The application of an ecological dynamics approach to the athletic development of youth basketball players: the use of parkour to develop fundamental movement skills

Mark David Williams

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School of Sport, Rehabilitation and Exercise Sciences

University of Essex

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Abstract

Youth athletic development models emphasise the development of fundamental movement skills (FMS) in preadolescent children before sports specific skills (SSS). However, in sports such as basketball, FMS and SSS are not necessarily separate. An alternative perspective, based on the ecological dynamics framework, suggests that sports can be used to develop transferable FMS and SSS concurrently. Parkour has been proposed as a *donor sport* to enhance movement skills and capabilities transferable to team sports athletes like basketball, although further research is needed.

This research investigates parkour's potential as a donor sport for youth basketball players from an ecological dynamics perspective. Based upon a meta-analysis of bodyweight-only neuromuscular training programmes on motor control in youth athletes aged 8-18 years and basketball coaches' perceptions of FMS, a narrative review explored parkour's role in developing adaptable movement skills. A cross-sectional study compared the biomechanical properties of the parkour tic-tac skill and the basketball lay-up shot, revealing that the parkour action resulted in significantly higher maximum acceleration, suggesting it could enhance propulsive capabilities of the lower limb.

Two intervention studies examined parkour's effects on youth basketball players, revealing that although parkour did not outperform conventional athletic development training, it promoted greater engagement and enjoyment. Thus, parkour may effectively increase movement skills and physical capabilities whilst keeping young players motivated.

Parkour offers a diverse repertoire of movement, which may be particularly beneficial for preadolescent players, potentially reducing the risks of single-sport specialisation while enhancing basketball-specific performance. For adolescent basketball players, parkour-based exercises could be included into strength and conditioning (S&C) programmes to improve transferable physical capabilities. By adopting the ecological dynamics framework, organisations and governing bodies responsible for the long-term development of youth basketball players can create more effective training strategies that combine motor learning, performance, and athletic development.

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Abbreviations

AD	Athletic Development
APHV	Age at peak height velocity
ASM	Athletic skills model
BMS	Basic movement skills
CMJ	Countermovement jump
CV	Coefficient of variation
DJ	Drop jump
DMSP	Developmental Model of Sport Participation
ES	Effect size
FMS	Fundamental movement skills
GMA	General Motor Ability
GMP	Generalised motor program
GRF	Ground reaction force
LTAD	Long-term athlete development
NGB	National governing body
NMT	Neuromuscular training
LU	Lay-up (shot)
PHV	Peak height velocity
PL	Physical literacy
PWV	Peak weight velocity
RAE	Relative age effect'
S&C	Strength and conditioning
SSS	Sports specific skills
TMS	Transitional motor skills
TT	Tic-tac
YPD	Youth physical development

Chapter 1

1.1 Introduction

Basketball is a sport played by two teams of five players whose aim is to outscore each other by successfully shooting the ball through the opponent's hoop which is positioned 10 feet above the ground at either end of a 28 m court. In both defensive and offensive scenarios, players' body size, speed, muscular power and change of direction speed, are considered important determinants of performance [1]. Moreover, from a physiological perspective, basketball is a sport that is characterised by bouts of intermittent activity with interdependent demands on both the aerobic and anaerobic energy pathways [2]. The typical movements executed by basketball players are shooting, rebounding, dribbling, passing and receiving the ball, and defensive and offensive manoeuvring (e.g., cutting and pivoting) which require impulsive muscular actions [3,4]. Although these characteristics are representative of all levels of play, including youth and elite, and across sexes, specific differences exist with respect to physical output levels in measures such as total distance covered and running intensities [5].

In the development of youth basketball players, basketball specific skills, such as dribbling and rebounding, are regarded as *fundamental* to performance [4]. Although these are regarded as core skills that are critical to successful performance in basketball, typically, fundamental movement skills (FMS) represent a group of movement-based skills that are unspecific to any one sport. More precisely, FMS are considered to represent the sequencing together of basic movement patterns involving two or more body segments [6]. From this more generalised perspective, FMS can be categorised as locomotor, object manipulation, and balance skills, the development of which is understood to be important to the physical activity levels of individuals across the lifespan [7,8]. Of pertinence, due to children's high neural plasticity in the first decade of life, it has been suggested that FMS should be predominantly developed in preadolescence [9–11]. In relation to this, as children approach adolescence, there is a peak in grey matter development before a non-linear decline occurs [12] with this decline potentially making the acquisition of new motor skills more difficult in older individuals. Accordingly, the notion of a '*golden period*' for motor learning has been suggested to exist in preadolescent children. However, despite the logic for a golden period for motor learning, there is little evidence to support the notion that FMS are more easily developed during preadolescence.

In the context of sports, FMS are considered to form the foundation for more complex skills associated with specific demands, which are governed by the rules and constraints imposed in each sport. From this perspective, the development of FMS through childhood and adolescence is considered imperative for the successful development of sports specific skills (SSS). Accordingly, within the scientific research literature relating to youth athletic development, an emphasis on FMS ahead of any SSS development is typically recommended [13,14]. Problematically, however, in the development of youth basketball players, an emphasis on early specialisation has been implicated in the high rates of injury seen in youth-level players [15]. Within the scientific research literature, early sport specialisation is defined as year-round participation in a single sport [16]. Where increased exposure to competition increases the risk of injury in youth basketball; of concern, the consequence of early sport specialisation may be the underdevelopment of FMS, thus compounding the risk of injury in the young player [17].

The development of FMS in the youth basketball player is thought to increase motor control and enhance physical capabilities that better prepare the musculoskeletal system for the physical demands of the sport. Accordingly, FMS development is thought to enhance and refine movement patterns, such as running, leaping and jumping actions, that are considered important to sports performance [18]. This may include the ability to engage different muscle groups, coordinate limbs, and maintain effective alignment during movement. Support for such a perspective is often inferred from research literature that has demonstrated the efficacy of neuromuscular training (NMT) programmes, which include a broad range of general activities, such as sprinting, jumping, change of direction movements, and full range-of-motion strengthening exercises [19]. Given the types of activities typically included in NMT programmes, to some degree they may be considered to be a means to develop FMS, especially with respect to locomotion, coordination and balance [17]. Indeed, in recent years, the implementation of NMT programmes within the warm-up practices of team sports has emerged as a strategy to develop FMS and other athletic capabilities that are otherwise at risk of not being developed due to factors such as early sport specialisation. Accordingly, both national and international governing bodies for sports (e.g., the Fédération Internationale de Football Association (FIFA) and the (English) Rugby Football Union (RFU)) have implemented their own versions of NMT programmes within the '*grassroots*' levels and talent pathways of their respective sports [20,21].

With the emergence of such NMT programmes being seemingly influenced by the strength and conditioning (S&C) field, their utilisation to diversify and develop FMS may be a limited strategy. Indeed, though the typical content of NMT programmes may present young athletes with exposure to broader movement skills than would be developed through the sport alone, there appears to be an over-emphasis on the development of skills that underpin S&C-based activities (e.g., plyometric and resistance training exercises). While these activities may be of importance as part of the youth athletic development strategy (e.g., to increase physical outputs, such as rate of force development), from the perspective of developing FMS, how this approach may contribute to the enhancement of SSS remains uncertain. This is particularly so given that the movement skills that are typically developed within NMT programmes are limited to those related to general athleticism such as sprinting; jumping and landing; as well as neuromuscular movement patterns including squatting, lunging, and pushing and pulling actions, all of which generally occur within single planes of motion [29,30]. From this perspective, competence in FMS is typically characterised by the ability to perform these skills with proficiency [22] and is often determined by the “functional” alignment of body segments [23]. For example, alignment of the knee over the ankle in the frontal plane during a single leg squatting task [24]. However, this type of constrained evaluation is not necessarily representative of the performance of skills within the context of sports such as basketball where highly-adaptable and varied movement patterns are a more common feature of skilled performance [25]. Therefore, while it appears logical that the development of FMS would be important to enhance the playing capabilities of youth basketball players, the extent to which this might be the case is not clear within the current scientific research literature. Moreover, the degree to which FMS activities form any such foundations for basketball specific skills to be developed has not been examined and thus any notion that the development of FMS is a necessary requisite for youth basketball players is limited to theory.

To better appreciate the role of FMS in the development of youth basketball players, theories of motor control and motor learning may provide more appropriate perspectives. Traditional ideas, such as those central to Adam’s closed-loop theory [26] and Schmidt’s schema theory [27] have been challenged by more recent perspectives, including dynamical systems theory and the ecological dynamics framework, which collectively present an alternative account for the novelty and diversity of human movement and motor skill performance [28,29]. However, ahead of consideration of the different theories for motor control and the development of motor skills, it is from a philosophical standpoint that movement skills should be explored to determine whether they are fundamental, and more precisely, *what exactly* they are fundamental *to* [30]. Accordingly, consideration of ontogenetic and phylogenetic movements is also necessary. While ontogenetic skills may account for culturally divergent perspectives of FMS, movements regarded as phylogenetic may represent those that transcend culture and, instead, in the absence of impairment, are typical of all humans, for example in the case of bipedalism [30]. Indeed, the developmental timeline that reflects the display of reflexive movements in the new-born baby and the milestone attainment of rudimentary movements in the early years of life, such as crawling, sitting, and eventually standing and walking, may pertain to phylogenetic abilities from which ontogenetic skills are then developed [18]. Therefore, it is the ontogenetic skills perspective that forms the basis for a critical examination of FMS from an athletic development perspective and, in turn, these skills' importance in the development of youth basketball players. Currently, however, the consideration of phylogenetic versus ontogenetic skills appears to be absent from the youth athletic development literature.

In recent years, the Athletic Skills Model (ASM) by Wormhoudt et al. [31] has emerged as a model of athletic development that has attempted to combine concepts from motor learning with constructs from other existing athletic development models (e.g., the long-term athlete development (LTAD) [32] and the Youth Physical Development (YPD)) models [33]. However, despite its global recognition and influence, the LTAD model has received criticism relating to a lack of evidence for its key characteristics, such as its purported *'windows of opportunity'*. In contrast, the YPD model is regarded as a more evidence-based alternative, though it is somewhat restricted to the S&C domain with an emphasis on the development of physical capabilities (e.g., speed, strength, and power) with little information presented in relation to the development of FMS and motor learning. Collectively, the LTAD and YPD models advocate for the development of FMS in childhood and during preadolescence though do not appear to provide a methodology by which this can be achieved. In contrast, the ASM has adopted the ecological dynamics approach to motor learning as its basis, which it integrates with ideas from both the LTAD and the YPD models to present a more comprehensive and holistic framework for the development of youth athletes. Moreover, based upon constructs from the ecological dynamics framework, the ASM proposes the concept of '*donor sports'* as a means to develop broad motor skills and movement capabilities whilst also accounting for the development of the perceptual component of skilled performance.

Donor sports are sporting activities that differ from the primary or '*target sport'* played by an individual which, through their concurrent participation, can help to develop perceptual and action capabilities that can be transferred back to the primary sport [34,35]. Accordingly, the use of donor sports may serve to provide young athletes with exposure to a greater breadth of movement skills which, in turn, may offset the risks relating to early specialisation, while also contributing to more diverse movement capabilities that are more representative of the types of movements that occur within sports-specific contexts. Of importance, given that there may also be a transfer of perceptual qualities, the donor sport concept may provide an effective strategy within youth athletic development to enhance sports-specific performance in a manner that is potentially more time-efficient than typical athletic development strategies (e.g., conventional NMT programmes). Accordingly, it may be that the donor sport concept would be well received by sports-specific coaches of youth athletes, especially where the specificity of training has been identified as an important factor for the implementation of NMT-based training [36].

Based on the donor sport concept, parkour has been proposed as an activity that may be used to develop both movement skills and perceptual capabilities for youth athletes competing in team sports [37]. Parkour is an acrobatic sport, requiring the performer to navigate and traverse obstacles within their environment in the fastest and most efficient manner possible [34]. Such requirements have an apparent overlap with those of basketball and may therefore present youth basketball players with a different physical activity that may be used within an athletic development strategy to cultivate movement skills and, in turn, enhance playing capabilities. Accordingly, this research aims to clarify the importance of FMS as a basis for the development of SSS in youth basketball players and, through an ecological dynamics lens, examine the potential for parkour as a donor sport that may be adopted for the athletic development of youth basketball players.

1.2 Aims of the research

Within the youth athletic development literature, more broadly [e.g. 9,10,21], the development of FMS ahead of sports-specific skills is suggested to form the necessary foundations to facilitate a young athlete's long-term development within their chosen sport. This is understood to occur through the development of a greater breadth of movement capabilities that may in turn mitigate against issues relating to early single sport specialisation. However, despite the emphasis placed on developing FMS ahead of SSS, absent from models of athletic development is information relating to the methodological and pedagogical coaching approaches that should be adopted to best develop such skills.

This research aims to explore FMS from an ecological dynamics perspective with specific consideration to the athletic development of youth basketball players. From this perspective, the research will consider a shift in discourse from traditional coaching perspectives to those based upon concepts from the ecological dynamics framework. The research will firstly examine the importance of developing FMS during preadolescence in comparison to adolescence in youth populations to determine whether a scientific basis for the golden period of motor development exists. To date, the only known evidence for the golden period of motor learning is limited to the meta-analysis of Behringer et al. [11] though their results predominantly related to the effects of resistance training on throwing, jumping, and running performance in children and adolescents and are therefore somewhat limited in their broader application to motor learning.

This research also aims to examine the donor sport concept and compare the effects of parkour-based training activities with conventional NMT and other S&C activities on the development of motor skills and athleticism in youth basketball players across different stages of maturation. Accordingly, this research will straddle multiple domains including motor control and learning, as well as youth athletic development and S&C. In particular, this relates to the work of Stafford et al. [34], and the ideas of Wormhoudt et al. [31] and their ASM for athletic development which, to date, has not been examined empirically. It is intended that the outcomes from this research will inform basketball national governing bodies and related organisations, while basketball coaches and sports science and medicine practitioners could implement such strategies to support the development of youth basketball players. A schematic of the studies can be observed in Figure 1.

Literature Review

- A review of relevant literature revealed gaps in current knowledge

- There is a dearth of evidence to support the notion of a golden period for motor learning that is often cited as the rationale for the emphasis on FMS development within youth athletic development literature.

- The value that coaches of youth basketball players place on athletic development activities that are not considered to be sports-specific suggests alternative strategies may be warranted.
- Of particular interest was whether athletic development of youth basketball players would benefit from the adoption of concepts from the ecological dynamics framework.

- Accordingly, the donor sport concept and use of parkour to develop movement skills as well as perceptual capabilities that could be transferred to basketball performance was an important line of enquiry.
- Initially, an undertaking of a meta-analysis to determine the effects of conventional NMT training was necessary to assess potential differences across stages of maturation.

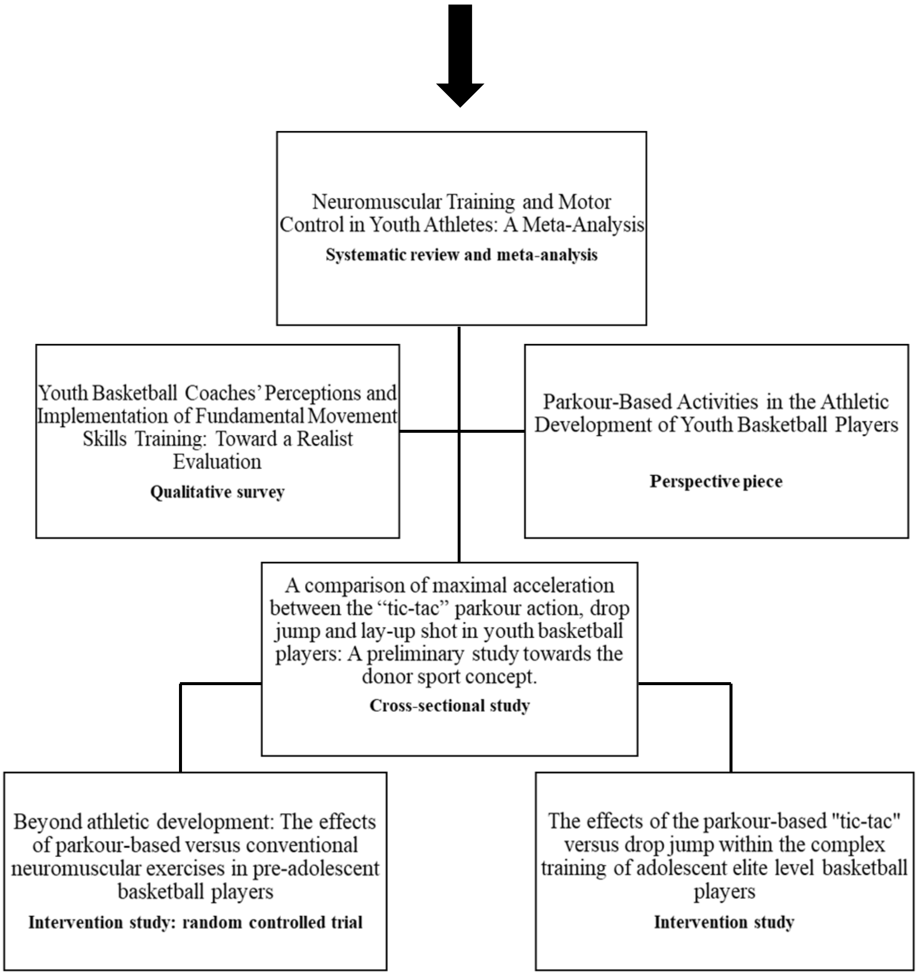

Figure 1.

Schematic of thesis structure.

1.3 Research Questions

- Does a golden period for motor learning exist in preadolescent youth?
- Are FMS valued and understood by coaches of youth basketball players?
- Using the ecological dynamics framework and the donor sport concept, can parkour be used to develop FMS in youth basketball players?

1.4 Outline of Study 1 - Neuromuscular Training and Motor Control in Youth Athletes: A Meta-Analysis

Citation

Williams MD, Ramirez-Campillo R, Chaabene H, Moran J (2021) Neuromuscular Training and Motor Control in Youth Athletes: A Meta-Analysis. Percept Mot Skills 00315125211029006

This meta-analysis investigated the effects of bodyweight-only NMT programmes on motor control of movement among youth athletes. Included were intervention studies examining the effects of NMT of up to 16-weeks duration in healthy males and females aged 8-18 years of age. Pooled estimates of effect sizes for changes in motor control across nine studies (12 comparisons) were calculated using the inverse-variance random effects model for meta-analyses. There was a moderate, significant effect in favour of NMT programmes (0.79 [0.38, 1.20]) on motor control. Analyses for age and stature revealed NMT programmes to be more effective in younger, shorter, and lighter individuals. Larger effect sizes were observed in males. These findings supported the notion that exercise to enhance motor control should be emphasised during pre-adolescence.

1.5 Outline of Study 2.1 - Youth basketball coaches' perceptions and implementation of fundamental movement skills training: Towards a realist evaluation

Citation

Williams MD, Hammond AM, Moran J (2021) Youth Basketball Coaches' Perceptions and Implementation of Fundamental Movement Skills Training: Toward a Realist Evaluation. J Teach Phys Educ 1–8

Where the development of FMS is emphasised within the athletic development of youth athletes, the purpose of this study was to investigate youth basketball coaches' perceptions and implementation FMS training within their practice. Coaches of youth basketball players from across different countries and continents (n= 79) were surveyed to determine their beliefs and experiences relating to their perceptions and implementation of non-basketball specific skills and FMS into practice. An analysis of descriptive statistics (means and frequencies) and reflexive qualitative thematic analysis were used to inform the results. It was found that the coaches had a comprehension of FMS and acknowledge their value in the long-term development of youth players. However, there appeared to be varying levels of implementation amongst the surveyed coaches. The findings suggest a need for governing bodies to develop innovative strategies to persuade youth basketball coaches to adopt non-sports specific movement skills to improve their practice. A strategy that adopts concepts from the ecological dynamics framework is recommended to support a move away from dichomomised perspectives of FMS and basketball-specific skill development, and instead emphasises their complementary nature and provides a better account for the complexity of skilled motor performance. Accordingly, to increase levels of implementation of FMS as well as the adoption of other non-basketball specific training content by coaches, tenets of the ASM (e.g., donor sports) may be utilised within the athletic development strategy of youth basketball players.

1.6 Outline of Study 2.2 - Parkour-Based Activities in the Athletic Development of Youth Basketball Players

Citation

Williams MD, Strafford BW, Stone JA, Moran J (2021) Parkour-Based Activities in the Athletic Development of Youth Basketball Players. Front Physiol 12:1808

Based upon the ASM's donor sport concept, parkour has been proposed as a method to increase movement capabilities in youth athletes engaged in team sports. However, in place of sports sampling, the practice of S&C has become a driving force behind developmental models for youth athletes, highlighted by the growing body of literature regarding youth athletic development training. The aim of this perspective piece was to explore how conventional S&C practice may not sufficiently develop FMS because of the typically narrow range of foundational exercises that are emphasised. Perspectives informed by the ecological dynamics framework are discussed, including the notion of donor sports and the use of parkour as a donor sport for youth basketball players. Parkour is proposed as a training modality that may be used to encourage movement diversity and adaptability as well as also a means to facilitate the transfer of conventional S&C training to basketball specific performance. Further, where parkour's use as a donor sport for basketball players might contribute to the transfer of training, it might also provide a means to enhance broad athletic capabilities beyond the those developed by basketball alone. Accordingly, parkour may offset the risks associated with early single-sport specialisation whilst, concurrently, it might develop athletic capabilities that are more specific to basketball than conventional S&C. From this perspective, parkour would form a valuable method within the athletic development strategy of youth basketball players.

1.7 Outline of Study 3 - A comparison of maximal acceleration between the "tic-tac" parkour action, drop jump and lay-up shot in youth basketball players: A preliminary study towards the donor sport concept

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Based upon the donor sport concept, the aim of this cross-sectional study was to compare acceleration outputs of the parkour-style "tic-tac" action, with the drop jump and the lay-up shot in youth basketball players. In this cross-sectional study, 25 youth basketball players (17 males, 13.80 ± 1.30 years of age; and 8 females, 15.00 ± 0.80 years of age) completed trials of each action while wearing a single inertial motion capture unit positioned at the lumbar spine. Maximum resultant acceleration was calculated from the raw data for each action. Using sex and maturation status as covariates, data were subsequently analysed using a Bayesian one-way repeated measures ANCOVA. Results resultant acceleration revealed the jump + sex model to be the best fitting, though the analysis of the effects found evidence for sex to be anecdotal. Post hoc comparisons revealed that the tic tac produced greater acceleration than the drop jump and the lay-up. These findings suggest that the tic tac may be used to develop propulsive acceleration relevant to the lay-up shot. Accordingly, there appears to be some merit in the utilisation of the tic-tac exercise within the athletic development practices of youth basketball players, which may lead to greater levels of implementation by coaches. The findings of this study may also extend to the use of other parkour-based actions

1.8 Outline of Study 4 - Beyond athletic development: the effects of parkour-based versus conventional neuromuscular exercises in pre-adolescent basketball players

Citation

Williams, M. D., Hammond, A., & Moran, J. (2023). Beyond athletic development: The effects of parkour-based versus conventional neuromuscular exercises in pre-adolescent basketball players. PLOS ONE, 18(7), e0288439. https://doi.org/10.1371/journal.pone.0288439

The implementation of NMT programmes has been found to be an effective strategy in the development of movement skills and athleticism in youth level athletes. The purpose of this study was to compare the effects of a parkour-based warm-up to a conventional NMT warm-up on the athletic capabilities of youth basketball players. Using a mixed quantitative and qualitative approach, prepubescent basketball players participated in an 8-week intervention study, requiring them to complete a 15-minute warm-up once per week before their regular basketball practice. Players were randomly assigned to the experimental groups and both groups were blind to each other's warm-up activities. A separate control group was formed of participants from a different club. Pre to post intervention measures of overhead squat performance, countermovement jump, and 10-metre sprint speed were recorded in all three groups. Additionally, pre-post measures were recorded for a timed parkour-based obstacle course for the two experimental groups. No significant between-group differences were found between pre- and post-test measures ($p > 0.05$), though effect sizes revealed improvements in both intervention groups versus the control. In the OHS, the conventional group increased knee flexion with the largest ES (0.71) compared with the parkour and conventional groups who both reduced in knee flexion (-0.63 and -1.12 respectively). Similarly, ES for the 10-m sprint times also reflected this pattern with values of 0.35, -0.14, and -0.37 for the conventional group, the parkour group, and the control group, respectively. Small ES for the CMJ were revealed for all three groups (conventional group = 0.14; parkour group = 0.09; control group = 0.11).

Whilst in the speed run, the conventional group were found to have improved with a larger ES (0.56) than the parkour group (0.37). Participants from both experimental groups were also invited to take part in a post-intervention semi-structured interview to discuss their experiences. *Enjoyment; Physical literacy;* and *Docility* were revealed as higher order themes, of which the two former themes appear to align to the wider concept of physical literacy. These findings suggest that the benefit of parkour may extend beyond athletic development and contribute to the development of physical literacy, which aligns to concepts from the ecological dynamics framework and, in particular, the interdependence of perception and action in the performance and development of motor skills. Collectively, the findings of this study indicate the non-linearity in motor development and highlight the dynamic and complex nature of athletic development training.

1.9 Outline of Study 5 - The parkour tic-tac action versus the drop jump as part of complex training within the strength and conditioning programme of talented youth basketball players

Under review

PLOS ONE

Using an ecological dynamics lens, the aim of this study was to examine the effects of two different complex training programmes on measures of physical performance amongst highly trained youth basketball players. Building upon the notion that parkour may serve as donor sport in the athletic development of youth basketball players, the conventionally utilised drop jump, and the parkour-based tic-tac jump were embedded within the S&C training programmes of youth basketball players for comparison of the effects. Fourteen talented adolescent basketball players completed twice a week one of two different 8-week complex training protocols (drop Jump, n = 7; tic-tac, n = 7) that were matched for prescribed workloads. Pre-post intervention testing protocols, which included jumping tests (countermovement, squat and 10-5 hop jumps), change-of-direction speed (5-10-5), sprinting (0-20 metres) and maximal strength (isometric midthigh pull) did not reveal significant effects according to group and group x time ($p > .05$). However, between group pre-post intervention differences revealed a large ES magnitude for the 0-10-m sprint times (0.82) in favour of the drop jump group, and medium ES magnitudes for the isometric midthigh pull (0.59) and the 5-10-5 test (0.45). In the CMJ, ES magnitudes for concentric peak force and eccentric deceleration impulse were found to favour the tic-tac group (0.59 and 0.47 respectively). However, ES magnitudes were found to be small for CMJ height (0.19, favouring the parkour group), squat jump height (0.35, favouring the drop jump group), the hop jump (0.18, with the larger decrease in reactive strength index observed in the tic-tac group), and the 10-20 m sprint (0.18, with the larger improvement revealed in the drop jump group). In addition, observations of individual participants' responses to the training programmes showed high interindividual variability. Accordingly, these results highlight the non-linear response to training and demonstrate the complex and highly individualised responses to training, which can be considered somewhat reflective of the dynamic and complex system that the human body represents. The current findings offer support for employing methods that encourage movement variability, such as parkour, within the S&C training of youth basketball players.

Chapter 2

Literature Review

2.1 The physical requirements of basketball

2.1.1 Game specific demands

Basketball is a team sport in which matches are played for 40-minutes across four 10-minute quarters [39]. According to the International Basketball Federation (FIBA), the height of the ring must be 3,050 mm (10ft) above the playing surface meaning players are often required to execute high volumes of jumps to score and rebound [40]. Teams consist of five players formed of two main positional groups: backcourt players; and frontcourt players [41]. The backcourt players can be further categorised into point guard and shooting guard, while the frontcourt players are typically subcategorised into small forward, power forward and centre, each with specific roles and associated skillsets [42,43].

Although it is characterised by multidirectional movements performed at high speeds [44], basketball is a sport that requires contribution from both the aerobic and anaerobic energy pathways [45,46]. Of pertinence to the movement profiles and physiological demands of basketball is the FIBA rule of a 24-second limited on possessions, and 8 seconds (out of the 24 seconds) to advance the ball past the half-court line [47]. Through time-motion analysis, a study by Ben [48] revealed that elite junior level players (age 18.2 ± 0.5 years) utilised a range of locomotion types and at varying intensities during competitive games, including jogging, sideways running and shuffling, sprinting and striding. Of particular note was the finding of Ben [48] that 22% of the total distance covered by players used sideward movements. Further highlighting the demands on both aerobic and anaerobic energy pathways, Puente et al. [49] found the average heart rate during competitive games to be 85-95% of maximum in experienced players aged between 19 and 35 years. Moreover, it was found that across the three positional groups (guards, forwards, and centres), the greatest proportion of distance was covered at zone 1 and 2 intensities (standing/walking/jogging) [49]. Further, across 40-minute matches, both males and females appear to exhibit the same relative activity patterns and physiological responses [50]. However, despite similar relative physiological demands, a study by Portes et al. [5] found that young male players performed significantly greater high-intensity and sprint distances across all playing positions compared to their female counterparts, therefore highlighting the existence of absolute intensity-based differences in basketball.

