motor competence on improved academic performance. Whilst Battaglia et al. (2019) found that their within-school PE programme (developmentally appropriate tasks and enjoyable play) initiated positive adaptions in motor competence and pre-literacy skills, no significant post-intervention differences were found between the intervention and control groups. Bedard et al. (2018) also found intervention-related improvements in motor competence and pre-literacy skills, yet post-hoc analyses found these improvements diminished upon completion of the intervention and when assessed at follow-up. This study also had a small sample size, did not include a control group, and adherence to some aspects of the intervention (i.e. at home practice) was poor. The overall level of experimental evidence relating to indicators of academic performance was undermined by a lack of rigour in assessing the potential influence of the interventional components (Ericsson, 2008).

Only the study of De Oliveira et al. (2018) analysed the intellectual functioning – motor competence path. Moreover, the study of De Oliveira et al. (2018) is the only study that looked at the moderating influence of intellectual functioning and reported that improvements in motor competence following a within school intervention occurred irrespective of participant intellectual functioning score pre-intervention (De Oliveira et al., 2018). The failure of intellectual functioning to moderate improvements in motor competence may highlight the less distinct formation of executive functions in pre-school aged children, although methodological limitations should be considered in this study (De Oliveira et al., 2018; Wiebe, Espy, & Charak, 2008).

7.5.5 Executive functions

The current review presents insufficient evidence for the relationship of motor competence and executive functions, with only a single study analysing the influence of executive functions on motor competence (Rigoli et al., 2013). Of the executive functions assessed, the most consistent relationship was found between motor competence and working memory, with five studies presenting some supportive evidence (Koutsandreou et al., 2016; Ludyga et al., 2020; Niederer et al., 2011; Osorio-Valencia et al., 2018; Rigoli et al., 2013). No clear construct-level relationship was found across these studies, with balance, running speed and composite motor competence all found to positively influence working memory. Working memory encompasses the ability to retain and act upon information (Donati et al., 2019). On a behavioural and neuropsychological level, working memory along with inhibition, is proposed to have strong alignment to motor competence, as these skills are often performed in contexts that demand high-order cognitive function and a repeated shifting of attention (i.e. sport participation). At a construct-level, it is purported that locomotor skills are more influential to working memory and similarly object manipulation skills have a greater influence on inhibition (Ludyga et al., 2019). However, there remains a lack of studies that have empirically investigated these domain-specific relationships. Several factors may contribute to the heterogeneity found in the study results included in this review. Firstly, there are notable differences in the tasks used to measure executive functions and the methods used for motor competence assessment (i.e. process- or product-orientated) across studies. Secondly, many of the studies include children of pre-school ages, where executive functions are proposed to be less defined (Ludyga et al., 2019; Wiebe, Espy, & Charak, 2008). Increasing the longitudinal evidence relating to adolescents will help in interpreting the maturity of motor competence skills and executive functions and identifying whether distinct developmental trajectories become evident (van der Fels et al., 2015).

Of the studies that investigated the influence of motor competence and a prescribed intervention on executive functions, some supportive evidence was reported for specific domains of executive functions. The study of Aadland and colleagues (2017b) does suggest a positive relationship between motor competence and adaptions for some executive functions at 10 years. When controlling for compliance to the intervention protocol, the analyses revealed significant effects of the intervention (increased within-school physical education, physical activity homework) on motor competence and composite executive functions score, without a similar effect on levels of physical activity (Aadland et al., 2017b). These per-protocol results can likely be attributed to the development of motor competence within an enriched physical activity context, and not primarily through the neurotrophic hypothesis according to which physiological adaptions associated with quantitative physical activity levels are viewed as the key causal mechanism (Aadland et al., 2017b; Best, 2010).

Koutsandréou et al. (2016) was the only study to offer a comparative assessment that included a second intervention group targeted at improving cardiovascular performance, along with the intervention focused on motor competence improvement. Interestingly, in this pre-adolescent sample, despite similar between-group improvements in motor competence, a greater improvement in working memory was found in the motor competence group. Additional support for the pathway of motor competence and executive functions is offered by Pesce et al. (2016) who found ball skill competence to mediate the influence of an enriched PE intervention (directed exploration, task complexity) on inhibitory function, with this mediated path subsequently moderated by the level of outdoor-play. Whilst Pesce et al. (2016) failed to find a similar influence to exist on attention and working memory updating, the study builds upon the aforementioned studies (Aadland et al., 2017b; Koutsandréou et al., 2016) by identifying a causal relationship (motor competence – executive functions) and in similarly reporting a heightened role of object control skills as a mechanism to positive cognitive development. Reporting the relationship between motor competence and executive functions as potentially developmental and domain specific, these experimental studies do offer some support to accumulating evidence provided by cross-sectional studies (Albuquerque et al., 2021; Livesey et al., 2006; Ludyga et al., 2019; van der Fels et al., 2015).

7.5.6 Social-emotional development

In total, 4 studies investigated the relationship of motor competence and social-emotional development, although only a single study (Taunton et al., 2018) investigated the reverse path (social-emotional development - motor competence). Taken together, there was consistent supportive evidence for the motor competence – social-emotional development path. Although few studies assessed this relationship, in finding a positive influence of motor competence, the evidence does provide agreement to the results of earlier cross-sectional studies and those completed in a clinical setting (Lingham et al., 2012; Piek et al., 2007). It is hypothesised that the influence of motor competence on social-emotional development is apparent from early-childhood, with poor motor competence contributing to difficulties in the social domain (i.e. social isolation, fewer peer interactions), and these difficulties potentially leading to the development of coping strategies such as avoiding physical activity participation (Cairney et al., 2013; Fitzpatrick & Watkinson, 2003; Hill et al., 2011; Payne et al., 2013). The study of Gu et al. (2018) provides support for this hypothesis, as motor competence was found to influence psychosocial development, but also in analyses not eligible for the current review, motor competence was found to indirectly influence mental health outcomes through moderate- to vigorous-intensity physical activity (MVPA) and sedentary behaviour. It is also suggested that object manipulation skills may have a greater influence as these underpin active play to a greater extent than locomotor and balance skills, and there is some support for this in the included studies (Gu et al., 2018; MacDonald et al., 2016).

All of the studies eligible for the current review included children aged four-six years, and the results highlight that the social-emotional consequences of poor motor competence are apparent from young ages. Indeed, prior evidence has shown this relationship to exist as early as kindergarten (Piek et al., 2008), and it is suggested that the strength of relationship increases into adolescence as a consequence of consistent exposure to secondary stressors, along with a more prominent influence of mediating and moderating variables (Lingam et al., 2012; Skinner & Piek, 2001). The study of Robinson and colleagues (2016) did examine the efficacy of a motor skills intervention on self-regulation. Although, despite the encouraging results for both motor competence and self-regulation in the intervention group, as an efficacy trial there were a number of limitations that negatively influenced the strength of the reported results (i.e. a single assessed measure of self-regulation). Initial evidence that the relationship may be reciprocal was also provided in a separate study, where a more positive score in facets of temperament (baseline) was associated with greater improvement in motor competence post-intervention (Taunton et al., 2018). However, it is important that this hypothesised relationship continues to be rigorously investigated, specifically the path of social-emotional development - motor competence, as it has previously been proposed that it is motor competence that proceeds social-emotional development (Mancini et al., 2016). Moreover, social-emotional health is a key indicator of wider psychosocial health and academic behaviour, along with a wider health identity, especially in adolescence where it is associated with dysfunctional behaviour and poor mental health (Kassin et al., 2013; Timler et al., 2019).

7.5.7 Strengths and limitations

In synthesising observational and experimental evidence, the current review has a number of key strengths and provides an important overview of the current evidence regarding all of the paths relating to the relationship between motor competence and cognitive and social-emotional development. This review is the first to present a synthesis of longitudinal observational and experimental evidence, with no applied date restriction, and in presenting effect sizes calculations for all studies where possible. The review also comprises important considerations that should be addressed in future empirical research. In not including cross-sectional evidence, it has provided opportunity to build a clearer interpretation of the developmental and domain-specific relationship between aspects of motor competence and cognitive and social-emotional development. Moreover, synthesising experimental evidence affords opportunity to understand the importance of the interaction between motor competence and contextual mechanisms on cognitive and social-emotional outcomes. Lastly, the development of a conceptual model is a central component of this review, as it provides an underpinning model through which research questions can be formulated and future research guided.

There are several limitations associated to the current review that should be acknowledged. In attempting to develop a stronger understanding of the contextual influence on the relationship between observed outcomes, the authors included studies where the analysis of outcomes was completed in parallel. Despite providing scope for wider analysis, including experimental studies that assessed outcome changes individually must be considered when interpreting the statements included within this review. The low number of studies and the large variability in assessment methods and outcomes within the studies made it difficult to reach clear assertions as to the strength of evidence. Furthermore, the high level of between-study heterogeneity and the small number of studies included within this review meant that a meta-analysis were not possible. Also, despite calculating the effect sizes for analyses where possible, the failure of a number of studies to report the required information limited full application of this. Lastly, the study eligibility criteria meant that many primary analyses were not included as they had analysed motor competence and fine motor skills together as a single outcome. Therefore, many of the analyses reflect correlation analyses whereby confounders were not controlled for.

7.5.8 Future directions

As highlighted in earlier systematic reviews (Gunnell et al., 2019; Pesce et al., 2021), there has been an exponential increase in primary studies investigating the role of chronic and acute physical activity in promoting positive cognitive development. Aligned to this, there has been a collective effort to better understand the position of motor competence as a key underpinning mechanism for this relationship. However, the evidence base remains indeterminate for a number of the investigated domains, with this fostered by many studies lacking in methodological rigour, and failing to sufficiently report on contextual and moderating factors (Ma et al., 2021). For experimental studies, greater emphasis needs to be directed towards ensuring thorough process evaluations are reported, providing researchers opportunity to consistently identify those characteristics of an intervention that may prompt a causal or moderating influence on study outcomes (Ma et al., 2021). It is also important that researchers display awareness of the ambiguity that surrounds the measurement of cognitive constructs, together with ensuring that there is agreement between the measurement task being used and the operational term selected (Tomporowski, 2009). Researchers must also work to limit threats to internal validity, such as the influence of using the same cognitive test form at different time-points, and in also acknowledging the potential role of natural cognitive maturation (Tomporowski, 2009). A further consideration for researchers is the ecological validity of selected motor competence assessments, and whether the instrument provides opportunity for a robust understanding of the relationship between motor competence and cognitive and social-emotional outcomes. From an ecological perspective, it is hypothesised that it is the variability and constraints that exist within a context that underpin the associated development of executive functions, and wider cognitive outcomes (Pesce et al., 2019). Therefore, motor competence assessments such as the Dragon Challenge or the Canadian Agility and Movement Skill Assessment (CAMSA) may provide opportunity to gain greater insight into these specific relationships than closed-skill assessments that present fewer performance-related constraints (i.e. TGMD-3, MACB; Barnett et al. 2020). Also, at present, the large variety of motor competence assessments that have been used render comparative analysis difficult. Moreover, many studies have conducted their primary analysis using a composite-level measure of motor competence which doesn’t provide opportunity to establish domain specific influences. Future studies should look to ensure that construct-level motor competence is also included in primary analysis. Lastly, to develop understanding of how the trajectories of biological and cognitive maturity influence the relationship of these outcomes with advancing age and specific to sex, more studies including adolescent samples are needed where these moderating influences are accounted for within study designs.

7.6 Conclusion

The review presents a conceptual model to promote research that has a strong rationale and can evidence a consideration for the contextual and developmental influences that moderate the relationship between motor competence and cognitive and social-emotional development. To date, too many studies have approached the role of motor competence in influencing cognitive and social-emotional outcomes from an exploratory position, without a clear consideration for the mechanisms underpinning their hypotheses. As such, there are high levels of study heterogeneity and the evidence base is difficult to synthesise, with conclusions therefore remaining speculative at this point. However, whilst acknowledging the limitations of the data presented, supportive evidence for individual paths hypothesised in the conceptual model is presented within this review. Specifically, observational evidence offers support for the influence of motor competence on aspects of academic performance, although clear patterns of domain-specific relationships are still not manifest. Whilst some experimental studies provide preliminary support for the alignment between the underlying processes responsible for executive functions and those required to successfully engage in enriched movement interventions. Moving forward, it is important that researchers ensure their study design encompasses the moderating influences that will assist in further developing understanding within this field.

Thesis map

	Study		Outcomes
1.	Sex-related differences in the association of fundamental movement skills and health and behavioural outcomes in children	***Aim***	To evaluate the sex-related influence on FMS competence during late childhood, and to identify if this subsequently influences the association of FMS with further health-related benefits.
		Key findings	For boys, object control skill competence had a direct association with perceived sports competence and an indirect association with sedentary time (through perceived sports competence). For girls, although locomotor skills were found to predict VPA Irrespective of sex, perceived sports competence was associated with sedentary time. The study supports a holistic approach to health-related interventions and highlights a key association of perceived sports competence and the time children spend sedentary.
2.	The Influence of Biological Maturation on Performance Characteristics of the Overhand Throw and Horizontal Jump in Youth	***Aim***	To identify the influence of sex and biological maturity on performance characteristics of the horizontal jump and overhand throw, and to investigate the association of these FMS with perceived sports competence.
		Key findings	Irrespective of sex, agreement between technical and outcome performance characteristics was strongest in the post-PHV group. Perceived sports competence was most strongly associated with product-oriented horizontal jump performance in the post-PHV group for girls. A maturational influence was only found for product-oriented horizontal jump performance, with this between the pre- and post-PHV groups.
3.	The importance of skill competence as a as a key predictor of the energy expenditure associated with performing fundamental movement skills	***Aim***	To evaluate the influence of biological and developmental characteristics, along with skill competence on the energy expenditure associated with the performance of isolated FMS
		Key findings	Boys were found to have a higher associated absolute and relative energy expenditure across all skill performances. A significant sex and maturity interaction was found in boys with absolute $\dot{V}O_2$ ($l \cdot min^{-1}$) as the outcome. For the kick and hop, level of skill competence was found to influence both relative and absolute associated energy expenditure.
4.	The influence of motor competence on broader aspects of health: a systematic review of the longitudinal associations between motor competence and cognitive and social-emotional outcomes	***Aim***	1. To evaluate and summarise evidence pertaining to the longitudinal relationship of motor competence and cognitive and social-emotional outcomes. 2. To present a conceptual model outlining the proposed influence of motor competence on the development of cognitive and social-emotional outcomes during childhood and adolescence.
		Key findings	Overall, the strength of evidence supporting the positive influence of motor competence on cognitive and social-emotional outcomes was inconsistent and weak, with many studies considered to have poor internal and external validity. Few studies investigated the reverse path of the relationship (cognitive and social emotional development – motor competence), with those studies that did presenting similarly indeterminate evidence.

5.	Potential moderators of the association between fundamental movement skills and academic attainment in adolescence	***Aim***	To identify the association between object control skills and locomotor skills with subject-specific academic attainment in adolescents and to assess whether these associations are moderated by sex, perceived sports competence, BMI z-score and/or maturity offset.
		Key findings	

8.0 Study 5

8.1 Potential moderators of the association between fundamental movement skills and academic attainment of adolescence

8.2 Introduction

Fundamental movement skills (FMS) are proposed as a crucial foundation for the development of complex movement patterns involved in physical activity and sport (Gallahue et al., 2012; Seefeldt, 1980). In the conceptual model of Stodden and colleagues (2008), FMS are hypothesised to have a vital role in instigating a positive, or negative, spiral of physical activity engagement in youth, whilst similarly influencing health-related fitness and self-efficacy (Lubans et al., 2010; Robinson et al., 2015). Though the Stodden et al. model (2008) emphasises the influence of FMS on physical, psychological and social development, increasingly, studies have explored the potential association between aspects of motor competence (i.e. FMS) and cognitive development and functioning (van der Fels et al., 2015). Indeed, there is some evidence of positive associations between FMS and working memory, processing speed and academic attainment (van der Fels et al., 2015).

The systematic review of Erickson and colleagues (2019) supports the acute and chronic influence of physical activity, and to a lesser extent aerobic fitness, on cognitive performance. However, there remains ambiguity as to the key mechanisms governing these associations. Specifically, in addition to the volume and intensity of physical activity, the type and quality (i.e. cognitive stimulus, social engagement) are also considered to have a crucial role in promoting improvement across cognitive domains (Tomporowski et al., 2015). It is suggested that FMS and skill acquisition have a moderating influence on the association of enriched physical activity (i.e. physical activity requiring a variance of athletic and participatory opportunities; Button et al., 2020) and cognitive stimulation (Pesce et al., 2016). In interventions that have sought to promote physical activity using methods involving minimal cognitive stimulation, little influence on cognitive outcomes have typically been reported (Diamond & Ling, 2016).

Both behavioural and neuropsychological explanations are also proposed to underpin the association of motor and cognitive performance (Van Der Fels et al., 2019). From a behavioural perspective, FMS, as goal-directed movements, are strongly aligned with cognition, and facilitate participation in movement-rich activities which are demanding of higher order cognition (Ludyga et al., 2019; Van Der Fels et al., 2019). With regard to the influence of neural adaptations, it is proposed that there are key overlaps in the neural networks activated during motor and cognitive function, with both controlled by similar areas within the brain (e.g. frontal lobes, cerebellum, and basal ganglia; Leisman, Moustafa, & Shafir, 2016). Given the role of FMS as a pre-cursor of physical activity (Robinson et al., 2015; Utesch et al., 2019), elucidating the influence of FMS on cognitive tasks will assist in informing the development of physical activity interventions.

Cognitive components related to executive functions (i.e. working memory, processing speed, inhibitory control) have been found to be positively associated with academic attainment (Donati, Meaburn, & Dumontheil, 2019). The influence of FMS on academic attainment is proposed to occur through the cognitive constructs of executive function and metacognition (i.e. thoughtful decision making). Specifically, visual motor skills (e.g. visual processing, eye-hand coordination) are reported to be associated with higher order cognitive function, raising the question as to whether object control rather than locomotor skills are more influential to academic attainment (Pesce et al., 2016). Whether the association between executive functions and academic attainment is consistent across childhood and adolescence remains a topic of contention, with some suggesting an increasingly domain-specific relationship with advancing age (Donati et al., 2019). However, many previous studies (Botha & Africa, 2020; Ludyga et al., 2019; Son & Meisels, 2006) have only analysed the association of FMS and cognitive outcomes in pre-pubertal children and have only employed product-oriented protocols (i.e. the outcome of a movement) to assess FMS, therefore failing to provide insight into the influence of the technical characteristics of the selected movements.

Adolescence is a crucial phase in cognitive development, characterised by a period of marked neurobiological change (Foulkes & Blakemore, 2018). Moreover, early adolescence is accompanied by an increasing influence of potential confounders (i.e. self-perception, maturity, autonomy) that may moderate the association of FMS and academic attainment (Esteban-Cornejo, Tejero-Gonzalez, Sallis, & Veiga, 2015). Underpinning many of these changes are the sex-specific trajectories of biological and cognitive maturation. Maturity-related changes are proposed to directly influence the association of FMS and academic attainment and to also influence the association indirectly through the roles of confounders such as self-perception (Malina, Cumming, & Silva, 2016; Sherar, Cumming, Eisenmann, Baxter-Jones, & Malina, 2010). The onset of puberty is earlier in girls and is associated with an increase in body fat, and, especially in early-maturers, is associated with an increase in psychosocial challenges (Haapala et al., 2020; Malina et al., 2004). This also coincides with a period of lower biological drive to be physically active, irrespective of sex (Malina, Cumming, & Silva, 2016). Considering the sex-specific influence of maturation, as well as the earlier attainment of cognitive maturity in girls, it is proposed that distinct, sex-specific patterns may emerge in the association of FMS and academic attainment (Haapala et al., 2020).

Therefore, the present study aimed to identify the association of object control skills and locomotor skills with subject-specific academic attainment in adolescents and to assess whether these associations are moderated by sex, perceived sports competence, BMI z-score and/or maturity offset.

8.3 Methods

8.3.1 Participants

Overall, 162 children (70 girls; 12.8 ± 1.5 years) from a single secondary school in South Wales, UK participated in this study. Prior to data collection, informed parental/guardian consent and child assent were obtained. From the initial sample, 17 did not complete the FMS assessment and five did not have recorded data for academic performance, leaving a final sample size of 140 (62 girls; 12.8 ± 1.9 years). No significant anthropometric or performance differences were found between those included or excluded. Ethics approval was granted by Swansea University College of

Engineering Research Ethics Committee (reference PG2018-065). The Declaration of Helsinki was adhered to throughout this research.

8.3.2 Anthropometrics

All anthropometric measurements were conducted by a trained practitioner in a controlled setting. Standing height and body mass were measured to the nearest 0.1 cm and 0.1 kg, respectively, using portable calibrated scales (Seca 899, Seca Ltd, Birmingham, UK). Body Mass Index (BMI) was subsequently calculated and age- and sex-specific z-scores determined using the LMS table from the 2007 World Health Organization growth charts (WHO, 2007). The predictive equation of Mirwald et al. (2002) was used to estimate biological maturity as predicted years from age at peak height velocity (APHV).

8.3.3 Fundamental movement skills

To assess fundamental movement skill proficiency, the Test of Gross Motor Development - version 3 (TGMD-3; Ulrich, 2020) was used. The TGMD-3 is a validated protocol (Webster & Ulrich, 2017) that primarily measures process-oriented movement competence across 13 FMS within two subsets: object control skills (n = 7) and locomotor skills (n = 6). Each fundamental movement skill is performed twice and is scored on the presence or absence of specific technical criteria. The number of performance criteria differ by skill (ranging from 3-5), with each criterion scored (1) if present and (0) if absent, giving a total possible raw score of 54 and 46 in the object control skills and locomotor subset, respectively. Prior to commencement of the protocol, each child was provided with a demonstration of each skill and given opportunity to complete a practice effort. For all FMS, children were instructed to perform each skill to the best of their ability. Fundamental movement skill performance was recorded using an iPad (3rd generation; Apple Inc., Cupertino, CA, USA), with post-priori analysis conducted by two trained researchers (PH and MM).

8.3.4 Perceived sports competence

To assess the role of self-perceived skill competence, the sports competence construct from the Children and Youth Physical Self-Perception Profile (CY-PSPP) was used (Fox & Corbin, 1989; Whitehead, 1995). The CY-PSPP comprises of six individual constructs, with each construct including six items scored using a Likert scale (1-4). Within each construct, participants were asked to select a statement that they most associated with (e.g. Some kids wish they could be a lot better at sports BUT other kids feel that they are good enough at sports) and to then select either: "sort of true for me" OR "really true for me". The sports competence construct has previously been used for measuring perceived fundamental movement skill competence and has been shown to demonstrate acceptable construct validity and internal consistency (Barnett, Morgan, et al., 2008a; De Meester et al., 2016b).

8.3.5 Academic attainment

Academic attainment was assessed using data from the national numeracy and reading tests of Wales. For the current study, age-standardised scores from the numeracy procedural, numeracy reasoning, and reading tests were included (Hwb.Gov.Wales, 2019). The questions assess understanding and comprehension. The numeracy reasoning test measures how well children can use what they know to solve everyday problems, whilst the numeracy procedural test measures competence in number, measuring and data skills (Hwb.Gov.Wales, 2019). The reading tests are made up of short questions based on two or more texts (Hwb.Gov.Wales, 2019). The assessments were conducted in the summer term (2019), with all subsequent measurements and assessments (TGMD-3, perceived sports competence, anthropometrics) conducted in the autumn term (2019).

8.3.6 Statistical analysis

Descriptive data were calculated for all variables and are presented as the mean and standard deviation (SD). An independent samples *t*-test was used to assess the effect of sex on FMS, BMI z-score, perceived sports competence, and academic attainment, with Pearson correlation coefficients (*r*) used to examine associations between these variables. Path analysis (AMOS Version 26 [IBM SPSS Statistics Inc., Chicago, IL, USA]) using maximum likelihood estimation was performed to analyse the hypothesised associations between FMS and independent academic test performance (*Figure 9*). An alpha level of 0.05 was used for all statistical analyses. Prior to conducting path analysis, the data were examined for evidence of multicollinearity and to ensure normality. The variance inflation factor (VIF) was calculated by conducting regression analyses for all independent variables. In the current study, the VIFs of included variables were all below the VIF threshold of 3.0 (Dormann et al., 2013), indicating the absence of high intercorrelations. To assess model fit, chi-squared by degrees of freedom ratio (χ^2/df), Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI) and Tucker-Lewis Index (TLI) were used. A χ^2/df ratio <3 was considered acceptable (Iacobucci, 2010), whilst values >0.90 were considered acceptable for the TLI and CFI indexes. For the RMSEA, the cut-off value of < 0.08 was regarded as acceptable (Hu & Bentler, 1999; Schumacker & Lomax, 2010). The moderating role of sex on the association between fundamental movement skill competence and academic attainment was assessed by performing a multi-group analysis, comparing a fully constrained model, in which all paths are constrained to zero for both sexes, to an unconstrained model. A significant χ^2 test identifies sex-specific differences within the model. The moderating effects of perceived sports competence, BMI z-score and biological maturity were analysed using the interaction-moderation approach in AMOS. Firstly, all variables were transformed and presented as standardised scores, the interaction term was then constructed (e.g. object control skills*perceived sports competence) and included within the model. If a moderating effect was present, the interaction term would be statistically significant.

Table 13. *Participant characteristics (mean ± SD)*

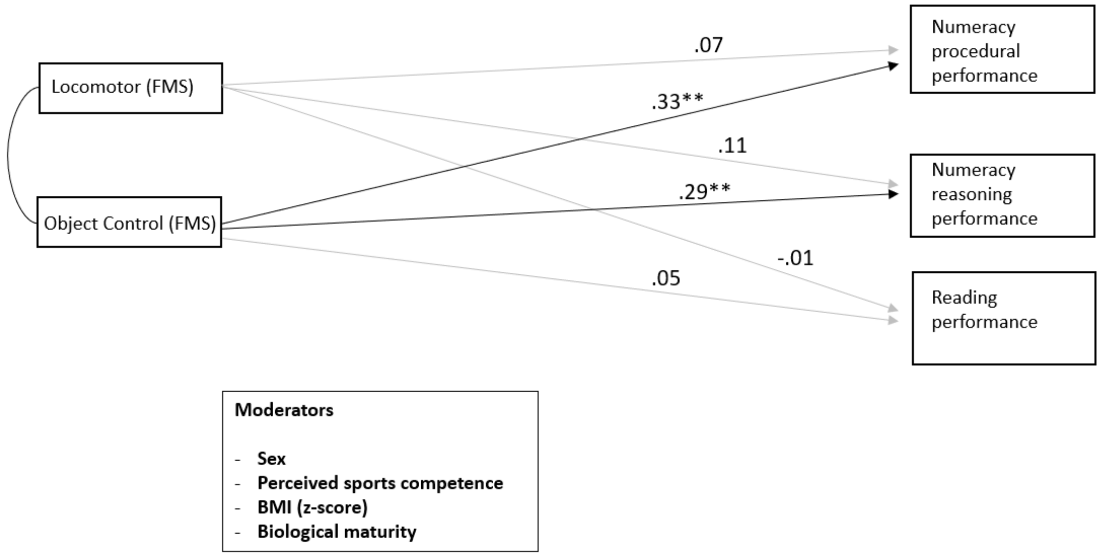
Variables	Boys (*n* = 78)	Girls (*n* = 62)	All (*n*= 140)
Age (years)	13.0 ± 1.5	12.6 ± 1.5	12.8 ± 1.5
BMI ($kg \cdot m^{-2}$)	21.2 ± 4.4	21.7 ± 4.8	21.4 ± 4.6
BMI z-score	0.5 ± 1.5	0.1 ± 1.2*	0.3 ± 1.1
APHV (yrs)	-0.8 ± 1.6	0.1 ± 1.1*	-0.4 ± 1.5
Object control skills (0-54)[a]	46.4 ± 6.6	35.4 ± 7.6**	41.5 ± 8.9
Locomotor skills (0-46)[a]	36.4 ± 5.6	35.8 ± 5.1	36.1 ± 5.4
Perceived sports competence(6-24)[a]	19.8 ± 3.8	17.1 ± 4.3**	18.6 ± 4.3
Numeracy procedural (70-140)[b]	109.2 ± 14.4	103.0 ± 11.5*	106.4 ± 13.5
Numeracy reasoning (70-140)[b]	105.6 ± 13.0	102.3 ± 11.9	104.2 ± 12.5
Reading (70-140) [b]	105.4 ± 13.2	106.2 ± 13.5	105.7 ± 13.3

Means ± SD. BMI = Body mass index; APHV = Predicted age at peak height velocity
*Significant difference between boys and girls ($p < 0.05$)
** Significant difference between boys and girls ($p < 0.01$)
[a] Range for raw score of construct
[b] Range for age-standardised assessment score

8.4 Results

As shown in Table 13, boys were more competent in object control skills, had a higher perceived sports competence and performed better in the numeracy procedural assessment. The path model (*Figure 9*) displayed excellent model fit regardless of fit index (CMIN/DF = 1.231; CFI = 0.995; TLI = 0.974; RMSEA = 0.048). Object control skill competence, but not locomotor skill competence, was associated with numeracy procedural (β = 0.33; 95% CI: 0.16 to 0.49) and numeracy reasoning (β = 0.29; 95% CI: 0.13 to 0.45), but no significant paths were found between either fundamental movement skill construct and reading performance. The association between FMS and academic performance was similar irrespective of sex, with no difference between the fully constrained and unconstrained model (CMIN/DF 3.454, DF 6, p = 0.75).

Similarly, the interaction of maturity offset with FMS did not moderate the association between FMS and academic attainment. As shown in *Figures 10 and 11*, perceived sports competence did moderate the association between object control skills and numeracy procedural (β = 0.16; 95% CI: 0.03 to 0.32) and reading performance (β = 0.25; 95% CI: 0.10 to 0.39). Furthermore, a higher BMI z-score moderated the association between object control skills and numeracy reasoning (β = 0.17; CI: 0.01 to 0.33).



Note: Black arrows denote statistically significant path; Grey arrows denote statistically non-significant path
* ($p < 0.05$) ** ($p < 0.01$)

Figure 9. Path analysis diagram illustrating the association of locomotor and object control skills with aspects of academic attainment, and the moderating roles of sex, perceived sports competence, BMI z-score and biological maturity

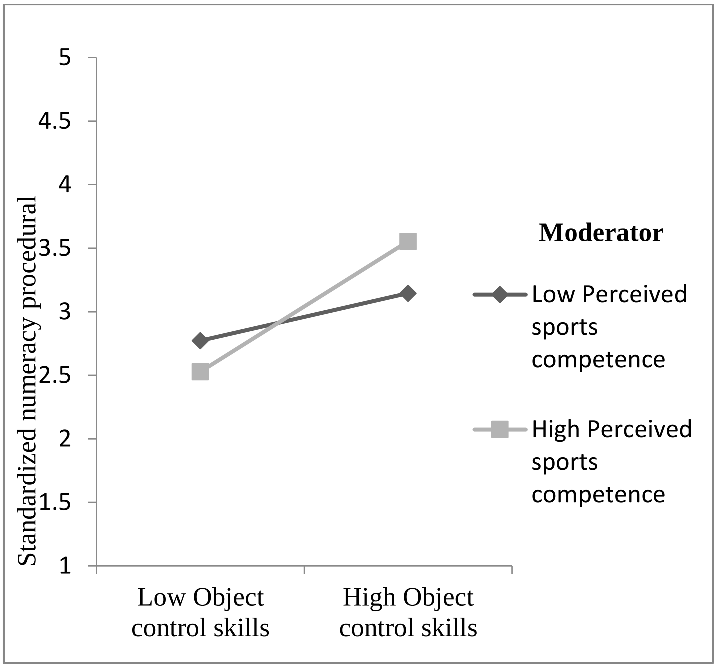


Figure 4. Moderating effect of perceived sports competence on the association between object control skill competence and numeracy procedural performance

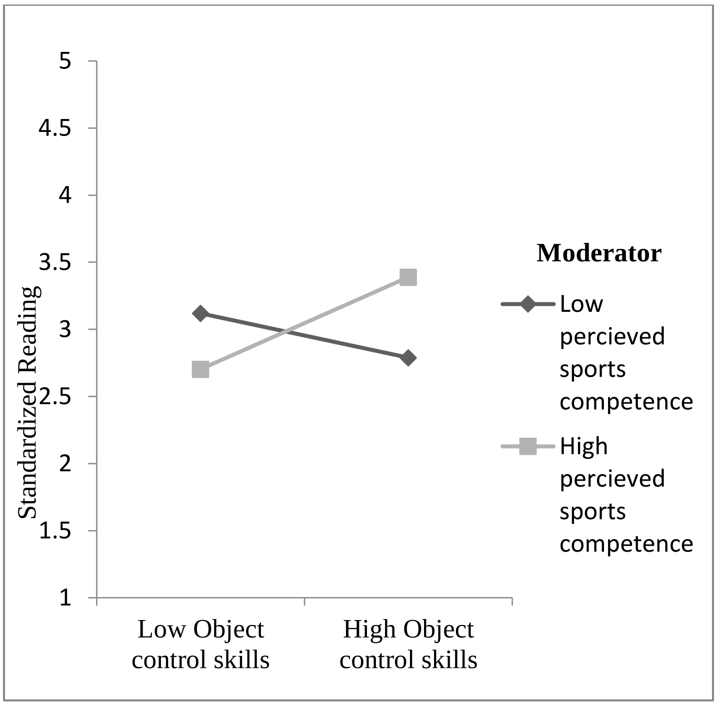


Figure 5. Moderating effect of perceived sports competence on the association between object control skill competence and Reading performance

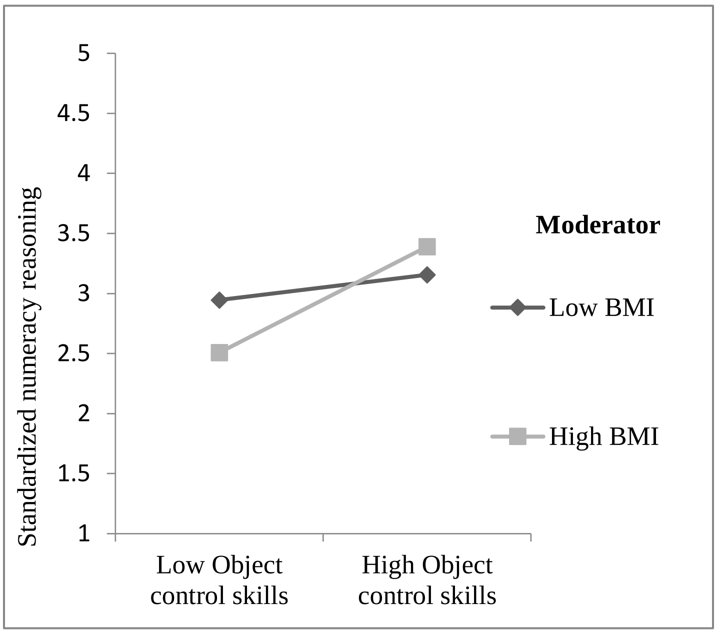


Figure 6. Moderating effect of BMI z-score on the association between object control skill competence and Numeracy reasoning performance

8.5 Discussion

The aim of the present study was to investigate the association of object control and locomotor skill competence with aspects of academic attainment in adolescents, and to determine the influence of specific moderating variables. The primary finding was that object control skill competence, but not locomotor skill competence, was strongly associated with academic attainment. In addition, perceived sports competence moderated the association between object control skills and numeracy procedural and reading performance, although this moderation was small. These results provide further support for a potential heightened role of object control skills in promoting positive cognitive development.

Previous studies have highlighted the association between FMS and enhanced cognitive development, as well as emphasising the importance of FMS as a mediator in the association of physical activity and cognition (Pesce et al., 2016; Van Der Fels et al., 2019). In the current study, only object control skills were associated with academic attainment and this was only evident for performance in the numeracy-based assessments (procedural and reasoning). These findings offer some support to the notion that the association between fundamental movement skills and academic attainment is domain specific (Donatit et al., 2019; Ludyga, Pühse, Gerber, & Herrmann, 2019). Although complex, the association between sensorimotor ability (i.e. object control skills) and numeracy could be explained by an overlap in the neural processes involved in numerical, and spatial and temporal representation (Donati et al., 2019; Pesce et al., 2019; Tomporowski et al., 2015). It is proposed that these representations are processed by the same underlying neurological processes (Giles et al. 2018). Indeed, it is plausible that this association is strongly influenced by inhibitory control, as processes relating to inhibitory control have been found to be important for successful performance in both object control skills and mathematical tasks (Brookman-Byrne, Mareschal, Tolmie, & Dumontheil, 2018; Ludyga et al., 2019). The association found in the current study could correspond to the execution of object control FMS in open-skill sport settings and similarly aligned activities where the child is required to shift attention between evolving constraints (Ludyga et al., 2019; Pesce et al., 2016). The influence of inhibitory control on performance in ball game sports has been reported in adolescent youth previously (Marchetti et al., 2015). It was further anticipated that an association between locomotor skills and reading performance would be evident, as both tasks are deemed to rely largely on automisation (Westendorp et al., 2011). However, this was not found in the current study. Whilst surprising, this may reflect the lack of sensitivity in the TGMD-3 locomotor skill construct to correctly discriminate locomotor skill competence in adolescents (Estevan et al., 2017).

Importantly, the current study expands on previous evidence by highlighting the role of perceived sports competence as a potential moderator of the association between FMS and academic attainment. Specifically, perceived sports competence weakly moderated the association between object control skill competence and numeracy procedural and reading performance. Constructs relating to self-concept (i.e. perceived competence, self-worth) have been identified as correlates of FMS and academic attainment independently (Barnett et al., 2016a; Honicke & Broadbent, 2016). Although further supporting evidence is needed, the current results may reveal the possible role of perceived sports competence in influencing the engagement of adolescents in cognitively stimulating physical activity. As such, a high perceived sports competence may underpin the confidence of adolescents to consistently participate in the types of physical activity that are strongly influenced by FMS and that therefore promote cognitive adaptions. Self-perception has been proposed as a key characteristic that is central to the efficacy of physical activity interventions aimed at improving cognitive functions (Tomporowski & Pesce, 2019. In addition, participants in the current study were pubertal, and in girls especially, this may have increased the role of self-perception, specifically in indirectly influencing behaviour relating to FMS and the classroom (i.e. peer-relations).

In contrast to perceived sports competence, biological maturity and sex were not found to moderate the association of FMS and academic attainment. Although a stronger association between motor competence and cognition has previously been found in boys (Haapala et al., 2019), this was in a younger sample (6-9 years). In the current sample, the more advanced cognitive and biological maturation of girls may have masked the between sex disparity found in pre-pubertal children (Haapala et al., 2020). The direct importance of biological maturity to both FMS and academic attainment remains contested. Moreover, as participants in the current study were predominantly pubertal and post-pubertal this may have constrained the potential to comprehensively assess a maturity-related effect. A surprise finding in the current study was that a higher BMI z-score moderated the association between object control skills and numeracy reasoning performance, though this moderation was weak. Obesity has been shown to negatively influence fundamental movement skill competence and academic attainment. For mathematical tasks especially, obesity-related effects are proposed to be more evident, as they are associated and invoked by the same areas of the brain (Martin et al., 2017). In addition, indirect effects of obesity share commonalities between outcomes (i.e. low physical activity levels, psycho-social problems, mental health). However, there remains limited evidence associating an unhealthy weight status to a lower object control skill competence (Barnett et al., 2016a). Also, the age of the participants in the current sample may limit the validity of using BMI z-score to identify unhealthy weight status, as this does not allow consideration for maturity-related growth trajectories. Given that this does not denote a causal relationship, it may in fact indicate that those achieving a higher academic performance (numeracy reasoning) have developed competence in object control skills, and continue to participate in enriched physical activity despite a higher BMI.

It is important to acknowledge some limitations of the current study. Firstly, the cross-sectional approach limits our understanding of the developmental trajectories of FMS and academic attainment. Also, the findings would be strengthened by including a measurement of physical activity and sport participation, as this would provide scope to investigate the mediating role of FMS in promoting participation in different contexts of physical activity. Lastly, to fully understand the influence of biological maturation on the association between FMS and academic attainment, it would be beneficial to include pre-pubertal participants, and to assess the influence of maturity across all maturity classifications.

8.6 Conclusion

In conclusion, the results provide strong evidence for the association between object control skill competence and numerical academic performance in adolescents. In contrast, locomotor skills were not found to be associated to any of the academic assessments in the current study. Taken together, these findings highlight the importance of object control skills and to a lesser extent, perceived sports competence to specific aspects of academic attainment. Furthermore, the results highlight that future research is warranted to uncover the role of cognitively enriched physical activity as a mechanism for promoting this association between object control skills and academic attainment.

Thesis Map

	Study		Outcomes
1.	Sex-related differences in the association of fundamental movement skills and health and behavioural outcomes in children	***Aim***	To evaluate the sex-related influence on FMS competence during late childhood, and to identify if this subsequently influences the association of FMS with further health-related benefits.
		Key findings	For boys, object control skill competence had a direct association with perceived sports competence and an indirect association with sedentary time (through perceived sports competence). For girls, although locomotor skills were found to predict VPA Irrespective of sex, perceived sports competence was associated with sedentary time. The study supports a holistic approach to health-related interventions and highlights a key association of perceived sports competence and the time children spend sedentary.
2.	The Influence of Biological Maturation on Performance Characteristics of the Overhand Throw and Horizontal Jump in Youth	***Aim***	To identify the influence of sex and biological maturity on performance characteristics of the horizontal jump and overhand throw, and to investigate the association of these FMS with perceived sports competence.
		Key findings	Irrespective of sex, agreement between technical and outcome performance characteristics was strongest in the post-PHV group. Perceived sports competence was most strongly associated with product-oriented horizontal jump performance in the post-PHV group for girls. A maturational influence was only found for product-oriented horizontal jump performance, with this between the pre- and post-PHV groups.
3.	The importance of skill competence as a as a key predictor of the energy expenditure associated with performing fundamental movement skills	***Aim***	To evaluate the influence of biological and developmental characteristics, along with skill competence on the energy expenditure associated with the performance of isolated FMS
		Key findings	Boys were found to have a higher associated absolute and relative energy expenditure across all skill performances. A significant sex and maturity interaction was found in boys with absolute $\dot{V}O_2$ ($l \cdot min^{-1}$) as the outcome. For the kick and hop, level of skill competence was found to influence both relative and absolute associated energy expenditure.
4.	The influence of motor competence on broader aspects of health: a systematic review of the longitudinal associations between motor competence and cognitive and social-emotional outcomes	***Aim***	1. To evaluate and summarise evidence pertaining to the longitudinal relationship of motor competence and cognitive and social-emotional outcomes. 2. To present a conceptual model outlining the proposed influence of motor competence on the development of cognitive and social-emotional outcomes during childhood and adolescence.
		Key findings	Overall, the strength of evidence supporting the positive influence of motor competence on cognitive and social-emotional outcomes was inconsistent and weak, with many studies considered to have poor internal and external validity. Few studies investigated the reverse path of the relationship (cognitive and social emotional development – motor competence), with those studies that did presenting similarly indeterminate evidence.
5.	Potential moderators of the association between fundamental movement skills and academic attainment in adolescence	***Aim***	To identify the association between object control skills and locomotor skills with subject-specific academic attainment in adolescents and to assess whether these associations are moderated by sex, perceived sports competence, BMI z-score and/or maturity offset.
		Key findings	Object control skill competence, but not locomotor skill competence, was strongly associated with academic attainment. In addition, perceived sports competence moderated the association between object control skills and numeracy procedural and reading performance, although this moderation was small.

9.0 Thesis Synthesis

The primary aim of this thesis was to investigate the influence of biological and growth-related factors on the development and health-related associations of fundamental movement skills (FMS) in late childhood and adolescence. An underpinning proposition of the model authored by Stodden and colleagues (2008) is that the relationship between FMS and health-related outcomes is developmental, existing across the lifespan, and not restricted to childhood. However, despite the health-enhancing influence of FMS in children being consistently researched (Barnett et al., 2021; Robinson et al., 2015; Schott & Holfelder, 2015; Utesch, Bardid, Büsch, & Strauss, 2019), there remains a paucity of studies that have sought to understand the role of FMS into and during adolescence (Barnett et al., 2021; Robinson et al., 2015). In capturing the influence of biological maturation on fundamental movement skill proficiency and the association of FMS with health-related and cognitive outcomes, **Studies 2, 3** and **5** provide further insight into the developmental role of FMS during adolescence. Specifically, this thesis has extended our understanding of the moderating roles of biological maturation, weight status, and sex, and also mediators such as perceived sports competence that warrant consideration when assessing the role of FMS in child and adolescent populations. The thesis also presented a conceptual model in which the mechanisms underlying the relationship between FMS and cognitive and social-emotional outcomes are hypothesised. This model can be utilised to guide future interventions and to advance our understanding of how FMS and physical activity interact to influence a wider range of health outcomes. Taken together, the studies within this thesis support the notion of FMS as a holistic construct that act as a precursor for the positive development of physical, psychological, and mental health outcomes.