In addition to the energy system demands, the multi-directional requirements of basketball have also been highlighted through time-motion analysis studies [49–51]. Indeed, previous research has shown that changes in movement type occur approximately every one to two seconds [28,31,39]. Basketball-specific skills, including rebounding the ball, dribbling, shooting, and blocking opponents [52] are utilised by offensive players to evade their opponents, which defending players must react to accordingly [44,52]. Therefore, in both offensive and defensive facets of the game, players are required to perform high volumes of acceleration and deceleration movements [53]. In their systematic review, Petway et al. [54] found that the total number of accelerations per game ranged from 43 to 145, whilst the total number of decelerations ranged from 24 to 95 per game in elite level performance. However, the total number of high intensity accelerations, defined as movements greater than 3.0 $m \cdot s^{-2}$, was found to be 1 to 15 per game while the total number of high intensity decelerations (greater than -3 $m \cdot s^{-2}$) ranged from 4 to 40 [54]. Furthermore, in the study by Vázquez-Guerrero et al. [55], a greater acceleration to deceleration ratio has been seen to occur in movements characterised by maximal deceleration and accelerations (greater than 3 m·s^{-2}) [55]. However, in the same study, Vázquez-Guerrero et al. [55] found that the number of moderate accelerations was higher than the number of moderate decelerations. Of pertinence, these characteristics appear to hold regardless of sex [56]. By comparison, in junior level players, male players have been found to perform significantly more decelerations than female players, predisposing them to higher acceleration to deceleration ratios [5]. Although nuanced, the extant body of research highlights the importance of acceleration and deceleration to basketball players across levels and between sexes.

Jumping is another key characteristic of basketball which, in addition to the high volumes of accelerations and decelerations, places external load on players [57]. Volumes of between 42 and 56 jumps per game have been reported [58], although elsewhere this number has been found to be substantially higher, which is suspected to be based upon level of performance [59]. For example, in a National Collegiate division I women's squad, Ransdell et al. [59] observed increased volumes of jumps per game on average across a four year period, from 81.9 ± 24.0 in year one to 99.7 ± 38.2 in year four. Importantly, year four of the study was the squad's most successful with respect to the win-loss record, highlighting the changing physical demands of the basketball in relation to performance. Of further support, the systematic review by Espasa-Labrador et al. [60] found that player load, which describes the external loads experienced by a player as measured using global- and local-positioning systems and through inertial movement analysis, was greater at higher competitive levels. Indeed, this finding appeared to support the earlier study by Power et al. [61], which also highlighted differences in jump volumes according to level of play. Of pertinence, both the studies by Espasa-Labrador et al. [60] and Power et al. [61] included female-only basketball studies within their systematic reviews and, in contrast to these findings, studies of male basketball players [e.g., 62,63] have shown jump frequencies between competitive levels to be more nuanced. For example, Ferioli et al. [63] observed collegiate players competing in division I to jump 29 ± 12 times compared to divisions II and III, who performed 26 ± 10 and 23 ± 12 jumps on average, respectively. In contrast to this trend, however, division VI players were found to perform 27 ± 14 jumps. This may reflect differences in other actions within the time-motion analyses, particularly those occurring at lower intensities compared to players competing at higher levels of competition. However, in general, it cannot be discounted that differences observed between studies may reflect variation in the technologies used to determine match activities [61]. Nonetheless, as was highlighted with respect to accelerations and decelerations, there are likely numerous contributing factors to the volume of jumps executed in a game. For example, in contrast to the findings of Ransdell et al. [59], Fox et al. [64] found the number of jumps performed be higher in games that resulted in losses compared to games that resulted in wins. To explain their results, Fox et al. [64] suggested that this may be the result of defensive teams attempting to contest more shots and gather rebounds when in a losing position. However, in the same study by Fox et al. [64] the results revealed differences in jump volumes and intensities based on playing home versus playing away. Nevertheless, what is clear from the research literature is that jumping is a frequently performed action within basketball which, when combined with the high volumes of accelerations and decelerations, places a high external load on to players regardless of sex and level of competition.

Despite the body of research highlighting the physical demands of basketball, the research is limited to the sports-specific characteristics derived from analysis of match demands. Although this information is of obvious importance, how it is utilised to inform the development of physical athletic development strategies for basketball players and, more specifically, those at youth level of the sport, is an important area of future research. Indeed, based upon the highly variable demands of basketball performance, future research leading to the formulation of an effective training strategy that accounts for such variability is necessary.

2.1.2 Physical performance correlates

Due to the high-intensity nature of basketball, physical fitness is understood to be an important contributing factor to performance [65,66]. Indeed, across different levels of play, research has shown a number of physical fitness qualities to correlate with basketball-specific performance [67–69]. For example, Zhang et al. [68] found positive significant correlations between coordination, balance, trunk strength and relative average power and 3-point shooting accuracy in a 90-second dynamic shooting test. Similarly, significant correlations have previously been reported between physical performance measures (e.g., jump height and sprint speed) and points scored per game in youth basketball players [70]. Further support is found in the study by Fort-Vanmeerhaeghe et al. [69], who revealed a number of competition-based statistics to be significantly correlated to performance in physical fitness tests in elite level under 16 and under 18 female players. Of note, the average number of assists and steals and were found to significantly correlate with sprint speed (-0.653, $p < 0.01$), change of direction speed (-0.701, $p < 0.01$), repeated sprint ability (-0.476, $p < 0.01$), and the Abalakov jump (a form of countermovement jump with the use of arm swing) (-0.446, $p < 0.01$). Accordingly, the enhancement of such physical capabilities can be considered important within the long-term strategy of aspiring young players.

Further supporting the importance of physical capabilities in youth players, the study by Torres-Unda et al. [71] found that players aged 13-14 years selected for an “elite” team, displayed greater physical output levels than their peers who were not selected, including significant differences in sprint times ($p < 0.05$), CMJ height ($p < 0.05$), and endurance capabilities ($p < 0.05$). However, Torres-Unda et al. [71] also revealed a significantly larger maturity offset in the players selected for the elite group, who were taller, heavier, and more muscular than the non-elite players, indicating the influence of biological maturity on physical capabilities. Indeed, the discriminate nature of physical qualities has elsewhere been found to be sex and age group dependent [72]. In the comparative study by Joseph et al. [72], under 16 and under 18 males and females selected at a state trial to compete in a national championship were compared against their unselected peers across a range of performance-related measures. In comparisons of under 16 male players, no significant differences were observed in any of the variables, although there was a moderate effect size for chronologically older players being selected over younger players. In the under 18 players, similarly, there were no significantly different variables between selected and non-selected players. In contrast, however, in the female under 16 cohort, significant moderate differences were found for 20-m sprint times, suggesting speed to be a discriminatory physical quality for selection in that group. This was also found for the selected under 18 female cohort who, it was also revealed, had a significantly higher CMJ compared to their non-selected peers. To explain their results, Joseph et al. [72] suggested that the differences observed between males and females may relate to participation rates and the size of the pool of players from which selections were made.

Given the apparent importance of physical capabilities to basketball-specific performance, talent identification processes may well be susceptible to bias towards young players that are taller and heavier than their peers [73,74]. Indeed, in youth basketball, the bias of selection in favour of larger players has been identified in what has been termed the ‘relative age effect’ (RAE) [75]. The RAE refers to the potential physical advantages of early maturing players compared to their later maturing peers, relative to a critical age cut-off date [76]. The RAE phenomenon has been previously highlighted in youth soccer and basketball [75,77,78] where a greater proportion of players born in the first months of the year was identified in players participating in national competitions [75]. However, importantly, the RAE remains an area of contention, as is highlighted by the study of de la Rubia Riaza et al. [79] which highlighted the equivocal nature of the phenomenon when accounting for different variables, including sex, level of competition and playing position. For example, de la Rubia Riaza et al. [79] found that the RAE appeared to exert a greater impact on male players compared to females. However, this may well relate to the differences between males and females with respect to the size of the player pool from which selections are made [80]. Indeed, in the study by Kelly et al. [80], which looked at the RAE in English basketball, a significant difference ($p < 0.001$) was observed in the birth quarter selection distributions for males when compared with national norms for birth distributions. In contrast to the male cohorts, however, Kelly et al. [80] did not observe a significant difference in the older female (under-16, under-18, and under-20) cohort they studied, though the RAE was still evident. Although Kelly et al. [80] revealed a significant difference in the younger female cohorts (aged under-12 to under-15), therefore suggesting a decreasing influence of RAE as players progressed to the higher levels of performance and competition, it is plausible that the RAE occurring within younger age groups further reduces the pool from which players are subsequently selected from in the future. Accordingly, despite the existence of the RAE, it may appear to be less pronounced as players progress in age, especially in female cohorts where less players participate [79,80]. Most pertinently, despite evidence that appears to highlight the existence of discriminatory physical qualities for selection, it is likely that, as a result of growth and maturation, older players display greater physical capabilities [e.g., 81,88] than their younger counterparts.

2.2. Athletic development

Athletic development is a term that encompasses the physical development of youth populations in relation to health-, skill-, and performance-related fitness [13]. The implementation of athletic development strategies has existed since the era of the Eastern Bloc when the relative success of communist countries, such as the German Democratic Republic, is thought to somewhat relate systematic talent identification and development programmes [81,82]. However, in more recent decades, different models have been developed including the LTAD model by Balyi and colleagues [83], the Developmental Model of Sport Participation (DMSP) by Côté [84], the Athletic Skills Model (ASM) by Wormhoudt [31], and the Youth Physical Development (YPD) model produced by Lloyd and Oliver [33]. Although the DMSP may be more accurately considered as a talent development model [13], each of these models similarly aim to provide a systematic and structured approach to the development of children and adolescents playing and competing in sports [9,85]. However, whilst each of the models share similar characteristics, the LTAD model, which was originally created in 1995 by Balyi and Way [32] for the development of Canadian athletes to perform on the international stage, is perhaps the most widely recognised. The LTAD model presents a framework that aligns the development of physical fitness components to chronological age brackets and, to some degree, attempts account for biological age (or stage of maturation) and the associated physiological changes that occur in line with it [9,86,87]. Within the LTAD model, five age-related stages are identified, with specific aims and training foci [83]: FUNdamental (6-9 years of age), Learn to train (8-12 years of age), Train to train (11-16 years of age), Train to compete (15-23 years of age), Train to win (18+ years of age) [9]. Although not without criticism [e.g., 67,68,73] , since its inception, the LTAD model has been adopted by a number of sporting associations and, through its worldwide influence, is considered important in the advancement of training youth populations [13].

2.2.1 Early single-sport specialisation

The stages of the LTAD model relate to one of its core underlying principles which is to delay early specialisation in a single sport in favour of the opportunity to develop a broad array of motor skills and establish athletic competency [87]. *Sport specialisation* typically refers to an individual's year-round commitment to a single sport, which has been a growing trend in youth sports in recent decades [89]. Although the most obvious benefit of specialisation is the development and refinement of sports-specific motor skills, and cognitive processing strategies including pattern recognition and decision making, early single-sport specialisation does not necessarily lead to higher levels of performance in the future [90–92]. Of pertinence, in the study of youth basketball players by Arede et al. [16], players identified as being "more specialised" based upon responses to a questionnaire that included years of playing basketball and a retrospective account of training volumes, were found to be outperformed by their "less specialised" counterparts across a range of physical performance measures. Moreover, the differences were observed in both the under-13 male and under-13 female cohorts included [16]. However, the differences between less specialised and more specialised male groups were not found to be significant, whilst significant differences were observed in the squat jump (p = 0.05) and the countermovement jump (p = 0.03) in the female cohort [16]. Given the chronological age of the participants, however, Arede et al. [16] further analysed their results using a univariate analysis of covariance (ANCOVA) to test the effect of maturity offset as a covariate within the physical performance measures. The results of the ANCOVA revealed that in males, the less specialised group outperformed the more specialised group in power output measures across all jump types as well as sprint power [16]. Similarly, the less specialised females were found to have outperformed the more specialised females across the same power output measures, as well as in squat jump performance [16]. Therefore, in accordance with models of athletic development, although there may be short-term benefits to basketball specific performance, problematically, it appears that single-sport specialisation may come with a cost with regards to the wider development of youth players that includes their athletic capabilities.

Of further concern, early single-sport specialisation can lead to socio-psycho-physical impairment, such as over-dependence and burnout [82,93]. Moreover, early single sport specialisation has been associated with risk of overuse injuries [89,94,95]. This has been evidenced within the research literature [95–97]. For example, in a large study of adolescent female athletes, including basketball, soccer, and volleyball players, Hall et al. [95] found that single sport specialisation increased incidence of patellofemoral pain by one and a half times, and was associated with a four-fold greater risk for patellar tendinopathy when compared to multiple sport athletes. Similarly, in an epidemiological study of youth level basketball players (aged 11-18 years), Owoeye et al. [96] found that overuse knee injuries were highly prevalent across both males and females. In basketball, overuse injuries at the knee are commonly and colloquially referred to as "jumper's knee" though often this is indicative of what is clinically known as patellar tendinopathy [57], which represents inflammation of the tendon, thought to occur when there is repetitive overuse, the persistence of which can lead to a chronic condition [98]. The study by Owoeye et al. [99] revealed that across a season, a total of 98 players from a cohort of 515 male and female players reported at least one episode of patella tendon pain in a league season (9.5 weeks in duration). Although the precise conditions that contribute to patellar tendinopathy remain unclear, the association with repetitive loading through repeated jumping and cutting-based actions appear to be a major contributing factor [99]. Moreover, the onset of the condition is thought to relate to the underdevelopment and immaturity of musculoskeletal structures that are inadequately prepared for increased volumes of repeated load [100]. Accordingly, and in support of the emphasis on early diversification principle that characterises the DMSP, LTAD, ASM and YPD models, research [e.g., 13,75,81] has pointed to the implementation of diversified exposure to a wide array of movement patterns and skills to offset the burden placed upon the structures of the lower limbs [102]. Similarly, the programming of a diverse array of movements has been suggested to occur through management of external load volumes, participation in other physical activities that require different movement patterns, as well as the implementation of neuromuscular training exercises (NMT) [17,96,103], which again appears to support athletic development models' advocacy for the avoidance of early sport specialisation.

Some of the criticism of the original LTAD model related to volumes of training and the model's advocating of the 10,000-hour rule which, based on the work of Ericsson et al. [104], suggested the development of expertise in a given domain required 10,000 hours (or 10 years) of deliberate practice [13,104]. Although the 10,000-hour rule became highly popularised [105], it also received heavy criticism for its overly generalised perspectives on the development of expertise through time spent on deliberate practice, irrespective of natural abilities [106]. Moreover, the extrapolation of the 10,000-hour rule, which was based upon biographical reports of expert musicians (violinists and pianists), to the development of expert (or elite) performance in sports has also been questioned for its relevance and appropriateness to performance [13,107]. From this perspective, for the LTAD model to have aligned itself with the 10,000-hour concept appears to be somewhat at odds with the notion of early diversification and, instead, could be construed as contradictory to its stated aims by seemingly promoting extensive volumes of practice that may be considered analogous to those typical of sport-specialisation. However, notwithstanding questions over the validity of the notion of 10,000 hours or 10-years to develop expertise [e.g. 89,91] , the premise of the role of deliberate practice by Ericsson et al. [104] was that genetic capabilities alone would not determine expert levels of performance, which is a point that Ericsson made in a subsequent rebuttal to criticism of the original theoretical framework [109]. Therefore, in accordance with the purpose of the LTAD, the advocation of the 10,000-hour rule would appear to have represented somewhat of a guiding principle relating to the time required to develop athletic capabilities most effectively.

Whilst early single-sport specialisation is considered unfavourable within models of long-term athletic development, this perspective has been questioned for being overly simplistic [110]. Moreover, despite its prominence within discussions relating to the development of youth athletic populations, there is a lack of scientific research on the topic of single-sport specialisation [111]. Indeed, studies that support the practice of sports sampling over single-sport specialisation [e.g., 123,124] typically utilise retrospective perspectives of elite performers which, despite providing valuable insights, demonstrate only a limited understanding and is subject to bias. One of the main issues in relation to single-sport specialisation research is the lack of a consistent definition, a situation that is further confounded by the extent to which the definition encompasses both deliberate practice and competition, rather than observing the two as distinct entities [113]. However, a 2021 Delphi study by Bell et al. [114] aimed to develop a consensus definition that could be universally applied across research as well as in applied clinical and sports practices. The results of the Delphi study led to the consensus statement that sport specialisation is the *"intentional and focused participation in a single sport for a majority of the year that restricts the opportunities for engagement in other sports and activities"* [114]. Although the consensus statement appeared to encompass both deliberate practice and competition, it did not address specific details such as the intensity of practice, which has been previously questioned as a confounding variable within the single-sport specialisation research [113]. Accordingly, there is an important distinction between specialising in programmes that are highly-demanding on time and intensity, such as those within sports talent systems, and that where single sport-specialisation occurs under less demanding circumstances [115]. From a talent identification perspective, where it can be inferred that training and competition levels would be intensified compared with typical volumes and intensities experienced, how to better manage the development of the youth athletes and avoid the previously mentioned issues (e.g., injury, overtraining, and burnout) remains an ongoing area of debate [116].

Towards resolving the issue of single-sport specialisation, it is likely that potential solutions reside within the talent identification and development programmes of sports organisations and national governing bodies (NGBs) [116]. Accordingly, a more comprehensive long-term strategy may include the careful management of youth player workloads (volumes and intensities), and clear messaging for key stakeholders (i.e., players, coaches, and parents) regarding the value of exposure to diverse motor skills and physical activities for improved performance capabilities and the reduction in risk factors for injury [111,116]. Indeed, within basketball, the National Basketball Association (NBA) and USA Basketball have attempted to address the issue of early single-sport specialisation by developing specific guidelines for participation in the sport at youth level that included the recommendation that specialisation is avoided prior to the age of 14 years [17]. Furthermore, the guidelines encouraged engagement in diverse sports, as well as neuromuscular injury prevention programmes, which consist of a broad range of physical activities to reduce the risks associated with single-sport specialisation [117]. However, although based upon scientific research, the recommendations of best practice published by the NBA and USA Basketball were developed upon the opinions of an expert panel [17]. Therefore, no direct empirical studies have been undertaken to support the recommendations regarding the effects of the consensus recommendations on the development of youth basketball players. Moreover, there is no presentation of a clear strategy for how the recommendations should be implemented.

2.2.2 Growth and maturation considerations

Growth and maturation processes span the first two decades of life and, owing to the distinct general pattern of measurable changes in shape and structure of the developing body, have been described as the s-shaped pattern of post-natal growth [118,119]. While growth is predominantly concerned with quantitative increases in body size, maturation relates to progressive stages of biological development towards adulthood [120].

Although chronological age and biological age are related, due to individual variations in the timing of the adolescent growth spurt, in addition to other biological changes associated with growth and maturation [121], the two do not occur concurrently [121]. Therefore, the use of chronological age to guide the training strategy within athletic development models has been deemed to be inadequate compared to methods that determine maturation [13,33]. The typical methods used to measure maturation include skeletal age, via radiographic assessment of the hand-wrist skeleton (e.g., Greulich-Pyle), and assessment of secondary sex characteristics (e.g., Tanner Staging) [121–124]. However, non-invasive, and more practically accessible somatic assessments of maturation status, have been established through the utilisation of anthropometric measurements, which have now become common place within youth athletic practices [122,125]. Accordingly, the use of predictive equations, combining anthropometric measurements to provide an estimation of maturity offset [125], are based upon observed typical patterns of growth in specific populations [118].

Much of the understanding of the typical patterns of growth has been derived from the plotting of growth rates from individual height records to which mathematical modelling has been applied [121]. Most notably, the seminal work of Tanner, Whitehouse and Takaishi [126] utilised longitudinal data from the Harpenden Growth Study to determine standards for height and weight velocities from birth [127–129]. Similar studies conducted in various geographical locations [e.g., 144–146] have highlighted anthropometric differences and identified potential changes in growth patterns, both geographically and over time [131]. However, despite differences relating to geographical region, the pattern of growth identified by Tanner, Whitehouse and Takaishi [126] of children through to adolescence appears to remain relatively consistent [133]. Specifically, as an individual transitions from childhood to adolescence, the occurrence of the adolescent growth spurt, which is characterised by an accelerated increase in height and body mass, as well as other substantial biological changes, such as sexual dimorphism ensue [126,134,135]. Despite being highly individual, secular changes in stature (or height) across both males and females are deemed to follow a relatively uniform pattern [131]. This is characterised by a period of accelerating height velocity which, from the point of "take-off", continues to accelerate until peak velocity, termed peak height velocity (PHV), is reached [118]. As a result of PHV, changes in stature of ~8 cm/ year in girls and 10~ cm/ year in boys may be observed [121,122,134]. However, more substantial changes in stature from the point of take-off to PHV have been reported [136]. Moreover, based upon sex-specific mean observed ages at PHV ± 1.0 year for the total sampled population, individuals may be categorised as early, on-time, or late maturing [137]. Based upon these categorisations, differences in velocity curves have been observed [138,139]. For example, Carrascosa et al. [140] revealed the greatest changes in stature (34.6 ± 2.4 cm in females; and 34.6 ± 2.3 cm in males) to occur in the participant group the authors categorised as very early maturing individuals compared with the participant group defined as very late maturing (18.9 ± 2.1 cm in females; and 21.2 ± 1.3 cm in males) from the onset of the adolescent growth spurt through to full adult height females. The same considerations can also apply to the age at which PHV occurs though, typically, this occurs between the ages of 10-12 years in girls, and 12-14 years in boys [121,135]. However, demonstrating the complexity of the growth spurt, the longitudinal study by Chen et al. [141] found differences in final height in late adolescence to be affected by both intensity of the growth spurt and its duration. Accordingly, within their cohort, individuals that experienced a short duration PHV grew at a lower rate (e.g., 7.8 cm / year) compared to individuals with a long duration PHV (e.g., 8.9 cm / year). Nonetheless, in terms of the general pattern, following PHV, there is a deceleration period before cessation of growth that reflects the attainment of adult height, which typically occurs by the age of 15 years in females and 16 in males [122,142]. The duration of the rapid acceleration period of growth typically lasts one year, whilst the more gradual deceleration period can last up to 16 months [143]. Of pertinence, with respect to patterns of growth, the lower limb typically grow ahead of other body segments, which is similarly observed during the adolescent growth spurt where, a pronounced distal-to-proximal pattern occurs [144,145]. Indeed, during PHV, the growth of the lower limb is the first to peak followed by stature and the upper limb, with the length change of the trunk occurring last [144–146]. Accordingly, the ratio of sitting height to standing height can be utilised to determine patterns of growth [131,146]. Although dependent upon sex, geographical location, and high levels of individual variation, commonly, the ratio between sitting height and standing height has been found to display a pattern of change from 0.68 during infancy to 0.52 during adolescence [131], highlighting the changes in lower limb relative to the trunk during the adolescent growth spurt.

In addition to PHV, an accelerated period of change during the adolescent growth spurt is also reflected through increases in body mass. The age at which peak weight velocity (PWV) occurs has been found to correspond with the age at PHV (r = 0.93 in boys and 0.82 in girls), though the correlations between the magnitude of the peaks for PWV and PHV have been found to be low (r = 0.29 in boys and 0.18 in girls) [126]. In males, PWV occurs in accordance with PHV, with an increase on average of 9kg per year; whilst in females the average is 8.3 kg per year though, compared to males, there appears to be a greater lag between PWV and PHV of ~6 months [135]. Although lean muscle mass increases during the adolescent growth spurt across both sexes, this appears to be more pronounced in males compared to females, owing to the influence of male sex hormones [135,147]. Furthermore, in females, there is an increase in body mass at the late stages of puberty [126,147]. In contrast to PHV, which is largely genetically determined, due to the influence of environmental factors on body mass, the use of PWV is not deemed to be as appropriate for the detection of the onset of puberty and the adolescent growth spurt [122].

In accordance with patterns of development relating to growth and maturation, athletic development models have, to varying degrees, attempted to use a scientific evidence-based approach to align stages of maturation to particular training foci [13,86]. Indeed, contemporary perspectives on athletic development [13,31,32] recognise the requirement to account for differences in maturational status.

Typically, studies relating to athletic development have utilised estimations of chronological age at PHV (APHV) and, in turn, approximations for the timing of when the PHV in an individual will occur. Indeed, the use of APHV is considered to be the standard for non-invasive measures of maturational status [148] and, within athletic development-based studies, the most commonly utilised is the formula by Mirwald et al. [149]. Originally, data from children who were four years from PHV and three years past PHV, as determined within the longitudinal Saskatchewan Paediatric Bone Mineral Accrual Study (BMAS), Mirwald and colleagues developed predictive equations to estimate maturational status of boys and girls [149]. To verify their equation, samples from the Saskatchewan Growth and Development Study and the Leuven Longitudinal Twin Study were combined with the BMAS, providing a total of 200 boys and 161 girls (all of European ancestry) [137,149,150]. By using the maturity offset as the dependent variable in the study's multiple regression analysis, the use of stature, sitting height, body mass, and chronological age (equations 1 and 2) were found to predict timing of PHV or, as is termed '*maturity offset',* within an error of ± 1 year with 95% confidence intervals [149].

Girls: Maturity Offset (years) = -9.376 + (0.0001882 x (leg length x sitting height)) + (0.0022 x (age x leg length)) + (0.005841 x (age x sitting height)) – (0.002658 x (age x mass)) + (0.07693 x (mass by stature ratio x 100))

Equation 1.

Boys: Maturity offset (years) = -9.236 + (0.0002708 x (leg length x sitting height)) + (-0.001663 x (age x leg length)) + (0.007216 x (age x sitting height)) + (0.02292 x (mass by stature ratio x 100)).

Equation 2.

More specifically, the standard errors of the equations by Mirwald et al. are 0.569 year in girls and 0.592 in boys, therefore both have a standard error of approximately seven months [122,137,149]. In practice, a negative maturity offset value derived from the equation indicates a child who is pre-PHV, whilst a zero value would indicate a child who is experiencing their PHV, and a positive value would indicate an individual who is post-PHV [122]. Furthermore, owing to the standard error in the equation of Mirwald et al. [149], youth populations are considered to be pre-PHV with an estimated maturity offset of -3 to >-1 years from PHV and post-PHV with an estimated maturity offset of >1 to +3 years from PHV, while a range from -

1 to 1+ years from PHV is regarded as circa- or mid-PHV [151]. However, ± 0.5 years has also been utilised as a threshold to determine the maturity classifications [152], with some observational studies opting to exclude participants with a maturity offset of -1 to -0.5 years and +0.5 to +1 years from PHV [e.g., 123] and < -0.5 to > 0.5 years from PHV [154], depending on the aims of the study. However, the equation by Mirwald et al. [149] has been questioned for its level of accuracy, especially relating to its validity in predicting maturity offset across different populations according to race and ethnicity [130]. Nevertheless, since 2002 its number of citations are in the thousands and, likely owing to its practicality, the equation has been widely used to inform guidance related to the prescription of sports-related activities [130]. Moreover, attempts to modify and improve the equation by Mirwald et al. [149] have also displayed their own fallibilities [137,152,155]. Therefore, the utilisation of the equation by Mirwald et al. [149] still provides researchers and practitioners with a useful means to estimate maturity offset, provided that standardised collection procedures for the recording of anthropometric data are followed and, to account for limitations in its predictive capabilities, periodic reassessment is undertaken [150].

2.2.3 Adolescent awkwardness

Notwithstanding the need for caution that was previously discussed in relation to the utilisation of predictive equations for the calculation of maturity offset, an estimation for the timing of PHV is an important consideration for youth level athletic populations, where intensified training regimens and competition coincide with the aforementioned physical and biological changes [150]. In relation to this, increases in stature and mass during puberty have been implicated in the so-called *adolescent awkwardness* phenomenon [156]. Characterised by impaired motor coordination [9], this observed “clumsiness” may occur as a result of changes in limb lengths relative to the torso [157], as well as delays between changes to muscle length and cross-sectional areas [88], although temporary limb length discrepancies have also been implicated [158]. Further, it has also been purported that the phenomenon may be the result of an underdeveloped ability to estimate an internal model of body orientation [159]. Irrespective of the precise mechanism, any impaired coordinative ability of a young athlete in addition to high volumes of single-sports practice and competition, have been implicated in increased risk of sustaining injuries [88,157].

Despite the above, it is plausible that adolescent awkwardness is more prominent in relatively taller adolescents. Indeed, in the study by Wachholz et al. [159] that compared postural control between adolescents and adults during a tandem stance (one foot placed in front of the other, with the toes of the rear foot in contact with the heel of the lead foot) it was found that taller adolescents and adults displayed greater postural variance. This suggests that height may be the contributing factor to the phenomenon, which is pertinent to sports that favour stature as an important characteristic. For example, in basketball, where players' mean heights and body masses have been found to exceed the age specific 75th percentiles of US reference data [16], and has been identified as a defining feature of elite youth basketball players compared to non-elite level players [71]. However, in a study by John et al. [160], youth soccer players in different stages of maturation, were assessed in the Balance Error Scoring System assessment of static balance and it was revealed that the players with the lowest maturity offset scored lowest in the test (i.e. they displayed more errors in the assessment). Given that the participants determined to be at PHV were on average ~10 cm shorter than the participants determined as post-PHV by itself, stature may not necessarily the key contributor to adolescent awkwardness. Indeed, similar to the findings by John et al. [160], Read et al. [161] also observed reduced performance in youth soccer players considered to be at the start of their growth spurt (therefore circa-PHV), who performed the single leg hop for distance test. In their study, Read et al. [161]

revealed that the players at under-12 (average age 11.2 ± 0.6 years) and under-14 (average age 14 ± 0.5 years) years of age performed better in terms of hop distance than the under-13 (average age 12.87 ± 0.6 years) year group, a finding that the authors suggested was related to the adolescent awkwardness phenomenon. To support this conclusion, Read et al. [161] reported that larger percentage changes in leg length were observed between the under-12 and under-13 groups, indicating that the under-13s were commencing their growth spurt. However, within their results that compared the hopping distances based upon estimated maturational status, no significant differences were observed between the pre-PHV and circa-PHV groups, with only the post-PHV group being found to have performed significantly better than the other two groups [161]. Nonetheless, compared to the post-PHV players who had a mean stature of ~176 cm, the circa-PHV group were shorter by over 10 cm, therefore reinforcing the notion that, by itself, change in stature is not directly responsible for the adolescent awkwardness phenomenon. Therefore, although the underlying mechanisms remain uncertain, an acknowledgement of the potential negative impact of the adolescent growth spurt on performance is important within the athletic development of youth athletes, particularly from a movement competency perspective. Accordingly, the recommendation for youths experiencing adolescent awkwardness is to reduce training and competition loads, and to enable a period of motor re-learning of previously developed skills and movement patterns [162]. Such an approach is similarly suggested within the YPD model and the ASM, both of which recommend that during PHV, basic coordination-focused activities should be reintroduced to facilitate the young athlete's navigation of this period [31,33]. This strategy might be of particular importance within sports that favour the characteristic of stature, such as basketball. Indeed, given the previously discussed preferential selection of taller players (e.g., 73,144,145) youth players experiencing the adolescent awkwardness phenomenon and increased risk of injury. Therefore, in talent programs, those responsible for selecting youth players for representative squads should consider the maturation status of each individual. However, to date, such considerations do not appear to be widely utilised within basketball coaches' practice [13,146] . Therefore, future research should explore how to better increase awareness of player maturation status within the coaching practices of youth level basketball coaches.