9.1 Biological maturation

The influence of biological maturation on health-related outcomes in youth has been highlighted previously (Lloyd & Oliver, 2012; Malina, Bouchard, & Bar-Or, 2004), with numerous studies reporting the influence of increasing maturity on physical activity and discrete aspects of health-related fitness (HRF; Cumming, Sherar, Esliger, Riddoch, & Malina, 2014; Malina, Cumming, & Silva, 2016; Malina, Rogol, Cumming, Silva, & Figueiredo, 2015; Sherar, Cumming, Eisenmann, Baxter-Jones, & Malina, 2010). Building on this evidence, this thesis collectively investigated the direct and indirect influence of advancing maturity on fundamental movement skill competence, and the association of these skills with health-related outcomes. Notably, **Studies 1, 2, 3** and **5** found no evidence of a maturational influence on aspects of fundamental movement skill competence when assessed using a process-oriented (technique) protocol. The absence of a maturation effect might be because there was a ceiling effect such that further improvements couldn't be identified in adolescents. However, it was only the catch skill (**Study 1**) where pre-adolescent children demonstrated a consistent level of proficiency, with a mean score of (4.8 ± 1.5) from the six available scoring criteria. Therefore, the thesis may indicate that, irrespective of sex, the changes associated with increasing maturity, such as cognitive, neurological and somatic, are not associated with an accelerated improvement in technical competence. Indeed, a plateau or even regression in motor competence for some FMS has been proposed by some as a potential outcome of the inverse association between the maturity-related growth spurt (i.e. changes in limb length) and sensorimotor function (Bisi & Stagni, 2016; Quatman-Yates et al., 2012). This is in accord with the results from **Study 2** in which jump performance was found to decrease, albeit not significantly, from circa- to post-PHV groups for both girls and boys. A regression in skill competence may also relate to the lack of adequate opportunities to maintain fundamental movement skill proficiency. Specifically, if an adolescent is not proficient in the movement skills deemed important for successful participation in sport-related activities, alternative developmental opportunities for FMS are likely to limited (Brian et al., 2020). This emphasises the role of Physical Education (PE) and wider curriculum design, especially as children transition into secondary-level education, to ensure that all children receive on-going exposure to skill development across a wide-range of contexts.

In contrast to FMS assessed using a process-oriented protocol, maturational status was found to influence product-oriented (outcome) fundamental movement skill performance, specifically in boys **(Study 2).** Although a maturational influence on product-oriented outcomes was expected in boys, the majority of previous research has focused solely on athletic populations, and may therefore not be indicative of the developmental relationship evident in a wider demographic (Malina et al., 2004; Pichardo et al., 2019). Interestingly, the maturational influence on outcome performance found in **Study 2** appears to become increasingly underpinned by a higher technical competence in post-PHV boys. In girls, the absence of a similar direct maturational influence on product-oriented competence may reflect the collective physical, psychological and emotional changes associated with increasing maturity, which have been found to negatively influence constructs of physical activity (Sherar, Cumming, Eisenmann, Baxter-Jones, & Malina, 2010).

The lack of agreement between the two methods of skill measurement in **Study 2** crucially highlights the influence that assessment choice may have on the predictive validity of FMS in children and adolescents, specifically when biological age is not controlled for. In pre- and circa-PHV children, the variance between process- and product-oriented results may be aligned to the inter-individual differences in growth and development at these ages. **Study 2** suggested that, particularly in boys, caution is needed when interpreting fundamental movement skill competence from a standalone product-oriented assessment. A failure to account for biological maturation when using a product-oriented assessment may provide practitioners with a restricted insight into the movement development milestones of their cohort. The evidence presented in this thesis suggests that, irrespective of sex, the alignment between the two measures of fundamental movement skill performance (outcome or technical) is found to strengthen following the period of PHV. This may reflect the greater stability in performance found in post-pubertal children. Moreover, boys who are highly competent in FMS are able to fully utilise the physiological adaptions (i.e. increased muscle mass) associated with advanced maturity, with this likely contributing to the widening differentiation in competence levels found in post-PHV children (Radnor et al., 2018). **Study 3** supports this notion, given that increasing maturity and skill competence were both found to be associated with the relative $\dot{V}O_2$ ($l\cdot kg^{-1}\cdot min^{-1}$) of the five performed FMS, suggesting that children and adolescents with poor mastery perform a restricted movement that does not exert the same performance characteristics as those identified as proficient. From an ecological perspective, the lack of alignment in performance measurement and the need to consider the potential influence of maturity-related changes may reinforce the benefit of adopting a circuit-based approach, such as the Dragon Challenge (Tyler, Foweather, Mackintosh, & Stratton, 2018), that allows for a more ecologically valid assessment of fundamental movement skill competence. Though it is important to note that the Dragon Challenge is currently only validated for use in 10- to 14-year-old children (Tyler et al., 2018).

9.2 Perceived self-competence

The use of path analysis in **Studies 1** and **5** enabled the identification of specific moderating factors that influence the association between FMS and health-related outcomes. Taken together, the studies identified perceived sports competence as a key moderator that requires consideration prior to and during adolescence. Specifically, **Study 1** found sex-specific associations between FMS and perceived sports competence, vigorous-intensity physical activity (VPA) and time spent sedentary in late childhood. The results are in accord with Bolger et al. (2019) who found perceived competence to have a direct influence on physical activity levels in late childhood. However, there continues to be ambiguity relating to the respective influence of perceived and actual fundamental movement skill competence as children transition into adolescence, as well as the developmental influence on the level of agreement between both elements of fundamental movement skill competence. Indeed, the interchangeable use of assessment methods favoured for measuring perceived and actual fundamental movement skill competence, coupled with the changing influence of FMS towards specific contexts of physical activity as children transition into adolescence, further compounds the lack of agreement. For example, as hypothesised in this thesis, during adolescence it could be speculated that the association between FMS and perceived sports competence is of greater interest than perceived skill competence, as the physical activity behaviours have transitioned from free-play and exploration towards an increased emphasis on sport-related activities.

Building on the findings of **Study 1, Study 5** provided further support for the importance of perceived sports competence to health-related outcomes, with perceived sports competence found to moderate the association between object control skill competence and each of numeracy procedural and reading performance. The results of **Study 5** may indicate that perceived sports competence acts as a barrier to adolescents fully utilising their fundamental movement skill proficiency in sport-related physical activity. Indeed, those with a positive perceived competence are more likely to engage in physical activity that has a cognitive complexity, and it is this cognitive stimulus that is hypothesised as a key mechanism in the association between physical activity and cognitive outcomes (Pesce et al., 2016). In contrast, as found in **Study 1**, those with low perceived sports competence may be more likely to withdraw from cognitively stimulating physical activity and are therefore at a higher risk of leading more sedentary lifestyles and having poorer cognitive outcomes.

A key outcome of **Studies 1** and **2** was that the non-veridicality evident in the association between FMS and perceived sports competence that has previously been reported in childhood (Moran et al., 2018), was also found in this thesis to continue into and during adolescence. In earlier research it was postulated that the weak association between perceived sports competence and FMS in childhood may be aligned to a reduced cognitive maturity (Bolger et al., 2018b; Harter, 1999). There is strong evidence regarding the direct- and indirect-effects of maturity on lower physical self-perception levels in girls (Cumming et al., 2020, 2012; Moore et al., 2020). However, during adolescence, additional constraints should be considered, namely those associated with the social-emotional, cognitive, physical, and behavioural changes that occur during this period (McGrane et al., 2018). These may include the influence of maturation on the association of FMS with a wider set of domains relating to self-perception and identity and may also be aligned to a greater participation in sport-related contexts, with less value being placed on involvement in non-competitive activities (Timler et al., 2019). The findings presented in this thesis highlight the complexity of assessing perceived competence in adolescence. The exception to this was the association between locomotor skill competence (process- and product-oriented) and perceived sports competence found in **Study 2**, which strengthened with increasing maturity in girls. Importantly, boys may not relate the performance of isolated FMS to their competence in primarily sport-related activity, a notion which is supported in **Study 2** where the only significant association between FMS and perceived sports competence was found in girls. Similarly, as proposed by Malina and colleagues (2016), for some adolescents self-perceived competence may have little influence on whether they engage in physical activity. Again, this may imply that a circuit-based assessment that can be more aligned to a wider movement competence that is more contextually associated to adolescent physical activity behaviours is warranted.

9.3 Cognition

Despite a growing number of studies investigating the association between FMS and cognitive outcomes, the lack of a conceptual model to guide research has hindered the impact of published findings at a policy level. As such, insight into the specificity and the developmental association between FMS and cognition remains limited (van der Fels et al., 2015), with few studies providing a strong rationale for their findings. The systematic review **(Study 4)** presented a number of key findings relating to the current evidence base and highlighted key recommendations for future research. Notably, there is a need for studies to undertake construct- and domain-specific analyses to provide greater insight into the hypothesised associations between FMS and cognitive and social-emotional outcomes. Moreover, whilst for some paths (motor competence – working memory, motor competence – academic attainment) there is supportive evidence, many of the studies did not control for moderating/mediating influences, and as such the strength and applicability of the findings is limited. A further finding was that few studies investigated the association between FMS and cognitive and social-emotional outcomes in adolescent samples, despite the influence of these outcomes on a positive academic experience and their importance to children being able to capably transition into employment opportunities. Addressing the points raised in the systematic review (**Study 4**) and congruent with prior cross-sectional studies (Donati et al., 2019a; Haapala et al., 2019), **Study 5** provided empirical evidence supporting the association between FMS and academic attainment (Donati et al., 2019; Haapala et al., 2019). Importantly, **Study 5** included an adolescent sample, as well controlling for the influence of moderating variables.

Building on earlier studies (Pesce et al., 2016; van der Fels et al., 2015) which identified visual perception as a key moderator in the relationship between physical activity and cognition, **Study 5** found a significant association between object control skills and numeracy performance. Specifically, as previously highlighted, perceived sports competence was found to moderate the association between object control skill competence and numeracy procedural and reading performance, suggesting that perceived sports competence acts as a possible barrier to adolescents fully utilising their FMS proficiency in sport and physical activity. Pesce et al. (2016) propose that object control skills are strongly associated with academic attainment as the development and performance of these skills often occurs in cognitively engaging contexts, and it is this cognitive stimulus that is a key mechanism in strengthening the association between physical activity and aspects of cognition. As presented in the systematic review **(Study 4)**, experimental evidence has already shown a stronger association between cognitively enriched physical education (PE) over traditional PE delivery (Pesce et al., 2016). From an intervention perspective, this is an important finding as it promotes a balance in the approach of practitioners, between the potential greater physiological benefits associated with fitness promotion and the health-enhancing outcomes associated with continuing to develop and challenge movement. Whilst in **Study 5** the results were specific to numeracy attainment, they provide further support for the integration of enriched, cognitively stimulating PE within primary and secondary education. However, embedding the continued development of FMS within PE and the wider curriculum remains a challenge, not least because of time constraints. As such, a strong evidence base is required to support the value that greater integration of FMS and enriched physical activity can have on the academic attainment and school associated-behaviour of school-aged children.

9.4 Strengths and Limitations

This thesis presented an original investigation into the role and influence of FMS in late childhood and adolescence. The sample sizes and demographics of the participants across **Studies 2, 3** and **5** are a key strength and are representative of the demographics for children in South Wales. Through the relationships developed with the respective schools, data was collected for anthropometric, psychological and cognitive measures, including academic assessments undertaken as part of the National Curriculum in Wales. This data can also subsequently be utilised as the basis for ongoing longitudinal follow-up. The path analysis performed in **Studies 1** and **5,** and the use of linear mixed modelling in **Studies 2** and **3** gave opportunity to gain an increased understanding of the variables that moderate the association between FMS and health-related outcomes in late childhood and adolescence. Specifically, path analysis provided an approach whereby the direct and indirect influence of both maturation and perceived competence on the association of FMS with psychological, behavioural, and cognitive outcomes could be measured. This is important as although there remains a lack of consistent evidence relating to the direct influence of maturation on FMS, an indirect influence of maturation on domains of self-perception and additional constructs of physical activity has been previously found (Moore et al., 2020; Sherar et al., 2010; Timler, McIntyre, Rose, & Hands, 2019).

Whilst this thesis has made several important contributions to the understanding of fundamental movement skill development and the continued role of FMS during adolescence, it is important to consider various limitations which should be addressed in future research. First, although curtailed by COVID-19, the lack of additional time-points to enable longitudinal investigation restricted the ability to fully delineate the influence of maturity on FMS, as well as the developmental relationship of FMS with health and academic attainment. Indeed, analysing the influence of maturity longitudinally would have provided an insight into the inter- and intra-individual developmental trajectories relating to FMS, and how these influence the relationship of FMS with the assessed outcomes. Also, with the exception of **Study 1**, the studies in this thesis did not include physical activity as an outcome variable. Although a reciprocal relationship between FMS and physical activity has been proposed, there remains a paucity of research analysing this relationship beyond childhood (Holfelder & Schott, 2014; Lubans et al., 2010; Robinson et al., 2015), with few studies that have investigated whether FMS remain crucial to physical activity behaviour during adolescence (Hands, Larkin, Parker, Straker, & Perry, 2009; Jaakkola et al., 2019; Lima et al., 2017).

Within this thesis, perceived sports competence was used as a measure of perceived fundamental movement skill competence, which has previously been criticised for lacking specificity to the FMS being performed (McGrane, Belton, Powell, Woods, & Issartel, 2016). Consequently, skill-specific perceived competence tools have been presented as a means to achieve a true measure of a child’s fundamental movement skill perception (Barnett, Ridgers, Zask, & Salmon, 2015b; McGrane, Powell, Belton, & Issartel, 2018). However, the Children and Youth Physical Self-Perception Profile

(PSPP-CY; Whitehead, 1995) was selected as it provided the opportunity to identify the additional constructs of self-efficacy that become increasingly important during adolescence (De Meester et al., 2020). Indeed, assessing perceived sports competence was deemed important due to its role in determining whether children choose to actively engage in physical activity and sport. As sport participation becomes a prominent component of adolescent physical activity, perceived sports competence may offer strong insight into the value of FMS to youth physical activity engagement. Moreover, during adolescence it is likely boys will relate their fundamental movement skill competence to a sporting context more strongly than girls and in contrast to younger children who would likely relate it to their proficiency in completing isolated skills (De Meester et al., 2020).

Finally, in **Studies 2,3 and 5**, FMS were assessed using the Test of Gross Motor Development - Version 3 (TGMD-3) protocol, and as such the limitations associated with this assessment must be considered when evaluating the findings. It is pertinent to note that both fundamental movement skill protocols used in this thesis (Get Skilled, Get Active; TGMD-3) were subjective in nature. However, assessor training was completed prior to the initial pilot study, and inter- and intra-reliability was assessed and found to be adequate for all studies, with two trained assessors involved across all data collection points. For some FMS, there was evidence of a 'ceiling effect' (i.e. run, catch), which has previously been shown to affect the validity of results (Logan et al., 2017; Webster & Ulrich, 2017). However, as an assessment, the TGMD-3 protocol has been found to demonstrate reliability and validity (Issartel et al., 2017; Murray, 2020). Moreover, this thesis, in accord with recent research (Bolger et al., 2020; O' Brien et al., 2016a; Philpott et al., 2020), reveals that there remains little evidence of competence-related increases between mid-childhood and adolescence. Incorporating a more dynamic assessment of FMS, such as the Dragon Challenge (Tyler et al., 2018), may have provided a stronger insight into the importance of movement competence to health-related outcomes. As a dynamic circuit based assessment of movement competence, the Dragon Challenge is more reflective on the constraints-based movements that underpin various physical activity behaviours and sport participation during adolescence (Tyler et al., 2018).

9.5 Future Directions

Collectively, the studies within this thesis have further highlighted the importance of FMS to a range of health-related outcomes prior to and during adolescence. Reinforced by global trends of insufficient physical activity levels and fundamental movement skill proficiency in youth, it is important that future research investigates the developmental patterns of FMS during adolescence. Further studies are warranted to ascertain the specificity (i.e. analyses at a construct level rather than composite level) of the influence of FMS on associated health-related outcomes in adolescence, and the extent to which there is stability in these relationships. An ecological approach offers a model to guide understanding of the predisposing, reinforcing, and enabling factors of physical activity during adolescence, and to also identify whether the influence of FMS is maintained from a lifespan perspective (Malina et al., 2016; Tyler et al., 2020). Longitudinal and interventional studies also provide an opportunity to develop an understanding of fundamental movement skill-related trajectories during adolescence and are therefore strongly advocated. Furthermore, assessing the respective longitudinal influence of moderating variables, such as domains of self-perception and HRF, would give practitioners a foundation from which to establish effective and sustainable interventions. Person-centred analyses, such as multilevel regression analyses should also be utilised to determine the alignment of FMS with moderators, such as maturation and self-perception, to identify whether there is consistency in the influence, or if it is indeed more pronounced for some profiles (Bardid, De Meester, et al., 2016; De Meester et al., 2016a).

From a governing perspective, it is crucial that a continued effort is made to reduce the sex-specific disparity that currently exists in the development of FMS. Overall, this thesis highlights that many of the sex-related development patterns remain consistent from childhood throughout adolescence, and in some instances, become more pronounced with advancing age. Given this, a concerted effort should be made to expose all children, irrespective of sex, to a diverse range of sports and cognitively challenging movements. This would likely challenge current developmental patterns, where many girls transition into adolescence lacking the actual and perceived competence to confidently immerse themselves in many of the sport and physical activity opportunities. Addressing these challenges, both prior to, and upon commencing secondary-level education, should be a key focus of the PE curriculum. To achieve this within education, it is important that, irrespective of sex, children are provided with the opportunity to develop all FMS in a stimulating and inclusive environment, where they become motivated to participate in a range of sporting contexts (Barnett et al., 2016b; Tompsett et al., 2017). This is in contrast to pedagogical approaches that increasingly restrict the confidence for movement exploration and fundamental movement skill development (Philpott et al., 2020). There is also a need to identify appropriate strategies to resolve the issues related to the recent impact of COVID-19 associated restrictions (Bates et al., 2020). This thesis highlights that the health-related issues that will likely ensue aren't just constrained to young children but will likely be evident across childhood and adolescence.

To gain further insight into the influence of biological maturity on FMS, future studies should utilise device-based measures to provide analysis of how the adolescent growth spurt affects aspects of fundamental movement skill execution. This may enable a clearer understanding of whether there is commonality in the regressions that occur for specific skills, and whether these are indeed sex-specific. From a practitioner perspective, this would facilitate the ability to intervene at crucial periods of accelerated growth and offer a stronger approach to understanding the influence of inter-individual differences on the development of FMS. Device-based measurement may also offer a solution to overcoming some of the weaknesses that limit the application of fundamental movement skill assessment in a practical setting, such as a substantial time commitment and the need for trained assessors (Grimpampi, Masci, Pesce, & Vannozzi, 2016). A key factor in determining the widespread usability of device-based assessments of FMS will be the identification of the optimal positioning on the body for sensors and the minimal numbered sensors needed to obtain clinically important results (Clark, Bisi, Duncan, & Stagni, 2021). Indeed, Swain (2020) presented initial support for the validity of a single device-based measurement unit for identifying competent and non-competent execution of the overhand throw. Swain (2020) also presented a visualisation of the data that could be offered to the end-user (i.e. practitioner or school-aged children) as a valuable tool from which the learning and assessment experience can be improved. The use of kinematic data from software, such as the Kinect system (Microsoft Corporation, Redmond, WA) has been proposed as a further cost-effective and reliable method for automated assessment (Ward, Thornton, Lay, & Rosenberg, 2017). These developments are especially pertinent to the school setting, where time constraints and a lack of teacher training limit the widespread implementation of process-oriented assessments (Ward et al., 2017). They may also provide an analytical approach with greater sensitivity than current protocols that may fail in identifying specific inter-individual competency differences.

9.6 Considerations for practical application

In line with the findings presented in this thesis, it is important that practitioners tasked with developing FMS and physical literacy can adopt pedagogical practices that aim to embody a whole systems approach and provide the best opportunity to facilitate the development of competent and confident learners (Mandigo et al., 2018; Rudd et al., 2020). Specifically, the findings advocate for a move away from reductionist approaches to FMS, physical activity and sport participation and instead promote the design of enriched environments that challenge children to explore and execute movement solutions (Button et al., 2020; Rudd et al., 2020). Although there are distinguishable differences between the individual perspectives associated with a whole systems approach, there are a set of overarching principles that should underpin the delivery of an enriched and engaging programme:

- A consideration for the type of context a programme is being delivered in and the influence this may have on the complexity level of delivery, the extent of social contact and the emotional engagement of children (Pesce et al., 2021). For example, Rudd et al. (2021) use a gymnastics lesson to demonstrate how rather than a linear, authoritative approach, where children progress through a series of isolated skill performances, a practitioner can instead use a softer approach and utilise all of the available equipment to promote specific affordances and a range of movement solutions. Practitioners can also foster positive adaptions through integrating the natural environment into their delivery.
- Aim to challenge "hot" executive functions, such as inhibition and self-regulation by creating an environment that promotes emotional engagement and demands children

to utilise affordances (Pesce et al., 2021). For example, the practitioner can introduce additional constraints to movement tasks that challenge and foster further movement solutions, this could include adding further participants into game situations (i.e., defenders in netball or football) or introducing additional task constraints (i.e., a reduced playing area).

- Practitioners should fulfil the role of an environment architect, to ensure the context promotes problem-solving, self-selected risk taking and functionally variable movement patterns (Roberts et al., 2019). For example, the practitioner should aim to identify aspects of the lesson that can be student-led. In addition, the practitioner can aim to introduce multiple stations so that the learners are not required to spectate for long periods.
- Promote functionally variable movement patterns by manipulating task constraints so that learners are offered variation but also repetition (Davids et al., 2006; Roberts et al., 2019). For example, practitioners can change the size of equipment being used (i.e., larger, softer bouncing tennis ball to traditional ball), the size of the environment (i.e., reducing the size of a sport court) and increasing or decreasing the number of participants. All of these can evoke movement solutions in children if implemented in alignment with their competence.
- To foster engagement, motivation and enjoyment from learners the context should accommodate for children of different movement competencies and self-confidence. For example, practitioners may need to tailor the design of delivery to support children across the continuum of physical competence, this can be achieved through grouping children into smaller, developmentally aligned stations. In addition, practitioners should consider the influence that mixed sex groups and maturational differences may have on outcomes such as self-concept.