2.2.4 Stages of maturation and "windows of opportunity"

Determining stage of maturation is considered to be important to inform practitioners and coaches about the readiness of an individual for the introduction of different training stimuli in accordance with developmental markers, such as concentrations of anabolic hormones and other factors relating to growth and maturation [166–168]. However, whilst there may be merit to aligning the stage of maturation to specific training stimuli, the original LTAD model has been criticised for its proposed *windows of opportunity* concept [9,85,169]. The notion of windows of opportunity implies the existence of periods of sensitivity to training stimuli [13]. In relation to an individual's stage of maturation, such periods represent times at which the effectiveness of such stimuli is apparently augmented owing to maturational changes [85,169]. As indicated within their updated 2013 edition of the LTAD, Balyi et al. [32] based the windows of opportunity concept to a large extent on the work of Scammon (1930), which charted the development of neural, and hormonal processes. Seemingly, it is from these developmental charts that Balyi et al. [83] determined the period of middle childhood to be a key timeframe during which emphasis should be placed on neuromuscular capabilities in the form of skills, balance, and coordination; and adolescence (spanning PHV) as the key period for the development of physical fitness qualities [169]. Whilst this appears to present a logical rationale, from a physiological perspective, the windows of opportunity concept has been criticised for its lack of supporting evidence from scientific research [9,121]. However, the

YPD model, which is considered to provide greater scientific rigour than LTAD model [166], similarly suggests that during middle childhood (between the approximate ages of 5-9 years of age in females and 5-11 years of age in males) there should be an emphasis on the development of FMS and force-related qualities, including strength, speed, and power [13,33,86]. Providing support for this, Moran and colleagues [170] found speed training to be more effective in youth pre-PHV than PHV. Moreover, in support for the notion of a period of sensitivity in relation to hormonal changes during adolescence, which is the purport of both the LTAD and YPD models, Moran et al. [168,171] identified greater adaptive responses to resistance training in more mature male and female youths. Indeed, the findings of Moran et al. [168,171] from the authors' meta-analyses were similarly observed in a separate systematic review by Slimani and colleagues [172], thus appearing to demonstrate the existence of periods of greater sensitivity to training stimuli dependent upon stage of maturation. Accordingly, in support of the recommendations of the LTAD and YPD models, the incorporation of maturation-aligned training activities may augment the naturally occurring changes within the growing bodies of children and adolescents, a concept that has been termed "synergistic adaptation", [87,173]. Importantly, however, these adaptive responses may relate to the maturity-related changes, upon which training stimuli is superimposed [168]. That is, positive adaptations that are apparent in response to the training stimuli are simply those that are naturally occurring due to maturation.

Despite the existence of some empirical support for the synergistic adaptation concept, problematically, somewhat lacking within the athletic development models is a lack of specific information relating to the physical fitness quality that this would most efficaciously benefit [85]. For example, regarding the training of sprint speed, the distinction between acceleration speed or maximal velocity speed, and whether this relates to bipedal locomotor or other forms of locomotion, such as swimming or cycling. In other words, the two models are overly simplistic in their purports and associated recommendations. Indeed, further confounding this is the training age or history of training exposure in youth athletic populations and the dose-response to training [9]. Using the example of sprint speed once again, the methods by which to train this physical quality are not explicitly stated nor are they differentiated by previous training experience. For example, heavy resisted sprinting has been found to improve sprint times in adolescent soccer players with a S&C training experience of at least six months using loads based upon a back squat one repetition maximum [174]. However, without the stimulus of heavy resistance, such improvements may not have been attained which, therefore, would have appeared to have refuted the concept of synergistic adaptation. Conversely, in the absence of a young athlete having any prior training experience, training stimuli may lead to transferable training adaptations not necessarily targeted by the training exercises. For example, following a period of training, improvements in back and front squat strength capabilities were found to have a positive effect on 30-m sprint times in youth soccer players in the study by Sander et al. [175]. These results suggest that, at a younger training age, there is a positive transfer of training of one physical quality to other qualities, which is perhaps less related to synergistic adaptation than it is to the extent of an individual's prior training experience. Indeed, emphasising this further, four weeks of dynamic balance training in adolescent basketball players, has been found to significantly improve change of direction speed [176]. Therefore, the concept of periods of sensitivity for the development of physical qualities should be considered with respect to the specifics of the task or activity as well as the training history of the young individual [85]. In light of this, a more appropriate framing for periods of sensitivity might be considered as a young athlete's current and highly individual potential for adaptative response to a given training stimulus [177]. However, issues of semantics aside, clearly there is obvious complexity in determining the most efficacious and appropriate long-term training strategy for stages of maturation due to the challenges involved in undertaking prospective and longitudinal empirical studies [166]. Thus, while the YPD model is understood to be more robustly underpinned by scientific research compared with the LTAD model [86], the same limitations exist across both though the YPD model has likely benefitted from hindsight and research informed pragmatism [178].

Irrespective of any counterarguments to the scepticism relating to the windows of opportunity concept, perhaps the greatest criticism of the LTAD model [e.g., 9,68,96,135] has derived from the position of Bayli et al. [32] which appears to hold that if these opportunities are "missed", there are implications for the long-term prospects of the youth athlete [121]. Indeed, within the original iteration of the LTAD model, the authors state that athletes who miss the [Training to Train] stage will "never meet their full potential, regardless of [any] remedial program" thereafter [32]. There is, however, little evidence to support this contention and, concerningly, this perspective has been suggested to be potentially harmful to the long-term development of young athletes through demotivation to focus on training for which the window of opportunity has been "missed" [9,119,166]. Perhaps out of recognition of this error, in the updated 2013 version of the LTAD model, Balyi et al. [32] suggest that training subsequent to the window of opportunity remains beneficial though to a lesser extent than it might have been. However, again using their windows analogy, Balyi et al. [32] state that adaptations outside of the "fully open" window, would not be as effective nor efficient, therefore appearing to reaffirm their original contention. As has already been highlighted, however, there appears to be little evidence to support such a claim and children and adolescents are able to make substantial improvements across all physical fitness qualities throughout the childhood and adolescence [9,13]. Indeed, further evidence in opposition to the LTAD model's window of opportunity is found in the meta-analysis by Collins et al. [179]. The results of the meta-analysis revealed that resistance training in youth (aged 8-17 years) appeared to exert a positive effect on FMS [7,179,180]. The meta-analysis included intervention studies that had examined the effects of resistance training on different measures relating to jumping, sprinting, and throwing, all of which were considered by the authors to represent FMS. The results of the meta-analysis revealed significant intervention effects for each of the outcomes (standing long jump, vertical jump, squat jump, sprint, and throw) in favour of the intervention groups. To explain their findings, Collins et al. [179] stated that the neural alterations brought about in response to resistance training, including motor unit recruitment and coordination, may lead to changes in motor competency and, in turn, the development of FMS. However, within their moderator analysis, Collins et al. [179] found there was a larger effect of resistance training in individuals involved in organised sport than those that were not identified as participating in organised sport for the squat jump (Hedges' *g*: 0.949 versus 0.251) and the standing long jump (Hedges' *g*: 1.658 versus 0.227). These moderator findings may indicate that some level of proficiency in jumping-based activities already existed in the youth identified as participating in organised sport that enabled them to enhance these capabilities in response to resistance training to a greater extent than those not engaged in organised sports. However, in the context of the suggestion by Balyi et al. [32] that any "missed opportunities" to develop would have implications for the long-term prospects of the youth athlete, to the contrary, the findings of Collins et al. [179] appear to add to the aforementioned research that demonstrates that, in youth athletes, there remains the continued potential for adaptation and development of the full spectrum of skills and physical capabilities, albeit the sensitivity of these to change may vary based on an individual's stage of maturation.

Not necessarily discussed within youth athletic development-based research literature is whether, from a sports-specific perspective, early development of neuromuscular capabilities, including speed, agility, and coordination, may contribute to more enhanced performance capabilities within sports. Accordingly, future research should consider how the development of motor competency and physical capabilities form a basis for more effective acquisition of SSS and the enhancement of sports-specific performance.

2.2.4 Pre-Adolescence: a golden period for motor development?

In accordance with the LTAD model's contentions regarding "critical periods" and the "trainability" of physical fitness qualities, there may be credence to the importance the model places upon the development of FMS during preadolescence [9,181]. Indeed, owing to the high levels of neuroplasticity in brain during preadolescence, this period of development has been suggested to be the ideal window to develop long-lasting competence in FMS [181]. Accordingly, this period of time has been referred to as a *golden period* for motor skill learning [182]. As the LTAD model claims, the golden period for motor skill learning is considered to be crucial for participation in sports and physical activities across the lifespan [183,184]. However, to determine the merit of such claims, it is important to consider general patterns of motor development throughout childhood, which are characterised by phases of continuity and discontinuity [30]. Motor development is defined as the process by which a child acquires movement patterns and motor skills [185]. However, while substantive motor development occurs across childhood and adolescence, it should be regarded as a process that occurs across the life course [186,187], and can therefore be more accurately understood as the changes in motor behaviour through the lifespan [188]. Nonetheless, it is before adulthood that motor development occurs with the steepest trajectories of improvement in these skills [181,185]. Accordingly, developmental milestones from birth and through childhood and adolescence including developmental subcategories relating to growth and associated changes to strength, biomechanical properties, and cognitive capabilities, are important considerations towards the understanding of motor development and motor learning. This includes the acquisition of movement patterns and learning of complex motor skills [18,188].

2.2.4.1 Nervous system development

From birth, new-born infants display a number of reflexes, such as the grasp reflex and Moro and startle reflexes [185]. Primitive reflexes, or what are also referred to as “motor primitives”, represent neural synergies that activate specific muscle groups during the performance of motor tasks [171,172]. From this perspective, basic movements are thought to be largely composed of a small number of motor primitives that typically disappear at around three months of age and, in most cases, by the stage of infancy [185,189,190]. Another such reflex is the "stepping reflex", displayed when parents hold their baby in a standing position, causing them to make walking-like movements with their legs when their feet touch a surface [191]. The stepping reflex is believed to be a primitive reflex that supports the development of walking [192,193]. Similarly, the spontaneous kicking reflex, displayed as 'air-stepping' and supine kicking, is also a characteristic movement of newborn infants. Unlike the stepping reflex, which typically disappears after a few months, the kicking reflex appears to persist. [192,193]. Although, the stepping reflex and spontaneous kicking are considered to be related, the disappearance of one and persistence of the other have given rise to debate over their independence [192,193]. However, work in this area by Thelen and colleagues [e.g., 198,200,201] appears to suggest that the disappearance of the stepping reflex may be explained by greater body mass through increased body fat levels ahead of the subsequent development of muscular strength. Elsewhere, however, it is suggested that cortical maturation inhibits the stepping reflex and increased myelination of the cortical-spinal tract enables the return of stepping under volitional control [191]. Irrespective of such debate, from a motor development perspective, these reflexes are understood to represent neural networks that form the basis for locomotor-related movements which are naturally occurring and altered by the gradually maturing central nervous system [185,193].

As a child develops from newborn to later infancy, reflexive movements are thought to be replaced by what are termed rudimentary movements, which are considered to be the first forms of voluntary movement [196]. Accordingly, the lower brain centres' control over movement is gradually replaced by the motor area of the cerebral cortex [196]. Accordingly, unlike with primitive reflexes, intentionality, as demonstrated through goal-directed motor coordination, is an emergent characteristic of rudimentary movement in infancy [197]. However, walking independently, which is a key milestone in an infant's development, is not possible until sufficient strength, anti-gravity reflexes, and balance have been developed and the nervous system is able to effectively control muscular coordination [198]. Until walking is achieved, infants will typically progress through milestones, including rolling to supine and to prone, crawling, sitting up, standing with support, walking with support, and walking alone [185]. This process takes infants, on average, 12 months to complete though it can range from 8 to 18 months [191]. Importantly, throughout this period the infant child develops greater neuromuscular control, and the rudimentary skills create new possibilities for movement exploration, leading to an increased motor repertoire [188]. Moreover, from the onset of upright posture, through movement exploration, the infant learns to manipulate objects, anticipate inertial forces, and control the body's momentum with greater precision [197] (Figure 2).

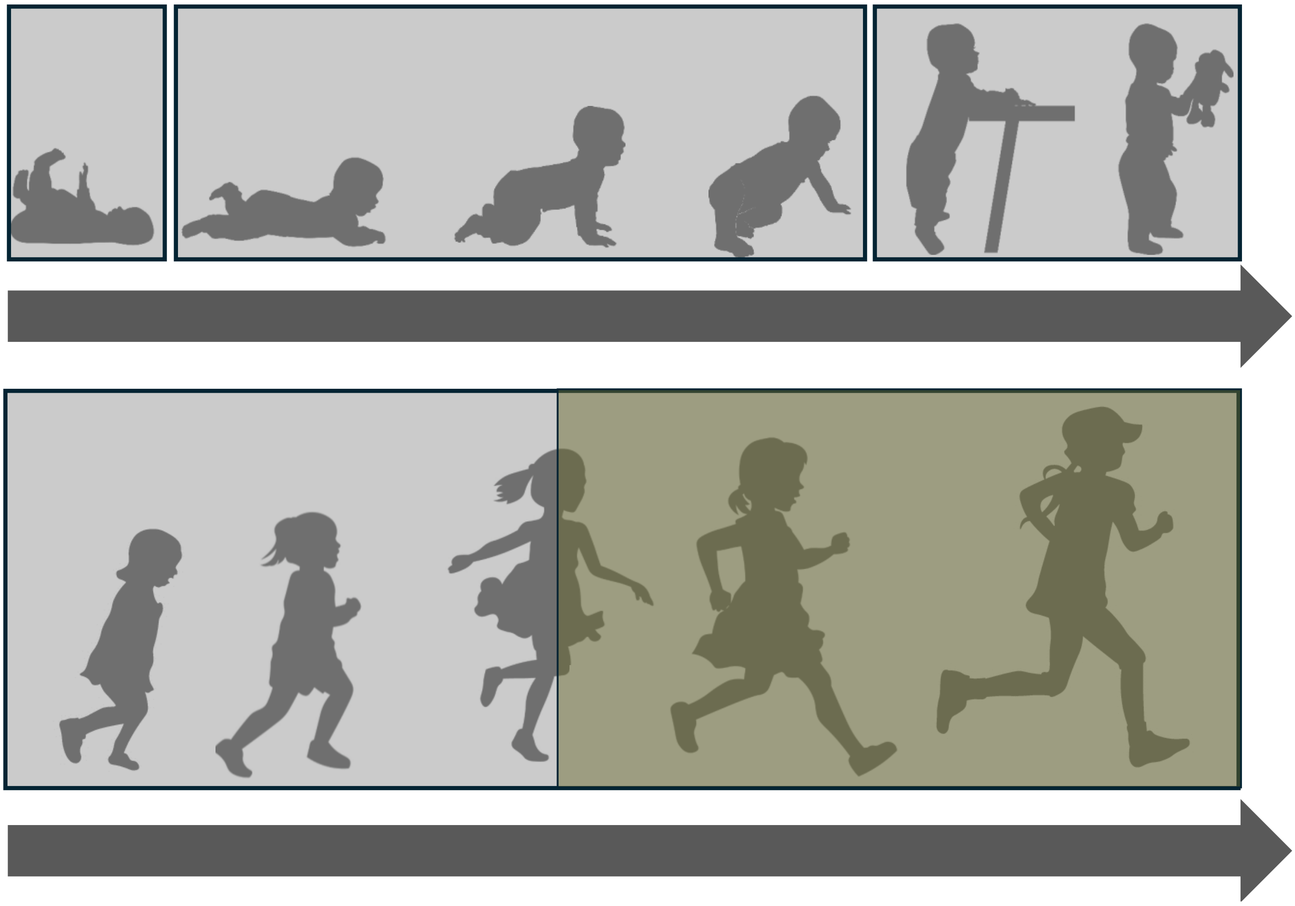

Figure 2. From reflexes to the golden period of motor learning Top row, from left to right in the top row: the primitive reflexes displayed in the newborn infant are gradually replaced with rudimentary movements, which are characterised by intentionality, enabling infant to explore. Once the infant possesses enough muscular strength standing and walking become possible, and the development of fundamental movement phase ensues. row from left to right: Through exploration, the infant leans to refine their movements and display greater control and precision. Middle childhood, the period between the ages of ~8-12 years, is considered as critical for the development of FMS.

Throughout infancy and into middle childhood, the rudimentary movement phase is understood to be replaced by the fundamental movement phase [196]. As has already been described, FMS are regarded as the building blocks for more complex movement skills [7]. Extending upon this definition, in the classic text "Fundamental Motor Patterns" by Wickstrom [198] an account of the attainment and progression of movement patterns in accordance with the motor development of a child is presented. Within the text, it is stated that "fundamental skills" are underpinned by fundamental motor patterns [198]. From this perspective, Wickstrom [198] defined a movement pattern as a series of movements that are organised in a particular time-space sequence, whilst a fundamental motor pattern represented a general pattern of movements, the composite of which contribute to the performance of a fundamental skill. Subsequent to the work of Wickstrom, however, to account more broadly for the outcome and goal-directed properties, as well as the functional need beyond the movement itself, the term fundamental motor skills has been preferentially utilised over FMS [30]. Nonetheless, despite discrepancies in the terminologies, learned motor skill is evident throughout early and middle childhood, and alongside the growing and maturing body. Moreover, and of greater pertinence, across these periods, exploration and practice of movement leads to continuous refinements of motor skills [30,198,199].

Given the apparent importance of motor development in the early stages of life, it would appear that early childhood represents a crucial time to develop motor skills [200]. Indeed, once independent locomotion is possible, it is as a result of exploration and experimentation with movement that progress in motor skill development is achieved [185]. However, although there appears to be a lack of consensus relating to the age at which the so-called golden period occurs, often it is considered to occur later into childhood, typically between the ages of eight and twelve years [181,182]. The rationale for the preadolescent period being regarded as being "critical" for motor development relates to brain plasticity and changes that are understood to occur in response to the maturation process around the pubescent growth spurt [181]. Brain plasticity, which refers to the brain's ability to structurally and functionally change and reorganise in response to behavioural demand [201], is thought to reduce as the maturing individual progresses into adulthood [202]. Such reduction in plasticity may relate to reductions in grey matter volume which starts to decrease around the onset of puberty [203,204]. With specific regard to motor skills, grey matter within the caudate nucleus of the basal ganglia, which is a brain region long understood to play in role in the control of movement, follows an inverted U-shaped trajectory and peaks in girls at around 7.5-years of age in girls, and 10-years of age in boys [12].

2.2.4.2 Synaptic pruning

Further to the changes to grey matter during adolescence, another feature of the developing brain through this period is that of "synaptic pruning" [181]. Synaptic pruning refers to the culling of underutilised neural pathways and is widely thought to account for the decline in grey matter volume [205]. Moreover, the pruning process describes an extensive remodelling of large subsets of axons, dendrites and synapses to form highly precise and mature neural circuits [206]. The process of synaptic pruning is understood to lead to greater efficiency within the brain region by reducing the neural activity necessary for performance of a given task [207]. In humans, this process is understood to occur in two main periods: the first two years from birth, and secondly, during adolescence [208]. Accordingly, it is estimated that up to 50% of the neurons in the child's brain do not survive through to adulthood [181,209]. While underutilised synapses are eliminated, through myelination of motor neurons, other synapses and related neural networks are strengthened, as per the Hebbian theory of plasticity which states that "neurons that fire together wire together" [210]. As a result of myelin formation around the axon of the motor neuron, the brain is able to process information faster and more efficiently due to faster conduction velocity of action potentials [211]. Given that motor learning occurs when a skill or set of skills is repeatedly practiced, in response, the associated neural pathways are thought to be preserved and reinforced thus contributing to greater retention through adolescence [181,212]. Therefore, despite early childhood being a crucial period of motor development, it may be that to optimise motor learning, the preadolescent period of development is indeed the most important in terms of the cultivation of motor skills.

Such perspectives, in turn, appear to support the golden period of motor learning and, indeed, the notion of a critical period within the LTAD model.

Although a golden period for motor learning appears to be underpinned by the scientifically sound account of brain plasticity, there is little direct evidence for the occurrence of synaptic pruning with respect to motor learning [213]. Instead, the pruning process has been implicated for the changes in behaviour relating to reward, thrill-seeking, and risk [205,209]. Therefore, despite the underpinning logic attributing the golden period for motor learning to the brain plasticity, empirical scientific research to support claims relating to the criticality of preadolescence for motor learning is limited and thus, currently, it remains largely theoretical. Indeed, typically, evidence for the golden period is based upon studies that demonstrate only that physical activity levels are associated with motor competence [e.g., 163–165]. For example, the systematic review by Logan et al. [215] found positive relationships between motor competence and physical activity and inferred that this influenced physical activity levels into adolescence. However, this should not be construed as evidence for a golden period for motor learning. Similarly, the importance of motor competence was also highlighted in the study by den Uil et al. [216], which investigated relationships between perceived motor skill competence, actual motor skill performance, and physical activity levels, across different age groups. The den Uil et al. [216] study revealed an association between physical fitness and motor competence and physical activity that was apparent throughout the different age groups. Again, as with the Logan et al. [215] study, whilst the results demonstrate that motor competence may well be important to continued physical activity in adolescence, it does not provide direct evidence for the golden period for motor learning. Accordingly, currently, there appears little evidence relating to neural processes in response to motor learning and instead point to habitual factors developed through early exposure and engagement with physical activity.

Perhaps more compelling than the findings of Logan et al. [215] and den Uil et al. [216] towards demonstrating a golden period for motor learning, is the study by Drenowatz and Greier [183]. In this study, the authors undertook annual assessments in school children (aged ~10 years) across a four period and compared motor competence, assessed through the Deutche Motorik Test (DMT) 6-18 assessment protocol (consisting of a power, speed, coordination, and agility measures) with sports participation and media consumption time (encompassing television viewing and use of a computer). The results of Drenowatz and Greier [183] revealed a positive relationship between club sports participation and higher levels motor competence, while an inverse relationship was observed between media time and motor competence. Moreover, in support of a golden period of motor learning, high volumes of media time appeared to impair motor development in subsequent years, thus indicating the importance of engagement in physical activities to develop motor skills in childhood [183]. Further, although it was observed that higher motor competence was associated with participation in club sports, at the age of 10 years, sports participation appeared to have only a limited effect on further development of motor competence in the subsequent four years of the study. Therefore, as was suggested by Drenowatz and Greier [183], it is possible that as the individual enters adolescence, participation in sports alone is no longer sufficient to develop motor competence, which may be indicative of a changes nervous system plasticity. However, currently, such a perspective remains limited to conjecture, though, this would indeed appear to align to ideas from the LTAD and YPD models, as well as the ASM, all of which suggest that the participation in sport alone may be of limited value to longer-term development [31,33,83].

Although the study of Drenowatz and Greier [183] appears to provide longitudinal evidence to support the importance of developing motor skill competency in middle childhood, a key limitation to the study's wider implications was that it did not evaluate the biological maturity status of its participants. Therefore, it remains uncertain whether differences may have existed based upon biological age as opposed to chronological age, which was used in the study. Given that their study included male and female cohorts, as has already been discussed, it is entirely plausible that some of the children may have been experiencing their pubescent growth spurt across the four-year period. Furthermore, the study would have certainly included individuals who would have displayed growth and maturation-related changes. To this point, however, although sex was not distinguished in the main analysis (using a multivariate analysis of variance), subsequent logistic regression was used to examine associations between age and sex. The regression analyses revealed no differences in overweight/obesity rates and media consumption compared to boys. However, boys were found to have performed significantly better that their female counterparts across physical fitness measures, which may have reflected the significantly greater levels of sports participation in boys compared to girls (51% vs. 31%, $p < 0.01$). Despite these findings, no differences in motor competence were found between boys and girls when compared to age- and sex-specific reference values, except for in the standing long jump, which was found to be greater in boys compared to girls. Nonetheless, owing to the increasing divergence that occurs between males and females in response to puberty [122], the inclusion of maturity offset and separate evaluations of male and female cohorts would have provided more valuable insights and is a recommended practice for all researchers in this domain in the future. Notwithstanding this limitation, the results of Drenowatz and Greier [183] present somewhat stronger evidence than other correlational studies for the importance of motor skill development during middle childhood and ahead of adolescence which, in turn, appear to support the golden period of motor learning occurring in during the preadolescent years.

Beyond correlational studies, evidence in support of the preadolescent golden period of motor learning is found in the meta-analysis by Behringer et al [11] that examined the effects of strength training on motor performance skills in children and adolescents. The meta-analysis, which included 34 studies (51 combined effect sizes (ES), revealed a combined mean ES of 0.52 for the jumping, running, and throwing motor skill types included, therefore demonstrating the effectiveness of resistance training on performance in these skills. However, in the subgroup analyses, which included comparisons by age as well as according to motor skill type, a significant negative correlation coefficient was revealed for age of participants ($r = -0.25$, $p < 0.05$), suggesting that the effects of resistance training were greatest in children compared to adolescents. Although the estimated mean age of all analysed participants was 13.2 years (± 3.12), from the included studies, 476 participants were subcategorised by maturational status based upon the Tanner stages. Accordingly, subgroups were identified: pre- to early pubertal stages (Tanner stage 1-2), and intra- to post pubertal stages (Tanner stage 3-5). However, many participants in the study had not been classified within the respective intervention studies the meta-analysis included. Therefore, the maturation-based subgroups were not used as the moderator in the analysis and, instead, age in years was used as the moderator variable. As has previously been discussed, against the backdrop of complexity in relation to maturation and the milieu of physical and biological changes experienced at an individual level, the use of chronological age is an obvious limitation of the Behringer et al [11] findings, which reflected the limitations of the studies that were included in the meta-analysis. Despite acknowledgment of this limitation, to explain their age-related findings, the authors suggested that changes to underlying neural mechanisms may have accounted for the differences observed [11]. From this perspective, as has already been discussed, ahead of adolescence neural mechanisms including motor unit coordination, firing rates and recruitment, are considered to be the primary adaptations in response to strength training stimuli [217,218]. Accordingly, the findings of Behringer et al. [11] that observed larger ES in children compared to adolescents appear to align with the previous discussed ideas relating to neural plasticity in preadolescent youth. Further, a separate subgroup analysis within the Behringer et al [11] study, which compared athletic versus non-athletic populations revealed similar differences in effects in response to resistance training as those observed between children and adolescent participants. To explain this, the authors also pointed to neural mechanisms and suggested that in the same way that the child participants were more responsive to the training interventions than adolescents, the non-athletic participants may also have been able to enhance performance in the motor skills more readily than their athletic counterparts. From this perspective, Behringer et al [11] stated that perhaps a ceiling effect to motor learning may have been responsible for the observed differences, suggesting that greater learning effects were possible due to a lack of what it termed “coordinative experience”. Extending upon this, Behringer et al [11] also suggested that for the older and more experienced (athletic) participants within their meta-analysis, the stimulus (e.g., intensity and volume) provided by the interventions may not have been substantial enough to elicit adaptations. Again, this would appear to support the notion that preadolescent children have a greater propensity to develop motor skills than adolescents, which reflects both a low stimulatory threshold for training adaptation in preadolescence, combined with the absence of biological and physical change that add further complexity to athletic development training of adolescent youth. Adding to this perspective, in relation to the separate analyses of each motor skill, ES were found to be largest for throwing-based outcome measures (ES: 0.99, 95% confidence intervals (CI): 0.19-1.79) compared to jumping (ES: 0.54, 95% CI: 0.34-0.74) and running (ES: 0.53, 95% CI: 0.23-0.83) related measures. Although limited to speculation, it may be that the finding was indicative of lower skill in throwing compared to running and jumping, which may be more commonly utilised than throwing in children and adolescents, irrespective of whether they from an athletic or non-athletic population. Indeed, Lester et al. [219], who investigated movement skills across age groups in Irish youth, revealed poor throwing efficiency against criterion-based Test of Gross Motor Development (TGMD-2) across the three age groups it observed (school year groups 1-3, age range 12.31-16.41 years). However, similarly poor levels of proficiency were also observed by Lester et al. [219] in both horizontal and vertical jumping assessments though, of note, the vertical jump was assessed using the Victoria Fundamental Motor Skills manual (in contrast to the TGMD-2). Nonetheless, across each cohort, running skill was found to display the highest percentages of skill proficiency (year 1: 74.7%, year 2: 79.1%, year 3: 82.8%). Therefore, within the study by Behringer et al. [11], it is entirely plausible that the notion of the ceiling effect may have been more pronounced in the jumping and sprinting motor skills due the them being utilised on more regular a basis. However, Behringer et al. [11] expressed caution regarding the finding relating to throwing performance, having suggested that this may have related to the relatively low number of included studies (n = 8) that assessed the effects of resistance training on throwing performance.