9.7 Personal reflection

Since embarking on this PhD I have consistently been afforded opportunities to engage with many incredible academics and practitioners, all of whom have had a lasting influence upon me. It is therefore important to summarise how these interactions have shaped my development and led to me challenging my personal interpretation of the role of FMS during this PhD.

As I sit here reflecting on my thesis, I am very much aware that I now approach the role of FMS from very much a holistic perspective, with this becoming more firmly established as my journey has progressed. That is, I believe the inter-connectedness of FMS with physical, mental and socio-emotional health should underpin the classification and assessment of FMS. At the outset of my PhD, my approach to FMS was considerably more linear and reductionist. Whilst I believe along with others (Rudd et al., 2020) that there will remain a place in research and assessment for closed setting skill execution, I now approach the elaborative statements often adjoining closed skill standardised assessments more cautiously. In part, this may have been influenced by my study findings that evidenced the role of moderators and mediators on FMS. Indeed, whilst standardisation can facilitate understanding of fundamental movement skill competence at a population and global level, it does not flex to individual diversity. I therefore think that attempts to separate the body and mind should be avoided and where possible acknowledge the importance of including aspects relating to how the learner would interact with their environment. I see great value in integrating perception, motivation, enjoyment and confidence into assessments.

As proposed by Etnier et al. (2020) we are now entering a nuances stage in physical activity – cognition research, with a need to further understand the role of moderators and mechanisms. Recognising this, I believe some incredible insight can be gained from undertaking research that addresses the roles of contexts and mechanisms in the development of physical literacy and FMS. Increasingly, the influence of FMS within cognitively enriched interventions is being proposed as a key underpinning element in the physical activity - cognition relationship. In agreement with Pesce et al. (2021), I believe, to build on this, a greater understanding of the context characteristics (i.e., cognitive enrichment, instructor expertise, level of enjoyment) is pivotal in on-going experimental research studies. Whilst there is accumulating evidence supporting the role of FMS in influencing cognitive outcomes, the crucial aspiration must be to understand within which context and through which mechanisms does this occur. If the role of FMS and cognitively enriched delivery can be consolidated, I think there are great strides that can be made at a policy level.

9.8 Summary

Overall, the studies included within this thesis have advanced our understanding of the role and importance of FMS during late childhood and adolescence. Crucially, the studies have highlighted the continuing influence of FMS on health-related outcomes and academic attainment during adolescence. However, worryingly, the studies provide further evidence that few children are achieving the expected proficiency in FMS by late childhood and adolescence. **Study 2** showed that if practitioners are using a process- or product-oriented assessment of FMS across late childhood and adolescence, then consideration of the influence of maturity stage is required, and as a suitable alternative to current process- and product-oriented assessments, a circuit based approach may offer a more valid assessment protocol. This is particularly pertinent as the global assessment and implementations of interventions to promote FMS in secondary-level school aged children will likely increase in the coming years. A key finding of **Study 3** was the association between fundamental movement skill proficiency and the associated energy expenditure of skill performance. From an intervention perspective, this provides further support for the development of fully competent movement patterns in children, as it offers the opportunity to increase the health benefits associated with sport participation. Indeed, the implications of this will become clear as improvements in device-based analyses allow for greater insight into the influence of movement proficiency on the levels and types of physical activity. In presenting the association of object control skills and aspects of academic attainment, **Study 4** provided crucial evidence supporting the wider adoption of FMS and enriched PE within the school curriculum. Whilst the association between FMS and physical and psychological outcomes is now established, recognition of the importance of FMS within educational programmes is now warranted.

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11.0 Appendices

Appendix I

Pre-exercise screening questionnaire

Children Physical Activity Readiness

Questionnaire & Health Screening Consent Form

Date:

The purpose of this form is to ensure that we provide every participant with the highest level of care. There are a small number of children or adolescents who may be at risk when participating in an exercise / physical activity session. Completion of this questionnaire is mandatory, and your child cannot participate in any Swansea University exercise session until it has been submitted to a Swansea University researcher.

Childs name:	**Childs date of birth:**
Parent / Guardian Name:	**Current Age of Child:**
Address:	
Emergency contact details:	
Mobile Number:	**Work Telephone Number:**
Email:	

Health Questions:

Does your child have, or has he / she ever experienced any of the following? Please tick:

	Yes	No
High or Low blood pressure		
Elevated blood cholesterol		
Diabetes		
Chest pains brought on by physical exertion		
Childhood epilepsy		
Dizziness or fainting		
A bone, joint or muscle problem with arthritis		
Asthma or respiratory problems		

Any sustained injuries of illnesses		
Any allergies		
Is your child taking any medication		
Has your doctor ever advised your child not to exercise		
Is there any reason not mentioned above why any type or physical activity may not be suitable for your child		

If answered 'YES' to any of the above questions, please give full details here:

Is there anything else we should know about your child that has NOT been addressed in the Health questions on this form?

If your child has any known allergies, has the researcher in charge of your session been made aware of medication you are taking and where to find this?

In the absence of a parent/guardian, I understand that my child is responsible for monitoring him or herself throughout the exercises, and should any unexpected symptoms occur, would cease participation and inform the researcher.

In the event that medical clearance must be obtained before my child's participation in an exercise session, I agree to contact the GP to obtain written permission prior to the commencement of the exercise activity, and that the permission is given to the researcher where a copy of the medical advice will be kept on file.

I understand that if my child fails to behave in a manner that is polite and social, he / she could be suspended from that activity.

Video/Photography Consent

I understand that occasionally my child may appear in promotional photography/video clips of Swansea University and that material may be used by Swansea University websites and other promotional material.

Please tick here ☐ if photographs are NOT permitted

By signing this form, I the parent/guardian of the aforementioned child, affirm that I have read this form in its entirety; I have answered the questions accurately and, to the best of my knowledge, will inform Swansea University of any future changes.

I the parent/guardian of the aforementioned child give permission for him/her to participant in Swansea University research sessions and understand that Swansea University researchers taking the exercise sessions cannot be liable for any loss of personal injury

Parent/guardian's signature: Date: Please print name:

Researcher(s) signature: Date:

Appendix II

I.D

Name:____________________________

What I am like (PSPPC)

This questionnaire is all about you! The following questions ask you about your interests in physical activity. Please read the following instructions carefully before starting the questionnaire.

- To answer each question you need to carefully read about each question.
- Once you have read both situations you need to decide which of the situations is most like you.
- Next decide whether the situation is “really like you” or “sort of like you” and mark or colour the box either side.
- Please choose only one answer per question

	Really True for me	Sort of True for me				Sort of True for me	Really True for me
1			Some kids do very well at all kinds of sports	BUT	Other kids don't feel they are very good when it comes to sports.		
2			Some kids feel uneasy when it comes to doing vigorous physical exercise	BUT	Other kids feel confident when it comes to doing vigorous physical exercise.		
3			Some kids feel that they have a good-looking (fit-looking) body compared to other kids	BUT	Other kids feel that compared to most, their body doesn't look so good.		
4			Some kids feel that they lack strength compared to other kids their age	BUT	Other kids feel that they are stronger than other kids their age.		
5			Some kids are proud of themselves physically	BUT	Other kids don't have much to be proud of physically.		
6			Some kids are often unhappy with themselves	BUT	Other kids are pretty pleased with themselves.		
7			Some kids wish they could be a lot better at sports	BUT	Other kids feel that they good enough at sports.		
8			Some kids have a lot of stamina for vigorous physical exercise	BUT	Other kids soon get out of breath and have to slow down or quit.		
9			Some kids find it difficult to keep their bodies looking good physically	BUT	Other kids find it easy to keep their bodies looking good physically.		
10			Some kids think that they have stronger muscles than other kids their age	BUT	Other kids feel that they have weaker muscles than other kids their age.		
11			Some kids don't feel very confident about themselves physically	BUT	Other kids really feel good about themselves physically.		

	Really True for me	Sort of True for me				Sort of True for me	Really True for me
12			Some kids are happy with themselves as a person	BUT	Other kids are often not happy with themselves.		
13			Some kids think they could do well at just about any new sports activity they haven't tried before	BUT	Other kids are afraid they might not do well at sports activity they haven't tried.		

14	☐	☐	Some kids don't have much stamina and fitness	BUT	Other kids have lots of stamina and fitness.	☐	☐
15	☐	☐	Some kids are pleased with the appearance of their bodies	BUT	Other kids wish that their bodies looked in better shape physically.	☐	☐
16	☐	☐	Some kids lack confidence when it comes to strength activities	BUT	Other kids are very confident when it comes to strength activities.	☐	☐
17	☐	☐	Some kids are very satisfied with themselves physically	BUT	Other kids are often dissatisfied with themselves physically.	☐	☐
18	☐	☐	Some kids don't like the way they are leading their life	BUT	Other kids do like the way they are leading their life.	☐	☐
19	☐	☐	In games and sports some kids usually watch instead of play	BUT	Other kids usually play rather than watch.	☐	☐
20	☐	☐	Some kids try to take part in energetic physical exercise whenever they can	BUT	Other kids try to avoid doing energetic exercise if they can.	☐	☐
21	☐	☐	Some kids feel that they are often admired for their good-looking bodies	BUT	Other kids feel that they are seldom admired for the way their bodies look.	☐	☐
22	☐	☐	When strong muscles are needed, some kids are the first to step forward	BUT	Other kids are the last to step forward when strong muscles are needed.	☐	☐
23	☐	☐	Some kids are unhappy with how they are and what they can do physically	BUT	Other kids are happy with how they are and what they can do physically.	☐	☐
24	☐	☐	Some kids like the kind of person they are	BUT	Other kids often wish they were someone else.	☐	☐

	Really True for me	**Sort of True for me**				**Sort of True for me**	**Really True for me**
25	☐	☐	Some kids feel that they are better than others their age at sports	BUT	Other kids don't feel they can play as well.	☐	☐
26	☐	☐	Some kids soon have to quit running and exercising because they get tired	BUT	Other kids can run and do exercises for a long time without getting tired.	☐	☐
27	☐	☐	Some kids are confident about how their bodies look physically	BUT	Other kids feel uneasy about how their bodies look physically.	☐	☐

28	☐	☐	Some kids feel that they are not as good as others when physical strength is needed	**BUT**	Other kids feel that they are among the best when physical strength is needed.	☐	☐
29	☐	☐	Some kids have a positive feeling about themselves physically	**BUT**	Other kids feel somewhat negative about. themselves physically.	☐	☐
30	☐	☐	Some kids are very happy being the way they are	**BUT**	Other kids wish they were different.	☐	☐
31	☐	☐	Some kids don't do well at new outdoor games	**BUT**	Other kids are good at new games right away.	☐	☐
32	☐	☐	When it comes to activities like running, some kids are able to keep on going	**BUT**	Other kids soon have to quit to take a rest.	☐	☐
33	☐	☐	Some kids don't like how their bodies look physically	**BUT**	Other kids pleased with how their bodies look physically.	☐	☐
34	☐	☐	Some kids think that they are strong, and have good muscles compared to other kids their age	**BUT**	Other kids think that they are weaker, and don't have such good muscles as other kids their age.	☐	☐
35	☐	☐	Some kids wish that they could feel better about themselves physically	**BUT**	Other kids always seem to feel good about themselves physically.	☐	☐
36	☐	☐	Some kids are not very happy with the way they do a lot of things	**BUT**	Other kids think the way they do things is fine.	☐	☐

Section F: How important are these things to how you feel about yourself as a person?

[Perceived Importance Profile]

	Really True for me	Sort of True for me				Sort of True for me	Really True for me
1	☐	☐	Some kids think it's important to be good at sports	**BUT**	Other kids don't think how good you are at sports is that important.	☐	☐
2	☐	☐	Some kids don't think that having a lot of stamina for energetic exercises is very important to how they feel about themselves	**BUT**	Other kids think that having a lot of stamina for vigorous exercise is very important.	☐	☐
3	☐	☐	Some kids think it's very important to have a good-looking (fit-looking) body in order to feel good about themselves as a person	**BUT**	Other kids don't think that having a good-looking body is important at all.	☐	☐
4	☐	☐	Some kids think that being physically strong is not all that important to how they feel about themselves as a person	**BUT**	Other kids feel that it's very important to be physically strong.	☐	☐
5	☐	☐	Some kids don't think doing well at athletics is that important to how they feel about themselves as a person	**BUT**	Other kids feel that doing well at athletics is important.	☐	☐
6	☐	☐	Some kids feel that having the ability to do a lot of running and exercising is very important to how they feel about themselves as a person	**BUT**	Other kids don't feel it's all that important to have the ability to do a lot of running and exercising.	☐	☐
7	☐	☐	Some kids don't think that having a body that looks in good physical shape is important to how they feel about themselves	**BUT**	Other kids feel that it's very important to have a body that looks in good physical shape.	☐	☐
8	☐	☐	Some kids think that having strong muscles is very important to how they feel about themselves	**BUT**	Other kids feel that it's not at all important to have strong muscles.	☐	☐

Appendix III

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)

Sport and Health Portfolio, College of Engineering

APPLICATION FOR ETHICAL COMMITTEE APPROVAL OF A RESEARCH PROJECT

In accordance with A-STEM and College of Engineering Safety Policy, all research undertaken by staff or students linked with A-STEM must be approved by the A-STEM Ethical Advisory Committee prior to starting data collection.

Applications for approval should be submitted on this form. The researcher(s) should complete the form in consultation with the project supervisor. Where appropriate, the application must include the following appendices: (i) Participant Information Sheet, (ii) Participant Consent Form, (iii) Participant Health Screening Questionnaire.

After completing and signing the form students should ask their supervisor to complete and sign the declaration section. Staff members should submit the form directly to the Chair of the A-STEM Ethical Advisory Committee.

Applicants will be informed of the decision of the Committee via email to the project leader/supervisor.

1. TITLE OF PROJECT

Developing objective assessment methods of fundamental movement skills through visualisation.

2. NAMES AND STATUS OF RESEARCH TEAM

Name	**Status**	**Specific Task**	*(DBS) check* Disclosure and Barring Service	**First Aid**

Dr Kelly Mackintosh	Supervisor	Co-supervisor of MSc	Yes	Yes
Dr Melitta McNarry	Supervisor	Co-supervisor of MSc	Yes	Yes
Prof Gareth Stratton	Supervisor	Data analysis	Yes	n/a
Dr Bronagh McGrane	Researcher	Data analysis	n/a	n/a
Dr Alex Montoye	Researcher	Data analysis	n/a	n/a
Dr Karin Pfeiffer	Researcher	Data analysis	n/a	n/a
Dr Mark Holton	Researcher	Data analysis	No	n/a
Dr Iwan Griffiths	Researcher	Data analysis	n/a	n/a
Miss Maeve Murray	Postgraduate student	Data collection and Analysis	Yes (*QTS 2008) Access NI	Yes
Mr Phillip Hill	Postgraduate student	Data collection and Analysis	Yes	Yes
Mr Rory Mcintire	Undergraduate student	Data collection	Yes	No
Mr Jack Davies	Undergraduate student	Data collection	Yes	No

**Qualified Teacher Status*

3. RATIONALE

Fundamental movement skills (FMS) are goal-directed movement patterns and consist of locomotor, object control and stability skills performed in the bipedal position (Burton & Miller, 1998). FMS allow children to move from location to location and to react in an appropriate way to a range of stimuli (Krebs, 2000). Children are expected to develop these FMS in the fundamental movement phase of development which occurs from age 3 to 7 years. During this phase, children practice their gross- and fine-motor skills. They are involved in advancing and enhancing FMS such as running, kicking, jumping, throwing, and striking. Children in this phase first learn the skills individually and then merge them with other skills to form more advanced skills (Gallahue, Ozmun, & Goodway, 2012). FMS are used in every-day life, and mastery of these skills among children and adolescents is an important contributor of future participation in sports and physical activities (Booth et al., 1999; Williams et al., 2008). The importance of gaining insight into a FMS and physical activity behaviour association is emphasised by physical inactivity now being one of the most prevelent risk factors of non-communicable diseases worldwide (World Health Organization, 2016). Ozmun and Gallahue (2016) highlight that children should have these FMS mastered by the age of 10 years in order to progress to sport-specific skill development. It is important to note that this advancement does not occur naturally and children do not just acquire these skills as a result of maturation - they must be taught (Clark, 2007; Haywood & Getchell, 2002). However, analysis of biological maturity may offer insight into the developmental patterns of FMS, and help in tracking them across childhood and adolescence. Developing FMS gives children a platform to lead a habitual physically activity life as they have skills which can be transferred from one sport to another.

It is important that children's development of FMS is assessed and monitored in order to intervene and provide support where needed. However, the assessment of these skills is subjective and also time consuming for a teacher to complete for all children. This purpose of this study is to develop an objective assessment tool to standardise the measurement of skill development, and ascertain whether there is a maturational influence upon the performance of these movements. Specifically, accelerometers will be used to visualise movement patterns during specific skills which will subsequently be developed into simple, visual tools for teachers to use when assessing a skill.

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5. AIMS and OBJECTIVES

The aim of the current study is to ascertain whether we can objectively measure children completing FMS and use this measure to develop visualisation tools to aid in the objective assessment of proficiency.

6. METHODOLOGY

6.1 Study Design

We will undertake a mixed cross-sectional and longitudinal study of 100 participants who are boys and girls and are aged between 6-16 years old and are free from any physical or neurological conditions (e.g. dyspraxia) that affect the way they move.

Participants will be recruited through primary and secondary schools and it is envisaged that this will be in the surrounding area of the university. An invitation letter/email will be distributed which will provide information regarding the study and it’s aims and a request to formally invite participants from the school to take part. In this letter it will also request a meeting (if so desired by the school) between the research team leader(s) and the schools (prior to addressing potential participants) to gauge interest in participation. A formal presentation and recruitment will be made directly to potential participants outlining the project aims and extent of participant involvement.

Due to the age of participants and their categorization as a vulnerable population, special considerations have been made for recruiting members and disclosure of involvement in the study with parents/ guardians. Simplified, age appropriate information will be provided for the participant during recruitment for the study and during data collection at the laboratory. Discretionary information regarding participants and their involvement in the study will be informally noted by the data collection team to provide a positive laboratory environment for the participant(s). The participants will perform the test of gross motor development

(TGMD-3) procedure either at the Biomechanics laboratory at Swansea University Bay Campus or at the present school gymnasium (subject to risk assessment). Each participant will be expected to take part in an injury prevention and preparation warm up and then perform 13 skills three times (1 practice, trial 1 and trial 2) to the best of their ability. The total time of involvement for the participant in the laboratory is envisaged to take up to 90 minutes (inclusive of demonstration time by researcher), this will include time being allocated for the participants to have their anthropometric measurements recorded.

Following on from the completion of the practical assessment, the entire cohort will be asked to wear an ActiSleep+ monitor for 7 consecutive days at an issued date, subject to participant consent. The participants will also be asked to keep an activity log to record any instance that may require them to remove the accelerometer.

To gain insight into an association with a parameter of current health status, participants will be asked to complete an incremental ramp exercise test to determine peak $\dot{V}O_2$ and the gas exchange threshold (GET) on a cycle ergometer at the Physiology laboratory at the Swansea University Bay Campus.

6.2 Experimental Procedures

Prior to any testing procedures, participants and their parents/guardians will be provided with an information sheet and asked to provide written informed assent and consent, respectively (Appendix B and C). General health screening using a children's PARQ (Appendix A) can be used to provide assurance for participant suitability to take part without risk. The general laboratory risk assessment by the A-STEM will be adhered to and other health and safety checks (clearing and appropriate storage of sports equipment and monitors) will be undertaken by the researcher(s) to maintain the health and safety of participants and research team during testing. Participants will be asked to complete the Edinburgh handedness questionnaire before their standing height, sitting height, body mass are measured by a researcher of the same sex.

After this, the participants will complete the TGMD-3 FMS assessment. The TGMD-3 is a process orientated assessment tool which assesses 13 FMS (run, gallop, skip, hop, horizontal jump, slide, two-handed strike of a stationary ball, one hand forehand strike of self-bounced ball, one hand stationary dribble, two hand catch, kick a stationary ball, overhand throw, underhand throw) through the observation of individual components within the skill. It is a newly developed tool based on the widely used and highly valid and reliable TGMD-2 (Ulrich, 2010). Every participant will complete the 13 skills to the best of their ability. Before participants perform the skill, a demonstration will be given to them by the researcher. The participant will then perform the skill with no prompting or feedback given during the test itself. They will have one practice go and 2 trial attempts at each skill. The trial attempts will be recorded on a video camera and later assessed by the researcher. During this process, participants will be asked to wear 7 accelerometers (each wrist, hip, knee and ankle and one on the centre of the chest).

Participants will also be asked to complete an incremental ramp exercise test to determine peak $\dot{V}O_2$ and the gas exchange threshold (GET) on a cycle ergometer at two determined occasions across the study. During this test, participants will perform 3 min of baseline cycling at 0 W, after which the work rate will be increased at a rate of 20-25 $W \cdot min^{-1}$ until volitional fatigue. Volitional fatigue shall be defined as an inability to maintain the required cadence despite strong verbal encouragement in addition to subjective indications such as hypernea, facial flushing, sweating and an RER in excess of 1.1. During the test, the participants will be instructed to maintain a pedal cadence of 70-80 rpm. Breath-by-breath pulmonary gas-exchange variables (Oxycon; Jaeger, Germany) and beat-by-beat cardiovascular variables will be collected continuously throughout the test. Five minutes active and 10-minutes passive seated recovery will then follow. Maximal effort verification will then be performed, whereby a 3-min warm-up will precede a 'step' transition to a constant work rate equivalent to 110% peak power output, as reported in both children (Barker et al. 2009) and adults (Poole et al. 2008). This work rate will be maintained until voluntary exhaustion. Finally, participants will complete five minutes active recovery. Participants will be familiarised with the cycle ergometer prior to the start of the test and verbal assurances will be sought at regular intervals throughout that participants are happy to continue.

To enable the researchers to ascertain a relationship between FMS competency and physical activity habits, each participant will be asked to wear a monitor that will enable the research team to analyse their current physical activity level. The ActiSleep+ Monitor® (Actigraph, Pensacola, FL, USA) will be used to measure and record the quantity and frequency of body movement in order to provide an objective and accurate measure of physical activity. This has been previously validated for use with school children by Pate, O'Neill, and Mitchell (2010). Participants will be asked to wear the accelerometer on the right mid-axilla line at the level of the iliac crest for 7 full days, only removing it if they are undertaking contact or water based activities. Activity diaries will be used to log why the accelerometers were taken of and for how long.

6.3 Data Analysis Techniques

Custom made data cutting software

The data from the accelerometer will initially be segmented into individual skills using Swansea university custom-made software. This software will be used to correct any acceleration and geomagnetism offsets.

Framework 4

Framework 4 is another custom-made software developed by Swansea university. This software will be used to create a G-Sphere, a custom visualisation, from the individual skill files. The g-spheres produced will be grouped according to subjective skill rating to ascertain if differences are evident and categorially according to the G-sphere.

Subjective assessment of the TGMD-3

The researchers will complete the analysis using the TGMD-3 assessment tool and the videos which were recorded during data collection. For each skill, there are up to 6 individual components (for example in the kick a component would be to strike the ball on the laces of the foot). For each component which is present participants will score a 1 and if a component is performed incorrectly or absent, they will get a 0. This will then result in a total score for each skill. The higher the score achieved the more proficient the participant is. Once the G-Sphere's and the TGMD-3 sheets are completed they can be compared to each other to see the scores given for each skill.

Maturational assessment

The anthropometric measurements of each participant (sitting height, standing height and body mass) will be used to complete a non-invasive maturational assessment. Standing and sitting height will be recorded using a Holtain stadiometer, Holtain Ltd. Pembrokeshire, U.K. Body mass will be recorded using a Seca 899, Seca Ltd, Birmingham, U.K. The researchers will use the predictive equation proposed by Mirwald *et al* (2002) to calculate the years to peak height velocity (PHV) for each participant.

The Tanner self-assessment method will require the participant, based on whether they are male or female to choose one illustration from a group of five on a standardised sheet. Together with the data from the PHV predictive equation, this data will allow for a greater insight into the concomitant processes of growth and maturation.

Assessment of peak $\dot{V}O_2$ and the gas exchange threshold (GET)

The gas exchange data will be interpolated to 1-s intervals and peak $\dot{V}O_2$ taken as the highest 10-s stationary average during the test. The gas exchange threshold (GET) will be determined by the V-slope method (Beaver et al. 1986) as the point at which carbon dioxide production begins to increase disproportionately to $\dot{V}O_2$ as identified using purpose designed software developed using LabVIEW (National Instruments, Newbury, UK). The most appropriate model to describe the cardiovascular and muscle deoxygenation variables as a function of percentage peak $\dot{V}O_2$ will be determined by comparing the linear, ($Y = a + bX$), general quadratic ($Y = a + bX + c(X)^2$) and sigmoid relationships ($Y=a/(1+exp^{-(-c+dx)})$) using least-squares and maximum likelihood estimation for linear and non-linear regression, respectively

(Graphpad Prism, Graphpad Software, San Diego, CA). The best fitting model will be determined on the basis of the R^2 values, the residual sum of squares and the F-value.

Measuring physical activity

The ActiSleep+ Monitor® (Actigraph, Pensacola, FL, USA) will be used to measure and record the quantity and frequency of body movement in order to provide an objective and accurate measure of physical activity. This has been previously validated for use with school children by Pate, O'Neill, and Mitchell (2010). Participants will be asked to wear the accelerometer on the right mid-axilla line at the level of the iliac crest for 7 full days, only removing it if they are undertaking contact or water based activities. Activity diaries will be used to log why the accelerometers were taken of and for how long. Accelerometers will be set with a 100Hz epoch. Sustained periods of 20 minute or longer at zero counts will be considered to be non-weartime (Catellier et al., 2006). The weartime criterion the research team will aim for will be set at 3 weekdays and 1 weekend day, above the recommended criterion (Rich et al., 2013) daily weartime aim will be set at 8 hours. As suggested by Trost, Loprinzi, Moore, and Pfeiffer (2011), Evenson, Catellier, Gill, Ondrak, and McMurray (2008) cut points will be used to determine level of activity.

6.4 Storage and Disposal of Data and Samples

Data will be stored on the personal computers of the lead researchers (MAM, KM) for the duration of the study. These computers will be encrypted and protected by a password known only by the individual research team member. These two researchers plus JD and RM will hold the anonymised data throughout the study duration.

Personal details will be destroyed at the end of the study (e.g. name) and only non-identifiable data will be stored. We seek approval for storage for up to 7 years so that anonymous data could be reviewed to answer further important questions that might arise over this time. Following this, MAM and KM will be responsible for disposing of the data.

6.5 Dietary supplementation

N/A

7. LOCATION OF THE PREMISES WHERE THE RESEARCH WILL BE CONDUCTED.

Biomechanics Laboratory, B110 Engineering East

Dr Melitta McNarry/Dr Kelly Mackintosh will be present as first aiders

8. PARTICIPANT RISKS AND DISCOMFORTS

There aren't any significant risks associated with the study. If the participant follows our instructions which will ensure that they are properly warm for the activity, then the risks will be minimised. There is a small risk of injury from the activity (as in any Physical Education class), however there will be trained first aiders on hand to deal with any injuries which may occur and the activities being completed are typical for their age. Throughout the assessment session there will always be at least one person qualified in first aid present.

Participants will undertake maximal exercise during this study which is associated with physical discomfort such as a high heart rate and breathing rate and local muscular fatigue. The acute risks associated with exercise are very small and this will be further minimised by health screening prior to undertaking exercise.

The accelerometers may cause a slight skin irritation if the monitors are worn too tightly. The research staff will ensure that the accelerometers are comfortable and adjust them during the testing if the participant is uncomfortable at any point.

There is a small risk of psychological discomfort relating to the sexual maturity assessment. To negate this risk, participants will be provided with a private setting in which to complete the form and will be assured that only the researchers and their supervisors will have access to these. Participants will also be reminded that for those who wish, they will be allowed to complete the assessment at home, to be returned to school the following day. The anthropometric measuring will take place in a private setting away from the main group, and the researchers will ensure that a risk assessment is completed prior to commencing.

9. INFORMATION SHEET AND INFORMED CONSENT

The submission should be specific about the type of consent that will be sought, which should be indicated below:

- Have you included a Participant Information Sheet for the participants of the study? YES/~~NO~~

- Have you included a Participant Consent Form for the participants of the study?
  YES/~~NO~~

10. COMPUTERS

The answers in this question should be YES, but the question has been included in order to stress the importance of adherence to the Data Protection Act in research activity

- Are computers to be used to store data?
  YES/~~NO~~

- If so, is the data registered under the Data Protection Act?
  YES/~~NO~~

11. STUDENT DECLARATION

Please read the following declarations carefully and provide details below of any ways in which your project deviates from these. Having done this, each student listed in section 2 is required to sign where indicated.

- ***"I have ensured that there will be no active deception of participants.***
- ***I have ensured that no data will be personally identifiable.***
- ***I have ensured that no participant should suffer any undue physical or psychological discomfort***
- ***I certify that there will be no administration of potentially harmful drugs, medicines or foodstuffs.***
- ***I will obtain written permission from an appropriate authority before recruiting members of any outside institution as participants.***
- ***I certify that the participants will not experience any potentially unpleasant stimulation or deprivation.***
- ***I certify that any ethical considerations raised by this proposal have been discussed in detail with my supervisor.***
- ***I certify that the above statements are true with the following exception(s):"***

Student/Researcher signature:

Date:

Appendix IV

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)
Sport and Health Portfolio, College of Engineering

CHILD INFORMATION SHEET
(*Version 1.0:* Date: *18/09/17***)**

Study title
Developing objective assessment methods of fundamental movement skills through visualization.

Principal investigators

Name:	[redacted]	[redacted]
Address:	[redacted]	[redacted]
Telephone:	[redacted]	[redacted]
Email:	[redacted]	[redacted]

Please read this information sheet carefully and think about whether you are happy to take part. Feel free to ask questions about any information included in this document or discussed by the researchers.

What is the study about?
We want to see how we can make the way that teachers assess how you move better through pictures.

Why have I been asked to take part?
You have been asked if you would like to take part because you are healthy and aged 6-16 years old. You should also not have any problems that change the way you move.

What will happen if I decide to take part?
If you decide to take part, we will measure how tall you are when sitting and standing and how heavy you are. We will also measure the circumference of your waist. You will be asked to also complete a handedness questionnaire so we can work out which hand you use most. During the testing, we will give you 7 monitors to wear, one on each wrist, hip and ankle and

one on the chest which you will wear whilst you complete 15 fundamental movement skills. We will show you what you need to do before each skill, and you will then try each one three times while we video record you doing it.

The skills we will ask you to perform will be a run, gallop, skip, hop, horizontal jump, slide, two-handed strike of a stationary ball, one hand forehand strike of self-bounced ball, one hand stationary dribble, two hand catch, kick a stationary ball, overhand throw and underhand throw. You will have an opportunity to practice the skill after it has been demonstrated by the researcher.

Lastly, we would like to measure your physical activity levels. To help in this, you will be asked to wear a physical activity monitor for 7 days. You will also be asked to keep an activity log to record when they remove the monitor. Handing out and collecting the accelerometers will take approximately 1 hour.

What are the possible risks and discomforts?
Don't worry there aren't any significant risk or discomforts within the study. When you follow our instructions and complete the proper warm up then there is even less risk of any injury. The activities you will do are just like the skills you would perform in a PE class at school.

Will I benefit from taking part in this study?
You will get to find out how we can measure how you move and how this can be turned into pictures!

Do I have to take part in this study?
It is totally up to you if you want to take part in this study and you can stop at any time. Please feel free to ask any questions before agreeing to take part and at any time during the study.

Can my participation in the study end early?
If you decide to take part in the study that is great and even if you sign up you can withdraw whenever you like!

Will my participation in the study be kept confidential?
Yes! No one will know who you are in the study as we don't use your name. The researchers will allocate an ID code to your name that will link with the data we collect so that your name is never used. We will not share any personal information about you with anyone.

What if I have questions?
If you have questions about the study, either now or in the future, you can contact the study's principal investigator [redacted] Should you have any concerns regarding an ethical aspect of this study please contact [redacted]

Thank you for your time and we look forward to your response.
We hope you will want to participate!

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)
Sport and Health Portfolio, College of Engineering

PARTICIPANT ASSENT FORM

(*Version 1.0:* Date: 18/09/2017**)**

Project Title:
Developing objective assessment methods of fundamental movement skills through visualisation.

Contact Details:

Name:	[redacted]	[redacted]
Address:	[redacted]	[redacted]
Telephone	[redacted]	[redacted]
Email:	[redacted]	[redacted]

		Please initial box
1	I confirm that I have read and understood the information sheet for this study and have had the opportunity to ask questions.	
2	I know that it is my choice to take part and that I can stop doing so at any time, without giving any reason, and without any problems.	
3	I am happy to have my picture taken and be video recorded.	
4	I understand that sections of the data collected will be looked at by responsible individuals at Swansea University or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have	

	access to these records and understand that analysis will be done on anonymous data where my name is unknown.	
5	I understand that the findings of this study may be published and that all data is anonymous.	
6	I agree to take part in the above study.	

Name of Participant Date Signature

Name of Person taking consent Date Signature

Researcher Date Signature

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)
Sport and Health Portfolio, College of Engineering

PARENT/ GUARDIAN INFORMATION SHEET
(*Version 1.0:* Date: 18/09/2017**)**

Project Title:

Developing objective assessment methods of fundamental movement skills through visualisation.

Principle Investigators:

Name:	[redacted]	[redacted]
Address:	[redacted]	[redacted]
	[redacted]	[redacted]
	[redacted]	[redacted]
Telephone	[redacted]	[redacted]
Email:	[redacted]	[redacted]

Thank you for being interested in our project. Please read this information sheet carefully and think about whether you are happy for your child to take part. It is important to say at this point that the decision to take part is entirely up to you and that your child will not be at a disadvantage for future studies should you decide for them not to participate.

What is the purpose of the study?
The purpose of the study is to investigate the assessment of fundamental movement skills proficiency in children using objective measures. Secondly, to ascertain whether the skill proficiency of the children changes as they grow, and their physical activity habits change.

Why has your child been chosen?
Your child has been asked if they would like to take part because they are 6-16 years old and free of any physical or neurological conditions that affect the way they move. However, this does not mean your child has to take part in the study. This is voluntary and you have the right to withdraw them from the study at any time.

What will happen to your child if they take part?
If you decide for your child to take part, we will measure their sitting and standing height, weight and waist circumference, before asking them to complete a handedness questionnaire for us to work out their dominant hand. Following this, we will give your child 7 monitors to wear, one on each wrist, hip and ankle and one on the chest. They will wear the monitors whilst they complete 13 fundamental movement skills. Before performing the skills, a demonstration

will be given to your child by the researcher. After this, your child will be asked to perform each skill three times while they are observed by the researchers and video recorded.

The skills we will ask your child to complete are: run, gallop, skip, hop, horizontal jump, slide, two-handed strike of a stationary ball, one hand forehand strike of self-bounced ball, one hand stationary dribble, two hand catch, kick a stationary ball, overhand throw and underhand throw.

Following on from their participation in the movement assessment, children will be asked to wear a physical activity monitor for 7 consecutive days. They will also be asked to keep an activity log to record when they remove the accelerometer. Handing out and collecting the accelerometers will take approximately 1 hour.

What are the possible disadvantages of taking part?
There aren't any significant risks or discomforts associated with the study. If your child follows our instructions which will ensure that they are appropriately warmed up for the activity, then the risks will be minimised. There is a reduced risk of injury from the activity (as in any Physical Education class) and there will be trained first aiders on hand to deal with any injuries should they occur.

What are the possible benefits of taking part?
Your child might find it interesting to see how we assess movement proficiency and how this leads to unique visualization tools!

Do they have to take part in this study?
Their participation in this study is completely voluntary and you are free to withdraw them at any time, for any reason, without penalty or prejudice from the investigator and/or research assistants. They will not be treated differently if at any time you wish to withdraw them from the study. Please feel free to ask any questions of the investigator and/or research assistants before signing this form and at any time during the study.

Can their involvement in the study end early?
If you provide permission for your child take part in the study, you still have the right to decide at any time that you no longer wish them to continue to take part.

Who will see the information that is collected?
All information gathered will be stored on password protected hard drives using unique participant ID codes. The original copy aligning your child's participant ID code and identifying information will be stored in a locked office at Swansea University. Their information will be combined with information from other children taking part in the study. When we write about the study to share it with other researchers, we will write about the combined information we have gathered. Individuals will not be identified in these written materials. We may publish the results of this study; however, we will keep all names and other identifying information private.

What if I have questions?

This study has been approved by Council of Engineering Research Ethics Committee and if you have specific concerns or if you have questions about the study, you can contact the study's principal investigator, [redacted] Should you have any concerns regarding an ethical aspect of this study please contact [redacted]

Thank you for your time and we look forward to your response

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)
Sport and Health Portfolio, College of Engineering

PARENT/GUARDIAN CONSENT FORM
(*Version 1.0:* Date: *18/09/17***)**

Project Title:
Developing objective assessment methods of fundamental movement skills through visualisation.

Contact Details:

Name:	[redacted]	[redacted]
Address:	[redacted]	[redacted]
Telephone	[redacted]	[redacted]
Email:	[redacted]	[redacted]

	Name of Child (participant): ________________________________	**Please initial box**
1	I confirm that I have read and understood the information sheet dated 18/09/17 (Version: 1.0) for the above study and have had an opportunity to ask questions.	
2	I understand that my child's participation is voluntary and that they are free to withdraw at any time, without giving any reason and without their medical care, school work or legal rights being affected.	
3	I agree for my child to have their photo taken and to be video recorded.	
4	I understand that sections of the data collected will be looked at by responsible individuals at Swansea University or from regulatory authorities where it is relevant to my child's participation in the research project. Analysis will be done on anonymous data. I give permission for these individuals to have access to these records.	
5	I understand that the findings of this study may be published and that all data is anonymous.	
6	I agree for my child take part in the above study.	

Name of Parent/Guardian	Date	Signature
Name of Person taking consent	Date	Signature
Researcher	Date	Signature

Appendix V

APPLICATION FOR ETHICAL COMMITTEE APPROVAL OF A RESEARCH PROJECT

All research with human participants, or on data derived from research with human participants that is not publicly available, undertaken by staff or students linked with A-STEM or in the College of Engineering more widely must be approved by the College of Engineering Research Ethics Committee.

RESEARCH MAY ONLY COMMENCE ONCE ETHICAL APPROVAL HAS BEEN OBTAINED

The researcher(s) should complete the form in consultation with the project supervisor. After completing and signing the form students should ask their supervisor to sign it. The form should be submitted electronically to coe-researchethics@swansea.ac.uk.

Applicants will be informed of the Committee's decision via email to the project leader/supervisor.

1. TITLE OF PROJECT
Validity of accelerometers to accurately assess energy expenditure in isolated fundamental movement skill performance

2. DATE OF PROJECT COMMENCEMENT AND PROPOSED DURATION OF THE STUDY
01/05/2019, with a proposed study length one year.

3. NAMES AND STATUS OF THE RESEARCH TEAM *State the names of all members of the research group including the supervisor(s). State the current status of the student(s) in the group i.e. Undergraduate, postgraduate, staff or other (please specify).*
Dr Melitta McNarry – Supervisor Dr Kelly Mackintosh – Supervisor Phil Hill – PhD student Mayara Silveria Banchim – PhD Student   DBS Checked Postgraduate research students DBS Checked and supervised undergraduate students

4. RATIONALE AND REFERENCES

*Describe in **no more than 200 words** the background to the proposed project.*
In all sections below that detail your study and its aims please use language suitable for a lay audience.

Physical activity (PA) in childhood and adolescence is positively associated with multiple health-enhancing benefits (muscle/bone strength, lower rates of chronic diseases, improved lipid profiles) (Janssen and LeBlanc, 2010; Tremblay et al., 2011; Janz et al., 2015; Tremblay et al., 2016). Moreover, many adult diseases relating to inactivity have their origins in childhood (Kohl & Cook, 2013). To promote PA engagement, age-appropriate guidelines relating to the type and amounts of PA have been provided (DoH, 2011). Children and adolescents (5-18 years) are encouraged to participate in 60 minutes of moderate to vigorous physical activity (MVPA) daily, including vigorous activities that are muscle strengthening (DoH, 2011). PA guidelines are formed through firstly, measuring the respective metabolic equivalent of task (MET) of various PA types and then secondly, proposing a summed duration that should be spent engaging in activities of identified intensity thresholds (Ainsworth et al., 2011).

Fundamental movement skills (FMS) are foundational movements that become the ‘building blocks’ to more advanced movement skills that are common to many forms of sport and physical activity (Barnett et al., 2009; Gu et al., 2017). In childhood and adolescence, the performance of these skills is common in free-play, PE lessons and through participation in sport practice. Despite the influence of FMS upon the PA of children, our understanding of the energy expenditure required to perform repeated efforts of these skills is limited (Sacko et al., 2018). Furthermore, little insight has been provided into the influence of skill competence and maturation on the energy expenditure of performing FMS. This may lead to significant inaccuracies in how energy expenditure is presently being quantified in this population.

5. OBJECTIVES

State the objectives of the project, i.e. one or more precise statements of what the project is designed to achieve.

To assess the contribution of skill competence and maturation on the energy expenditure of adolescents performing fundamental movement skills using indirect calorimetry

6.1 STUDY DESIGN Outline the chosen study design (e.g., cross-sectional, longitudinal, intervention, RCT, questionnaire etc)
Cross-sectional, incorporating quantifiable performance-based measures.

6.2. STUDY DESIGN *- state the number and characteristics of study participants* *- state the inclusion criteria for participants* *- state the exclusion criteria for participants and identify any requirements for health screening* *- state whether the study will involve vulnerable populations (i.e. young, elderly, clinical etc.)* *- state the requirements/commitments expected of the participants (e.g. time, exertion level etc)*
A convenience sample of ≈40 school-aged children (8-16 years) free from any physical or neurological conditions (i.e. dyspraxia) will take part in this study following institutional ethics approval. An initial invitational email will be distributed to participants / schools which will outline the aims of the research and which will request a meeting (if so desired by the school) between the research team leader(s) and the relevant teacher(s). This is to ensure a full breakdown of the project is provided prior to recruitment. Following this, a formal presentation will be given to potential participants to outline the research project and answer any further questions. Due to the age of participants and their categorisation as a vulnerable population, special considerations have been made for recruiting members and disclosure of involvement in the study with parents/ guardians. All parents / guardians of participants will be sent an information sheet, parent consent form and pre-screening questionnaire (Appendix A). No participants will be included in the study without prior screening via a health questionnaire completed by their parent/guardian (Appendix A). The participants will perform a total of 5 skills from the test of gross motor development (TGMD-3) (Ulrich, 2017) at the Biomechanics laboratory at Swansea

University Bay Campus. Each participant will be expected to take part in an injury prevention and preparation warm up. Following this they will be asked to perform the skills to the best of their ability. The total time of involvement for the participant in the laboratory is envisaged to be no longer than 90 minutes (inclusive of demonstration time by researcher), this will include time being allocated for the participants to have their anthropometric measurements recorded. It is expected that any physical activity performed during the study will be no greater than moderate-vigorous intensity, and as such would be similar in exertion to jogging or free-play in the playground.

6.3. PARTICIPANT RECRUITMENT

How and where will participants be recruited? How will you ensure that these methods of recruitment do not compromise the ability of the research participant to freely consent to and withdraw from the study?

Participants will be recruited through primary and secondary schools and it is envisaged that this will be in the surrounding area of the university. An initial invitational email will be distributed to participants / schools which will outline the aims of the research and which will request a meeting (if so desired by the school) between the research team leader(s) and the relevant teacher(s) to ensure a full breakdown of the project is provided prior to recruitment. Following this an age-appropriate formal presentation will be given to potential participants to outline the research project and answer any further questions that they have relating to their participation.

All parents/guardians of participants wishing to take part will be sent an information sheet (attached), parental consent form (attached) and pre-screening questionnaire (Appendix A). In instances where a school class/group has recorded an interest in participating, an 'assent assembly' or group presentation will take place to inform the participants of the content of the information sheet at an age appropriate level. During this time, they will also have the opportunity to ask any questions. Participant assent in paper form (attached) will be collected prior to any testing taking place.

6.4 DATA COLLECTION METHODS

- describe all of the data collection/experimental procedures to be undertaken
- state any dietary supplementation that will be given to participants and provide full details in Section 6.5
- state the inclusion of participant information and consent forms (and assent forms where necessary in appendices)
- Where you are asking research participants to undertake physical activity consider appropriate health screening processes. Note that the ACSM have updated their guidelines in a consensus statement dated 2015.

The general and device specific laboratory risk assessments completed by the principle researchers will be adhered to and undertaken by all researchers. This is to ensure health and safety of the participants and research team is maintained during attendance to the department.