An important consideration related to the study by Behringer et al. [11] is the apparent contrasting findings those of the previously discussed meta-analysis by Collins et al. [179], which did not observe moderator effects of age in response to resistance training on any of the FMS included as outcome variables. However, despite significant intervention effects being identified for all outcomes in the Collins et al. [179] study, separate effects for each outcome were found to be smaller than those observed by Behringer et al. [11]. For example, in the throwing skill, the Hedges g ES was revealed to be 0.405 in the Collins et al. [179] study, compared with 0.99 in the Behringer et al. [11] study. Of further pertinence, as was the case in the Behringer et al. [11] study, Collin's et al. [179] used chronological age as the moderator variable, rather than maturation status. This would have provided a more critical evaluation of the effects of resistance training on motor skills. In contrast to the Behringer et al. [11] study, which included participants with an average age of ~13 years in the meta-analysis, Collins et al. [179] included what appeared to be a broader age range of 8-17 years. However, the Collins et al. [179] study did not provide a mean age for the participants included within their meta-analysis to make a more direct comparison with Behringer et al. [11]. Therefore, it is possible that the differences between the two studies are based upon differences in the age ranges of the cohorts that were included. Again, this highlights the need for youth-based research studies to utilise maturational status in addition to chronological age. Further, where the calculation of maturation status in not possible, research studies could utilise other variables (e.g., height and body mass) which, in addition to chronological age, would provide further indication of the maturity statuses of the participants. Further still, by observing the effects of strength training on motor skills, it could be argued that both the studies by Behringer et al. [11] and Collins et al. [179] provide evidence of training transfer of strength training, rather than the effects of motor learning per se. Therefore, while it may be that the effects of strength training may elicit positive results on different motor skills that can be considered as fundamental, the intervention studies included in the two meta-analyses do little to indicate how motor learning may vary based upon age and, indeed, across the different stages of maturation.

In contrast to the notion of preadolescence representing the golden period of motor learning, an experimental motor learning study by Solum et al [182] found no differences in the rate of learning between 10-year-olds, 18-year-olds, and 40-year-olds in a dart throwing task. Using their non-dominant hand, participants were required to throw darts at a dartboard that was scaled to their individual height. Participants completed a total of 200 throws distributed equally across two days. Solum et al [182] found no significant differences during the pre-test trials and all groups were found to significantly improve their scores from pre-test to post-test. Moreover, the absolute change in performance was not revealed to be significantly different although both older groups were significantly better in their pre-post-test performance than the 10-year-old group. In response to their findings, the authors questioned the existence of a golden period for motor learning during the years preceding adolescence and suggested that baseline levels of competence may be a confounding variable within related research [182], which would again indicate a ceiling effect. However, as was put forward in the discussion of their results, Solum et al [182] noted that, anecdotally, the 10-year old participants appeared to lose concentration in the throwing task earlier than the two older groups' participants, perhaps caused by a lack of augmented feedback which was a condition amongst each cohort. Indeed, participants were only afforded visual feedback provided by the outcome of their previous throw, which Solum et al [182] suggested may have been more challenging to the children compared to the older participants. Moreover, as was perhaps highlighted by the more variable performance across throwing trials, the child group was reported to alter its throwing strategy far more readily following a throw that missed the target compared to their older counterparts, thus highlighting differences in cognitive processing that may, at least in part, explain the findings of Solum et al [182]. Indeed, elsewhere, Schärli et al. [220] highlighted that postural control varies according to visual gaze. In their study, Schärli et al. [220] that compared balancing on a slackline between 8-year old children and adults, the children were found to move their gaze significantly more than the adults ($p = 0.016$). In addition, the head-in-space rotation of the children was also significantly greater than that shown by the adult cohort ($p < 0.001$). Of pertinence, in their post-testing measures that occurred following two practice sessions, the child participants were found to be less effective compared to adults at balancing on the slackline [220]. Therefore, the results of Schärli et al. [220] may be further indicative of concentration and cognitive capabilities having influenced the results of the study by Solum et al [182].

In contrast to the contentions typical of athletic development models [13,32,33,83], whether the preadolescent period is any more sensitive than other stages in terms of the development of motor skills remains uncertain. Despite claims that the LTAD model is grounded in scientific research (as is asserted by Balyi et al [32] in the updated version of the model), the notion that 'missing out' the critical period of development will be detrimental to a child's long-term development and sporting achievements does not yet appear to be supported by empirical studies. Currently, the evidence for a golden period for motor learning appears to be limited to the studies that have observed positive associations between motor competence and engagement in physical activity. However, evidence relating to the plasticity of the central nervous system and the learning and development of FMS is scarce.

2.3 Fundamental movement skills

2.3.1 What constitutes a fundamental movement skill?

The performance of a skill classically refers to the execution of an action to achieve a specific outcome [221]. Moreover, to distinguish between a skill and an ability: a skill is said to depend on practice or experience for its execution, while an ability is a genetically derived trait or characteristic that remains unmodifiable through practice. [186]. However, the use of the nervous system is itself an ability and, therefore, performance of a motor skill is based upon this ability. Accordingly, a motor skill, may be defined as the ability of the nervous system to control movement to achieve a goal [200,221]. With regard to defining FMS, it is important to acknowledge that the abbreviation of *movement* is often utilised interchangeably with *motor* [7]. Indeed, in a systematic review by Logan et al [180], the term *movement* was used more frequently than the term *motor* within the scientific research literature, indicating what the authors' suggested was a purposeful shift by researchers towards the more general term "movement".

As has already been described, FMS are typically defined as the "building blocks" for the development of more advanced skills, including those commonly required in sports and games [180]. Therefore, the skills that FMS include are object manipulation (e.g., ball control, such as throwing and catching), locomotor (e.g., walking, running, jumping, crawling), and balance-related skills such as tumbling, evading, reaching, and maintaining a stance or posture [18,180]. Elsewhere, the list of FMS has been more comprehensively extended to include bouncing and dribbling of a ball, swimming, cycling and skills related to resistance training, all of which require their own unique patterns of coordinative execution [18]. However, arguably, these are all applications of the existing FMS classifications which merely serve to represent different forms of locomotion, object manipulation and balance that may exist across different cultures [7].

Historically, within definitions of the components of physical fitness, the subcategories of skills that have come to be determined as *fundamental* were recognised as "skill-related fitness" components, which encompassed capabilities of the nervous system such as coordination, reaction time, and balance [222,223]. However, the concept of FMS has been in existence for many decades after first being proposed within the motor learning literature by the previously discussed work of Wickstrom [198]. In accordance with the previously mentioned definitions, Wickstrom [198], defined a fundamental skill as an activity with a general goal, whilst a fundamental motor pattern referred to the general pattern of movements that were used in the performance of a fundamental skill [180]. Pragmatically, however, in accordance with contemporary research relating to FMS [7,180], Wickstrom [198] accepted the tendency towards the interchangeable use of terms.

Within the book, *Fundamental Motor Patterns* , by Wickstrom [198], a detailed account of the development of movement patterns in early childhood through to full maturity is presented, with an emphasis placed on the attainment and progression of ever more refined patterns of execution across time [30]. The skills that Wickstrom accounted for were walking and running, jumping, throwing and catching, and striking and kicking [198], thus there is an obvious link between the ideas of Wickstrom and current thinking of what constitutes a FMS [180,224]. Accordingly, the ideas of Wickstrom [198] can be regarded as pivotal towards contemporary perspectives of FMS, including the research in which the work is often cited [e.g., 176,204,205] and, in turn, within youth athletic development models. Certainly, within the LTAD model, the FUNdamentals stage, which includes walking, running, throwing, catching, kicking and striking, is indicative of the influence of Wickstrom [198], as indeed are YPD model and ASM, both of which similarly imply the necessary development of technical competency ahead of the development of more complex skills [31–33]. Thus, there is a long-established perspective that the development of FMS are antecedents to the development of skills executed in different contexts, such as within sports performance [199].

2.3.2 The proficiency barrier to advanced skill development

Where the development of FMS is considered imperative to the learning of more complex skills [7], conversely, the underdevelopment of FMS is thought to contribute to what has been termed a "*proficiency barrier"* that limits the learning of more complex skills [226]. The proficiency barrier, which was first proposed by Seefeldt (1980), refers to a hypothesis that describes a critical level of competence in FMS required for the development of context-specific skills [228]. Similar to the work of Wickstrom [198] which observed changes in movement patterns in accordance with developmental periods, Seefeldt, highlighted the progression of motor skill development alongside the key stages of child development [229]. However, within Seefeldt's conceptual model, it was postulated that children who did not reach a minimum level of FMS proficiency would fail to acquire more advanced skills [226]. Of pertinence, Seefeldt (1980) positioned the proficiency barrier between the attainment of FMS and what he termed *transitional motor skills* (TMS) which, within the model, serve to underpin the development of SSS [229]. Accordingly, from this perspective, the development of FMS forms the important basis for the development of skills that are more complex in nature. Such skills may include refined versions of FMS, or indeed combined versions of FMS, for example, running and dribbling, and throwing and catching within games, which can be eventually developed towards SSS [230,231]. Therefore, the notion of TMS presents a segue from FMS to SSS, and accounts for a what may be thought of as a highly important developmental stage that is not typically highlighted within athletic development-related literature.

Despite the proficiency barrier being regarded as an important phenomenon within the field of motor learning [226], there appears to be a dearth of direct scientific research-based evidence for its existence [232]. Indeed, as was previously discussed in relation to the so-called golden period for motor learning, much of the evidence for the proficiency barrier appears to relate to associations between motor competence and levels of physical activity participation or capabilities in "health-related fitness" assessments [229]. For example, De Meester et al. [230] observed that children's motor competence, assessed using the Gross Motor Development-2 assessment tool, was a predictor for the attainment of recommended daily guidelines for physical activity. Similarly, Abrams et al. [228], found that levels of motor competence had an apparent bearing on physical fitness levels in children and adolescents aged 10-18 years. Specifically, it was observed that participants who performed at or below the 25th percentile for motor competence across the sample were below the expected levels in a test of cardiorespiratory fitness. Moreover, in the grip strength test, only 21% of those found to be in the 25th percentile for motor competence were found to demonstrate grip strength at or above the 80th percentile of the allometrically scaled scores. Therefore, as was indicated by the authors, the results of Abrams et al [228] appeared to demonstrate that physical fitness levels may be limited in children who possess low levels of motor competence.

Other studies have attempted to empirically investigate the existence of a proficiency barrier between the FMS and TMS [226,231]. The study by Pacheco et al. [231] recorded children aged 5-10 years performing FMS in the form of the Test of Gross Motor Development-2 (TGMD-2), and TMS which was assessed using a basketball-based timed running dribble test. Performance in the assessments was analysed for associations and revealed positive correlations between FMS and TMS. Specifically, in the comparisons between the sum of running and bouncing criteria with the sum of the dribbling criteria, the sigmoidal-fitted model represented the strongest correlation ($R^2 = 0.52$), revealing that the two FMS appeared to be important contributors to the running dribble test that, beyond linear correlation, had a stronger correlation with performance when the sum of running and bouncing competence was higher. Further, Pacheco et al. [231] observed a change in TMS performance when a TGMD-2 threshold score was attained which, in support of Seefeldt's hypothesis, the authors' suggested indicated the existence of a proficiency barrier between FMS and TMS.

Using the same approach with regard to assessment of FMS and TMS as Pacheco et al. [231], dos Santos et al. [226] undertook an intervention study across 10-weeks to examine the potential existence of the proficiency barrier following practice of FMS (isolated skills e.g., running and stationary dribbling) and TMS (dribbling a basketball while running at speed). Similar to Pacheco et al. [231], dos Santos et al. [226] used the TGMD-2 test battery to assess FMS and the same timed speed dribbling test. The results of dos Santos et al. [226] revealed a similar FMS threshold requirement to that of Pacheco et al. [231], corroborating that performance in the TMS was dependent upon a critical score in the TGMD-2 test scores for isolated running and stationary bouncing. Moreover, based upon the intervention, it was found that only participants that achieved a score above the FMS threshold were able to display superior performance in the TMS after the intervention programme [226]. Despite improvements being made by all participants based upon the intervention, the results suggested that for the TMS-based element of the intervention to be of more benefit, a threshold level of FMS, or competency in isolated versions of the skills, was necessary. This was perhaps the result of the variable practice conditions used within the TMS practices, which implemented different conditions, including unopposed and opposed versions of the speed-dribbling activity. Collectively, the findings of dos Santos et al. [226] and Pacheco et al. [231] appear to provide some empirical evidence for a proficiency barrier that goes beyond other studies that have not directly measured associations between FMS and TMS. However, a study by Ribeiro et al. [233], which built upon methods from Pacheco et al. [231], compared less complex jumps (e.g., the CMJ and standing long jump), described by Ribeiro et al. as fundamental, with sport-specific skills from track and field athletics (e.g., the long jump and high jump). The findings suggest that the concept of a proficiency barrier is more nuanced than previously understood. For example, when controlling for age, the results of their linear correlational analyses of the skills showed low correlations in general. The highest correlations were observed between the standing long jump and the high jump (0.63) and the long jump (0.58). However, in the results of the sigmoid relationships, the R^2 were even less compelling. For example, the standing long jump and the long jump was found to be 0.48, which suggested there to be no existence of a threshold (barrier) beyond which greater proficiency can be attained. Nevertheless, further analyses undertaken by Ribeiro et al, which utilised the first two components for each skill that were identified by the authors through principal component analysis, revealed specific components of the jumps to be pertinent to performance in the sports-specific skills. For example, within their results, the first component of the standing long jump and long jump were indicative of better performance. However, the second component did not show the same pattern, indicating that there was a divergence in its importance to performance. This pattern was also observed between the CMJ and the high jump. The final pairing, however, between the leap and hurdle transposition did not display the same pattern of similarity between the two components. Nonetheless, despite these observations, patterns that were similar were not necessarily found to be indicative of better performances in the sports-specific skills, highlighting that, in the context of this study, proficiency in given FMS may not be important. Accordingly, Ribeiro et al. suggested that motor development was dependent on a multiplicity of paths, rather than reliant upon the development of prerequisite movement skills.

Although the proficiency barrier hypothesis by Seefeldt has a logically derived rationale and, more recently, through empirical research that utilises more complex study designs and analysis techniques, it is apparent that the proficiency barrier concept is not straightforward and instead is highly nuanced. Accordingly, other broader and more philosophical questions relating to FMS are required to better understand the extent to which the proficiency barrier may inhibit development across a range of contexts [229]. For example, to what extent focused practice on TMS or SSS could improve proficiency in these skills without first attaining motor competence in FMS? And the effects of a programme of FMS versus a programme of TMS on enhancement of SSS? Currently, there is a paucity in the empirical research relating to such questions.

2.3.1 Criticism and confusion of the Fundamental Movement Skills concept

Despite the FMS concept pervading models of youth athletic development and associated scientific literature, it is not without criticism. For example, in a critique of the FMS concept, Newell [30] contended that [fundamental] movements are different from [fundamental] motor skills. Although this appears to be merely a semantics based contention, Newell [30] argued that movement is a term that focuses narrowly upon the biomechanical properties of a skill, without necessarily accounting for the movement goal or its functional requirement. Indeed, the classic work of Wickstrom [198] was very much focused on the form of movement execution without any reference to goal-based properties of the movement and how these may have influenced movement pattern execution. Therefore, as argued by Newell [30], despite the influence of Wickstrom [198] on youth athletic development models, the work is devoid of the key component of how a skill is defined [221]. Such a view is of pertinence to achieving a better understanding of the importance of FMS, especially given that the work of Wickstrom has been so influential. Certainly, Newell [30] appeared to agree with the ideas of Wickstrom [198] in relation to the developmental progression of movement patterns and motor development throughout childhood and adolescence. However, such observations do not provide a thorough analysis of the factors that shape and influence the development of movement patterns. Therefore, while of importance, Wickstrom's observations present only a limited contribution to the critical examination of the FMS concept

Some contemporary perspectives relating to FMS have also questioned the use of the term 'fundamental' [e.g., 18,35] , suggesting that the term is not appropriate to the types of skills that are typically considered to be FMS. Indeed, such criticism relates to the implication that such skills are imperative which, when considered outside of the context of athletic development, FMS, including throwing, kicking and jumping, may not be regarded as imperative. Further criticism relates to the lack of acknowledgement of cultural divergence and how individual needs and capabilities may differ [7,30]. The contention surrounding use of the term 'fundamental' within FMS can be succinctly summarised with the "fundamental for what" question, which highlights the difficulty in defining precisely the movement skills that should be included [30]. Accordingly, amended versions of the FMS acronym have been proposed to more appropriately define skills that are considered to serve as building blocks for more advanced skill development, including *foundational movement skills* [e.g., 18] and *functional movement skills* [e.g., 234]. However, other authors have proposed more substantial changes, including *'basic movement skills'* [e.g., 235] , and *'athletic motor skills'* [e.g., 236], the latter of which has been proposed to specifically define movement capabilities that pertain to athletic development and the S&C domain [238]. Other authors [e.g., 179] have opted for fundamental *motor* skills in place of *movement*. Although both are used interchangeably [7], a motor skill is defined as *"a skill that requires voluntary body and / or limb movement to achieve its goal"*, whilst movements represent *"behavioural characteristics of specific limbs or a combination of limbs that are component parts of an action or motor skill"* [221]. Motor skills, therefore, utilise movements of the human body to accomplish goal-directed outcomes [239]. However, in the case of active (as opposed to passive) movement, the goal can be a specific movement pattern itself (e.g., standing from a sitting position) thus highlighting interdependency between the concepts of motor skills and movement [30]. Accordingly, the use of the term *movement* in

FMS instead of *motor*, while not necessarily accurate according to classical motor learning definition, can be considered to be appropriate [7].

Adding further complication to the definition issue, in place of FMS, Liefeith et al. [10] have proposed the term *'generic movement ability'* to represent underpinning preparation for the development of more complex skills, such as those required within sports. Indeed, within the scientific literature there exists an apparent conflation between motor skills and motor abilities [240,241]. Motor abilities are postulated to comprise factors such as reaction time, multi-limb coordination, control precision, speed of movement and characteristics relating to force production [241]. However, as with the study of FMS, there exists a longstanding debate regarding the different motor abilities of the human body [242,243]. By definition, motor abilities are considered to be general traits or capacities that underpin the performance of motor skills [186] and, unlike motor skills, are thought to be relatively stable and largely unmodifiable by practice [242,243]. Accordingly, terms such as 'athletic talent' and 'natural athleticism' have been utilised to describe individuals who are deemed to possess high levels of motor abilities relevant to sports [243]. Furthermore, individuals who have been observed to excel across different sports have been considered as displaying 'athletic ability', which led to the existence of what has been more formally regarded as 'general motor ability' [186]. Linked to this, the *general motor ability* (GMA) *hypothesis*, which considers many different motor abilities be highly related, holds that the level of GMA in individual influences their performance in any given motor skill [244]. Accordingly, an individual with a high degree of GMA would display proficiency in all motor skills [186,241]. There is, however, a lack of evidence to support the GMA hypothesis, with research [e.g., 244,245] revealing low correlations between relevant motor abilities. Therefore, in contrast to a GMA, research appears to support the *specificity of motor abilities hypothesis* by Henry [247], which considers motor abilities of relatively independent [221]. Accordingly, performance in a task that is reliant on a specific ability is not indicative of performance in another task which, instead is reliant on a different specific ability.

Despite motor abilities being considered to be largely genetically determined [241], as is observed within the extensive S&C-based scientific literature [e.g., 169,170,217,247–249], certain motor abilities, such as muscular strength, can be enhanced through physical training [251,252], which contradicts the classic definition of ability. Indeed, returning to muscular strength as an example, which is typically defined as *"the ability of a given muscle (or group of muscles) to express force against an external resistance"* [251,252], is modifiable on the basis due to a number of different factors, including neural alterations (e.g., recruitment of motor units, intramuscular coordination, and rate coding) and morphological changes (e.g., muscle and connective tissue hypertrophy) [250,251,253]. Therefore, the expression of strength may be better thought of as the manifestations of enhanced neural and morphological components which themselves represent different motor abilities.

In response to historical misinterpretations of the nature of various motor abilities, Burton and Rodgerson [241] published their taxonomy of movement skills and GMA [241,243]. Within their taxonomy, the authors presented four hierarchical levels of the motor domain with the GMA at its base. In ascending order, above the base level are 'movement foundations', 'movement skill sets', and at the top level, 'movement skills'. According to Burton and Rodgerson [241], the GMA is inferred from performance of an array of different skills; however, it is neither a movement skill in and of itself, nor a combination of skills. A more recent perspective that builds on the ideas of Burton and Rodgerson's taxonomy and suggests that a general motor ability is not directly measurable but rather is inferred from the performance of FMS [241]. However, such performance in FMS may be strengthened by enhancement of Burton and Rodgerson's movement skill foundations, such as flexibility, strength, balance, and reaction time [243]. Equally, performance of a skill may indeed be limited by a particular movement skill foundation, thus affecting its execution. For example, a limitation related to an individual's balance may lead to poor movement skill performance Thus, from this perspective motor abilities are constructs that underpin the movement skill foundations. While this does little to define specific motor abilities of the human body it makes clearer the distinction between a motor ability and a motor skill. From such a position, future research that examines the importance of FMS development in youth athletes should utilise consistent terminology that accurately distinguishes between motor abilities and skills to help develop a clearer and more objective understanding.

2.3.2 Evaluation of fundamental movement skills

Motor competence is defined as the degree of skilled performance across a wide range of motor tasks and relates to movement quality, coordination and control to achieve a particular motor outcome [230]. The assessment tools typically used to measure FMS competence include evaluations of locomotion, object manipulation, and balance tasks [254]. An example of a widely implemented assessment tool for the evaluation of FMS competence is the Test of Gross Motor Development (TGMD-2) developed by Ulrich (2000) [254]. The TGMD-2, which requires an assessor to score FMS against competence-based performance criteria, is regarded as a process-oriented assessment tool (Freitas et al., 2015). Other process-orientated measures, such as the Preschooler Gross Motor Quality Scale and the Objectives-Based Motor Skill Assessment Instrument, utilise time-consuming technique-based criteria to evaluate FMS competence [256]. In contrast, outcome-oriented assessment tools, such as the Manchester Motor Skills Assessment, have been designed to be implemented with greater efficiency than process-oriented tools [257,258]. However, despite such tools being found to have high levels of validity and reliability across a multitude of competency-based assessments [e.g., 256,259], each is subjectively determined by the test administrator who rates the performance against the assessment tool's scale. Therefore, although such predetermined batteries of goal-directed movement patterns (the motor skill) are purported to be representative of gross motor competence, the extent to which they evaluate all the skills that are important to performance of more advanced skills (e.g., SSS) is questionable. Indeed, the original iteration of the TGMD was replaced by TGMD-2 following reviews that highlighted deficiencies relating to the reliability of some of the subtests as well as a lack of stratification of normative values to reflect age, sex, and race [260]. Therefore, the extent to which the competency-based assessment tools can evaluate an individual's FMS competency is unavoidably limited due to the arbitrarily chosen skills. Accordingly, such approaches are open to continual scrutiny and criticism. Moreover, within the context of FMS underpinning SSS, the very notion of FMS being evaluated according to competency-based criteria has been a key criticism [30]. Indeed, in much the same way that the assessment of physical capabilities (e.g., sprint speed and strength) in talent identification pathways provides only a limited cross-sectional evaluation of a given individual's skill level, these tools do little to offer insight into longer term development [261]. Accordingly, the value of subjectively determined skills in competency-based assessment tools can provide only limited insight. Further, such assessment tools are predicated on the notion of a hierarchy whereby FMS competency serves as the necessary "gateway" to the subsequent learning of SSS [188]. However, this idea has been challenged under the premise that, within the context of games that more closely resemble sports, such as tag games, skilled performance relies not only on FMS but also on spatial and strategic awareness which combine to influence how a movement is executed [262]. For example, in a tag game, the use of a reaching motion of the upper limb whilst running to tag an opponent is a necessary skill governed by the very nature of the game. However, based upon the hierarchical notion of FMS, such a skill would only be possible once competence in running had been attained, which represents a developmental strategy that is considered to be detrimental to the development of skilled performance [262]. How such competency tools to assess FMS should be decided remains a considerable challenge.

Determining how FMS underpin the acquisition and development of SSS remains an area of uncertainty. Accordingly, in contrast to assessing competency in FMS per se, research is required to better understand the interdependency between FMS and SSS. This is of particular importance to the previously discussed single-sport specialisation issue, which exists under the premise that earlier specialisation in children will better enable them to progress to higher levels of performance [82]. Through more critical understanding of the role of FMS, more favourable strategies of assessment can be developed that satisfy both long-term athletic development outcomes and, in the case of youth wishing to progress within a chosen sport, the requirement to develop SSS.

2.3.3 Phylogenetic/ontogenetic fundamental movement skills

Given the commonly accepted "building block" analogy of FMS, it is perhaps necessary to philosophically consider perspectives of movement skills and their purpose. However, firstly, to facilitate such an appraisal, it is important to biologically distinguish between skills that are considered typical across all human-species, termed phylogenetic motor skills, and those which develop through cultural influence and individual experiences, defined as ontogenetic skills [30,229]. Phylogenetic motor skills can be thought of as naturally occurring and essential for survival and, therefore, according to the Colins English dictionary definition of the word, would appear to reflect the term 'fundamental' most accurately. In contrast, ontogenetic skills are not necessarily required for survival and are instead learned because of cultural influence [263]. However, importantly, the classification of skills as phylogenetic and ontogenetic exist with a degree of relativity as opposed to being absolute distinctions [263]. This is highlighted by the locomotive skill of running, which, notwithstanding injury or impairment, can be regarded as phylogenetic due to the bipedal act of running being typical in all human beings. However, in many sports (e.g., football, tennis, and basketball) running can be regarded as a fundamental skill for performance. Conversely, swimming may be considered to be a survival skill to children [264] though it is not phylogenetic and instead reflects social-cultural influences [265,266]. Therefore, an appreciation of different contexts is important, including cultural differences as well as consideration of individuals with disability and impairment [7]. Accordingly, from a philosophical standpoint, the "fundamental for what" question is an important one to pose, the response to which will be dependent upon the specific context.

In the context of basketball, the ontogenetic skills that may be considered fundamental are dribbling, shooting and passing [267,268] which, in accordance with the traditional FMS categories, are considered to relate to object manipulation. In the absence of these SSS, playing basketball would not be possible and, therefore, the use of the term fundamental would appear to be warranted. However, the already discussed physical demands of basketball indicate that running, jumping, and change of direction are all entirely necessary to performance, thus these locomotion-based skills can also be considered fundamental. Furthermore, in addition to object manipulation and locomotion skills, balance skills, such as evading, reaching, and maintaining stance may also be thought as fundamental to basketball performance [18,180]. Therefore, the three categories typically used to define FMS may be considered imperative to basketball performance. While each of the specific skills that fall within the FMS categories may be regarded as ontogenetic, as has already been discussed, there is an overlap between skills that are typically understood to be phylogenetic (e.g., bipedal running). Such overlapping skills are necessarily adapted and refined to meet the specific requirements of the sport of basketball. However, in accordance with the perspective that the acquisition of ontogenetic is skills culturally-determined, the relative levels of importance placed upon their development will likely differ based upon a broad range of factors, including coach education and experience, sex, level of play, and geographic location [50]. Therefore, while the necessary skills for basketball are ubiquitous, the importance that should be placed upon developing them and, indeed, how best to develop them, remains an area of uncertainty.

2.3.4 Transfer to sports specific skills

In the context of sports specific skills (SSS) development, FMS are regarded as the underpinning skills upon which SSS can be learned and developed [180]. However, transfer and development of FMS to SSS is not clear within the scientific research literature. Skill transfer relates to the influence of a previously developed skill on the acquisition of a new skill or performance within a new environment or context [227, 259]. Intra-task transfer refers to the transfer of a practiced skill in one context to a novel context, whereas the influence of a previously learned skill to develop a new skill is referred to as inter-task transfer [270]. Moreover, the transfer of skill can be regarded as 'positive' where the previously learned skill supports the learning of another; or negative, where a previously learned skill inhibits the development of a new skill [186,221]. Within motor learning research, the *identical elements theory* and the *transfer-appropriate processing theory* represent the two most prominent perspectives used to explain positive transfer of skills [221,271]. The identical elements theory considers the level of similarity between the skill and context to be important in terms of the degree to which transfer may occur [271]. The transfer-appropriate processing theory is based upon the cognitive processing similarities between the two motor tasks [221]. In the case of the identical elements theory, the transfer between sports of a common classification (e.g., racquet sports), is explained by the similarities between the stimulus characteristics [272]. Within the transfer-appropriate processing theory, however, the determining factor for transfer relates to the coherence of constraints (e.g., principles, rules, or laws) linked to information processing and problem solving [221,272]. Accordingly, transfer is considered to be possible between two different classifications of sports (or contexts) despite not sharing similar movement characteristics [221].