Prior to any testing procedure taking place, informed written assent (attached) will be sought from each participant, with the chance to ask any questions or opting not to participate given prior to this. Once the relevant consent, assent and pre-screening forms are obtained, anthropometrics will then be taken by a researcher of the same sex as the participant, with shoes off, pockets emptied and heavy outer clothing (i.e. heavy coat/jumper) removed. Standing height will be taken using a calibrated stadiometer, sitting height will be completed with the use of a calibrated sitting stadiometer, body mass will be taken using a calibrated scales with the monitor (separate from the scales) positioned so only the researcher can see it.

Following a briefing, a warm up, and a subsequent practice performance, each participant will be fitted with 7 (GT9X, Actigraph, LLC) accelerometers and 7 GeneActiv (Activinsights Ltd, UK) accelerometers positioned on the dominant wrist, non-dominant wrist, chest, dominant waist, non-dominant waist, dominant ankle, non-dominant ankle. The accelerometers will be set to record at 100Hz and 1 s epochs. The recorded data will be analysed using actilife software (Actigraph, LLC) the GENEActiv Post Processing software (version 3.1).

The participant will then be fitted with the mobile gas analyzer (MetaMax 3B; Cortex Biophysik, Leipzig, Germany). The analyser will be warmed and calibrated according to manufacturer instructions prior to each measurement. For each skill performance, breath-by-breath analysis will be undertaken to measure energy expenditure. The additional weight of the equipment will not exceed (850 gr).

Participants will complete 5 skills in total from the TGMD-3 protocol (Overhand throw, one handed strike, kick, hop, slide). The TGMD protocol is a process orientated assessment tool which assesses a range of FMS i.e. (run, horizontal jump (HJ), slide, two-handed strike of a stationary ball, one hand forehand strike of self-bounced ball, two hand catch, overhand throw, underhand throw) through the observation of individual components within the skill. It is a newly developed tool based on the widely used and highly valid and reliable previous TGMD protocols (Ulrich, 2010). Prior to the participant performance, the skills will be demonstrated, and a practice opportunity will be provided by the researcher. The participant will then perform the skill with no prompting or feedback given during the test itself.

For the overhand throw skill, participant performance will also be analysed using the Bruininks-Oseretsky Test of Motor Proficiency-2 protocol, which assesses the participants accuracy of throw.

Participants will perform each isolated skill in blocked bouts of 3 minutes, with each effort prompted at intervals of 10 secs, similar to previously conducted studies (Sacko et al., 2018; Duncan et al., 2019). Each effort will be prompted through the researcher and a timed signal.

On the completion of the 3-minute effort, a rest period of no less than 5 minutes in a seated position will be allocated to the participant for appropriate recovery to the standard resting metabolic rate of 3.5 ml/kg/min (Bielinski, Schutz, & Jequier et al., 1985). Once resting metabolic rate is achieved and the participant is ready to commence, the following trial will begin. To minimize injury risk, isolated skills will be sequenced so that an object control skill is always followed by a locomotor skill.

Performance of the skills will be recorded (Apple Ipad, Apple Inc, 2019) so that analysis of the skill performance can be performed *post hoc* by the principle researcher. Following analysis, the videos will be stored on a password protected university storage system. Upon termination of the storage duration, all videos will be disposed by a supervisor (Dr Melitta McNarry).

6.5 DATA ANALYSIS TECHNIQUES

- *describe briefly the techniques that will be used to analyse the data*

Mean $\dot{V}O_2$ energy expenditure will be recorded for two minutes of each FMS trial (0-30 secs and 2 minutes 30 secs – 3 minutes being removed). This is to ensure that MET values were at the required rate and accurate of the performance.

Post hoc analysis of FMS competence will be completed using the TGMD-3 and Bruininks-Oseretsky Test of Motor Proficiency-2 protocols. This requires each skill effort to be separated into individual performance characteristics i.e. a step with supporting leg in the overhand throw).

Receiver operating characteristic (ROC) curve analysis will be performed to determine validity of accelerometer placement for each FMS (Jago et al., 2007).

Descriptive statistics will be calculated for the total sample and by sex and reported as means (± SD). Average MET's for each skill will be reported, along with differences between sex, maturation and skill competence.

Specific statistical techniques will but likely include ANOVA, MANOVA, PCA, multivariate regression and Pearson's correlation or the non-parametric equivalents.

SPSS Statistics for Windows, Version 25.0 (Chicago, IL: IBM Corp.) was used for data analysis.

6.6. STORAGE AND DISPOSAL OF DATA AND SAMPLES

describe the procedures to be undertaken for the storage and disposal of data and samples

- identify the people who will have the responsibility for the storage and disposal of data and samples

- identify the people who will have access to the data and samples

- *state the period for which the raw data will be retained on study completion (normally 5 years, or end of award. But data should not be retained for longer than is necessary for the purposes of the research project.)*

- *Please confirm that where data is being stored away from Swansea University (for example on cloud based services) that procedures are still in line with GDPR legislation.*

Storage of all data will be contained on a password protected computer and external hard drive, which will only be accessible by the researcher and supervisors. All data will be backed up on an encrypted cloud-based server that will also be accessible by only the researcher and supervisors. Hard copy data will be stored in a securely code-locked filing cabinet within the post grad office. The researcher will take full responsibility for the storage and disposal of all paper-based data. The data will be stored for 7 years after award of degree, after which the data will be disposed of by Dr M. McNarry

To ensure anonymity, participant's identity will be coded on all data sets. Participant name and ID codes will only be accessibly by the researcher and supervisors.

6.7 HOW DO YOU PROPOSE TO ENSURE PARTICIPANT CONFIDENTIALITY AND ANONYMITY?

Each participant will be assigned a unique research identification code under which all of the data collected will be stored. Identification code assignment will be stored on a password protected computer and document, stored securely at Swansea University, with only the principle researcher(s) granted access. All parental consent forms, child assent and information sheets will be stored securely at the university. Furthermore, any paper-based data will be non-identifiable with the participant ID code present and stored securely by the principle researchers.

7. LOCATION OF THE PREMISES WHERE THE RESEARCH WILL BE CONDUCTED.

- list the location(s) where the data collection and analysis will be carried out

- identify the person who will be present to supervise the research at that location

- If a first aider is relevant, please specify the first aider and confirm that they

possess the first aid qualifications appropriate for this form of research

All research will be conducted in the Biomechanics Lab within the School of Sports and Exercise Science at Swansea University. All principle researchers are first aid trained, with an AED within the vicinity of the research location present. All non-named researchers will always be supervised by one of the named researchers present on this document.

8. POTENTIAL PARTICIPANT RISKS AND DISCOMFORTS

- identify any potential physical risk or discomfort that participants might experience as a result of participation in the study.

- identify any potential psychological risk or discomfort that participants might experience as a result of participation in the study.

- Identify the referral process/care pathway if any untoward events occur

Each participant will be briefed prior to the commencement of testing by talking through the protocol and given time to ask any questions relating to the testing.

Due to the repetitive nature of the skill performance an adequate preparation warm-up will be performed by each participant to minimise any injury risk relating to muscular exertion.

Should a participant be deemed unsuitable to participate at any point during the testing, an informal meeting with the participant, their parent/guardian and the principle will be proposed. During the meeting, the reasons for the participant not being included will be discussed and the participant will be given time to ask any questions to reduce potential psychological distress or dissatisfaction.

The accelerometers could potentially become uncomfortable for some; although these accelerometers are usually worn for research comprising 7 days rather than the 60 minutes expected wear time in this study, therefore any discomfort is highly unlikely. Participants will be reminded that if at any point there is discomfort, the assessment can be paused/cancelled. Similarly, participants will be reminded that the study can be paused/cancelled if there is any discomfort relating to the wearing of the face mask.

Participants will undertake the skill performance during this study wearing a face mask and portable equipment that performs breath by breath gas analysis (MetaMax 3B (Cortex Biophysik, Leipzig, Germany)) this may potentially be associated with physical discomfort such as a high heart rate and breathing rate and local muscular fatigue. The acute risks associated with this intensity of exercise are very small and this will be further minimized by health screening prior to undertaking exercise.

9.1. HOW WILL INFORMED CONSENT BE SOUGHT?

Will any organisations be used to access the sample population?
Will parental/coach/teacher consent be required? If so, please specify which and how this will be obtained and recorded?

All parents / guardians of participants will be provided with an information sheet, parental consent form and health screening questionnaire (Appendix A). If a parent/guardian has more than one child taking part within the study, then they will be asked to complete individual consent and pre-screening for each child.

No participant will be allowed to complete the research without prior parental / guardian consent. An 'assent assembly' or presentation will take place to inform the participants of the content of the information sheet at an age appropriate level. During this time, they will also have the opportunity to ask any questions. Participant assent in paper form will be collected prior to any testing taking place.

Informed participant consent will be obtained prior to any research taking place at the beginning of each session. All participants will be informed of what will be asked of them at the beginning of each session, with the opportunity to ask any questions before giving consent. Any participant without parental/guardian consent (under the age of 16) will not be allowed to participate. All participant assent will be recorded, logged and processed by one of the principle researchers. A spreadsheet will be created, encompassing all aspects of the participant & parental consent forms with a Y indicating a YES for that particular point on the assent / consent form and a red filled cell denoting a NO for that specific point.

9.2 INFORMATION SHEETS AND CONSENT/ASSENT FORMS **Please ensure that your forms are written in clear, simple language enabling research participants to fully understand the project.**
☐ Have you included a participant information sheet for the participants of the study? YES ☐ Have you included a parental/guardian information sheet for the parents/guardians of the study? YES ☐ Have you included a participant consent (or assent) form for the participants in the study? YES ☐ Have you included a parental/guardian consent form for the participants of the study? YES

10. IF YOUR PROPOSED RESEARCH IS WITH VULNERABLE POPULATIONS (E.G., CHILDREN), HAS AN UP-TO-DATE DISCLOSURE AND BARRING SERVICE (DBS) CHECK (PREVIOUSLY CRB) IF UK, OR EQUIVALENT NON-UK, CLEARANCE BEEN REQUESTED AND/OR OBTAINED FOR ALL RELEVANT RESEARCHERS?.
If appropriate please provide a list below including the name of the researcher, and confirming that they have an up to date DBS check. Please also confirm the type of check (i.e. basic/enhanced).

11. HUMAN TISSUE ACT **Does your research involve the collection or storage of human tissue samples? Where not relevant please respond N/A. Where appropriate please provide further details.** Please note that University ethics committee approval is not sufficient to comply with legislation for the storage of relevant material for research.

12. STUDENT DECLARATION

Please read the following declarations carefully and provide details below of any ways in which your project deviates from these. Having done this, each student listed in section 2 is required to sign where indicated.

- ☐ ***"I have ensured that there will be no active deception of participants.***
- ☐ ***I have ensured that no data will be personally identifiable.***
- ☐ ***I have ensured that no participant should suffer any undue physical or psychological discomfort (unless specified and justified in methodology).***
- ☐ ***I certify that there will be no administration of potentially harmful drugs, medicines or foodstuffs.***
- ☐ ***I will obtain written permission from an appropriate authority before recruiting members of any outside institution as participants.***
- ☐ ***I certify that the participants will not experience any potentially unpleasant stimulation or deprivation.***
- ☐ ***I certify that any ethical considerations raised by this proposal have been discussed in detail with my supervisor.***
- ☐ ***I certify that the above statements are true with the following exception(s):***

Student/Researcher signature: (include a signature for each student in research team)

Date:

Where submitted electronically we will accept the lead supervisor/researcher's email of the application as confirmation that both they and other researchers on the project have discussed and are happy to adhere to the above.

13. SUPERVISOR'S APPROVAL

Supervisor's signature:
Date:

Appendix VI

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)

Sport and Health Portfolio, College of Engineering

PARTICIPANT INFORMATION SHEET
(Version 1.1, Date: 26/04/2019)

Project Title:
Assessing the energy expenditure of isolated fundamental movement skill performance in youth using indirect calorimetry and accelerometry

Contact Details:

Mr Phil Hill

Principle Investigator

[redacted]

1. Invitation Paragraph

Thank you for reading this sheet which tells you about our study. We would like you to join us at Swansea University in a study that will help you learn more about science, sport, and how you move. Taking part is up to you and it is fine if you don't want to.

2. What is the purpose of the study?

Playing, running and taking part in sport helps us stay healthy. To enjoy these activities, we need to be able to perform basic skills. We would like to learn how much effort it takes to perform some skills, and what things may change this. These skills include throwing and hitting a ball, hopping and sliding.

3. Why have I been chosen?

You have been asked because you are between the ages of 8 and 16 years old and go to a school in South Wales. If you choose to take part, you can stop at any time, and we won't try to change your mind.

4. What will happen to me if I take part?

Before you start and while you are taking part, you can ask us any questions. For your visit, you will come to the School of Sport and Exercise Sciences in the Swansea University (Bay Campus). When you arrive, we will see how tall you are and how much you weigh, you will then take part in a fun warm up and a practice of all the skills.

You will be asked to do five skills. The five skills are an overhand throw, a single hand strike of a ball, a kick, hopping and a slide (sidestep). You will be asked to do each skill for 3 minutes with a rest between each skill. When you are doing the skills, we will ask you to wear some small units (these look like watches) on 7 parts of your body (pictured below, left) and to wear a small mask on your face (pictured below, right). It is these that will allow us to see how much energy you are using. We will also video record you so that afterwards we can see how well you did for all the skills.

5. What are the possible disadvantages of taking part?

When you are doing the skills, they will get your heart pumping and sometimes will make you out of breath but when you stop you will quickly feel fine During the skills you can stop at any time if you want and there will always be an adult there to make sure you are ok.

6. What are the possible benefits of taking part?

You will have a great time with us, learning more about how we measure physical activity and why it is so important for young people. You will also get the chance to use equipment that only athletes usually get the chance to use!

7. Will my taking part in the study be kept confidential?

Yes, when you come to Swansea you will be given a one-off code, so no one knows who you are from your results. Your name details and scores will be stored on a computer with a password known only by us so only we will be able to see your information.

8. What if I have any questions?

You can ask any of the researchers a question before you come to the university or when you are there for to take part. Or if you prefer you can ask one of your parents or guardians to ask a question for you.

Re-iterate that further information can be obtained from the researcher contact stated above. Also state that the project has been approved by the College of Engineering Research Ethics Committee at Swansea University. If you have any questions regarding this, any complaint, or concerns about the ethics of this research please contact Dr Andrew Bloodworth, Chair of the College of Engineering Research Ethics Committee, Swansea University. A.J.Bloodworth@swansea.ac.uk. The institutional contact for reporting cases of research conduct is Registrar & Chief Operating Officer Mr Andrew Rhodes. Email: researchmisconduct@swansea.ac.uk. Further details are available at the Swansea University webpages for Research Integrity. http://www.swansea.ac.uk/research/researchintegrity/

Swansea University
Prifysgol Abertawe

Applied Sports Technology Exercise and Medicine Research Centre (A-STEM)
Sport and Health Portfolio, College of Engineering

PARENT/GUARDIAN INFORMATION SHEET
(Version 1.1, Date: 26/04/2019)

Project Title:
Assessing the energy expenditure of isolated fundamental movement skill performance in youth using indirect calorimetry and accelerometry

Contact Details:

Mr Phil Hill

School of Sport and Exercise Sciences, Swansea University

[redacted]

1. Invitation Paragraph

Thank you for taking the time to read this information sheet. This gives details about our study and hopefully provides you with the information you need to help your son/daughter decide if they want to take part. Whether they take part is entirely up to you and your child, and it doesn't matter which decision is reached.

2. What is the purpose of the study?

This study will look at how much energy is used to perform a number of movement skills. We call these fundamental movement skills. These skills, such as throwing, hopping, striking a ball, are skills that are important for physical activity and taking part in sport. We would like to learn how skill level and growth change the effort needed to perform these skills. Also, whether skill level is related to the energy needed to perform the skills.

3. Why has my child been chosen?

Your child has been asked to take part because they are between the ages of 8 and 16 years old and go to a school in South Wales. If they decide to take part, they can stop at any time without giving a reason.

4. What will happen to my child if they take part?

Before your child takes part in the project, they will be given an information sheet similar to this which will describe to the study to them. You and your child will also be given opportunity to ask any questions. For your child's research session, they will come to the School of Sport and Exercise in the Swansea University (Bay Campus). When they arrive, we will measure your child's standing and sitting height along with their weight, they will then take part in a warm up and a practice of the fundamental skills that they will be performing.

Your child will be asked to perform five skills in total. The five skills are an overhand throw, a single-hand strike of a ball, a kick, hopping and a slide (side step). Your child will be asked to perform each skill to the best of their ability for 3 minutes, with a seated rest following each skill performance. Each skill performance will not begin until their original resting condition has been reached. When they are performing the skills, they will be fitted with a mask to breathe through and a supporting harness, it is this that will allow us to see how much energy they are using. We will also ask your child to wear little watch like devices called accelerometers on seven body parts, these allow us to build a visualisation of their movement and can also be used to see how much energy they used. To allow us to assess the skills, we video record performances so that analysis can be completed at a later date.

5. What are the possible disadvantages of taking part?

In some of the skill performances your child may feel out of breath, although the intensity is not above that expected in a PE lesson or a sporting game/practice. Following each three-minute performance they will be given rest periods. During the skill performances your child will be reminded that they can stop at any time. If the equipment feels uncomfortable there will always be a researcher there to make sure they are ok.

6. What are the possible benefits of my child taking part?

Your child will be given an opportunity to take part in important research. They will also see how research is completed in the university and learn more about the background to our research and why we promote physical activity. It will allow them to see a different area of the sciences which they may not have had the opportunity to experience before.

7. Will my child's taking part in the study be kept confidential?

Yes, when your child starts the study we will give them a unique ID code, so no one can identify them from their data. All their personal information will be stored on a password protected computer and only members of the research team will be able to access their information.

Data Protection and Confidentiality

Your data will be processed in accordance with the Data Protection Act 2018 and the General Data Protection Regulation 2016 (GDPR). All information collected about you will be kept strictly confidential. Your data will only be viewed by the researcher/research team.

All electronic data will be stored on a password-protected computer file in room A108, Swansea University, Bay Campus. All paper records will be stored in a locked filing cabinet in room A108, Swansea University, Bay Campus. Your consent information will be kept separately from your responses to minimise risk in the event of a data breach.

Please note that the data we will collect for our study will be made anonymous, this will occur prior to the assessment day where each consenting participant will be provided with an anonymized identity number, thus it will not be possible to identify and remove your data at a later date, should you decide to withdraw from the study. Therefore, if at the end of this research you decide to have your data withdrawn, please let us know before you leave.

Data Protection Privacy Notice
The data controller for this project will be Swansea University. The University Data Protection Officer provides oversight of university activities involving the processing of personal data and can be contacted at the Vice Chancellors Office.

Your personal data will be processed for the purposes outlined in this information sheet. Standard ethical procedures will involve you providing your consent to participate in this study by completing the consent form that has been provided to you.

The legal basis that we will rely on to process your personal data will be processing is necessary for the performance of a task carried out in the public interest. This public interest justification is approved by the College of Engineering Research Ethics Committee, Swansea University.

The legal basis that we will rely on to process special categories of data will be processing is necessary for archiving purposes in the public interest, scientific or historical research purposes or statistical purposes.

How long will your information be held?
We will hold any personal data and special categories of data for seven years.

What are your rights?
You have a right to access your personal information, to object to the processing of your personal information, to rectify, to erase, to restrict and to port your personal information. Please visit the University Data Protection webpages for further information in relation to your rights.

Any requests or objections should be made in writing to the University Data Protection Officer:-

University Compliance Officer (FOI/DP)
Vice-Chancellor's Office
Swansea University
Singleton Park
Swansea
SA2 8PP
Email: dataprotection@swansea.ac.uk

How to make a complaint
If you are unhappy with the way in which your personal data has been processed, you may in the first instance contact the University Data Protection Officer using the contact details above.

If you remain dissatisfied, then you have the right to apply directly to the Information Commissioner for a decision. The Information Commissioner can be contacted at: -

Information Commissioner's Office,
Wycliffe House,
Water Lane,
Wilmslow,
Cheshire,
SK9 5AF
www.ico.org.uk

8. What if I have any questions?

Any questions relating to your child's participation can be directed via email or phone to the principle researcher or the supervisors on this project.
This project has been approved by the College of Engineering Research Ethics Committee at Swansea
University. If you have any questions regarding this, any complaint, or concerns about the ethics of this
research please contact Dr Andrew Bloodworth, Chair of the College of Engineering Research Ethics Committee, Swansea University. [redacted] The institutional contact for reporting cases of research conduct is Registrar & Chief Operating Officer Mr Andrew Rhodes. Email: researchmisconduct@swansea.ac.uk. Further details are available at the Swansea University webpages for Research Integrity. http://www.swansea.ac.uk/research/researchintegrity/.

PARTICIPANT ASSENT FORM
(Version 1.1, Date: 26/04/2019)

Project Title:
Assessing the energy expenditure of isolated fundamental movement skill performance in youth using indirect calorimetry and accelerometry

Contact Details:
Mr Phil Hill

Principle Investigator

[redacted]

Please initial box

1. I confirm that I have read and understood the information sheet dated 26/04/19 (version number 1.1) for the above study and have had the opportunity to ask questions. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected. ☐

3. I understand that sections of any of data obtained may be looked at by responsible individuals from the Swansea University or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to these records. ☐

4. I understand that data I provide may be used in reports and academic publications in anonymous fashion ☐

5. I agree to be video recorded during skill performance ☐

6. I agree to take part in the above study. ☐

______________________	________________	________________________
Name of Participant	Date	Signature

Name of Person taking consent	Date	Signature
Researcher	Date	Signature

APPLICATION FOR ETHICAL COMMITTEE APPROVAL OF A RESEARCH PROJECT

In accordance with A-STEM and College of Engineering Safety Policy, all research undertaken by staff or students linked with A-STEM or in the College of Engineering more widely must be approved by the College of Engineering Research Ethics Committee.

RESEARCH MAY ONLY COMMENCE ONCE ETHICAL APPROVAL HAS BEEN OBTAINED

The researcher(s) should complete the form in consultation with the project supervisor. After completing and signing the form students should ask their supervisor to sign it. The form should be submitted electronically to Coe-researchethics@swansea.ac.uk.

Applicants will be informed of the Committee's decision via email to the project leader/supervisor.