Within the scientific literature, studies [e.g., 260, 261] have demonstrated positive skill transfer. Of most pertinence to the concept of FMS underpinning SSS, the study by O'Keeffe et al. [273] included a group classified as a *fundamental throw group*, which practiced the overhead throwing skill, and a group classified as a *badminton group,* which practiced the overhead clear shot, in addition to a control group. Using a commonly utilised percentage of transfer calculation to determine inter-task transfer (equation 1), O'Keeffe et al. [273] revealed that the practicing of an overarm throw transferred to the badminton clear shot by 26%. Moreover, the fundamental throw group also showed significant changes in the javelin throw, with a calculated transfer of 57%. Interestingly, however, there were no significant changes in the javelin throwing performance or overhead throwing in the badminton group, demonstrating that SSS were not transferred.

$$\%Transfer = \frac{Experimental - Control}{Experimental + Control}\ x\ 100$$

(equation 1) [273]

In contrast to the findings of O'Keeffe et al. [273], Rienhoff et al. [270] observed positive transfer between two SSS. In their study, the accuracy of dart-throwing and basketball free-throw shooting in "skilled", and "less skilled" basketball players was compared. The skilled basketball players were found to be more accurate in the dart-throwing than the less skilled players. Through analysis of radial error based on *x*- and *y*-axis coordinates to assess accuracy as distance from the dart board's bullseye, the less skilled players were found to deviate to a greater extent on the *x*-axis compared to the more skilled basketball players. Based on their results, Rienhoff et al. [270] suggested that the more skilled players were able to transfer their free-throw shooting skill to that of dart-throwing, while the less skilled players were apparently unable to achieve this. To account for their findings, Rienhoff et al. [270] suggested that the skilled participants were able to utilise similarities between the movement patterns they are familiar with from basketball to that of the novel dart throwing skill. Interestingly, using eye movement analysis, Rienhoff et al. [270], also compared quiet eye, which is considered to be a perceptual skill and refers to a performer's gaze control at least 100 ms prior to the initiation of the final movement is the execution of a skill [270,274]. However, in contrast to the findings relating to throwing performance, quiet eye was not found to transfer between tasks in the skilled group. Based on this finding, the authors suggested that quiet eye might therefore be task specific and, rather than being transferable, it is developed overtime through deliberate practice [270]. Accordingly, it is plausible that while movement skills are transferable, task specific perceptual skills are not.

Explaining the different findings relating to the transferability to SSS between the O'Keeffe et al. [273] and Rienhoff et al. [270] studies, it may be that well-developed skills, such as the free throw shot in the skilled basketball players of the Rienhoff et al. [270], are more transferable owing to a more stable movement pattern and, potentially, less variability. Indeed, the skilled players in the Rienhoff et al. [270] study were experienced players, with an average playing experience of 12.9 (± 0.5) years, compared to their unskilled counterparts who were physical education students and possessed a maximum of three months basketball training. In contrast, none of the participants in the O'Keeffe et al. [273] study were described as having had experience in badminton or javelin. Accordingly, it could be inferred that the attainable level of transfer between skills is dependent upon how well-developed and stable the previously learned skill was. Further to this, in contrast to O'Keeffe et al. [273] who conducted their study in adolescents (mean age 15.8 ± 0.6 years), the average age of the participants in the Reinhoff et al. study [270] was ~25 years. Accordingly, it is entirely plausible that the younger participants in the O'Keeffe et al. [273] study did not possess well-developed movement patterns in the sport-specific badminton clear shot. In turn, these participants were unable to display transfer between the overhead clear shot and javelin throw. However, development of the overhead throw appeared to serve as a basis to learn the two SSS, thus demonstrating some evidence of FMS underpinning development of a more complex SSS. Therefore, it may be that the learning of FMS provides a basis for the development of SSS in instances when SSS are underdeveloped.

More evidence relating to FMS and SSS is observed in a study by Kokstejn et al. [275]. In their cross-sectional investigation, the relationship between FMS, physical fitness and soccer-specific skills in youth soccer players was found to be moderate to strong (r = 0.56-0.66). From their results, the authors concluded that FMS development in pre-adolescence may play an important role in SSS performance. The authors purported that FMS appear to provide the necessary building blocks for the development of more complex skills. However, it is plausible that another explanation for the correlational findings of Kokstejn et al. [275] is that the young soccer players that displayed better skills were simply able to also express greater proficiency in the FMS. That is, the more skilled soccer players were able transfer their SSS to FMS, rather than the other way round. Indeed, this is an argument that has been proposed by Mao et al.

[276] who, based upon the findings of their meta-analysis that investigated the effects of soccer practice on children's (aged 7-13 years) FMS, found positive significant effects on linear sprinting, horizontal jumping, and object control (e.g., throwing, striking, dribbling and kicking). Therefore, in contrast to the concept of FMS providing the building blocks for SSS, it is possible that proficiency in more complex skills (e.g., football) is transferred to FMS, which is highlighted through greater levels of proficiency in more basic skills. Accordingly, the development of locomotor, object manipulation, and balance, which represent the categories of FMS, may be developed through SSS, that are transferable to FMS. This would appear to contrast with the notion of FMS serving as building blocks for the development of more complex sport skills.

Further to the perspective that SSS may transfer to FMS are the results of another study by Kokstejn et al. [277]. In this study, Kokstejn et al. [277] used the TGMD-2 protocol to assess FMS in children aged 10-11 years of age and compared composite scores from the assessment with two soccer-based technical tests. Their results revealed significant moderate to strong correlations between FMS and the scores for the soccer-specific assessments (r = 0.50-0.77). Of note, FMS relating to object control was strongly associated with dribbling, and locomotor skills were strongly associated with dribbling. In addition, locomotor skills were significantly correlated with shooting time. Although the authors interpreted these results to mean that FMS were an important foundation of the football specific skills they assessed, it is not beyond the realm of possibility that it was the participants' competency in the football tasks that were transferred to the TGMD-2 assessment. Accordingly, the TGMD-2 was not necessarily indicative of FMS performance and, instead, may have been a measure of SSS. Adding credence to this perspective is that the participants in the Kokstejn et al. [277] study were referred to by the authors as *highly trained*, highlighted by an average training age of 6.3 ± 0.6

years, in relation to organised football. Indeed, the TGMD-2 battery includes an assessment of kicking a stationary ball as part of the object control subset of included tests and a running assessment as part of the locomotor subset. Given that the football specific assessments included a timed dribbling test and a shooting test, it may well be expected that performance in these more complex tasks was correlated with performance in the seemingly more basic tasks of the TGMD-2 battery. However, of note, through a multiple linear regression analysis, the results of Kokstejn et al. [277] revealed that the 'horizontal jump' and the 'catch' assessments from the TGMD-2 were the strongest predictors of performance in the soccer-specific tests, when a composite score for those particular tests was used. Given that these two skills are seemingly unrelated to soccer-specific skills, this finding appears to be contradictory to the notion that the assessed skills in the TGMD-2 that share skills with soccer would benefit. To account for this, however, within the TGMD-2, the catch, which requires the participant to catch a plastic ball that has been tossed underhand from 15 feet (4.57 metres), and the horizonal jump, which is assessed based upon the quality its execution, may be considered rudimentary skills compared with the complexity of the soccer-specific assessments. That is, the complexity of soccer-specific skills may be such that they are transferrable FMS, including those that appear unrelated, on the basis that they are comparatively simpler for the performer to execute. Therefore, the correlation between performance in the soccer-specific tests and the catch and horizontal jump assessments is likely to be expected.

In a similar and more recent study to that of Kokstejn et al. [275], Duncan et al. [278] found that FMS and perceived level of competence (reflecting strength, speed, and coordination) served as mediators to physical fitness and technical soccer skills. In their study, Duncan et al. [278] examined the relationship between physical fitness, FMS, perceived competence and technical soccer skills in players aged 7-12 years of age. In addition to the TGMD-2 battery, and soccer-specific assessments compared in the Kokstejn et al. [275] study, Duncan et al. [278] included a battery of physical fitness tests (15-m sprint, a standing long jump, and a seated 1 kg medicine ball throw) and the Perceived Physical Ability Scale for Children (PPASC). The PPASC is a valid and reliable assessment tool for children, which is utilised to assess self-perception of physical competence in strength, speed, and coordinative abilities [278]. Using path analysis, the results of Duncan et al. [278] revealed two significant ($p < 0.05$) mediated pathways: from physical fitness to technical skills via FMS; and from physical fitness to technical skills via perceived competence. In their interpretations of the results, Duncan et al. [278] suggested the reason that both FMS and perceived competence mediated the relationship between physical fitness and technical skills was related to the importance of FMS alongside physical fitness in the development of high level soccer performance. While this is indeed a plausible explanation, it also indicates the possibility of a transference of competency between FMS and SSS, as well as between skills and physical fitness. This is especially so, given that the physical fitness tests included skills that were similar to those assessed within the TGMD-2 (e.g., sprinting/running and standing broad jump /horizontal jumping). Therefore, it would appear logical that there would be some association identified by Duncan et al. [278]. Moreover, despite their young age (mean age = 9 ± 2.0 years), the participants in the Duncan et al. [278] study had a mean formalised soccer playing experience of 3.1 ± 1.5 years; thus it is likely that the development of both SSS and FMS would have occurred through their regular participation in organised football. As an extension of this, through their engagement in soccer, it is plausible that the participants in the study had also developed self-perception of their competence.

Although the notion that the development of FMS provides the necessary building blocks for the acquisition of SSS is logical, it is also somewhat simplistic. From a theoretical perspective, the notion of transfer of FMS to SSS would appear largely based on ideas from the aforementioned identical elements theory. While indeed there is empirical research that appears to support such a perspective, as has been discussed, the development of FMS may well occur through engagement in organised sport where the emphasis is on the acquisition and development of SSS. Moreover, in accordance with the transfer-appropriate processing theory, an additional benefit of FMS development through participation in organised sport would be the development of cognitive processes, such as problem solving and decision making, which are both crucial to sports performance. Therefore, there is a need for future research to investigate the role of FMS in the development of SSS more critically, which includes an appreciation that the transfer of FMS to SSS may well function in reverse, with the development of SSS also serving to enhance FMS. Importantly, such research should aim to examine how the skills are transferred and to what extent. Similarly, research that explores how FMS and SSS development may occur synergistically (as opposed to dichotomously) and concurrently is necessary so that more effective and time efficient strategies can be formulated to enhance them.

2.3.5 The role of FMS within youth athletic development

A key characteristic across the established athletic development models (e.g., DMSP, LTAD, ASM and YPD models) appears to be their advocacy for the development of FMS. For example, in relation to their original LTAD model, Balyi et al. [83] stated that the development of FMS will contribute significantly to future athletic success. Similarly, within the YPD model, it is stated that movement patterns must be correctly executed ahead of the development of more complex actions, such as those required in sports [33]. However, despite the contention that FMS serve as building blocks for the acquisition of more complex skills, there is a lack of critical and explicit information within the models regarding how they should be best developed [10]. Moreover, within the LTAD and YPD models, there is no information relating to the extent to which proficiency must be attained before progression to more complex skills (e.g., SSS) is possible. Adding ambiguity to this issue, both the LTAD and YPD models indicate that SSS can indeed be developed alongside FMS. For example, within the FUNdamental stage of the LTAD, there is an emphasis on the development of what it refers to as the "ABC's of athleticism" (e.g., agility, balance and coordination) as well as participation in multiple sports [279]. However, it is not clear whether it intended that each of the ABC's is developed independently through deliberate practice and to what extent the role of playing multiple sports contributes to the development of FMS. Adding to this apparent ambiguity, within the 2013 update of the model, Balyi et al. [32] indicated that a percentage of time can be allocated to the development of SSS, although this should predominately occur through activities such as small-sided games. Caveating this approach, however, Balyi et al. [32], suggested that such games should be free of technical and tactical constraints and used to teach "athletes how to play sports". Therefore, the specific aims and objectives of the approach are unclear, and the suggestion of developing FMS in greater proportionality compared to SSS using small-sided games is certainly ambiguous for any practitioner wishing to implement the LTAD model. To a lesser extent than the LTAD model, similar uncertainties are observed in the YPD model (figure 3), which suggests that children should be exposed to SSS during the pre-PHV period (as indicated by small font in the model structure) albeit to a lesser extent than FMS. Therefore, despite the central tenet of both the LTAD and YPD models that the cultivation of FMS is necessary for the development of the more complex SSS, this is not necessarily apparent within the two models and remains a largely theoretical claim that is not necessarily underpinned by the extant literature on the topic. As has already been discussed, the development of complex skills, such as SSS, may indeed be possible in the absence a curriculum of FMS development beforehand. While to some extent it appears that both the

LTAD and YPD models account for some level of co-development, of FMS and SSS, the lack of critical information provided in this regard limits one's understanding of whether this was the intended meaning. Therefore, although both models suggest somewhat of a dichotomised approach to the development of FMS ahead of SSS, this is confounded by their superficial

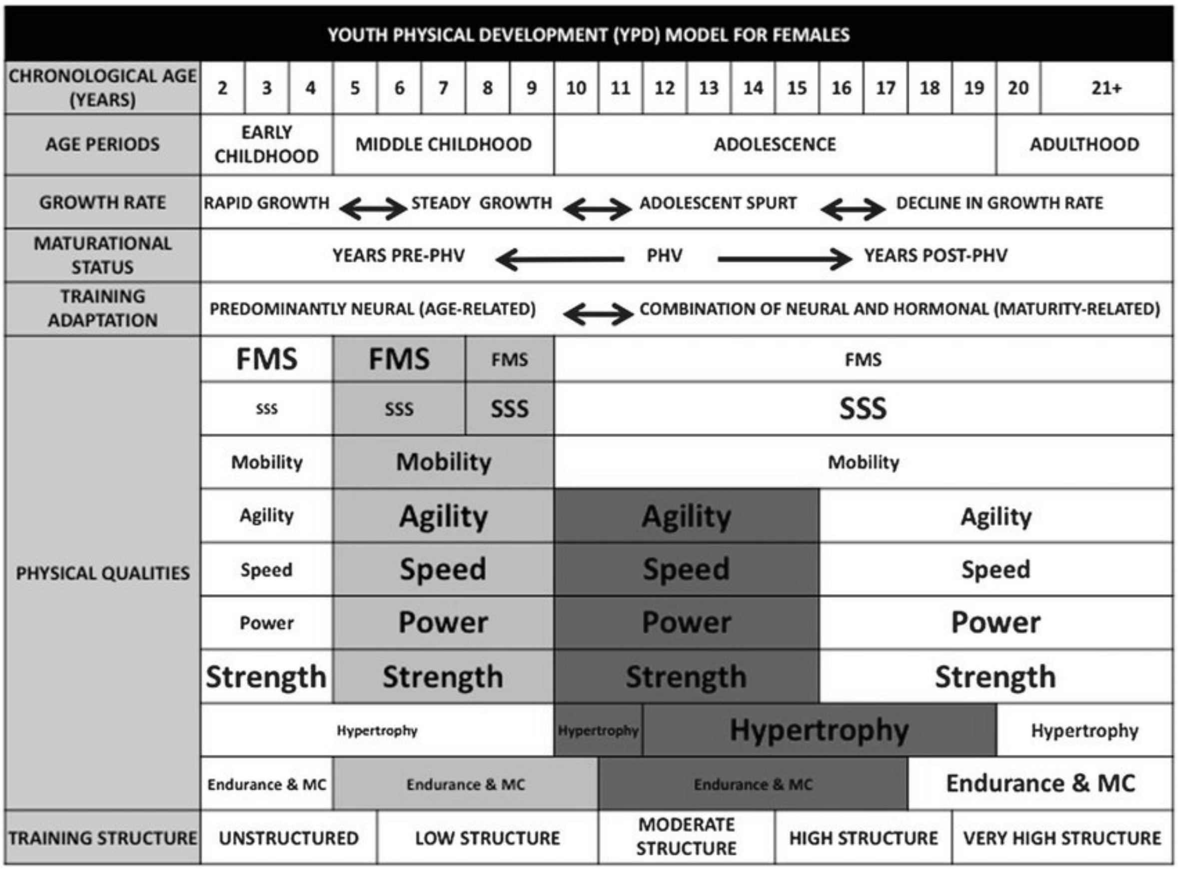

Figure 3. The YPD model for females by Lloyd and Oliver [33]. To note, the YPD for males is the identical except for the approximated timescales for the growth rate and PHV to account for differences between sexes.

recommendations that do not commit to any clear strategy for the development of these separate classifications of skill. In turn, this appears to undermine the perspective that FMS serve as the building blocks for the development of more complex skills. Accordingly, as has been a stated criticism of athletic development models, despite proclaiming the importance of developing FMS, the related discourse appears to address the issue only superficially [10].

Owing to the lack of explicit information pertaining to FMS development within the LTAD and YPD models, it is difficult to understand the respective rationales for their inclusion. It is possible that the emphasis on their inclusion is primarily based upon well-reasoned logic that FMS should be developed ahead of the introduction of more advanced skills and training methods. This may well be the case for the YPD which, as has been previously discussed, presents a model that is very much related to the S&C field. However, it is also reasonable to infer that the rationale for inclusion of FMS is to offset the risks associated with early commitment to a single sport (e.g., increased risk of injury and burnout). However, while the offsetting of the risks of single-sport specialisation appears an entirely worthy justification, as has already been discussed, it lacks in critical perspective as to the precise role that FMS play in the long-term development of youth athletes. Moreover, the message that specialisation is explicitly negative can be considered overly simplistic, and a more critical consideration is necessary [110,111]. For example, although exposing young and growing individuals to greater volumes of systematic training in a single sport may be considered to be a contributary factor for injury [88,280], whether this is the result of loads that are too high, or lacking in variation, appears to be somewhat devoid of consideration [110].

Concerns relating to early single-sport-specialisation and an associated lack of FMS development being an issue are generally limited to inferences within opinion pieces [e.g., 92,201,280,280] and correlational study designs [e.g., 101,281]. For example, in a study by Sugimoto et al. [101] it was revealed that young single-sport female athletes performed twice the training volume per sport compared to multisport athletes and, through a binary logistic regression model, increased weekly hours of training for a sport was found to be an independent risk factor for injury (aOR = 1.091, 95% CIs = 1.007–1.183, p = .034). Based on these findings, the authors suggested that performing other forms of training and participating in multiple sports may contribute to reducing the risk of overuse injuries. However, whilst acknowledging a number of limitations that give cause for caution over the findings of Sugimoto et al. [101] (e.g., the age range of the participants that spanned 12-18 years of age, and the performance measures used to determine injury risk), there is no indication that FMS and other SSS developed through participation in other sports would reduce the risk factors associated with injury. Similarly, a retrospective study by Frome et al. [283] that surveyed 2099 youth soccer players (mean age 13.2 ± 1.8 years) found that participants identified as specialised had decreased odds of reporting at least one previous injury compared to the non-specialised participants (OR, 0.78; 95% CI, 0.65-0.96). In addition, the specialised participants, who were characterised by only being engaged in soccer > 8 months per year, were found to have similar odds of reporting at least one previous lower limb injury to the non-specialised participants, who, in addition to >8 months per year soccer participation, did also engage in other sports, (OR, 0.79; 95% CI, 0.57-1.1) However, the non-specialised group were found to have significantly more upper limb and trunk injuries compared to the specialised group ($P = 0.011$), whilst the specialised group had significantly more severe injuries than the non-specialised group. Corroborating the findings of Sugimoto et al. [101], however, Frome et al. [283] also found a positive correlation between training ratio, which was defined as the ratio of weekly hours in organised sports over weekly hours in free play, and the number of previous injuries ($r_s = 0.09$, $P < 0.0001$). This particular finding revealed that, irrespective of group (specialised or non-specialised), participants with a training ratio of > 2 were significantly more likely to report more injuries than participants with < that 2. Thus, the findings of both Sugimoto et al. [101] and Frome et al. [283] provide evidence that total volume of participation in organised sports may be more concerning amongst youth in comparison to single-sport specialisation and an associated lack of FMS development. In turn, this could indicate that athletic development models, such as the LTAD and YPD models, are not necessarily reflective of empirical research that has highlighted the nuances that exist in relation to the issue of single-sport specialisation and skill development.

Shortcomings of the LTAD model have been highlighted in the literature [e.g., 85,283], with the validity of the model's recommendations being placed under extensive scrutiny. For example, Ford et al. [284] questioned the presence of a period of greater sensitivity to training for the development of FMS on the basis that no evidence appeared to exist other than the naturally occurring accelerated periods of motor development across childhood. Similarly, Van Hooren and De Ste Croix [85] indicate that the development of motor skills (including FMS) are not distinguished within athletic development models, which limits a more thorough understanding of whether a sensitive period may exist. As Van Hooren and De Ste Croix [85] highlight, the issue is even more challenging in situations where motor skill and physical capabilities may be interrelated, such as in the case with bipedal sprinting, making it difficult to observe the isolated development of one skill versus another. Therefore, although research studies that highlight risk of injuries in youth sports certainly provide a sound rationale for the recommendations for FMS development made within the LTAD and YPD models, they do not provide direct evidence for the requirement do develop FMS in ahead of SSS in childhood. This does not unequivocally suggest such an approach should not be adopted; however, the dearth of empirical research studies that account for the aforementioned ambiguity of the LTAD and YPD models, with regard to the development of FMS and SSS, must be acknowledged.

In contrast to the apparent ambiguity of the LTAD and YPD models regarding motor skill development, the ASM, presents a less dichotomised perspective in relation to FMS and SSS.

Moreover, importantly, the ASM details a method for the development of motor skills. In place of FMS, it refers to *basic movement skills* (BMS), for which it presents four categories, including *sport-specific-BMS*, *sport-adaptive-BMS*, *sport-related-BMS*, and *sport-supporting-BMS* [31]. Within the ASM, these categories are somewhat hierarchically organised. For example, the sport-specific-BMS represents the most narrowly focused skills including those with specific requirements for specialised equipment or specific environments (e.g., trampolining). At the base of this hierarchical structure, the sport-supporting-BMS reflecting the most broadly natured level of skills. Importantly, however, and in distinct contrast to the somewhat tentative suggestions within the LTAD and YPD models that SSS can be developed alongside FMS, the ASM advocates for the development of BMS through participation in multi-sports [31,236]. In doing so, the ASM appears to incorporate a *sampling years* stage similar to that of the DMSP, which involves participation in multiple sports between the ages of 6-13 years [86,285]. However, the ASM expands upon this and attempts to also account for motor learning through what is referred to as a *concentric* approach to the development of motor skills [236]. According to the ASM, the concentric concept encourages more versatile and adaptable movement capabilities through exposure to skills within different contexts (e.g., striking a ball in baseball, table tennis, cricket, and executing a volleyball smash shot) [31]. Moreover, the concentric approach is argued to contrast with linear forms of motor learning, which represents a more rigidly adhered to sequence of progression towards more complex skills [236]. Although the authors of the ASM state that the concentric approach is not a single methodology per se, and instead refer to it as a *skill-centred programme* [31], it does present a more explicit approach to develop FMS that is not apparent in the LTAD and YPD models.

2.3.6 Donor sports

Further highlighting the attempt by the ASM to provide guidance relating to the development of FMS is through its recommendation of the *donor sports* concept. While similar to some extent to the notion of sports sampling, donor sports are regarded as sports and activities that share similar FMS with a so-called '*target sport',* therefore facilitating the development and transfer of a broad range of motor skills from one to the other [31]. For example, the ASM suggests that the sport of badminton can serve as a donor sport for goalkeepers in football to improve their coordination and "footwork". Moreover, the sport of parkour has been purported to be a donor sport for team sport athletes, facilitating the development of physical qualities that can be transferred into sports-specific performance [34,35]. Thus, while the ASM places a similar emphasis on the development of FMS as the YPD and LTAD models, it also appears to more explicitly account for an overlap between FMS and SSS (Figure 4). That is, the development of either one regardless of the order in which they are learned and executed, contributes to the development of the other. As has already been discussed, a relationship between FMS and SSS appears to be logical. However, with regard to donor sports, there is a current lack of empirical research to support the described concept.

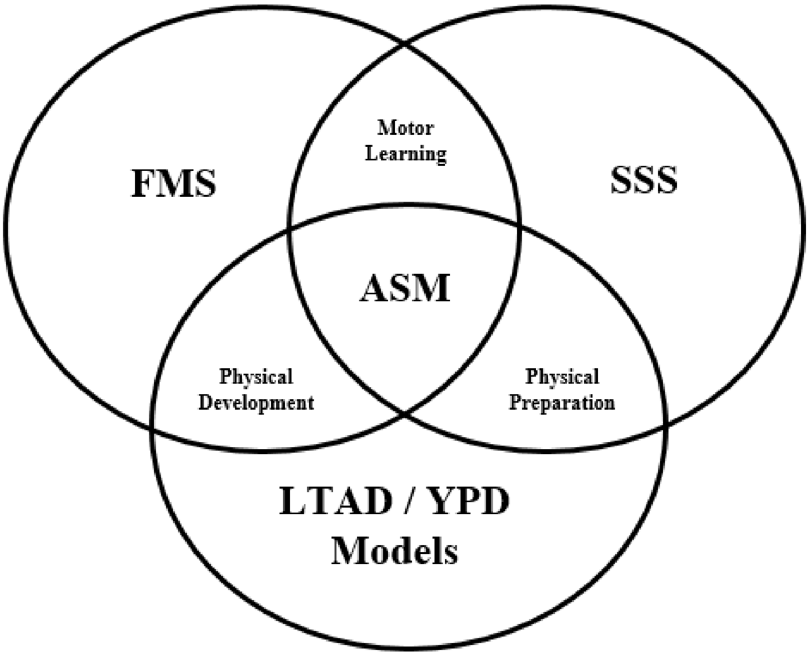

Figure 4. Venn diagram representing the shared characteristics between the different models of athletic development.

Despite a need for scientific empirical studies to support the ASM's concepts, its emphasis on motor learning is perhaps what distinguishes it most from the YPD model. Moreover, while both the ASM and YPD models are built upon concepts from the LTAD model, the ASM appears to be explicitly focused on the development of movement skills through the integration of motor learning theory and youth athletic development ideology. In contrast, the YPD model places emphasis on physical development, with strong apparent ties to strength and conditioning-related constructs [33]. Accordingly, based upon stages of biological maturation, the YPD model presents evidence-based guidance for the introduction of training for the development of different physical qualities such as strength, power, speed, and agility [38]. For example, to coincide with increased levels of circulating hormones considered responsible for protein synthesis, the YPD model suggests that resistance training be programmed to increase muscle hypertrophy in the post-PHV period of growth and maturation [33]. While the ASM does also provide similar guidance relating to the development of physical fitness capabilities in accordance with the stages of biological maturation, it states that within the model, all physical qualities (e.g., agility, stability, flexibility, power, and endurance) are linked to movement and coordination, and refers to them as ‘conditions of movement’ [31]. Accordingly, Wormhoudt et al. [31], the authors of the ASM, define the model as being the summation of “three intertwined building blocks” including FMS, physical qualities, and the conditions of movement in one integrated framework of athletic development. Thus, compared to the other models of athletic development, the ASM may be a model that more thoroughly accounts for the importance of motor skill development that is based upon the enhancement of movement capabilities across childhood and adolescence, with respect to the maturational changes that occur during that timeframe. However, in contrast to the YPD model, which with respect to the youth-based S&C training, is supported by a body of evidence [e.g., 168,171,250,286], there is a need for research to substantiate the ideas it purports. In particular, the donor sport concept, which presents a potentially useful means of developing diverse movement capabilities (FMS and SSS) that are transferable to a focus sport amongst athletes, requires empirical study. Should such studies provide evidence to support the donor sport concept, the implications for the athletic development strategy of organisations and governing bodies, such as Basketball England, could be substantial. Importantly, the donor sport concept may provide a method to develop FMS, which does not currently exist.

2.4 Theories of motor control and learning

As has briefly been discussed within previous sections of this literature review, the FMS concept requires consideration of multiple critical perspectives, including understanding of key milestones within motor development, a clear philosophical positioning, and clarity of terminology relating to theories of motor learning (e.g., skills versus abilities and skill transfer).

However, arguably, it is motor control and learning that are most important to understanding the role FMS plays within the youth athletic development strategy of youth basketball players.

Motor learning refers to the increased spatial and temporal accuracy of goal-directed movements in response to practice [186,287]. Moreover, it relates to internal processes of the body that lead to relatively permanent changes in the performance of motor skills [186]. Accordingly, motor learning may also be referred to as *procedural learning* [288]. As has already been discussed, motor skills utilise combinations of the human body's vast repertoire of motor abilities (e.g., coordination and balance) which, through practice, results in changes to cortical and subcortical neural circuits and, in turn, more refined and efficient execution of movements [288]. In contrast to motor learning, motor control represents the processes that support the planning and execution of movements, including neural, physical, and biological components [186,287].

Motor control theories have been utilised to develop an understanding of *degrees-of-freedom* (DOF), which relates to the multitude of ways that the human body is able to execute a movement to achieve the same specific goal [289,290]. Indeed, owing to an abundantly greater volume of neural inputs than outputs within the nervous system, the human body is regarded to be a highly "*redundant"* system [291]. Highlighting the extent of the so-called *redundancy problem*, redundancy within the human body includes anatomical (e.g., muscles, joints, and DOF), kinematic (e.g., velocities and trajectories), and neurophysiological (e.g., motor unit recruitment) forms [290]. The issue of redundancy of the human body was largely explored by Russian movement physiologist, Nicholai (also spelt Nikolai) Bernstein (1967) after whom, control of many degrees-of-freedom to perform a motor skill was named *Bernstein's degrees-*

of-freedom problem [292]. Within his essay *"On Motor Control"* [293], Bernstein summarised the problem of the "unusually rich mobility" of the human body as an issue of how to attend to and control all elements of complex movement simultaneously. Given that this is considered to be impossible through any executive cognitive function, according to Bernstein, the solution was that motor coordination overcomes excessive degrees of freedom by simplifying and limiting how motor skills are initially executed, thus turning the motor apparatus of the body into controllable systems [289,293]. Accordingly, Bernstein purported that during the initial stages of learning a new skill, the motor system of the human body utilises a strategy to greatly reduce the number of possibilities in the execution of that skill by "freezing degrees of freedom" [289]. Thus, early stages of learning are characterised by relatively rigid and fixed linkages between different parts of the body, making it easier for the motor system to manage and regulate [292]. However, through practice, according to Bernstein, the imposed constraints of the degrees of freedom are loosened, enabling greater levels of independent motion and, in turn, increased levels of skilled performance [186]. Therefore, the acquisition of coordination is regarded as the process of mastering redundant degrees of freedom by harnessing greater control and utilisation of the abundant movement possibilities that are available [292].

Evidence for the above described process has been found by Hodges et al. [294] in learning of the soccer *'chip'* shot using the non-dominant leg. Across nine days of practice (and a total of 425 practice attempts), Hodges et al. [294] observed reduced hip range of motion across the first five days of practice, after which it was observed to increase. Alongside the observed increase in hip mobility, participants were found to improve their accuracy in the chip shot, as was determined by the radial score which combined the height and width error scores relative to the target. Based on their results, Hodges et al. [294] suggested that across the nine days, there was a process of *'freezing'* and *'freeing'* of degrees of freedom in order to meet the requirements of the task which, during the initial stages of learning, was not necessarily effective nor precise. Accordingly, the freezing of degrees of freedom may be considered to create suboptimal and somewhat dysfunctional motor skill performance in the initial stages of learning; however, through extended practice and the progressive release of degrees of freedom, motor skill performance becomes more refined and fluid [292,295]. Thus, according to Bernstein, the freezing and freeing of degrees of freedom is the motor control solution utilised by the human body in the acquisition of motor skills [295], such as those which one might encounter on the basketball court. On this basis, motor control is concerned with how the nervous system manages degrees-of-freedom and its interactions with other body parts and the environment to produce coordinated movement [296]. In turn, motor learning may be regarded as the process by which motor control processes may be altered to meet the requirements of a given motor task. However, an alternative perspective is that motor skills develop out of motor control processes and, in turn, motor skills are simply a reflection of increased levels of motor control [287]. That is, that motor skills are not necessarily acquired and instead, they are developed through ever enhanced levels of motor control in response to practice. In either instance, theories of motor control are pertinent to the exploration of the FMS concept.

Traditional ideas on motor control had their basis in *information-processing theories* and were centred around the notion of '*motor programmes'* which function much like a computer programme does on stored commands, possessing a set of commands for the execution of a given movement skill [292]. It was from this perspective that the *"memory-drum theory"* was proposed by Henry (1960), within which motor programmes are stored as a set of commands and used to direct the neuromotor details of motor skill performance [27,186]. However, a point of criticism of the memory drum theory, was its suggestion that every motor skill would have its own motor programme [27]. In response, the so-called *storage problem* was used to challenge the memory-drum theory on the premise that the central nervous system would not possess the required storage for individual motor programmes [297]. Linked to the storage problem, further criticism related to what was termed the *novelty problem,* which was concerned with how novel skills were acquired and new motor programmes were to be formed [28,186]. Accordingly, the novelty problem related to the issue that unless there was an inherited motor programme for a movement skill, there would be no means to produce an action that had never before been produced, which was a position deemed to be incompatible with the obvious capabilities of the human body [28].

In addition to the memory-drum theory, another traditional motor control theory of influence was the closed-loop theory by Adams (1971) [298]. Where a closed-loop system is one that detects and nullifies error [26], within Adams' closed loop theory, motor control is characterised by a continual feedback process, with information from the limbs being used in comparison to a *perceptual trace* to determine correctness [186,298]. Moreover, to account for detection of error, in addition to the perceptual trace, the closed-loop theory holds that a second memory state, the *memory trace*, is responsible for selecting and initiating the movement which, once executed is taken over by the perceptual trace [186]. Accordingly, the memory trace results from practice and feedback relating to the movement (regarded as a "modest motor programme") [27], while the perceptual trace accounts for the guidance toward the correct position by comparing feedback regarding the actual position in space with the desired position [298]. Through these two memory states, during the movement, an individual compares incoming perceptual information (e.g., proprioceptive, visual, and audio) to those formed from previous experiences (within the perceptual trace) to determine whether or not adjustments must be made [27]. For example, in the act of dribbling a basketball towards the basket before attempting a lay-up shot, a performer will utilise perceptual information that will determine adjustments to their approach velocity and dribbling cadence to enable effective footwork to execute the lay-up shot. However, despite the strengths of Adams' closed-loop theory (e.g., its concern for learning novel tasks and its relative simplicity [27]), a key limitation of the theory was its inability to account for open-loop processes, whereby information during performance of a skill (termed '*online'* feedback) is not available to make corrections once the movement is initiated [186]. Typically, open-loop control has been considered to relate to rapid ballistic actions, where pre-planned instructions enable an action to be executed without feedback modification [292]. Therefore, the information processing-based closed-loop theory by Adams (1971) was deemed to offer an incomplete account of motor control and learning.

Out of dissatisfaction of Adams' closed-loop theory, Schmidt's (1975) schema theory, which is one of the most prominent theories of motor control and learning was conceived [297]. Schmidt's schema theory attempted to combine aspects of both open- and closed-loop control [27,186,292]. Moreover, through the retention of some of the features of the motor programme concept, Schmidt's schema theory also provided somewhat of a solution for the aforementioned storage and novelty problems [27,186,292,297]. Within psychology, a schema represents a rule or set of rules that provide a cognitive framework for the formulation of a decision [244,299]. Thus, with its origins in information processing theory [28], Schmidt's schema theory for motor control holds that two generalised memory structures responsible for the control and learning of motor performance: the generalised motor programme (GMP), and the recall schema [300]. The GMP represents "pre-structured" commands that specify a class of movement that can be altered in its movement parameters through specific response instructions [27]. Accordingly, the GMP represented Schmidt's solution to the storage problem in that a class of actions could be represented by the same GMP [292]. The second memory structure within schema theory, included two types of schema termed the *recall schema* and the *recognition schema* [28,186,292]. According to the theory, the recall schema is thought to be responsible for retrieval of the information and the shaping of the parameters that specify the precise nature (scaling) of a given movement [29,300]. The recognition schema, however, is considered responsible for the movement evaluation, and is purported to be formed of the relationship between the initial conditions, the environmental conditions, and the sensory consequences [186]. Through construction of both '*schemata'*, information related to each time a skill is performed, including sensory consequences and the response outcome become linked and then utilised to improve performance of the skill, even when executed under novel conditions [292].

The typical building block analogy used for to explain the purpose of FMS appears to align with concepts from the schema-related prescriptive theory of motor learning [239]. Specifically, the notion of GMP, that accounts for a class of motor programmes that share characteristics appears (e.g., forms of bipedal locomotion) to bear similarity to the typical categories of FMS (locomotion, object, manipulation, and balance), all of which encompass a diverse range of skills (e.g., running, crawling, skipping in the case of locomotion). Moreover, the very notion that the development of a basic version of a skill can be utilised to develop a skill that is deemed to be more complex, such as SSS, would appear to relate to another of the schema theory's concepts, termed '*parameters'*, which are purported to be supplied to the GMP to determine how it is to be executed in a particular instance (e.g., force, duration, and muscle selection) [186]. From this perspective, it is conceivable that the notion of FMS underpinning the development of skills that are more complex was formed. For example, the throwing action involved in throwing a dart and a paper aeroplane may share a throwing (object manipulation) GMP that is varied based upon parameters in relation to, for example, the amount of force that might be required to propel an object a specific distance. Thus, the increase in complexity relates to changes in the parameters, which Schmidt referred to as "*parameter learning"* and represents modifications made to the schema related to the specific motor skill even though the same GMP is utilised [28]. Similarly, for the execution of a vertical jumping action, elements of a squat pattern (e.g., triple flexion and extension of the lower limbs during the descent phase and the countermovement phase of the vertical jump respectively) may be inferred to derive from the same GMP. Indeed, within the S&C field, the use of what is termed *"complex training",* which typically pairs the performance of a heavily loaded lower limb strength exercise (e.g., the back squat) with the subsequent execution of a kinematically similar jumping exercise to increase neural activity [301–303], would appear to align with the notion of GMPs. Although complex training is not necessarily framed from a GMP perspective, the squat pattern is deemed to be ubiquitous in everyday activities (e.g., the act of sitting and standing) and general athleticism (e.g., in the performance of the countermovement phase of vertical jumping) and, therefore, development of proficiency in the skill is considered to form an important foundation upon which other athletic skills can be acquired and developed [238,304,305]. Certainly, this appears to be the perspective adopted within what is termed the *"Athletic Motor Skills Competencies"* (AMSC) guidelines, which extend from the YPD model by Lloyd and Oliver [33,238,306] and present guidence for the progressive development of athletic movement skills and capabilities based on technical competency. Indeed, the AMSC reinforces the notion of FMS as building blocks for more advance movement skills, emphasising that task complexity should only be increased in line with the capabilities of the individual [307]. For example, in their *conceptual decision-making process model'*, Lloyd et al. [307] stated that when complexity is added to a movement skill (e.g., increased movement velocity), it should be based upon consistent demonstration of competency in more basic versions of that particular skill by the trainee (e.g., static holds). Collectively, it appears that the building block analogy that has been typically employed as justification for the development of FMS has its basis in Schmidt's schema theory, which utilises the logic of a GMP to represent classifications of movement skills, much like the broad categorisations used to define FMS.

Compelling support for the existence of GMPs is found in comparisons for different jumping intensities. For example, Van Zandwijk et al. [308] found that the control of maximal and submaximal jumping followed a similar shape of the control signals of the activated musculature with no differences in EMG activity between the two intensities in many of the contributing muscles. The authors postulated that jumping at submaximal and maximal vertical jumping may utilise a generalised motor program (GMP) with differences only in the control signals of bi-articular muscles and resultant kinematic differences, characterised by less angular displacement of the hip and knee joints in submaximal jumping. In light of this, the GMP can be scaled through the manipulation of movement parameters, including force and speed of execution, to satisfy the required outcome as determined by the coach in a given scenario [29]. The findings of Van Zandwijk et al. [308] are supported by previous studies examining vertical jumping performance, which have observed similarities in muscle activation patterns and the use of power transfer via bi-articular muscles of the lower limb in a proximal-to-distal fashion [309,310]. Indeed, further evidence of this in vertical jumping was also observed in the more recent principle component analysis by Cushion et al. [311], whose findings supported the proximal-to-distal pattern and revealed only two functional degrees-of-freedom in vertical jumps without the use of contributory arm action. Moreover, in vertical jumping with the use of arms, only three degrees-of-freedom were reported. Collectively, the results of Cushion et al. [311] point towards anatomically governed mechanical constraints that dictate the action of vertical jumping, thus being indicative of a GMP for jumping actions. Indeed, the authors contend that the consistency displayed in jump execution is suggestive of an inherent feature of human movement, and therefore representative of a GMP [311]. However, despite the inherent anatomical constraints in vertical jumping, the execution of SSS in complex contexts (e.g., basketball) may not be fully explained by GMPs when it comes to motor control and learning.

While Schmidt's schema theory provided solutions to the shortcomings of traditional GMP theories, it was developed with a specific focus on discrete motor skills. Discrete motor skills are defined as those with an obvious beginning and ending, such as kicking or throwing a ball, and are therefore considered to predominantly relate to relative simple actions [186,244]. In contrast, *continuous skills* do not display a recognisable beginning and ending, such as driving a car or running, where the end point is arbitrarily determined [186]. More recently, to account for the continuous performer-environment interactions, the *ecological dynamics framework* has proposed contrasting perspectives on motor control [35,312].

2.4.1 Ecological dynamics

The ecological dynamics framework is formed from both ecological psychology and dynamical systems theory [313,314]. Within ecological dynamics, the ecological approach is based on the work of Gibson (1979), who founded ecological psychology in relation to his research on pilots and other service members within the U.S. Army Airforce during World War II [315]. Ecological psychology introduced a novel perspective on understanding perception and perceptual learning, offering insights into the relationship between the organism (individual) and their environment [316,317]. Meanwhile, Dynamical systems theory takes a multidisciplinary approach, which combines mathematics, physics, biology, psychology and chemistry to explain the complexity of systems that continuously change and evolve over various time scales [318,319]. Importantly, applying dynamical systems theory to motor control and development shifts the focus from a mechanical perspective to viewing humans as dynamic, complex systems [318]. The application of dynamical systems theory within ecological dynamics relates to the generic processes of *self-organisation* which refers to the spontaneous emergence of movement patterns due to internal and external constraints placed upon a system [312,319,320]. Such constraints represent boundaries that limit and enable the number of behavioural trajectories that a system can adopt [292]. In motor control, the dynamical systems perspective accounts for the relations between the CNS, the biomechanical and energetic properties of the human body as well as the constraints imposed by the environment and the task [321]. Thus, through the combination of both ecological psychology and dynamics systems theory, the ecological dynamics framework considers the performer-environment relationship to be the most relevant to the understanding of human motor behaviour [322].

Through the ecological psychology lens, information perceived from the environment specifies the parameters that dictate how a skill is performed [323]. Accordingly, ecological dynamics captures the link between perception and action, termed *perception-action coupling*, which accounts for the continuously altering environmental constraints and how the performer is able to adapt their motor behaviour to achieve a goal-directed outcome (Figure 5) [292,324]. In terms of traditional classifications of motor skills, therefore, in addition to the execution of continuous skills, the ecological dynamics perspective appears to present an account of the

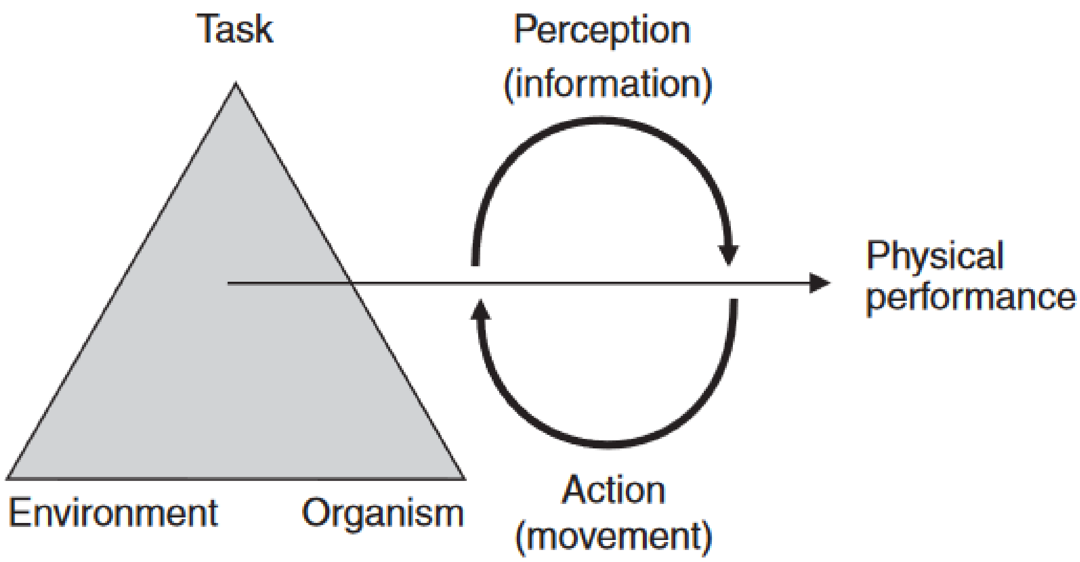

Figure 5. Newell's model of interacting constraints and the role of perception-action 'coupling' in physical performance (of motor skills) (321).

performance of *open-skills*, which represents skills performed in unstable and unpredictable environments [221]. For example, in basketball, which represents an open-skilled sport, perception-action coupling has been shown to occur through the decision-making of offensive players, in possession of the ball, in relation to the occupation of space by defensive players, and their distance from the basket [325] The execution of SSS (and indeed their development), therefore, are reliant upon practice environments that require the performer to perceive relevant information from their environment and shape their action accordingly.

2.4.2 Affordances

Within ecological dynamics, the opportunities for action that an individual perceives from their environment represent what is termed the *affordance landscape* [236,326,327]. Therefore, affordances are the opportunities for action within an environment which are detected by a performer [312]. Moreover, affordances are shaped by the combination of environmental properties (e.g., space, time, terrain, obstacles) as well as their own action capabilities in relation to the requirements of a specific task [34,328]. For example, a basketball player in possession of the ball near the basket detects space between defensive players and, based upon their role (and associated task) as well as their understanding of their own capabilities, determines that they are *afforded* the opportunity to move between the defenders and towards the basket to make a jump shot with the intention of achieving a score. The differences in this example can be related to the classification of skill type, with the vertical jump part of the jump shot movement representing a discrete action that possesses a clear beginning and end and, owing to the predictability of the environment in which it is performed, as well as the fact that the movement is being self-paced, it can also be considered to be a *closed-skill* [329]. On the other hand, although it may be considered to be somewhat of a discrete skill (though the beginning may not always be clear) the jump shot is shaped by a multitude of environmental properties (e.g., defensive players, distance from the basket, time left on the shot-clock) that make it less predictable and more ‘open’ in nature [330]. Accordingly, the jump shot could be considered a more complex skill than the vertical jump given the inherent elements of unpredictability that could potentially affect the intended outcome of the original movement. From this perspective, the learning and refinement of the vertical jump would provide very little basis for improving on performance of the jump shot which, to be improved would require specific and more representative practice that accounts for the performer-environment interaction and the intended outcome of the movement itself [331]. In the absence of such context, the performer would be unable to appropriately detect affordances within their environment (e.g., on the basketball court) to execute a lay-up shot, irrespective of their vertical jumping skill and capabilities. Therefore, the ecological dynamics framework does not appear to recognise the notion of FMS development as a necessary basis for the development of other SSS.

Adding to the notion of affordances, from the ecological dynamics perspective, movement is understood to be temporal and governed by the environmental characteristics unique to each specific situation [332]. In other words, movement is not entirely based upon previously acquired movement skill rather (or GMP and recall schema) [234] and instead manifests as a novel immediate solution unique to the requirements of each task an individual is presented with, at any given point in time. Although, more broadly, motor control is understood to occur via feedforward, reactive, and biomechanical mechanisms, all of which are adaptable and contribute to motor learning [333], the environmental constraints and the capabilities of the individual are also believed to hold significant influence over how movements are performed [239]. Therefore, in contrast to fixed movement patterns, through the practice of SSS within context-specific (or representative) environments, adaptable movement possibilities and muscle synergies, which represent neural organisations, are thought to be established [296,323,334].

The above critical assessment is undertaken not to undermine the importance and necessary requirement of deliberate practice in the development of skills. As has already been discussed, through practice, organisation of the musculature to accomplish the desired motor skill is refined so that a coordinative pattern is established [335]. As captured within the notion of freezing and freeing of degrees of freedom by Bernstein [292,293], novel and initially unstable coordination patterns become more stable with deliberate practice [336] which, at least in part, is thought to be related to improved control of segmental forces within the movement (e.g., coordination) [335]. While this highlights the importance of practice and the necessity of repeated trials of a given skill as a performer learns to control degrees-of-freedom [337], it further highlights the requirement of sports-specific practice in this context. Indeed, practice within sports-specific scenarios are considered to be particularly relevant to how adjustments to a movement skill occur in response to physical perturbations (e.g., unexpected changes to surfaces) and is reflective of the dynamical systems of the human body and its ability to self-organise to accomplish goal-directed outcomes [239,262]. From this perspective, the basic skill of vertical jumping, which is characterised by triple extension of the lower limbs [311], would not provide any prerequisite basis for the execution of a lay-up or jump shot due to the different patterns of execution and associated muscle dynamics, despite both being characterised as jumping actions. Moreover, given that the aforementioned environmental constraints imposed on performance of the basketball-specific skill (e.g., relative position of defensive players) [338], from a motor skill perspective, there would appear to be little benefit derived from the development of proficiency in the vertical jump. Absent from this argument, however, is any explanation of how SSS that are practiced in isolation (e.g., without context-specific environmental properties), may serve to increase performance capabilities of a specific skill (e.g., the jump shot) to any greater extent than a non-specific skill (e.g., vertical jump). Applying the logic that practicing a SSS without context-specific constraints would not be an effective strategy to improve the skill, by extension, there would be no benefit to such practice. However, with regards to FMS, through an ecological dynamics lens, there appears to be a disconnect with any notion these skills forming a basis for any enhanced development of SSS, especially when the context of the sport is considered.

2.4.3 Neurobiological degeneracy

Through an ecological dynamics lens, it may be that the value of FMS in athletic development is more abstract and can be framed more specifically as relating to a tenet of the framework termed *neurobiological degeneracy* [339]. Neurobiological degeneracy refers to the ability to reliably accomplish a given task through various coordinative muscular patterns [340]. For example, in a basketball-specific scenario, a player may adjust their shooting action to account for the positioning and actions of a defensive player [341]. Although the shot is accomplished, the coordinative pattern utilised will differ to other scenarios where the defensive player may utilise another strategy to prevent the offensive player from scoring. In this way, neurobiological degeneracy fundamentally differs from the previously discussed concept of redundant degrees-of-freedom, or *redundancy*, which is the classical concept in human motor control [296,342].

In contrast to degeneracy, redundancy represents repetition of structurally-similar components which are unable to produce outputs in different contexts [343]. However, it could also be that discreetly contained within the skill of the free throw shot, at the neuromuscular level, there is some form of variability in how the action is performed each time the shot is taken. Such movement variability has been proposed to contribute to a reduction to the risk of overuse injury through redistribution of repeated high forces to different tissues over time [102,338,344]. Indeed, the notion of redundancy relates to the phrase *"repetition without repetition"* coined by Bernstein (1967), which refers to how a learned skill can vary in how it is performed while achieving the desired outcome [345]. Although not directly providing evidence of this from a movement skill perspective, inferences can be drawn from research that highlights different movement strategies in response to injury. For example, James et al. [346]

revealed differences in temporal-related measures between healthy active participants and participants with a self-reported predisposition for overuse type lower limb injuries in drop landings from different heights relative to the participants' respective maximum vertical jump height. At 50% of maximum jump height, healthy participants were found to display significantly ($p < 0.05$) greater variability in time to peak moment in the knee joint variable compared with the participants that had a history of overuse injuries. However, in comparisons of peak moments, the participants with a history of overuse injuries were found to demonstrate significantly ($p < 0.05$) more variability in ankle peak moments at 100% of maximal vertical jump height. To account for their results, James et al. [346] speculated that at the lower relative landing heights, the healthy participants may have devoted less attention to the landing and, in turn, exhibited lower control of the movement (therefore, greater variability), compared to the other heights. On the contrary, the participants that had experienced overuse injuries may have expressed greater levels of control. Accordingly, it could be that the healthy participants displayed changes in their landing strategy that enabled them to better distribute the impact forces in the different landings. Potentially, this has implications for youth athletes, especially those with a high prevalence of overuse injuries, such as basketball players. Indeed, where an individual may adopt a particular movement strategy, such as a knee dominant landing, which places the most impact forces on structures around the knee joint [338], greater variability to distribute work would have an apparent importance. However, it is not currently understood whether movement variability in the form of redundancy can be positively affected in response to training interventions. Indeed, given that the freeing of degrees of freedom is typically thought to occur as a function of practice [347], it is logical to suggest that movement variability would be present in well-developed skills. For example, Button et al. [347] observed that more experienced basketball players tended to display greater range of motion variability at the wrist joint in the execution of the free throw shot compared with less experienced players, which may be representative of degrees of freedom having been released through extensive practice. Therefore, redundancy appears to be a concept that relates to sports-specific practice and proficiency in the execution of SSS.

The role of FMS and the rationale for their development may reside with the notion of neurobiological degeneracy and the ability of the body to execute a skill using different coordinative patterns [340,348,349]. This supposition has been previously proposed by Leifeith et al. [10], who contended that possession of a broad set of FMS provides the youth athlete with greater adaptability to cope with perturbation and changes in their sports-specific environment [350]. Accordingly, the development of FMS provides a mechanism for greater neurobiological degeneracy and, in turn, enhanced affordances. Indeed, Liefieth et al. [10] proposed that the possession of a broad range of movement skills leads to an increase in the movement solutions that can emerge. For example, in a basketball player who receives contact from a defensive player while in the act of executing the take-off phase of a lay-up shot may utilise their breadth of movement capabilities to alter their execution of the skill to maintain the intended outcome of scoring. While the same outcome is accomplished, entirely different kinematics may be utilised and, in turn, the execution of the skill may be visibly different to that which is typical (e.g., the use of a reverse lay-up that uses a different arm action to release of the ball). From this perspective, the development of FMS may alter the individual performer's movement capabilities relating (their individual constraints), presenting new coordinative opportunities and affordances. However, despite that logic that FMS would lead to more diverse movement capabilities that could be drawn upon by the performer, currently, no empirical studies exist to support the development of neurobiological degeneracy in the execution of SSS.

The concept of neurobiological degeneracy highlights the adaptability of the nervous system in motor task performance and has been previously observed in experienced ice climbers compared to less experienced individuals [351]. In the study by Seifert et al. [351] differences between experienced ice climbers and beginners were revealed in the range of angular positions of the upper and lower limb, with the experienced ice climbers utilising more varied angular positions of their ice tools. In addition, the experts were able to use a variety of different coordination patterns and movements in comparison to the beginners, which was highlighted in the ratios between different actions utilised by the climbers. For example, the ratio between ice tool swinging and hooking in beginners was found to be significantly larger (1.7 ± 0.7, $p < 0.05$) that than the experienced climbers (0.6 ±0.2). Based upon these findings, Seifert et al. [351] suggested that the experienced climbers were less reliant on the same coordinative patterns and movements and, instead, could utilise a variety of patterns that made for a greater breadth of affordances and more efficient climbing. However, as with the notion of redundancy, neurobiological degeneracy appears to be a phenomenon developed through the extensive practice of SSS and, therefore, the role that FMS could play in enabling the performer to utilise different movement strategies within sports-specific contexts is an area that has not yet been investigated empirically.

2.4.4 Self-organisation

To somewhat address the issue of establishing how the development of FMS may enhance the neurobiological degeneracy in young athletes, it may be pertinent to consider the process of self-organisation more thoroughly. As has been previously described, self-organisation refers to the human body's ability to adapt and utilise alternative coordinative patterns and movements to achieve a given motor task [234,292]. Through self-organisation, it may be that the utilisation of a broader and better developed set of FMS can be utilised without cognition (e.g., use of the working memory) on the part of the performer [352]. Instead, at a subcortical level, the CNS can adapt and self-organise to preserve the execution of the intended goal-directed outcome. This has been shown in studies investigating the effects of pre-exhaustive exercise on subsequent muscular performance in exercises requiring the same muscle groups [353]. In the study by Brennecke et al. [353], it was found that performance of a dumbbell exercise targeting the pectoral and deltoid muscle groups led to increased triceps branchii muscle activation in subsequent bench press performance when compared to performance without the pre-exhausting task. Moreover, no differences were observed to the temporal pattern and recruitment of motor units in the pectoral and deltoid muscle groups between the conditions. As suggested by Brennecke et al. [353], through afferent feedback, the nervous system is able to respond and select alternative coordinative solutions to perform an intended movement [353]. Further support for such adaptability is seen in research related to altered kinematics during exercises executed under different loads. In this regard, van den Tillaar et al. [354] observed non-linear trends in lower limb muscle activation and timing of activation under varying loads during barbell back squatting. Although the studies by Brennecke et al. [353] and Tillaar et al. [354] relate specifically to strength training, collectively, their findings appear to support the notion that while movement patterns may be relatively stable, they are adaptable to perturbed conditions which alter the coordinative execution of the intended motor task. Therefore, it is feasible that the development of FMS (and broad movement capabilities), would afford the nervous system greater latitude to self-organise during the performance of SSS, especially within the complexity of sports-specific contexts [322]. However, whether this is through processes relating to motor redundancy or neurobiological degeneracy is unclear. Nonetheless, there exists a logical argument that the development of broad motor skills and movement capabilities could contribute to greater levels of dexterity and coordination that can be drawn upon by the performer to execute SSS within sports-specific contexts.

2.4.5 Parkour as a donor sport

Building upon concepts from the ecological dynamics framework, an interesting and unique feature of the ASM [31,236], which aligns itself to the framework, is its proposed use of what it terms *"donor sports"*. Donor sports are regarded as a means of diversifying the sporting experiences of youth athletes through participation in an alternative sport to their chosen one, through which transferable skills and capabilities can be developed and transferred [31]. Importantly, within the ASM, Wormhoudt et al. [31] do not suggest avoidance of a single sport per se and instead propose the pairing of a donor sport to the chosen "target" sport of the youth athlete. Accordingly, the implementation of a donor sport alongside the target sport of a youth athlete may enable the simultaneous development of broad motor skills, whilst continuing the development of SSS as well as the perception-action coupling through sports-specific practice.