1. TITLE OF PROJECT
The development of fundamental movement skills across late childhood and adolescence

2. DATE OF PROJECT COMMENCEMENT AND PROPOSED DURATION OF THE STUDY
February 2019, with a proposed duration of 6 months

3. NAMES AND STATUS OF THE RESEARCH TEAM *State the names of all members of the research group including the supervisor(s). State the current status of the student(s) in the group i.e. Undergraduate, postgraduate, staff or other (please specify).*
Dr Melitta McNarry -Supervisor Dr Kelly Mackintosh – Supervisor Prof Dave Parry (Auckland University of Technology) Mayara Silveria Banchim – PhD Student Phil Hill – PhD Student Adam Runacres – PhD Student Zoë Marshall – PhD Student DBS Checked Postgraduate research students DBS Checked and supervised undergraduate students

4. RATIONALE AND REFERENCES

*With reference to appropriate sources of information (using the Harvard system), describe in **no more than 200 words** the background to the proposed project.*
The Sport & Exercise Department at Swansea University are proposing a new method by which to engage local schools and children with contemporary scientific research. This proposal has been put together as a result of research students coming together and realising that instead of all contacting schools independently, a focused approach could be more time efficient, co-ordinated, and professional manner to recruit. The idea is simple: introduce a ‘research week’ for local schools to learn more about physical activity, its role in everyday life, and have the opportunity to take part in research. We would visit each school, at a time convenient to them, bringing the necessary equipment to set up a mobile laboratory and field-testing environment allowing students to partake in various research projects. Participants will have the opportunity to take part in different activities while gaining an understanding of what the test is measuring, and why we are asking them to complete each activity. In addition, during these sessions the researchers will give talks about the research areas, research as a whole and curriculum specific topics. Visiting the schools, as opposed to schools visiting Swansea University, will allow the department to collect the necessary data, without placing undue time and financial burden on schools and students. There is clear demand for schools to be involved in research within the Swansea area, as multiple schools have already visited Swansea University, or researchers from the department have been to the schools to conduct the research. Therefore, this project would be well received and be a worthwhile investment of time and resources on the universities behalf. Another key benefit that comes off the back of the increased school participation is it gives us the opportunity to promote physical activity within children, as this is an underlying theme across all our research projects. With only 28% of children within the UK currently meeting physical activity guidelines, this has never been more crucial. This greater collaboration would allow for greater communication between the university and local schools, increasing the learning opportunities for local young people. Being a part of sport science research would allow children to see that science is not confined to laboratories and is in fact a wide ranging, diverse subject. It would offer an introduction into this ever-growing area of scientific exploration, which could also fit into the national curriculum, allowing students and teachers practical situations where they can apply the

knowledge they learn in the classroom. The lead researchers for that schools' research focus, would also go into the school and give a talk / presentation about the research so the pupils can see how what they are doing helps people and why we are doing the research.

5. OBJECTIVES

State the objectives of the project, i.e. one or more precise statements of what the project is designed to achieve.

The principle aim of this project is to further the understanding of the sex-specific development of fundamental movement skills, and how this development is influenced by biological age.

6.1 STUDY DESIGN

Outline the chosen study design (e.g., cross-sectional, longitudinal, intervention, RCT, questionnaire etc)

This study will be a cross-sectional design, incorporating quantifiable performance based measures and a questionnaire.

6.2. STUDY DESIGN

- *state the number and characteristics of study participants*
- *state the inclusion criteria for participants*
- *state the exclusion criteria for participants and identify any requirements for health screening*
- *state whether the study will involve vulnerable populations (i.e. young, elderly, clinical etc.)*
- *state the requirements/commitments expected of the participants (e.g. time, exertion level etc)*

Participants for this project will be school aged children and adolescents 8-18 years, with no known health condition which would prevent them from participating or undertaking the required exercises. No participants will be included in the study without prior screening via a health questionnaire completed by their parent/guardian (see relevant questionnaire in appendix A). All parents / guardians of participants will be sent a web link via the school with an online version of the information sheet, parent consent form (link in the consent section of this application) and pre-screening questionnaire (link in the consent section of this application). A minimum of two weeks will be allocated for parents to complete this, after which a paper version will be given to relevant participants for completion by parent / guardian. No participant will be allowed to complete the research without prior parental / guardian consent. An 'assent assembly' will take place to inform the participants of the content of the information sheet at an age appropriate level. During this time, they will also have the opportunity to ask any questions. Participant assent in paper form will be collected prior to any testing taking place.

Within school time, participants will complete the required assessments in small groups. Participants will be assessed in the space allocated by the school for the mobile testing area. The aim of this project is for schools to be able to include these sessions in their heathy schools plan. Currently, on advisement of school colleagues, these sessions will take place during scheduled physical education lessons.

At the beginning of each session, all participants will be grouped together for a talk by the principle researchers, explaining what to expect from the session and why the research is being completed. The participants will next be split (depending on the number of participants) into assigned groups. These groups will then rotate at set intervals to ensure completion of each activity during the session. Each research session will be led by one of the principle researchers supported by approved, supervised and DBS-checked post-graduate or undergraduate researcher.

At the end of each session, participants will come together for a debrief with the researcher, talking through the session. During this time, further research opportunities will be presented to all participants who will be given the relevant information, should they wish to take this opportunity. The research projects advertised will be the laboratory-based protocols including cardiopulmonary exercise testing, expiratory muscle training, high intensity exercise training intervention, and body composition profiling.

6.3. PARTICIPANT RECRUITMENT

How and where will participants be recruited?

Schools will be approached by the Swansea University engagement team with the offer to be involved in one of these research sessions. If schools are interested, contact details will be provided for the relevant researcher(s) whom will liaise directly with the school following initial contact. Each school will have full control over selection and numbers of pupils to be involved.

6.4 DATA COLLECTION METHODS

- describe all of the data collection/experimental procedures to be undertaken
- state any dietary supplementation that will be given to participants and provide full details in Section 6.5
- state the inclusion of participant information and consent forms (in appendices)
- refer to the use of the ACA/ACSM health screening questionnaire where appropriate (usually for high intensity/maximal effort exercise. Note that the ACSM have updated their guidelines in a consensus statement dated 2015. Any questions regarding this please contact the chair of the committee.)

Data collection will be completed by the principle researcher (listed above), supported by a minimum of one other DBS checked researcher, in the School of Sports and Exercise Science department laboratories. Prior to attendance for the session parental and age appropriate participant information, parental consent and the ACSM pre-screening questionnaire will be sent out in paper form with sufficient time prior to the session for signing, with the return of consent prior or during the session. All parents / guardians of participants will be sent a web link via the school with an online version of the information sheet, parent consent form (link in the consent section of this application) and pre-screening questionnaire (link in the consent section of this application). A minimum of two weeks will be allocated for parents to complete this, after which a paper version will be given to relevant participants for completion by parent / guardian. No participant will be allowed to complete the research without prior parental / guardian consent. An 'assent assembly' will take place to inform the participants of the content of the information sheet at an age appropriate level. During this time, they will also have the opportunity to ask any questions. Participant assent in paper form will be collected prior to any testing taking place.

The general and device specific fieldwork and laboratory risk assessments completed by the principle researchers will be adhered to and undertaken by all researchers. This is to ensure health and safety of the participants and research team is maintained during attendance to the department.

Prior to any testing procedure taking place, informed written assent will be sought from each participant, with the chance to ask any questions or not participate given prior to this. Once assent is obtained, each participant will be asked how they are feeling at that moment in time and undergo three blood pressure measures to ensure no hidden hyper/hypo-tension. Anthropometrics will then be taken by a researcher of the same sex as the participant at the beginning of each session with shoes off, pockets emptied and heavy clothing outer clothing (ie. heavy coat/jumper) removed. Standing height will be taken using a calibrated stadiometer, sitting height will be completed with the use of a calibrated sitting stadiometer, body mass will be taken using a calibrated scales with the monitor (sperate from the scales) positioned so only the researcher can see it.

30M Sprint

Participants will undertake a 5-minute low intensity running warm up to minimize injury and to prime them for optimal performance during the trials. A STALKER ATS II Radar Gun will be positioned 10m behind the start line, and record at a frequency if 46.875Hz, their speed. Participants will be instructed to sprint for 30m from a two-point standing start. All participants will complete 3 sprints, with at least 2 minutes rest in between each sprint to allow for full recovery between trials. Measures of height (cm), sitting height (cm) and body mass, obtained from anthropometric measures as described above, will allow the calculation of the underlying kinetics of the sprint. So for each sprint 9 parameters will be obtained and recorded: time to peak power (TPP), Peak Power (PP), Mean Power (MP), Relative peak and mean power (R_PP & R_MP), peak velocity (PV), mean velocity (MV), 30m sprint time (T30) and fatigue index (FI).

This protocol was approved in this population under the study code: **S/2015/008**

FMS

Participants will complete 4 skills from the TGMD-2 and 3 FMS assessment (run, hop, horizontal jump (HJ) and overhand throw. The TGMD protocol is a process orientated assessment tool which assesses 15 FMS (run, gallop, skip, hop, horizontal jump (HJ), slide, two-handed strike of a stationary ball, one hand forehand strike of self-bounced ball, one hand stationary dribble, two hand catch, kick a stationary ball, overhand throw, underhand throw) through the observation of individual components within the skill. It is a newly developed tool based on the widely used and highly valid and reliable previous TGMD protocols (Ulrich, 2010). Every participant will complete the 15 skills to the best of their ability. Before participants perform the skill, a demonstration will be given to them by the researcher. The participant will then perform the skill with no prompting or feedback given during the test itself. They will have one practice go and 2 trial attempts at each skill. The trial attempts will be recorded on a video camera and later assessed by the researcher, videos will be stored in a secure setting in the university on an encrypted hard drive. During this process, participants will be asked to wear 7 accelerometers (each wrist, hip, knee and ankle and one on the centre of the chest).

This protocol was approved for use within this population under the study code: **2016-113** approved on **27/09/2017**

Following on from TGMD assessment, participants will complete the HJ, the one leg hop and the overarm throw for a second time. The HJ and hop will be completed on a force platform,(Kistler Composite Force Platform Type 9260AA6, manufactured by Kistler Instruments Ltd). Each participant will again complete two repetitions of each movement, with one minute rest between each subsequent effort. For the overarm throw, the participant will complete the same action as they displayed in the TGMD protocol, with the ball being thrown into a supporting net. The A STALKER ATS II Radar Gun (Tx, USA) will be positioned behind the participant to gain a product measure of throwing speed. Each throw will be separated by a rest period of one minute.

Physical Self-Perception Profile For Children (PSPP-C)

Participants will complete the 44 item PSPP-C (Appendix B) questionnaire on their own, in a private setting supervised by a researcher and their teacher. The questionnaire is designed to gain insight into six specific components of physical self-perception (Attractive body adequacy/Sport competence/Strength competence/Physical condition adequacy/Physical self-worth/Global self-esteem). Individual questions contain two scenario options; the participant is then required to select the one they identify most to. To complete the questionnaire should take approximately seven minutes. This information will then be stored anonymously and will only be accessible by researchers using the allocated Identification code for that participant.

Further Testing Information

The participants will complete an incremental ramp exercise test to determine peak $\dot{V}O_2$ and the gas exchange threshold (GET) on a cycle ergometer. During this test, participants will perform 3 min of baseline cycling at 10 W, after which the work rate will be increased at a rate of 20-25 W·min^{-1} until volitional fatigue. Volitional fatigue shall be defined as an inability to maintain the required cadence despite strong verbal encouragement in addition to subjective indications such as hypernea, facial flushing, sweating and an RER in excess of 1.1. During the test, the participants will be instructed to maintain a pedal cadence of 70-80 rpm. Breath-by-breath pulmonary gas-exchange variables (Oxycon; Jaeger, Germany) and beat-by-beat cardiovascular variables will be collected continuously throughout the test. Furthermore, muscle oxygenation status will be assessed continuously using near-infrared spectroscopy on the *m. vastus lateralis*. Capillary blood samples will be obtained prior to and immediately following exercise for blood lactate analysis. Five minutes active and 10-minutes passive seated recovery will then follow. Maximal effort verification will then be performed, whereby a 3-min warm-up will precede a 'step' transition to a constant work rate equivalent to 110% peak power output, as reported in both children (Barker et al. 2009) and adults (Poole et al. 2008). This work rate will be maintained until voluntary exhaustion. Finally, participants will complete five minutes active assurances will be sought at regular intervals throughout that participants are happy to continue. recovery. Participants will be familiarized with the cycle ergometer prior to the start of the test and verbal.

Study Approval Number: **S/2015/008**

Habitual physical activity levels will be assessed over seven subsequent days using a GeneActiv worn on the participants preferred wrist and set to a measurement frequency of 20 Hz for 28 days. Participants will be asked to wear this monitor at all times over the 28-day period. On completion of these elements, we will arrange to meet the participant's parents at a convenient time and place to collect the monitors. At this meeting, parents will be provided with a personalized results sheet detailing their child's fitness parameters and reminded that if they have any questions to please contact one of the research team on the emails/telephone numbers provided

Approved as part of study code: **2018-043**

6.5 DATA ANALYSIS TECHNIQUES

- describe the techniques that will be used to analyse the data

Time to peak power, peak power, mean power and fatigue index will all be calculated using the methods described by Samozino and colleagues 2015 [1] using a macroscopic biomechanical model of power calculation. The raw velocity data will be fitted with a mono-exponential function ($Vh(t) = Vh_{max} \cdot (1 - e^{\frac{-t}{\tau}})$ to produce a smooth velocity-time curve using GraphPad Prism. Following integration and differentiation of the above equation horizontal ground reaction force can be calculated incorporating the individuals body mass $F_H(t) = m \cdot \alpha_H(t) + F_{aero}(t)$. Using the participants height the frontal area of the runner can be calculated ($A_f = (0.2025 \cdot h^{0.725} \cdot m^{0.425}) \cdot 0.266$) from which power can be calculated $P_H = V_h(t) * F_h(t)$. Thus, from one 30m sprint, nine anaerobic parameters can be calculated: Time to peak power (TTP), Peak Power (PP), Relative Peak Power (R_PP), Mean Power (MP), Relative Mean Power (R_MP), Maximum Velocity (V_Max), Average Velocity (V_AV), 30m Sprint Time (T30) and Fatigue Index (FI).

6.6. STORAGE AND DISPOSAL OF DATA AND SAMPLES

describe the procedures to be undertaken for the storage and disposal of data and samples
- identify the people who will have the responsibility for the storage and disposal of data and samples
- identify the people who will have access to the data and samples
- state the period for which the data will be retained on study completion (normally 5 years, or end of award)

All data will be stored in an anonymized fashion on a password protected computer that only the research team will have access to. The data will be stored for 7 years after award of degree, after which the data will be disposed of by Dr M. McNarry. Data will be stored for a longer period post award due to the longitudinal nature of part of this research, this will allow future authorized researchers to access this data to support further research.

Any paper-based data collection will be non-identifiable the participant ID code. This data will be stored in securely by the principle researchers

When obtained online parental consent will be exported to a word document by one of the principle researchers (AR,ZM,PH) and then saved as an encrypted document. After exporting to a secure word document, the responses online will also be screenshotted and placed underneath. Once these two steps have been completed then the record will be deleted off the survey monkey platform by one of the principle researchers (AR, ZM, PH). An identical protocol will be completed for the health screening questionnaire.

6.7 HOW DO YOU PROPOSE TO ENSURE PARTICIPANT CONFIDENTIALITY AND ANONYMITY?

Each participant will be assigned a unique research identification code under which all of the data collected will be stored. Identification code assignment will be stored on a password protected computer and document, stored securely at Swansea University, with only the principle researcher(s) granted access. All online parental consent forms will be saved under the participants participant number to ensure anonymity is kept throughout. Furthermore, any paper-based data will be non-identifiable with the participant ID code present and stored securely by the principle researchers.

7. LOCATION OF THE PREMISES WHERE THE RESEARCH WILL BE CONDUCTED. *- list the location(s) where the data collection and analysis will be carried out* *- identify the person who will be present to supervise the research at that location* *- If a first aider is relevant, please specify the first aider*
All research day testing will take place within the allocated space assigned to us by each school. A full risk assessment will be conducted for each school research space which will be agreed by the school prior to any testing taking place. All further research from recruitment following and within the research day will be conducted within the School of Sports and Exercise Science at Swansea University. All principle researchers are first aid trained, with an AED within the vicinity of the research location present. All non-named researchers will always be supervised by one of the named researchers present on this document.

8. POTENTIAL PARTICIPANT RISKS AND DISCOMFORTS *- identify any potential physical risk or discomfort that participants might experience as a result of participation in the study.* *- identify any potential psychological risk or discomfort that participants might experience as a result of participation in the study.* *- Identify the referral process/care pathway if any untoward events occur*
The accelerometer may become uncomfortable for some; to minimise the discomfort participants will be recommended to take a break from wearing it and asked to record the interval in the wear time diary. Each participant will be briefed prior to the commencement of testing by talking through the protocol and given time to ask any questions regarding the research or protocol. Debriefing will take place after all the testing has taken place and the participant has returned the accelerometer and wear time diary. This will involve talking through the testing, allowing time for any questions and informing them of the results of their tests, if they are interested. Should a participant be deemed unsuitable to participate at any point during the testing, an informal meeting with the participant, their parent/guardian and the principle. During the meeting, the reasons for the participant not being included will be discussed and the participant will be given time to ask any questions in order to reduce potential psychological distress or dissatisfaction. Participants will also be asked to undertake a running exercise (30m Sprint) which may cause an injury from tripping or insufficient warm-up. The risk of injury via tripping will be minimised by checking the footwear of the individual and walking the 30m distance checking for trip hazards. Injury via insufficient warm-up will be minimised by the researchers at this station performing a short, but comprehensive warm-up with the participants.

Participants will undertake a running exercise during this study may be associated with physical discomfort such as a high heart rate and breathing rate and local muscular fatigue. The acute risks associated with exercise are very small and this will be further minimized by health screening prior to undertaking exercise.

FMS and the additional HJ, hop and throw protocol should not be associated with any discomfort. There is a very small risk of muscoskeletal injury, but a warm up will be completed prior to each participant beginning their skill actions, and the researchers will check equipment and layout prior to each assessment. Furthermore, each participant will have completed a screening protocol prior to involvement. Each participant is made aware that they do not need to complete all skills within the protocol, and to alert a researcher if there is any concern.

The habitual monitoring should not be associated with any risks or discomforts beyond being aware that they are wearing two monitors. If participants feel uncomfortable at any time, they will be provided with contact details of the research team or, if they would like to talk to someone impartial, they will be directed to contact their GP.

9.1. HOW WILL INFORMED CONSENT BE SOUGHT?

Will any organisations be used to access the sample population?
Will parental/coach/teacher consent be required? If so, please specify which and how this will be obtained and recorded?

All parents / guardians of participants will be sent a web link via the school with an online version of the information sheet, parent consent form and health screening questionnaire (link: https://www.surveymonkey.co.uk/r/LGSWGKK). A minimum of two weeks will be allocated for parents to complete this, after which a paper version will be given to relevant participants for completion by parent / guardian. As part of the electronic consent (and pre-screening questionnaire) we will ask for the name of the child / children they are giving consent for, and their teaching class, due to the size of the study and the necessity for organizational means. If a parent / guardian has more than one child taking part within the study, then they will be asked to complete individual consent and pre-screening for each child. Finally, we have added two additional clauses on the consent form, the first regarding the return of accelerometers to the primary researchers, ensuring parents / guardians are aware it is also their responsibility to ensure the return of the accelerometers. Secondly, the fact that we are not able to diagnose with the techniques being used, we are not clinically trained, and data is being collected for research purposes only.

No participant will be allowed to complete the research without prior parental / guardian consent. An 'assent assembly' will take place to inform the participants of the content of the information sheet at an age appropriate level. During this time, they will also have the opportunity to ask any questions. Participant assent in paper form will be collected prior to any testing taking place.

Informed participant consent will be obtained prior to any research taking place at the beginning of each session. All participants will be informed of what will be asked of them at the beginning of each session, with the opportunity to ask any questions before giving consent. Any participant without parental/guardian consent (under the age of 16) will not be allowed to participate. All participant assent will be recorded, logged and processed by one of the principle researchers (AR, ZM, PH) with one being responsible for the processing of consent for each of the research days. A spreadsheet will be created, encompassing all aspects of the participant & parental consent forms with a Y indicating a YES for that particular point on the assent / consent form and a red filled cell denoting a NO for that specific point. This way it will be easily identifiable to the researchers which participants to include in academic publications, whose academic records to collect, and which participants wish to participate in further research opportunities.

9.2 INFORMATION SHEETS AND CONSENT/ASSENT FORMS
• Have you included a participant information sheet for the participants of the study? YES/NO • Have you included a parental/guardian information sheet for the parents/guardians of the study? YES/NO • Have you included a participant consent (or assent) form for the participants in the study? YES/NO • Have you included a parental/guardian consent form for the participants of the study? YES/NO

10. IF YOUR PROPSED RESEARCH IS WITH VULNERABLE POPULATIONS (E.G., CHILDREN, PEOPLE WITH A DISABILITY), HAS AN UP-TO-DATE DISCLOSURE AND BARRING SERVICE (DBS) CHECK (PREVIOUSLY CRB) IF UK, OR EQUIVALENT NON-UK, CLEARANCE BEEN REQUESTED AND/OR OBTAINED FOR ALL RESEARCHERS? EVIDENCE OF THIS WILL BE REQUIRED.
All researchers/undergraduate assistants are/will be DBS checked prior to undertaking any research for this project. Any non-DBS students or research assistants will never be left alone with a child or unsupervised by any DBS checked individual. Due to the set-up of this testing all researchers and participants will be together, and in line of sight of, everyone as it will all be fitted into a Sports Hall.

11. STUDENT DECLARATION

Please read the following declarations carefully and provide details below of any ways in which your project deviates from these. Having done this, each student listed in section 2 is required to sign where indicated.