Based upon the notion of donor sports, and from an ecological dynamics perspective, Strafford et al. [34] suggested that parkour could be used as a viable donor sport as part of the wider athletic development programme of athletes in a variety of team disciplines. Parkour, which is an activity characterised by the navigation of different obstacles, surfaces, and terrains, originates from George Hébert's *Méthode Naturelle*, which was a training model utilised to develop basic movement skills [355]. Moreover, parkour is characterised by a vast array of movement types including swinging, jumping, balancing, running and vaulting and may therefore be considered to be an "*acrobatic*" sport whose exponents must display extensive athleticism to achieve success [34,356]. Within their perspective piece, Strafford et al. [34] argued that the use of parkour could contribute to the development of what they termed *"functional athletic abilities"*, such as coordination, balance, change of direction skill, strength, and reaction speed, all of which could be transferred to a given target sport. In addition to this, the jump landing strategies typically utilised within parkour, which are characterised by lower ground reaction forces due to deeper flexion angles of the lower limb, may contribute to safer landings and more efficient eccentric force development in sports that require high volumes of jumping and landing, such as basketball [34,357]. Moreover, through its requirements for active problem solving while executing intricate manoeuvres, parkour may promote creative movement behaviours, whilst simultaneously providing a physical and psychological conditioning stimulus to the performer [313]. Accordingly, against the backdrop of youth athletic development and the contentions of the various models (e.g., LTAD and YPD models) advocating for the development of FMS ahead of SSS, it may be that through its use as a donor sport, parkour would satisfy the development of broader movement skills than those developed within the sport alone, while also accounting for concepts from the domain of motor learning, particularly those related to the ecological dynamics framework. Accordingly, this could facilitate the transfer of skills from parkour to the target sport, a point supported by a Delphi study by Strafford et al. [358] which included the perspectives of 21 talent identification and S&C coaches. In that study, the panel agreed that parkour-based training would be useful in the development of athletes' movement capabilities. Furthermore, the panel agreed that parkour-based training could play a role in developing movement skills within team sport athletes which are not strictly sports specific. These findings appear to support the previously discussed benefits that donor sports, such as parkour, could provide to sports organisations, national governing bodies, and administrators that are tasked with the design and implementation of an athletic development strategy. It could be that parkour provides a method that could enhance FMS and SSS concomitantly. Specifically, owing to the high jump volumes and high frequencies of changes in direction, the use of parkour-based training may be beneficial to youth basketball players

Of pertinence to the donor sport concept, Strafford et al. [34] contended that there must be an overlap between the affordances developed in the donor sport environment and that of the target sport for successful transfer of the enhanced capabilities to occur. Accordingly, any improvements in performance within the parkour environment would manifest within the target sport through increased affordances [313]. For example, the development of enhanced and diverse jumping capabilities using parkour could theoretically enable a youth basketball player to detect new opportunities to utilise these skills within basketball-specific scenarios, such as making a defensive rebound to collect the ball from an unsuccessful shot.

Despite encouraging research that suggests that parkour could be an effective donor sport for the development of FMS in youth athletes, it is not entirely clear to what extent overlapping affordances must be shared between the respective disciplines. Strafford et al. [34] made the argument for the enhancement of what are termed in the ecological dynamics framework as 'intrinsic dynamics', a concept which represents a performer's current capabilities (e.g., strength and postural stability). However, in contrast to conventional S&C-based activities to increase such capabilities, intrinsic dynamics may also account for perceptual and cognitive skills [328], which may contribute to a greater transfer of skill between the donor and target sports. To some extent, work by Sheppard and Young [359], previously highlighted the importance of the perceptual and decision making factors in agility based tasks. The authors presented a model that outlined the physical components of what they referred to as relating to *'change of direction speed'*, that encompassed training outcomes typically utilised within S&C programmes to develop agility. However, to emphasise the importance of decision making and perceptual skills, Sheppard and Young included a separate arm to the model that presented cognitive components, such as visual scanning, knowledge of situations, and anticipation. Collectively, the aim of their model was to highlight the interdependency of physical and perceptual-based components that influence agility-based performance so that S&C practitioners can make more critical decisions relating to programming of activities to enhance this quality. Therefore, the model by Sheppard and Young [359] was somewhat pivotal in adding a perceptual and cognitive dimension to the assessment and enhancement of sports-specific agility that had previously lacked widespread consideration within the S&C field. Importantly, it served to highlight that performance goes beyond physical capabilities and encompasses cognitive capabilities that influence performance. However, in contrast to the donor sport concept, as well as the ideas of Strafford et al [34], Sheppard and Young's model of agility was very much based upon sports-specific scenarios being included in the assessment of agility rather than the possibility that both physical and perceptual capabilities may be transferred from one sport to another. While the ideas of Sheppard and Young [359] may well be considered to align to the notion of neurobiological degeneracy, in which the performer can utilise different coordinative structures to execute a given motor skill, a notable difference is that the donor sport enables the development of broader skills that are adopted within the target sport, rather than exclusively through practice of the SSS.

Despite the attractiveness of the donor sport concept, however, there is limited amount research to support its efficacy. Indeed, only a single study by Strafford et al. [235] appears to give some indication of the validity of the claims relating to parkour as a donor sport for team sport athletes. The Strafford et al. study [235] compared a parkour-based timed *speed-run* of an obstacle course with more traditional performance variables typically used for physical assessment in the field of S&C. The researchers reported a large and significant correlation ($r = .824$, $p = 0.001$) between the speed-run time and time to complete the change of direction T-test in young adult parkour athletes (mean age: 23.58 ± 3.01) [235]. Moreover, measures of standing long jump, and CMJ were also found to significantly correlate with speed-run times.

Although their results were limited to parkour athletes, and despite the correlational nature of the study design, the Strafford et al. [235] study provides viable preliminary evidence that physical capabilities could potentially be developed through parkour-based activities. However, to date, no empirical studies have been undertaken to directly support the donor sport concept of the ASM. Thus, the donor sport concept is currently limited to theoretical concepts and empirical evidence is required to determine its validity as a strategy within the athletic development of youth athletes. Further, within basketball, where the implementation of parkour may well be of value, scientific studies related to its feasibility to implement and its efficacy in the development of the performance capabilities of youth players are needed.

2.5 Beyond athletic development: the physical literacy concept

Despite the apparent shortcomings of the models of athletic development (DMSP, LTAD, YPD, ASM) it would appear that the models promote a holistic approach to athletic development, considering the health and welfare of youth populations in the physical, psychosocial, technical and tactical domains [13,360]. Indeed, the LTAD model encompassed two pathways of development, one of which has already been discussed and relates to the development of elite athletes, while the pathway entitled *"active for life"* promotes physical activity throughout the life course [166]. The active for life pathway includes five key areas: retention of participants in sport and physical activity for life; motivating sedentary people to be physically active; transitioning athletes into wider roles outside of competing; facilitating continued participation across childhood and adolescence; and developing sports and physical activity leaders [32]. Such aims appear to very much align with the concept of physical literacy, which is defined by the International Physical Literacy Association as *"the motivation, confidence, physical competence, knowledge and understanding to value and take responsibility for engagement in physical activities for life"* [361–363]. Therefore, physical literacy represents a multidimensional construct that extends beyond physical capabilities and athletic development [364]. From this perspective, it is certainly the case that models of athletic development have attempted to account for broader outcomes than simply increasing physical capabilities, such as reducing the risk of lifestyle-related diseases (e.g., obesity and type II diabetes) and improving general well-being [14,236]. Indeed, the emphasis on development of motor skills during early and middle childhood in the discussed models of athletic development can be regarded to be somewhat of a strategy towards the development of physical literacy. For example, the promotion of early diversification before specialisation within both the DMSP and ASM is stated to be of benefit to psychosocial health and wellbeing, as well as the enhancement of physical competencies [236,285]. Moreover, within the DMSP, the notion of the *sampling years*, representing the period between ages 6-13 years, closely aligns with the FUNdamental stage of the LTAD, emphasising fun and enjoyment through engagement with a range of sports and physical activities [84]. Such a feature is also apparent within the YPD model, which regards itself as a "vehicle for athlete well-being" through a child-centred approach that contributes to physical and psychological health benefits alike [33]. Likewise, the underpinning rationale for the ASM includes a narrative relating to a decline in physical fitness of children and a rise in what it terms as *movement poverty*, as well as the potential future health implications of child inactivity [31]. Accordingly, models of athletic development can be considered to be for all youth rather than for the unitary purpose of sporting success [360]. Accordingly, in more contemporary literature the term "athlete development" has been replaced with "athletic development" to represent more general applications of such training outside of the sports domain [86]. Although this would appear to be somewhat contradictory to the LTAD model's origins (e.g., producing international sporting achievements) the underlying intention of the LTAD has always been for improved levels of coaching and organisational practice in the development of children and adolescents [32,365]. Indeed, alongside the performance-oriented pathway, a participation focused LTAD pathway was also developed under the overreaching aim of facilitating the people of Canada to be *'active for life'* through sports participation that was for enjoyment rather than pursuit of elite level success [32]. Accordingly, the early stages of the model (e.g., active start, fundamentals, and learn to train) provided a shared basis for all children, irrespective of whether the performance-oriented pathway or the participation-oriented pathway would be followed. Thus, Balyi et al. appeared to regard the development of FMS as a critical factor towards increasing physical literacy. Moreover, in their more recent iteration of the LTAD model, Balyi et al. [32] adopted the concept of physical literacy more explicitly and stated that the framework aimed to foster a positive attitude towards physical activity through the development of skills and attitudes prior to the onset of the adolescent growth spurt. However, despite its holistic intentions, there is little evidence of these outcomes within current practice [365]. Important to note, however, is that the LTAD model has provided a pragmatic framework to be developed upon as an ongoing process and altered in accordance with empirical research [178]. Therefore, sports organisations and national governing bodies, such as Basketball England, which have adopted and utilised aspects of the LTAD model as a basis, are themselves accountable for the implementation of the wider physical literacy concept. Instead, however, such organisations appear to have placed more emphasis on enhancement of physical performance (e.g., S&C-related components) rather than the broader and more long-term outcomes that are representative of physical literacy [10,366].

Although there is explicit mention of physical literacy within the LTAD and YPD models as well as the ASM and DMSP, in addition to the lack of empirical evidence for the attainment of such outcomes, there appears to be a narrow lens through which the physical literacy concept is viewed within the discussed athletic development frameworks. The physical literacy concept, which has existed for several decades, has been most notably highlighted through the work of Whitehead [367,368] who, upon the philosophical foundations of phenomenology, existentialism and monism, has argued for the importance of movement and physical activity in relation to the embodied experience. Accordingly, physical activity is subjectively experienced by the individual based upon their unique actions within a given situation and also, the way in which that individual perceives the environment around them [361,369]. Accordingly, despite youth athletic development models emphasising the development of technical and physical competency (and the long-term holistic benefits that may also be realised through this), which aligns somewhat to physical literacy concept, there is an apparent lack of acknowledgement and consideration given to broader constructs such as the environment within which certain skills are typically carried out. Accounting for this, at least to some extent, may be the ambiguity that exists regarding physical literacy, as well as the apparent dearth of empirical research into the concept, as has been argued by Bailey [366]. Accordingly, while the physical literacy is an attractive and seemingly important concept, there appears to be a lack of consensus relating to its implementation. However, borrowing from the LTAD model, the notion that FMS development provides the critical basis for the development physical literacy, due to its alignment to the ecological dynamics perspective, the ASM appears to present the most comprehensive account of movement that extends beyond mere physical athletic development, acknowledging the various perceptual, cognitive and contextual variables that can impact upon movement and skill acquisition. Indeed, the ASM supports the notion that movement is the net result of the individual executing both the task at hand whilst also negotiating the myriad of environmental constraints that can alter the context of that movement [31,34]. Accordingly, such a perspective can be considered to be more closely aligned to the philosophical underpinnings of the physical literacy concept (e.g., phenomenology) [369]. Moreover, owing to the supposed interdependency between perception and movement that the theoretical framework espouses, it may be that the use of the ecological dynamics perspective within the implementation of an athletic development strategy may better develop broader physical literacy constructs than models that place emphasis on the physical component alone. Indeed, as is encapsulated in the title of his article that challenges the ideas of Barnett et al. [370], Pot et al. [369] argue that *"meaningful movement behaviour involves more than the learning of FMS".*

2.6 Summary of the literature of review

To the best of the author's knowledge, not a single scientific study has been carried out with a view to elucidating the effects of an ecological dynamics-based approach on the development of FMS and the broader movement capabilities in youth athletic populations. Furthermore, no empirical research currently exists to explore the development of FMS in youth basketball players and the effects of these skills on basketball-specific performance, and how such effects may across different stages of maturation.

Within models of athletic development, the emphasis typically placed on the development of FMS ahead of the development more complex SSS appears to be grounded in logic that is centred on best practice, yet little attention appears to be given to the methods to develop them. Moreover, there is a paucity in the empirical research to support the need for FMS to be developed as a basis for the subsequent development of SSS, which calls into question the precise role of FMS within models of athletic development. Nonetheless, amid concerns over the implications of early sports specialisation, the development of broader movement skills than those specific to the sport, such as FMS, remains an important area of focus within youth-based training literature.

In the developing nervous system of children, naturally occurring patterns of motor development occur in accordance with growth and maturation. Based upon these developments, continuous exploration and practice enables the motor skills of children to become more refined. Accordingly, the years from middle childhood up to adolescence are thought to represent a golden period for motor learning. Although there is little scientific evidence to support a golden period for motor learning, it is against this backdrop that the notion of FMS development being of high importance has likely emerged. However, where both FMS and SSS represent ontogenetic skills that are culturally dependent, their ubiquitous level of importance during this golden period may also be questioned. Moreover, when considered in the context of motor learning theory and, specifically, the ecological dynamics framework, the importance of FMS development and the influence that FMS may have on the development of SSS, is unclear from within the current research literature. Specifically, where movement skills are thought to be governed by the interacting constraints of the individual, task, and the surrounding environment, there appears to be a disconnect in the rationale for FMS development prior to the learning of SSS that is devoid of consideration of perception and action coupling.

Despite the abovementioned concerns, from the ecological dynamics perspective, ideas relating to the dexterity of the nervous system, such as neurobiological degeneracy and detection of affordances, may provide a theoretical basis to critically examine the role of FMS and their potential influence on sports-specific performance. In relation to this, the donor sports concept proposed within the ASM, which is underpinned by the ecological dynamics framework, may be a method that could be utilised to develop broad movement capabilities that are transferable between sports. Accordingly, parkour has been suggested to be a donor sport that could develop physical and perceptual skills that could be transferred to team sports, such as basketball, which would enable youth athletes to develop an enriched repertoire of movement capabilities that contributes to improved neurobiological degeneracy and enhanced perception-action coupling within sports-specific performance.

Within youth basketball players, where the existence of a disconnect between athletic development strategies and the sport have been highlighted, the use of parkour as a donor sport may be an effective method to develop movement skills beyond those that are developed through the sport alone. Such a strategy may improve movement capabilities and adaptability in players to a greater extent that conventional S&C-based activities which, in contrast to basketball, are typically limited to fixed movement patterns.

Through a comprehensive and critical lens that combines ideas from the literature relating to athletic development, S&C, and ecological the dynamics framework, the intention of this research is to examine the importance of FMS development in youth, and to examine an effective method to enhance them. Accordingly, based upon the donor sport concept, the use of parkour-related training in youth basketball players will be investigated as a potential method that could be used to develop FMS and basketball-specific performance concomitantly. Such research could have implications for national governing bodies, such as Basketball England, and shape future perspectives in relation to the athletic the development of youth basketball players

Chapter 3

Neuromuscular Training and Motor Control in Youth Athletes: A Meta-Analysis

Journal citation

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Abstract

The purpose of this review was to determine the effects of bodyweight-only NMT programmes on motor control of movement among youth athletes. Three electronic databases were searched (CrossRef, Google Scholar, and PubMed), using the following inclusion criteria for selecting research studies: (a) healthy male and female participants aged 8-18 years who were engaged in organised sports; (b) interventions up to 16-weeks duration; (c) incorporation of a control group; and (d) interventions that utilised only exercises using participants' body mass. We calculated pooled estimates of effect sizes (standardized mean difference) for changes in motor control across nine studies (12 comparisons) using the inverse-variance random effects model for meta-analyses and 95% confidence intervals. Among the nine studies included in our meta-analysis, there was a moderate, significant effect in favour of neuromuscular training programmes (0.79 [95% CI: 0.38, 1.20], Z = 3.76 [$p = 0.0002$]) on motor control. Heterogeneity was high and significant ($I^2 = 77\%$ [$p = 0.00001$]). Moderator analyses for age and stature revealed NMT programs to be more effective in younger, shorter, and lighter individuals. In addition, larger effect sizes in males, and for programmes > 8 weeks in duration were observed. In conclusion, older and heavier an individual is, the less effective bodyweight-only NMT programmes became, particularly for female participants. These results reinforce the notion that exercise to enhance motor control should be emphasised during the pre-adolescence period of growth and maturation.

3.1 Introduction

Individual variations in the timing of the adolescent growth spurt, in addition to other biological changes associated with growth and maturation [121], including structural and functional alterations of the brain, and development of the neuroendocrine system [209], create complexity in the training and development of young athletes [121,371]. The point at which the fastest rate of growth occurs during the adolescent growth spurt has been termed PHV [371], typically occurring between the ages of 10-12 years in girls, and 12-14 years in boys [121]. This period can result in changes in stature of ~ 8 cm/year in girls and ~10 cm/year in boys [122]. Importantly, however, changes in body mass do not occur in parallel to increases in stature [372]. Such disparities between growth-related rates of change may be associated with a temporary reduction in motor coordination [373] termed "adolescent awkwardness," and they are purported to represent a period of impaired neuromuscular control as a result of increases in limb length in advance of muscular changes to strength [374], as well as possible temporary limb length discrepancies [158]. These physical and biological changes add further complexity to the learning of motor skills, which are understood to develop in a non-linear and unpredictable fashion [375]. In addition, intensive sports-specific training occurring during periods of significant maturational change are understood to increase the risk of traumatic and overuse injury occurrence [371]. Indeed, a substantial body of literature has addressed the associated problems of early sports specialisation and injury risk [9,13,93,376,377], with young athletes' heightened vulnerability around PHV having been previously highlighted in epidemiological studies of youth soccer [371,378].

The foregoing concerns have led to NMT programmes that better prepare children for the rigours of their sports [14,379,380]. In this context, NMT has served as an umbrella term for an array of these training interventions, incorporated within a programme of athletic development that includes exercises targeting muscular strength, mobility, balance, and impulsive movement [381,382]. Accordingly, enhancing athletic foundations in young athletes, and presenting a diversity of physical demands to the neuromuscular system are considered important means to both improve movement quality and mitigate the risk of injury [13,383].

A key objective of NMT programmes is to improve movement competency [384]. In light of this, NMT programmes can be considered important to the development of FMS that are commonly promoted in models of youth athletic development [10] and broadly defined as movement patterns that involve two or more body segments [6]. Typically utilised in athletic settings, FMS have been assessed against criteria for desirable technical execution that are thought to be an indication of movement quality and proficiency [384]. Consequently, FMS relate to motor control and represent the central nervous system's ability to orchestrate coordinated and purposeful movement in relation to the body's interaction with its environment [385]. Further, motor control in the execution of movement may be characterised by the maintenance of posture and balance in the presence of expected and unexpected perturbations [386]. Such characteristics are typically evaluated in the assessment of FMS proficiency [6].

Despite responses to training programmes being difficult to detect where the learning of new motor skills is necessary [375], in youth, generic programmes, such as "integrated neuromuscular training" [387], the "FIFA 11+" and "FIFA 11+ kids" warm-up protocols [377,388] have emerged to enhance athletic foundations in youth athletes [307,387]. Indeed, these programmes have been found to contribute to a reduction in injury risk through improved motor control, which in turn could enhance performance within sport [307]. Moreover, these programmes have appeared to be efficacious in mitigating the risk factors for injuries when they have been implemented in short bouts, such as within warm-up protocols [389]. For example, following 15 sessions of the "FIFA 11+" warm-up programme performed twice per week for 7-8 weeks, preadolescent female soccer players were found to have reduced knee valgus moment during a double-legged landing movement [388]. Similarly, in boys, the "FIFA 11+" kids programme, consisting of seven key movement patterns, including running, jumping and landing mechanics, and balance and coordination tasks [390,391], improved dynamic postural control, as well as jumping and change of direction abilities [377].

While the results of intervention studies provide evidence for the effectiveness of NMT in contributing to injury risk reduction, it remains unclear if changes in motor control are influenced by an individual's stage of biological maturation, as has been found in relation to other types of training [168,392]. It has previously been suggested that, due to children's high neural plasticity, FMS should be developed in preadolescence [9–11]. Spear [209] theorised that repeated exposure to FMS activities in middle childhood could lead to better retention of practiced skills as individuals mature through adolescence. This notion, however, has yet to be confirmed within the relevant literature. In the case of NMT specifically, there has been no review of pooled data from prior research to determine the effects of those NMT programmes that exclusively rely on bodyweight training on motor control for tasks such as jumping, dynamic balance or coordination. While a recent systematic review and meta-analysis by Faude et al. [393] investigated the efficacy of injury prevention programmes on neuromuscular performance, that study did not examine the effects of these programmes on motor control. In this systematic review and meta-analysis, we aimed to determine the effects of bodyweight-only NMT programmes on motor control of movement among youth athletes, and to evaluate the moderating effects of factors related to growth and maturation, sex, and programme duration. We surmised that the effects of NMT programmes on motor control would be moderated by body size, and that mass would be of value in the surveillance of youth athletes thus contributing to the research related to allometric scaling across stages of maturation [372,394].

3.2 Method

3.2.1 Experimental Approach to the Problem

This meta-analytical review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [395].

3.2.2 Literature Search

In October 2020, three electronic databases (CrossRef, Google Scholar, and PubMed) without date restrictions were searched. A systematic search followed by manual searches of electronic data bases and reference lists of relevant studies and reviews, including only articles published in the English language. Te following search terms were used in the systematic search: "Youth" OR "adolescents" AND "maturation" AND "neuromuscular programme" OR "foundational movement skills" OR "fundamental movement skills" AND "movement quality" OR "movement control." In selecting studies for inclusion, all seemingly relevant article titles within each data base were reviewed before examining article abstracts and then full published articles. The initial literature search was performed by the principal researcher.

3.2.3 Procedures

Data extraction was also undertaken by the principal researcher and reviewed by the supervisor. Data related to the main study characteristics from the included articles were entered into a spreadsheet created in Microsoft Excel. In instances where data were not reported clearly, article authors were contacted for clarification. In cases where this was not possible, the respective data set was removed from further analyses.

Only original, peer-reviewed research articles were selected for inclusion, and each study involved only healthy males and females with a mean age 8-18 years who were engaged in organised sports. To reduce the likelihood of influence from participants' maturational changes, only studies with interventions up to 16-weeks in duration were selected [392]. In addition, each included study was required to have compared an intervention group against a control group (continuing to participate in their typical sports practices), and intervention programmes were required to have utilised only exercises that utilised only the participants' body mass during performance, rather than any external loads. This was of importance to the investigation of the effects of exercises that could be easily implemented within the warm-up routines and practices of youth athletes, without the requirement of additional equipment and resources. Therefore, in accordance with the definition of NMT, the training programme could incorporate FMS and strength and conditioning activities, such as (bodyweight) resistance exercise, and plyometric training [19]. The outcome measures must have assessed motor control movement tasks involving the lower limb wherein either technique was measured against biomechanically desirable criterion [384], or dynamic balance was quantified. Therefore, these requirements included measures related to kinematic variables in tasks such as jumping, measures of dynamic balance and coordination (including qualitatively assessed movement patterns), and quantitively measured control of centre of mass, such as time-to-stabilisation. Measures related to concentric force production, which were metrics deemed not to be explicitly indicative of neuromuscular control, were excluded. In addition, study designs that did not involve comparison of two or more independent groups or that utilised cross-over designs were not included. The characteristics of the study participants in selected studies are displayed in Table 1.

Table 1. Summary of included studies

Author	Study group	Mean Age (yrs)	Mean Height (cm)	Mean Body mass (kg)	Sex (M/F)	Sport	Participants	Weeks	Mean Frequency	Mean session duration (min)	Intervention type	Test
Ayala et al.	Intervention 1 (FIFA 11+)	16.8 ± 0.7	173.9 ± 6.7	70.2 ± 3.5	M	Soccer	10	4	3	22.5	Warm up: running drills; lower limb strength; balance; muscle control; and core stability	Y-balance test, ROM of hip, knee, and ankle, single leg hop asymmetry, vertical drop jump, 10m and 20m sprint, Illinois agility test
Ayala et al.	Control 1	16.8 ± 0.7	173.9 ± 6.7	70.2 ± 3.5	M	Soccer	11					
Ayala et al.	Intervention 2 Harmoknee warm up programme	16.8 ± 0.7	173.9 ± 6.7	70.2 ± 3.5	M	Soccer	10	4	3	22.5	Warm up programme comprising muscle activation balance, strength, and core stability	
Ayala et al.	Control 2	16.8 ± 0.7	173.9 ± 6.7	70.2 ± 3.5	M	Soccer	10					
Baeza et al. [396]	Intervention (FIFA 11+)	13.45 ± 0.52	160 ± 7	53.18	M	Soccer	11	6	3	20	Warm up: running drills; lower limb strength; balance; muscle control; and core stability	Functional Movement Screen: deep squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, trunk stability push-up, rotary stability
Baeza et al. [396]	Control	13.36 ± 0.67	161 ± 5	57.09 ± 5.46	M	Soccer	11					
De Ste Croix et al. [397]	Intervention	13.1 ± 1.7	155.6 ± 9	49.5 ± 10	F	Soccer	71	16	3	20	Coach led warm-up: comprised of dynamic flexibility; plyometric	Leg stiffness in submaximal hopping test, two-dimensional knee kinematic analysis

											exercise; speed and agility. Player-led “robustness” session: bodyweight lower extremity and trunk strengthening and balance exercises.	of single legged countermovement jump
De Ste Croix et al. [397]	Control	12.8 ± 1.6	154.4 ± 8.9	51.4 ± 9.6	F	Soccer	54			13		
DiStefano et al. [398])	Intervention 1 (Traditional programme)	10 ± 1	144.41 ± 6.01	35.06 ± 5.60	Mixed	Soccer	19 (11 M, 8 F)	9	3	13	Warm up programme including, lower extremity strengthening, trunk strength, plyometric exercise, dynamic balance, multi-directional movement patterns	Single limb time-to-stabilisation test (preferred limb), double leg countermovement jump
DiStefano et al. [398]	Control 1	10 ± 1	141.48 ± 5.95	33.57 ± 5.39	Mixed	Soccer	12					
DiStefano et al. [398]	Intervention 2 (Pediatric programme)	10 ± 1	140.43 ± 7.06	33.31 ± 5.02	Mixed	Soccer	22 (11 M, 11 F)	9	2.5	13	Warm up programme including, lower extremity strengthening, trunk strength, plyometric exercise, dynamic balance, multi-directional movement	

											patterns, and a partnered agility run,	
DiStefano et al. [398]	Control 2	10 ± 1	141.48 ± 5.95	33.57 ± 5.39	Mixed	Soccer	12					
Lindblom et al. [399]	Intervention	14.2 ± 0.7	165.6 ± 6.5	53.9 ± 8.6	F	Soccer	23	11	2	15	Warm-up: Six exercises targeting core stability, balance, landing technique, knee alignment	Star excursion balance test, countermovement jump, modified Illinois agility test, 10- and 10-m sprint tests
Lindblom et al. [399]	Control	14.2 ± 1.1	164.2 ± 6.1	51.6 ± 7.4	F	Soccer	18					
O’Malley et al. [400]	Intervention (GAA 15 programme)	18.6 (18.4-18.8)	181.6 (179.6-183.7)	78.2 (76.2-80.2)	M	Hurling /Gaelic football	41	8	3	15	Running drills, muscle activation/ strengthening exercises, trunk strength, balance tasks, jumping exercises, Nordic hamstring lowers, sprint drills	Y-balance test, landing error scoring system (video analysed)
O’Malley et al. [400]	Control	18.3 (18.1-18.5)	178.8 (176.6-181.0)	74.8 (72.1-77.5)	M	Hurling /Gaelic football	37					
Pomares-Noguera et al. [377]	Intervention (FIFA 11+ Kids)	11.8 ± 0.3	144.7 ± 5.1	39.4 ± 5.5	M	Soccer	13	4	2	17.5	Running based game, jumping exercises, balance/ coordination task, stability exercise, tumbling	Y-balance test, 20-m sprint, Illinois agility test, slalom dribble, wall volley test, standing long jump, countermovement jump, drop jump, hip, knee, ankle range of motion
Pomares-Noguera et al. [377]	Control	11.8 ± 0.3	144.7 ± 5.1	39.4 ± 5.5	M	Soccer	10					

Thompson-Kolesar et al. [388]	Intervention 1 (F-MARC / FIFIA 11+)	11.8 ± 0.8	155 ± 8	42.3 ± 8.7	F	Soccer	26	8	2	25	Warm up: running drills; lower limb strength; balance; muscle control; and core stability	Double and single legged countermovement jumps, pre-planned cutting task, unanticipated cutting task. Motion analysis, kinetic and surface EMG analysis
Thompson-Kolesar et al. [388]	Control 1	11.2 ± 0.6	151 ± 9	38.2 ± 6.3	F	Soccer	20					
Thompson-Kolesar et al. [388]	Intervention 2 (F-MARC / FIFIA 11+)	15.9 ± 0.9	166 ± 4	58.2 ± 5.6	F	Soccer	20	8	2	25	Warm up: running drills; lower limb strength; balance; muscle control; and core stability	
Thompson-Kolesar et al. [388]	Control 2	15.7 ± 1.1	166 ± 6	57.7 ± 7.7	F	Soccer	17					
Zech et al. [401]	Intervention	15.7 ± 3.9	170.8 ± 9.4	57.4 ± 12.6	M	Field hockey	15	10	2	20	Warm up consisting of running drills, strength, balance, plyometric exercises	Star excursion balance test, balance error scoring system, time to stabilisation, postural sway
Zech et al. [401]	Control	14.1 ± 1.4	174.1 ± 13.8	57.6 ± 10.2	M	Field hockey	15					

3.2.4 Data Analysis

Meta-analyses were conducted to determine the effects of NMT programmes in youth participants using the computer programme, Review Manager (RevMan version 5.4, The Cochrane Collaboration. 2020). Means and standard deviations for a post-training measure of movement control were used to calculate effect sizes (ES) across studies. Applying a decision rule related to the most relevant outcomes to the research question [402] alongside a "logically defensible rationale" [403], we included Y-balance and star excursion test scores and measures of knee valgus and time to stabilisation on landing tasks. The inverse-variance random-effects model for meta-analysis was used to allocate a proportionate weight to trials based on the size of their individual standard errors [404], and this also accounted for heterogeneity across studies [405]. The obtained ES values were represented by the standardised mean difference and presented alongside 95% confidence intervals (CI). The calculated ES values were interpreted using the conventions outlined for standardised mean difference by Hopkins et al.. [406] (< 0.2 = trivial; 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large, > 4.0 = extremely large). In cases where there was more than one intervention group in a study, the number of participants in the control group was proportionately divided (means and standard deviations left unchanged) to facilitate comparisons across all participants [407].