✓***"I have ensured that there will be no active deception of participants.***
✓***I have ensured that no data will be personally identifiable.***
✓***I have ensured that no participant should suffer any undue physical or psychological discomfort (unless specified and justified in methodology).***

✓***I certify that there will be no administration of potentially harmful drugs, medicines or foodstuffs.***
✓***I will obtain written permission from an appropriate authority before recruiting members of any outside institution as participants.***
✓***I certify that the participants will not experience any potentially unpleasant stimulation or deprivation.***
✓***I certify that any ethical considerations raised by this proposal have been discussed in detail with my supervisor.***
✓***I certify that the above statements are true with the following exception(s):"***

Student/Researcher signature:

ADAM RUNACRES
ZOE MARSHALL
PHIL HILL

Date: 01/02/2019

12. SUPERVISOR'S APPROVAL

Supervisor's signature:
Date:

PARENTAL CONSENT FORM
(Version 1.1, Date: 26/04/2019)

Project Title:
Assessing the energy expenditure of isolated fundamental movement skill performance in youth using indirect calorimetry and accelerometry

Contact Details:
Mr Phil Hill

Principle Investigator
[redacted]

Please initial box

1. I confirm that I have read and understood the information sheet dated 26/04/19 (version number 1.1) for the above study and have had the opportunity to ask questions. ☐
2. I understand that my child's participation is voluntary and that they are free to withdraw at any time, without giving any reason, without their medical care or legal rights being affected. ☐
3. I understand that sections of any of data obtained may be looked at by responsible individuals from the Swansea University or from regulatory authorities where it is relevant to my child taking part in research. I give permission for these individuals to have access to these records. ☐
4. I understand that data collected on my child may be used in reports and academic publications in anonymous fashion ☐
5. I give permission for my child to be video recorded during skill performance ☐
6. I agree for my child to take part in the above study. ☐

______________________	______________	______________________
Name of Participant	Date	Signature
______________________	______________	______________________
Name of Person taking consent	Date	Signature
______________________	______________	______________________

Researcher   Date   Signature

CHILD ASSENT FORM
(Version 1.1, Date: 01/06/2018)

Project Title:
Swansea University Research Engagement Week

Contact Details:
Zoe Marshall (PhD Student)   Adam Runacres (PhD Student)   Phil Hill (PhD Student)   Dr Melitta McNarry
[redacted]

Please initial box

1. I confirm that I was at the assent assembly / have read and understood the participant information sheet given to me (dated: 01/06/2018, version number 1.1) for this study and have had the opportunity to ask any questions ☐

2. I understand that taking part is my choice and that I can choose to stop taking part at any time, without giving a reason, and it won't affect my participation in other research studies in the future. ☐

3. I understand that information collected about me by the researchers will only be looked at by people who can do so. I am happy for them to have access to it ☐

4. I am happy for my latest grades to be looked at by the researchers and I understand that it will not affect my education or effect my participation within this study ☐

5. I understand that the information collected by the researchers may be used in their work and published, but the information will be anonymous. This means that the information will not have my name on it or any information that links it to me. ☐

6. I am happy to take part in the physical activity monitoring part of this study and wear an accelerometer for 7 days. I also understand that it is my responsibility to bring this back into school before the end of the current term. ☐

7. I agree to being video recorded whilst I perform the movement skills. ☐

8. I understand that the heart and lung function stations are for research only and cannot tell me if I have an illness or not ☐

9. I agree to take part in the above study.

____________________	________________	________________________
Name of Participant	Date	Signature
____________________	________________	________________________
Researcher	Date	Signature

PARENT/GUARDIAN CONSENT FORM
(Version 1.1, Date: 01/06/2018)

Project Title:
Swansea University Research Engagement Week

Contact Details:
Zoe Marshall (PhD Student) Adam Runacres (PhD Student) Phil Hill (PhD Student) Dr Melitta McNarry

[redacted]

Please initial box

1. I confirm that I have read and understood the information sheet dated 01/06/2018 (version number 1.1) for the above study and have had the opportunity to ask questions. ☐
2. I understand that my child's participation is voluntary and that they are free to withdraw at any time, without giving any reason, without their medical care or legal rights being affected. ☐
3. I understand that sections of any of data obtained may be looked at by responsible individuals from the Swansea University or from regulatory authorities where it is relevant to my child taking part in research. I give permission for these individuals to have access to these records. ☐
4. I understand that data collected on my child may be used in reports and academic publications in anonymous fashion ☐
5. I understand that the research techniques used in this study are for research purposes only and not for diagnosis of any condition ☐
6. I give permission for my child to be video recorded during the fundamental movement skills station for research analysis purposes only ☐
7. I agree for my child's physical activity levels to be monitored by an activity monitor for 7 days. If I agree to this, I also understand that it is my child's and my responsibility to ensure the return of the monitor by the end of the current half term. ☐
8. I agree to my child taking part in the above study. ☐

Name of Parent	Date	Signature
Name of child giving consent for	Date	Signature
Researcher	Date	Signature

Appendix VII

TGMD-2 Object Control and TGMD-3 Balls Skills Scoring Script

TGMD-2 Object Control Skills			**TGMD-3 Ball Skills**			
Skill		**TGMD-2 Performance Criteria**	**Skill**		**TGMD-3 Performance Criteria**	***Research Team Notes***
Striking a stationary ball	C1	Dominant hand grips bat above nondominant hand	Two Handed Strike	C1	Child's preferred hand grips bat above non-preferred hand.	
	C2	Nonpreferred side of body faces the imaginary tosser with feet parallel		C2	Child's non-preferred hip/shoulder faces straight ahead.	*Change of action for feet*
	C3	Hip and should rotation during swing		C3	Hip and shoulder rotate and derotate during swing.	*Change of full action for swing*
	C4	Transfers body weight to front foot		C4	Steps with non-preferred foot.	*Change of action for foot*
	C5	Bat contacts ball		C5	Hits ball sending it straight ahead.	*Outcome change*
			One-hand forehand strike of self-bounced ball	C1	Child takes a backswing with the paddle when the ball is bounced.	
				C2	Steps with non-preferred foot.	
				C3	Strikes the ball toward the wall.	
				C4	Paddle follows through toward non-preferred shoulder.	

Stationary Dribble	C1	Contacts ball with one hand at about belt level	One-hand stationary dribble	C1	Contacts ball with one hand at about waist level	*Change of term for belt level as waist level*
	C2	Pushes ball with fingertips (not a slap)		C2	Pushes the ball with fingertips (not slapping at ball)	
	C3	Ball contacts surface in front of or to the outside of foot on preferred side		C3	Maintains control of the ball for at least four bounces consecutively without moving their feet to retrieve the ball	*Removal of action for ground contact for ball*
	C4	Maintains control of ball for four consecutive bounces without having to move the feet to retrieve it				
Catch	C1	Preparation phase where hands are in front of the body and elbows are flexed	Two-hand catch	C1	Child's hands are positioned in front of the body with the elbows flexed	
	C2	Arms extend while reaching for the ball as it arrives		C2	Arms extend reaching for the ball as it arrives	
	C3	Ball is caught by hands only		C3	Ball is caught by hands only	
Kick	C1	Rapid continuous approach to the ball	Kick	C1	Rapid, continuous approach to the ball.	
	C2	An elongated stride or leap immediate prior to ball contact		C2	Child takes an elongated stride or leap just prior to ball contact	
	C3	Nonkicking foot placed even with or slight in back of the ball		C3	Non-kicking foot placed close to the ball	*Change of wording for foot placement*
	C4	Kicks ball with instep of preferred foot (shoe-laces) or toe		C4	Kicks ball with instep or inside of preferred foot (not the toes)	

Overhand Throw	C1	Windup is initiated with downward movement of hand/ arm	Overhand Throw	C1	Windup is initiated with a downward movement of hand and arm	
	C2	Rotates hip and shoulders to a point where the nonthrowing side faces the wall		C2	Rotates hip and shoulder to a point where the non-throwing side faces the wall	
	C3	Weight is transferred by stepping with the foot opposite the throwing hand		C3	Steps with the foot opposite the throwing hand toward the wall	
	C4	Follow-through beyond ball release diagonally toward the nonpreferred side		C4	Throwing hand follows through after the ball release, across the body toward the hip of the non-throwing side	*Slight change of action for end direction of throw towards hip for TGMD-3*
			Underhand Throw	C1	Preferred hand swings down and back reaching behind the trunk.	
				C2	Steps forward with the foot opposite the throwing hand.	
				C3	Ball is tossed forward hitting the wall without a bounce.	
				C4	Hand follows through after ball release to at least chest level.	
Underhand Roll	C1	Preferred hand swings down and back, reaching behind the trunk while chest faces cones				

	C2	Strides forward with foot opposite the preferred hand toward the cones				
	C3	Bends knees to lower body				
	C4	Releases ball close to the floor so ball does not bounce more than 4 inches high				
		Total Number of Object Control Skills	6		Total Number of Ball Skills	7
		Maximum Score	48		Maximum Score	54

Appendix VIII

TGMD-2 and TGMD-3 Locomotor Skill Scoring Script

TGMD-2 Locomotor Skills			**TGMD-3 Locomotor Skills**			
Skill		**TGMD-2 Performance Criteria**	**Skill**		**TGMD-3 Performance Criteria**	***Research Team Notes***
Run	C1	Arms move in opposition to legs, elbows bent	Run	C1	Arms move in opposition to legs with elbows bent	
	C2	Brief period where both feet are off the ground		C2	Brief period where both feet are off the surface	
	C3	Narrow foot placement landing on heel or toe (i.e. not flat-footed).		C3	Narrow foot placement landing on heel or toes (not flat-footed).	
	C4	Non-support leg bent approximately 90 degrees (i.e. close to buttocks)		C4	Non-support leg bent about 90 degrees, so foot is close to buttocks.	
Gallop	C1	Arms bent and lifted to waist level at take-off	Gallop	C1	Arms flexed and swinging forward	*Change of terms for arm action*
	C2	A step forward with the lead foot followed by a step with the trailing foot to a position adjacent to or behind the lead foot		C2	A step forward with lead foot followed with the trailing foot landing beside or a little behind the lead foot (not in front of the lead foot)	
	C3	Brief period when both feet are off the floor		C3	Brief period where both feet come off the surface	

	C4	Maintains a rhythmic patter for four consecutive gallops		C4	Maintains a rhythmic pattern for four consecutive gallops	
Hop	C1	Non-support leg swings forward in pendular fashion to produce force	Hop	C1	Non-hopping leg swings forward in pendular fashion to produce force	
	C2	Foot of non-support leg remains behind body		C2	Foot of non-hopping leg remains behind hopping leg (does not cross in front of)	
	C3	Arms flexed and swing forward to produce force		C3	Arms flex and swing forward to produce force	
	C4	Takes off and lands three consecutive times on preferred food		C4	Hops four consecutive times on the preferred foot before stopping	*Difference in product outcome from 3 hops to 4*
	C5	Takes off and lands three consecutive times on nonpreferred foot				*Removal of fifth criteria and focus on hopping on both feet*
[redacted]	[redacted]	[redacted]	Skip	C1	A step forward followed by a hop on the same foot	
	[redacted]	[redacted]		C2	Arms are flexed and move in opposition to legs to produce force	
	[redacted]	[redacted]		C3	Completes four continuous rhythmical alternating skips	
Horizontal jump	C1	Preparatory movement includes flexion of both knees with arms extended behind body	Horizontal Jump	C1	Prior to take off both knees are flexed, and arms are extended behind the back	*Change of terminology for placement of arm i.e. body and back*

	C2	Arms extend forcefully forward and upward reaching full extension above head		C2	Arms extend forcefully forward and upward reaching above the head	
	C3	Take off and land on both feet simultaneously		C3	Both feet come off the floor together and land together	
	C4	Arms are thrust downward during landing		C4	Both arms are forced downward during landing	
Slide	C1	Body turned sideways so shoulders are aligned with the line on the floor	Slide	C1	Body is turned sideways so shoulders remain aligned with the line on the floor (score on preferred side only)	*Scoring on preferred side only for TGMD-3*
	C2	A step sideways with lead foot followed by a slide of the trailing foot to a point next to the lead foot		C2	A step sideways with the lead foot followed by a slide with the trailing foot where both feet come off the surface briefly (score on preferred side only)	*Scoring on preferred side only for TGMD-3*
	C3	A minimum of four continuous step-slide cycles to the right		C3	Four continuous slides to the preferred side	*Distinguishing preferred and non-preferred sides from left and right*
	C4	A minimum of four continuous step-slide cycles to the left		C4	Four continuous slides to the non-preferred side	
Leap	C1	Take off on one foot and land on the opposite foot	[redacted]			
	C2	A period where both feet are off the ground longer than running	[redacted]			

	C3	Forward reach with the arm opposite the lead foot	[redacted]			
		Total Number of Locomotor Skills	6		Total Number of Locomotor Skills	6
		Maximum Score	48		Maximum Score	46

Appendix IX

TGMD-2 and TGMD-3 Materials & Instruction

	SKILL	FMS	TGMD	MATERIALS	INSTRUCTIONS
1	Underhand Throw	Object Control/ Ball Skills	TGMD-3	Tennis ball 2 cones Wall (15 ft (4.6m) of space)	Attach a piece of tape 15 feet from the wall. Have the child stand behind the tape line facing the wall. Tell the child to throw the ball underhand and hit the wall. Repeat a second trial.
2	Underhand Roll		TGMD-2	Tennis ball 2 cones Wall (25 ft of clear space)	Place 2 cones against a wall so that they are 4ft apart. Measure and mark 20ft from the wall. Tell the child to underhand roll the ball to the wall between the cones. Repeat a second trial.
3	Overhand Throw		TGMD-2 TGMD-3	Tennis ball Wall (20ft of clear space)	Attach a piece of tape on the floor 20ft from a wall. Have child stand behind 20-foot line facing the wall. Tell child to throw the ball hard at the wall. Repeat a second trial.
4	Two handed strike		TGMD-2 TDMD-3	4inch lightweight ball, plastic bat, batting tee or other device to hold ball stationary	Place ball on batting tee at the child's waist level. Tell child to hit the ball hard. Repeat second trial.
5	One handed strike		TGMD-3	Tennis ball Small plastic tennis bat Wall	Hand the plastic paddle and ball to child. Tell child to hold ball up and drop it (so it bounces at waist height); off the bounce, hit the ball toward the wall. Point toward the wall. Repeat a second trial.

6	Dribble		TGMD-2 TGMD-3	8inch/ 10inch (20.3 – 25.4 cm) playground basketball Flat hard surface	Tell the child to dribble the ball four times without moving feet, using one hand and then stop by catching the ball. Repeat a second trial.
7	Catch		TGMD-2 TGMD-3	A 4-inch (10.2-centimenter) plastic ball, 15 feet (4.6 meters) of clear space, and tape or a marker	Mark off two lines 15 feet apart. The child stands on one line and the tosser stands on the other line. Toss the ball underhand to the child aiming at the child's chest area. Tell the child to catch the ball with two hands. Only count a trial in which toss is near child's chest. Repeat a second trial.
8	Kick		TGMD-2 TGMD-3	8/10inch ball (20.3 – 25.4 cm) Tape or marker Wall 30ft of clear space	Mark off one line 20ft (6.1m) away from wall and second one 8ft (2.4m) beyond the first line. Place ball on spot. Tell child to stand on other line 8ft away. Child is to run up and kick the ball hard toward the wall. Repeat for a second trial.
9	Run	**Locomotor skills**	TGMD-2 TGMD-3	60ft (18.3m) of clear space 2 cones	Place 2 cones 50ft (15.2m) apart. Make sure there is at least 8-10 ft (2.4-3.1ft) of space beyond cone for a safe stopping distance. Enough space for child to run around the cone. Tell the child to run as fast as they can from one cone to the other when you say "Go". Repeat for a second trial.
10	Skip		TGMD-3	A minimum of 30 feet (9.1 meters) of clear space, and two cones or markers	Place two cones 30 feet apart. Mark off two lines at least 30 feet apart with cones/markers. Tell the child to skip from one cone to the other cone. Repeat a second trial.
11	Gallop		TGMD-2 TGMD-3	25 feet (7.6 meters) of clear space, and two cones or marker	Place two cones 25 feet apart. Tell the child to gallop from one cone to the other cone and stop. Repeat a second trial.

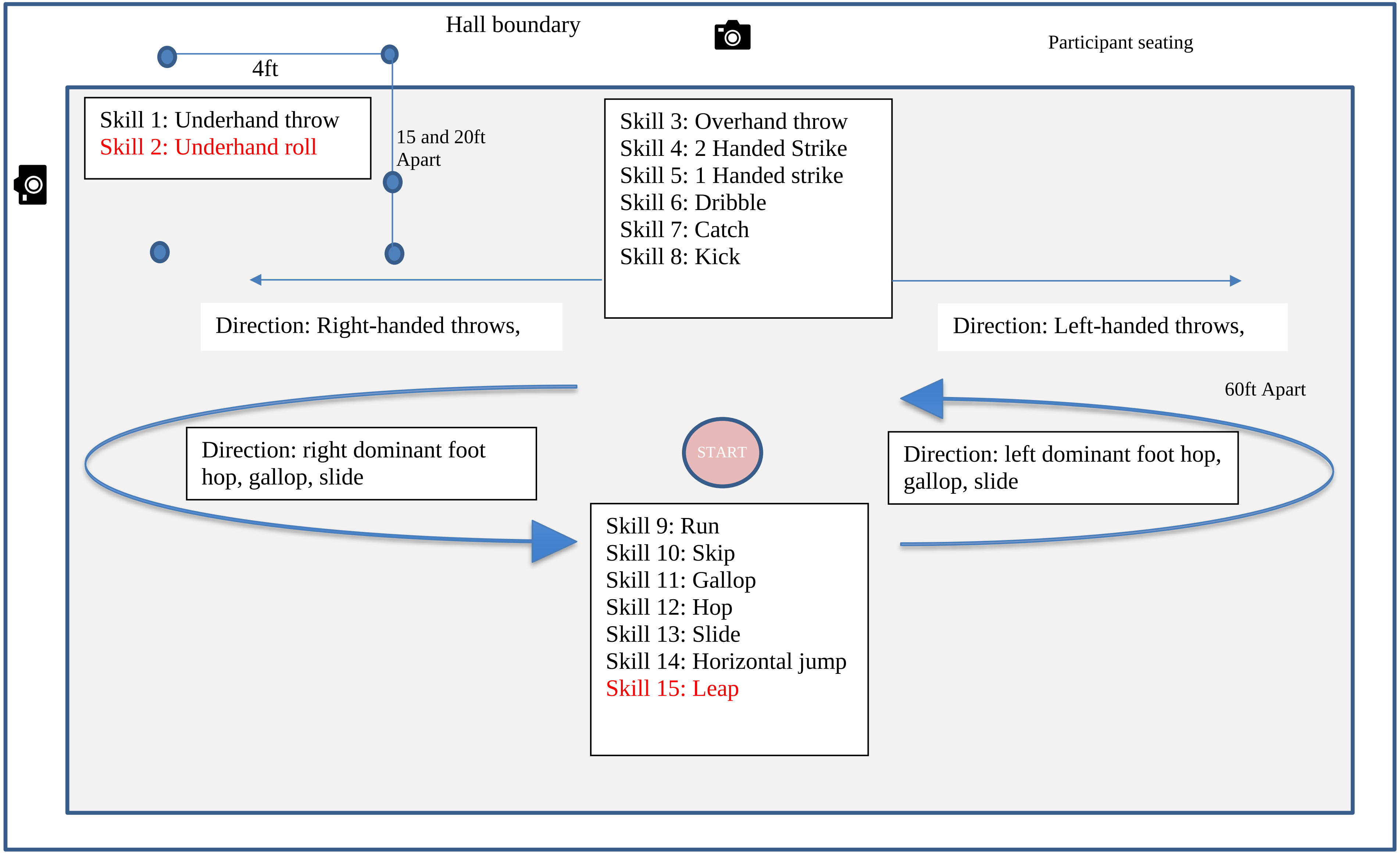
12	Hop		TGMD-2	A minimum of 15 feet (4.6 meters) of clear space, and two cones or markers	Tell the child to hop three times on his or her preferred foot (established before testing) and then three times on the other foot. Repeat a second trial.
			TGMD-3		Place two cones 15 feet apart. Tell the child to hop four times on his/ her preferred foot (established before testing). Repeat a second trial.
13	Slide		TGMD-2 TGMD-3	A minimum of 25 feet (7.6 meters) of clear space, a straight line, and two cones or markers	Place two cones 25 feet apart on a straight line. Tell the child to slide from one cone to the other cone. Let the child decide which direction to slide in first. Ask the child to slide back to the starting point. Repeat a second trial.
14	Horizontal Jump		TGMD-2 TGMD-3	A minimum of 10 feet (3.1 meters) of clear space, and tape or marker	Mark off a starting line on the floor, mat, or carpet. Position the child behind the line. Tell the child to jump far. Repeat a second trial
15	Leap		TGMD-2	A minimum of 20 feet of clear space	Child stand 10ft away from crossing point. Child asked to run and leap over the point. Repeat for a second trial.

Appendix X

FMS Research	TGMD-2 & tgmd-3					Project title:	Evaluating the developmental trajectories of FMS across late childhood and adolescence	
Approval number:	**2016-113**					**Researchers:**	Phil Hill *(DBS and First Aid)* Maeve Murray *(DBS and First Aid)* Charley Keen *(DBS and First Aid)*	
Age group:	**6-16 year old's (Boys and Girls)**					**Venue:**	Bay Campus Biomechanics Lab	
Identified Hazards	**(2) Severity 1-5**	**(3) Likelihood 1-5**	**(4) Risk Factor (Severity x Likelihood)**	**(5) Further measures required (Yes/ No)**	**(6) Hazards scoring 12 or more**	**(7) Existing Precautions**	**(8) Additional Actions**	**(9) Action by When**
Participant previous injury	2	3	6	No Action completed Signed consent from parent/ guardian to participate	n/a	Recruitment of participants with full fitness	n/ a	Start of November 2017 (by first testing date)
Slips, Trips, Falls	3	2	6	No Warm up undertaken and safe practice completed in demonstration and trial 1 and trial 2 performance	n/a	Shoelaces tied; removal of jewellery Equipment placed in safe area	First aid available at reception	Preparation time before each research session
Late parent pick-up	2	1	2	Researcher waits with participant in reception area and has emergency contact details for parents	n/a	Parents aware of pick up times and participants reminded to have	n/a	Research session

						contingency plan *parental consent form		
Non-participant safety	2	2	4	Clear instructions at beginning of session regarding “taking turns”	n/a	Bench for non-participants away from performance area on court	n/a	Research session

Appendix XI


Hall boundary
Participant seating
4ft
15 and 20ft
Apart
Skill 1: Underhand throw
Skill 2: Underhand roll
Skill 3: Overhand throw
Skill 4: 2 Handed Strike
Skill 5: 1 Handed strike
Skill 6: Dribble
Skill 7: Catch
Skill 8: Kick
Direction: Right-handed throws,
Direction: Left-handed throws,
60ft Apart
Direction: right dominant foot hop, gallop, slide
START
Direction: left dominant foot hop, gallop, slide
Skill 9: Run
Skill 10: Skip
Skill 11: Gallop
Skill 12: Hop
Skill 13: Slide
Skill 14: Horizontal jump
Skill 15: Leap