Heterogeneity was determined by I^2 values, which provide a percentage of the total variability in the ES owed to between studies variability [408]. Tentative classifications of heterogeneity were low, moderate, and high, and corresponded to I^2 values of 25%, 50%, and 75%, respectively [409]. Heterogeneity was assessed with the Chi^2 test to determine whether the observed differences were compatible with chance alone or, as indicated by a low *p* value, the variation in effect was beyond chance alone [410].

The Physiotherapy Evidence Database (PEDro) scale to assess the risk of bias and methodological quality of the eligible studies included in the meta-analysis, which evaluated the internal study validity using a 10-point scale (0-10; 0 = low risk; 10 = high risk) [411]. The median value of ≥ 6 was the threshold considered to represent a low risk of bias.

3.2.5 Analysis of Moderator Variables

To assess the potential effects of moderator variables, subgroup analyses were performed on moderators likely to influence the outcomes of the NMT programmes. Using the median split technique to form the subgroups, the selected moderators analysed included chronological age, stature, body mass, sex, and intervention duration. Studies in which the recruited sample included males and females were removed when sex as a moderator variable among the remaining sub-group of studies.

3.3 Results

3.3.1 Study Selection

A total yield of 1601 studies resulted from the search (200 from CrossRef; 981 from Google Scholar; and 420 from PubMed). Figure 6 shows the PRISMA flow diagram illustrating the number of excluded studies at each stage of the systematic review process. One study was not included because of the lack of data. Therefore, in total, nine studies met our inclusion criteria and were included in our meta-analysis. The included studies met the required standard to be considered at low risk of bias (median quality score = 6.0). These data are presented in Table 2.

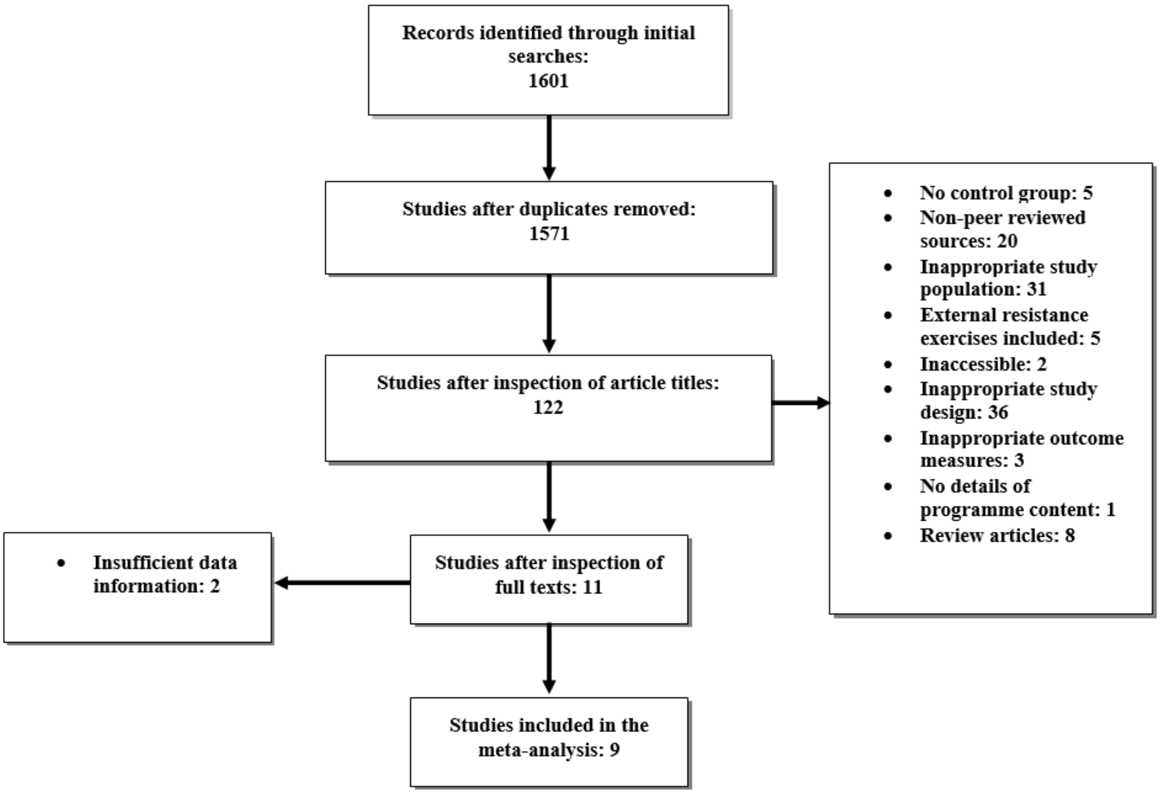

Figure 6 Study selection PRISMA flow diagram

Table 2. Results of PEDro scale showing risk of bias analysis in meta-analysed studies.

	1*	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Total**
Ayala et al.	1	1	1	1	0	0	1	1	1	1	1	8
Baeza et al.	1	1	0	1	0	0	0	0	1	0	1	4
De Ste Croix et al.	0	1	1	1	0	0	0	1	1	1	1	7
DiStefano et al.	1	1	1	1	0	0	0	0	1	1	1	6
Lindblom et al.	1	1	1	1	0	0	1	0	1	1	1	7
O'Malley et al.	1	1	1	1	0	0	1	0	1	1	1	7
Pomares-Noguera et al.	1	1	1	1	0	0	0	1	1	1	1	7
Thompson-Kolesar et al.	1	0	0	1	0	0	0	1	1	1	1	5
Zech et al.	1	1	1	1	0	0	0	1	1	1	1	7

*Item #1 is not used to calculate final rating.

3.3.2 NMT Programme Characteristics

The NMT programmes from the included studies utilised a range of training modalities, including plyometric, lower limb and trunk strength, balance, and running based exercises (see Table 1.). Three of the nine included studies used the "FIFA 11+" warm-up programme, which incorporated unilateral lower limb movement patterns, jumping and bounding exercises, and the "Nordic hamstring" curl. Other included studies implemented very similar programmes to the "FIFA 11+" that also included various forms of unilateral lower limb balance and multi-directional jumping-based exercises, as well as the "Nordic hamstring" exercise [400,401,412]. However, in two studies [398,399] as well as in the "Harmonknee" programme in Ayala et al. , the NMT programmes did not include the "Nordic hamstring" exercise. One study [377] utilized the "FIFA 11+ Kids" programme, specifically aimed at children below 14 years of age to develop general balance and coordination. Across all NMT programmes, prescribed sets for each exercise ranged from one to three. However, depending upon the exercise type, prescriptions of repetitions, distances, and durations differed between NMT programmes.

3.3.3 Main Effect

The primary meta-analysis in this study compared the effects of NMT programmes versus control groups on movement control in youth athletes. From the nine studies included, there were 12 experimental and 12 control groups included in the meta-analysis. From this analysis, there was a moderate, significant ES in favour of NMT programmes (0.79 [95% CI: 0.38, 1.20], Z = 3.76 [p = 0.0002]) on measures relating to motor control on movement tasks requiring dynamic balance or biomechanically desirable technique. Heterogeneity was high and significant (I2 = 77% [p = 0.00001]). These results are displayed in Figure 7.

	Intervention Group			Control Group				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Thompson-Kolesar (2018) 2	-0.01	0.01	20	-0.009	0.01	17	8.9%	-0.10 [-0.74, 0.55]
Zech et al. (2014)	3.3	12.9	15	3.6	7.5	15	8.5%	-0.03 [-0.74, 0.69]
Lindblom et al. (2012)	108.65	7	23	108.55	8	18	9.1%	0.01 [-0.60, 0.63]
Thompson-Kolesar (2018) 1	-0.008	0.01	26	-0.0107	0.01	20	9.3%	0.27 [-0.32, 0.85]
Pomares-Noguera et al. (2018)	102.1	14.3	13	96.4	7.4	10	7.7%	0.46 [-0.37, 1.30]
Ayala et al. (2017) 2	84.1	3.7	10	81.3	4.4	10	7.3%	0.66 [-0.25, 1.57]
Baeza et al. (2017)	14.45	1.29	11	12.9	2.25	11	7.5%	0.81 [-0.06, 1.69]
Ayala et al. (2017) 1	97.3	2.7	10	93.2	4.9	11	7.3%	0.98 [0.06, 1.90]
O'Malley et al. (2016)	92.3	4.14	41	87.05	5.65	37	9.9%	1.06 [0.58, 1.53]
De Ste Croix et al. (2018)	-2.7	1.7	66	-4.7	1.9	54	10.4%	1.11 [0.72, 1.50]
DiStefano et al. (2010) 2	2.11	0.52	19	1.11	0.27	11	7.1%	2.18 [1.23, 3.13]
DiStefano et al. (2010) 1	1.82	0.27	22	1.11	0.27	12	7.0%	2.57 [1.61, 3.52]
Total (95% CI)			**276**			**226**	**100.0%**	**0.79 [0.38, 1.20]**

Heterogeneity: $Tau^2 = 0.38$; $Chi^2 = 47.43$, df = 11 ($P < 0.00001$); $I^2 = 77\%$

Test for overall effect: Z = 3.76 (P = 0.0002)

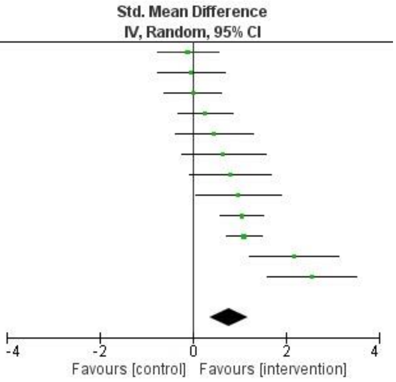

Figure 7. Forest Plot for all Included studies.

3.3.4 Effect of Moderator Variables

A summary of the effect of moderator variables can be found in Table 3. Heterogeneity between trials was revealed to be high across subgroups, except for intervention duration < 8-weeks, which was moderate. The subgroup analyses for age and stature revealed bodyweight-only NMT programmes to be more effective among younger (< 13.8 years), and shorter (< 162.6 cm) than among older and taller individuals. In terms of body mass, there was a larger effect among lighter individuals compared to heavier individuals. Regarding sex, larger effect sizes were found among males than females. For programme duration, there was a larger effect size for longer programmes (> 8 weeks) than shorter programmes (< 8 weeks).

Table 3. Summary of subgroup effect estimate.

Outcome or Subgroup	Trials	Effect Estimate	Test for Overall Effect	Test for Subgroup Differences
Age				
< 13.8	6	1.18 [0.54, 1.81]	Z = 3.62 (P = 0.0003)	P = 0.06
> 13.8	6	0.42 [-0.05, 0.89]	Z = 1.75 (P = 0.08)	
Body Mass				
< 53.9	6	1.04 [0.34, 1.74]	Z = 2.91 (P = 0.004)	P = 0.26
> 53.9	6	0.55 [0.10, 1.01]	Z = 2.37 (P 0.02)	
Stature				
< 162.55	6	1.18 [0.54, 1.81]	Z = 3.62 (P = 0.0002)	P = 0.06
> 162.55	6	0.42 [-0.05, 0.89]	Z = 3.76 (P = 0.0002)	
Sex				
Male	6	0.69 [0.33, 1.05)	Z = 1.11 (P = 0.27)	P = 0.37
Female	4	0.36 [-0.27, 0.98]	Z = 3.74 (P = 0.002)	
Duration				
< 8 Weeks	7	0.58 [0.23, 0.93]	Z = 3.21 (P = 0.001)	P = 0.26
> 8 Weeks	5	1.12 [0.24, 1.20]	Z = 2.50 (P = 0.01)	

3.4 Discussion

3.4.1 Main Findings

The purpose of this systematic review and meta-analysis was to assess the effects of bodyweight-only NMT programmes on motor control among youth athletes. The main findings revealed that bodyweight NMT programmes are effective in improving motor control on tasks requiring dynamic balance and/or a biomechanically desirable movement strategy.

NMT programmes are purported to enhance neural and muscular adaptations occurring in childhood development beyond the naturally occurring alterations in response to growth and maturation [9,413]. The results of this meta-analysis appear to support this, highlighting the effectiveness of bodyweight NMT programmes on improving motor control in children and adolescents engaged in organised sports. Specifically, where the results revealed the programmes to be effective versus control groups that participated in their regular sports-specific practices and/or competition alone, they suggest the requirement to address motor control through programmed intervention. By extension, therefore, sports-specific training practices without this supplementary training appear inadequate to develop FMS and to enhance neuromuscular control in youth athletes. Although it is reasonable to assume that the warm-up protocols performed by the control groups within the meta-analysed studies may have included activities that could be classified as FMS (combinations of running and stretching in the studies by Ayala et al. [414] and Pomares-Noguera et al. [377]), the implementation of an NMT programme serves to ensure repeated exposure (volume/ frequency) and progression of neuromuscular training exercises that contribute to enhanced neuromuscular control. Importantly, NMT programmes typically encompass general training modalities that target a wide range of movement skills and skill-related fitness capabilities [387], providing broad foundations for the development of more advanced sports-related skills [7]. Indeed, given the disparities in the exercises included and the exercise volumes prescribed within NMT programmes among the studies analysed, the findings of the meta-analysis suggest that youth populations may be responsive to a broad range of training stimuli in the form of different bodyweight exercises. Moreover, it appears that the magnitude of the stimulus need not to be substantially large to elicit positive effects on motor control. Nonetheless, a minimal stimulatory threshold does appear necessary given that the regular sports-based warm-up routines performed by the participants serving as controls were insufficient to impart the type of adaptations observed in the experimental cohorts.

In addition to the improvements to motor control that bodyweight NMT appears to elicit, another important feature of these results is that these improvements can be attained through time-efficient warm-up programmes. This finding supports the results of the systematic review and meta-analysis by Faude et al. [393], who evaluated the effects of NMT programmes, typically devised as warm-up based interventions, on neuromuscular performance including isokinetic force and straight-line sprinting. In the current meta-analysis, all included studies except De Ste Croix et al. [397] implemented NMT programmes as warm-ups performed ahead of the participants' primary sports activity. Such time-efficiency presents an attractive method for implementing athletic development focused training within traditional sports practice structures [415]. However, importantly, the efficacy of this approach may vary according to the existing level of motor control and movement competence of the individuals [416]. In NMT studies that have compared the effects that categorised participants by level of proficiency, greater improvements have been found among less proficient individuals [388,416]. This is highlighted in the findings of Thompson-Kolesar et al. [388] who observed varied responses across participants who performed the FIFA 11 + programme twice per week for 7-8 weeks. Baseline differences were suggested to account for some of these observations, with preadolescent girls displaying worse pre-intervention knee valgus in a two-legged jumping task, and consequently improving to a larger extent than adolescent females. Similarly, in their 16-week NMT intervention, De Ste Croix et al. [397] found larger differences between participants identified as displaying a large knee abduction moment in landings from a single leg CMJ compared with participants displaying a low knee abduction moment. Collectively, these findings suggest that the true efficacy of a NMT programme could be confounded by an individual's "ceiling for improvement" [417] as defined by the desired technical characteristics of the measured movement skill. However, limited availability of data in the included studies meant that proficiency could not be analysed as a potential moderator. Therefore, it is speculated that where NMT programmes are generic, it is likely that some individuals will not receive the appropriate stimulus.

Notwithstanding the lack of programme individualisation as potential limiting factor, Thompson-Kolesar et al. [388] stated that the preadolescent athletes in their study progressed to advanced versions of the exercises in their NMT programme. Intuitively, such progression should have increased the intensity of the stimulus for these individuals accordingly, though similarly to De Ste Croix et al. [397], a ceiling effect that impeded adaptation was noted. Although no reporting of how the advancing levels of the intervention affected their results, De St Croix et al. [397] state the likely need to further individualise the contents of the NMT programme so that each young athlete receives the appropriate training. While the findings of the two studies [388,397], perhaps unsurprisingly, suggest that the effectiveness of NMT programmes is likely dependent upon the initial level of motor control and movement proficiency, it is also entirely possible that unique programme characteristics have different neuromuscular effects on individuals, such as improved muscle activation strategies, that may not be detected by the utilised outcome measures [388,418]. Further, the results of De St Croix et al. [397] and Thompson-Kolesar et al. [388] may also reflect a non-linear motor learning process which, within contemporary theories of motor learning, considers each individual to be a complex biological system [419]. Accordingly, training responses may be difficult to detect due to the non-linearity of adaptation and not only because of an inadequate training stimulus. Although in relation to this study, such a perspective is limited to speculation, the extent of an NMT programme's effectiveness is likely to be highly individualised due to a multitude of factors.

3.4.1 Moderator Analysis

Potentially important moderators were related to participant maturational characteristics. Though some subgroup differences remained non-significant, NMT programmes were revealed to be less effective among heavier, taller, and chronologically older youth athletes, suggesting that maturational factors could have a disruptive effect on the extent to which an individual adapts to the imposed NMT stimuli. Importantly, these results suggest greater that challenges are posed to motor control training for larger and more mature individuals. In contrast to these results, in the meta-analysis by Faude et al. [393], older players (≥ 15 years) were found to respond to NMT programmes with larger effects than younger players (< 15 years). Although these measures included balance and stability with similar outcome measures utilised in the present meta-analysis, Faude et al. [393] appeared to combine static and dynamic balance as well as dynamic stability for their analysis. When analysed by subcategory, however, static balance was found to have a smaller effect than both dynamic balance and dynamic stability. Conversely, in the present meta-analysis, only dynamic task measures were included, which may therefore explain these differences. Therefore, it appears entirely reasonable to suggest that the results in the current meta-analysis may relate to greater challenges posed to motor control in larger and more mature individuals.

The findings of the current study support the notion that motor control and movement skill development is easier to develop in prepubescent children [13,14]. In the first decade of life, levels of neural plasticity and new myelin formation are high [420]. As individuals approach adolescence, there is a peak in grey matter development before a non-linear decline occurs [12], and this may contribute to a more difficult acquisition of new motor skills in older individuals. Similar to our findings, Wälchli et al. [421] previously found that dynamic balance improved more in younger children (< 12 years of age) than in older children. Furthermore, a meta-analytic review by Behringer et al. [11] examined the effects of strength training on motor performance skills and found age to be negatively correlated (r = -0.25; $p < .05$) with training-related improvements in motor skills that included jumping, running, and throwing. Collectively, these studies highlight the potential presence of a sensitive or *golden* period for motor learning in pre-adolescent children [182,422]. In contrast, however, rather than a representing a golden period, another possible explanation is that dependent upon the type of motor learning skill, different magnitudes of training stimuli are required to account for stage of maturation. As indicated by Behringer et al. [11] in reference to their results, it is possible that the resistance training stimulus applied within the included studies of their meta-analysis, were insufficient to elicit the same levels of improvement in the older participants that were observed in the younger participants. Therefore, whilst it may indeed be more difficult for older and more mature individuals to develop motor skills, this may not reflect a reduce capability for motor learning but, instead, the requirement of a different training stimulus compared to younger and less mature individuals. Nonetheless, given that motor skills may be developed with a relatively lower stimulus in younger and less mature, it is logical that this period is capitalised upon.

Another interesting result from our moderator analysis was that NMT programmes were more effective among males than females. This finding may relate to differences in female maturational processes, including decreased neuromuscular control, and associated imbalances in muscle strength and activation patterns [19]. However, another important consideration is allometric scaling, which may provide greater insight into the effects of physical growth in males and females [372]. Previously, Pellino et al. [372] found that girls outperformed boys in the standing broad jump when allometric modelling was used to normalise performance for anthropometric characteristics, further highlighting the complex effect of growth and maturation on physical performance. Indeed, increases in mass and stature, alongside increases in knee valgus angle [33], cause a different set of challenges for females than those experienced by males, and these might help to explain this finding. Females typically display decreased knee stability with a concomitant increase in joint torque loads following PHV [423]. Therefore, NMT programmes should gradually become more individualised in their designs in order to account for sex differences around PHV [14].

In terms of intervention duration, advantages to longer intervention periods (>8 weeks) were observed, supporting Faude et al. [393] who also found larger effects from longer training periods. These findings may be explained by the combined effects of exercise diversity and relatively low magnitude of stimuli in NMT programmes. The programmes included in the present meta-analysis each incorporated a broad range of activities, including landing tasks, multi-directional movement patterns, and sprinting within singular training bouts. Such diverse within-session activity logically limits the magnitude of the adaptations that can occur due to low levels of exposure to the applied stimuli within a given session. Accordingly, this increases the duration of the training period necessary to elicit a tangible adaptation. In support of this, NMT programmes implemented within warm-up protocols have previously been found to be effective for a training period of up to six months [389]. Indeed, in the meta-analysis by Faude et al. [393], a moderate effect was found in balance/ stability tasks for NMT training > 23 weeks, while < 23 weeks revealed an effect size that was negligible. A trade-off may therefore exist between the convenience of NMT programmes implemented within the warm-up and the required duration to yield improvements in motor control over time. On this basis, programme durations longer than eight weeks may be required for positive alterations in motor control to be achieved.

3.5 Limitations and Directions for Further Research

There are limitations to the current study requiring they be interpreted with a degree of caution. First, two of our included studies [388,396] scored below the median quality score for risk of bias (see Table 2). These low scores for both studies related to the criterion for blinding of the respective participants and assessors that increased potential bias within the outcome measures. In addition, heterogeneity owing to between-study variability limited the generalizability of these findings [409]. This between-study variability may relate to the disparate methods used across the various included studies. Furthermore, the univariate nature of our subgroup analyses limited an understanding of the study interventions' broader outcomes and any multivariate interactions. Beyond these limitations, the included studies did not include an assessment of the participants' maturity status, which is a limitation on the part of the research designs of the studies. In studies on youth, calculation of maturity offset must always be included in addition to chronological age, body mass and stature. Indeed, such assessment would provide a better insight into the effects of NMT programmes based upon the participants' stage of maturation. Moreover, this information would provide improved understanding of the impact of growth on motor control and substantiate the believed importance of broad and diverse development of FMS and general physical fitness qualities in youth populations that extend beyond sports performance [424].

3.6 Conclusion

The implementation of NMT programmes are understood to better prepare children for participation in organised sport [14,379,380]. Such programmes target improved motor control, which is of particular importance in individuals around the period of the adolescent growth spurt when coordination may be temporarily impaired [374]. Based on the findings of this meta-analysis, the incorporation of bodyweight NMT programmes, within the warm-up, appear to be effective in improving motor control in youth athletic populations. Importantly, these effects seem to be larger in less mature individuals as indicated chronological age, stature, and body mass. These findings may relate to increased neural plasticity occurring during preadolescence, representing a potential *golden period* for motor learning. Based upon the characteristics of the included studies, as a general recommendation to improve motor control, strength and conditioning practitioners could expose youth athletes to NMT-based warm-ups performed two to three times per week across a timeframe of at least eight weeks. Importantly, these programmes should target a range of physical qualities relating to neuromuscular control. In this regard, it appears that generic programmes such as the "FIFA 11+" can provide adequate stimulus. However, for older and larger youth athletes, more individually tailored training may be warranted, and may include greater training volumes.

Chapter 4

Youth basketball coaches' perceptions and implementation of fundamental movement skills training: Towards a realist evaluation

Citation

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Abstract

The purpose of this study was to investigate youth basketball coaches' perceptions and implementation of FMS. Snowball and criterion-based sampling approaches were used to survey youth basketball coaches' (n=79) beliefs and experiences relating to their perceptions and implementation of non-basketball specific skills and FMS into practice. Realist Evaluation inspired the analysis of descriptive statistics (means and frequencies) and reflexive qualitative thematic analysis to inform the results. It was found that the participants had a comprehension of FMS and acknowledge their value in the long-term development of youth players. However, there appeared to be varying levels of uptake amongst the surveyed coaches. The findings suggest there is a need for governing bodies to develop innovative strategies to persuade youth basketball coaches to adopt and implement FMS to improve their practice.

4.1 Introduction

Athlete development models in youth sports are often criticised due to a lack of emphasis on generalised FMS [10,90,425]. Furthermore, FMS are considered foundational for the development of SSS, which experts have argued, that if left undeveloped may limit future performance [16,426,427]. In part, this perspective is based upon the logic that the learning of basic skills should precede the development of more advanced and complex skills, that SSS are thought to represent [6]. In addition to this, there is the notion that a greater the breadth of FMS will result in better opportunities will for skill adaptation to occur in sports-specific contexts [428]. FMS have conventionally been classified as locomotor, ball manipulation, and stability skills [7]. Hulteen et al. [18] have extended conventional definitions to include more diverse movement skills such as leaping and hopping, cycling, treading water, and swimming, all of which can be honed through practice and instruction. From early childhood, rudimentary goal-oriented movements, form the basis for more advanced movement patterns (e.g., locomotive) to be developed [18]. Thus, the development of rudimentary throwing and catching skills can later be refined and specified for ball games that require similar skills such as American football, baseball, and basketball [31].

Previous research has tended to focus upon associations between FMS and physical activity levels, rather than transfer to SSS [cf. 9,33,419]. Systematic reviews by Holfelder and Schott [8] and Logan et al. [215] have highlighted the relationship between childhood FMS competence and uptake of physical activity during adolescence. Further, a substantial body of research [e.g., 102,372,420] has advocated for the use of FMS-based training to mitigate the risk of injury and burnout resulting from early sports specialisation. For example, Bell et al. [431] revealed through their meta-analysis that youth level athletes who were categorised as highly-specialised (i.e. participating in a single sport) were at a significantly greater risk of injury compared to those categorised as moderate and low specialisation (participating in multiple sports). However, there is a lack of dearth of empirical research investigating the importance of FMS development of movement quality and the enhancement of SSS. Although to initiatives have been developed to emphasise the development of FMS in children, encouraging coaches to incorporate them into programs of physical activity, these have tended to focus upon combatting the risks associated with early specialisation [13,284,413]. Such initiatives, however, appear to be devoid of the development of FMS for the purpose of enhancing sports-specific performance through motor learning concepts, such as transfer of training and the adaptability of skills within sports specific contexts [432].

In 2016 the NBA released its youth basketball guidelines that were compiled by a multidisciplinary panel of experts [17]. In addition to participation recommendations and the promotion of sports sampling, the guidelines recommended the incorporation of neuromuscular training (NMT) programmes (Youth Basketball Guidelines), which typically include FMS based activities and are designed to be included within warm-up routines ahead of the main body of training [383,433]. Through a range of non-sports specific exercises, NMT programmes typically target balance, the stretch-shortening cycle, and lower limb strength and power, which contribute to improved neuromuscular control [383,393]. Furthermore, although not exclusively, NMT programs commonly include athletic movement skills that underpin S&C exercises, such as squatting and hip flexion patterns, which have been associated with indicators athletic performance [13,153,261]. Moreover, NMT programmes have been found to reduce risk factors for injury across youth athletic populations [398,414,434], and improve motor control, movement quality and physical performance [380,397,435].

Despite the NBA's initiative being focused on FMS and, and discourses relating to the promotion of youth athlete health and wellbeing, the adherence by coaches of youth has been found to vary [36,436,437]. A recent study by Owoeye et al. [36], found that coaches altered NMT programmes based on perceived relevance to performance as well as player interest. Owoeye and colleagues' findings suggest a lack of comprehension for the importance of FMS in the holistic development of youth basketball players' performance capabilities. Given that it appears prudent for youth basketball coaches to incorporate non-basketball specific FMS content within their coaching practice, the current calls by the NBA (and other National Sporting Organisations) to incorporate FMS may be failing to gain traction with professional coaching personnel. Therefore, the purpose of the present study was to investigate youth basketball coaches' perceptions of FMS and the extent to which FMS are included within their coaching practice. This study is concluded with a discussion on how a greater understanding of coaches' perceptions of FMS would improve the development of youth basketball players.

4.2 Methods

We used a mixture of snowball and criterion-based, sampling approaches to recruit potential participants [438,439]. We utilised online survey methods because we were interested in surveying individuals from any nation who identified as basketball coaches (i.e., the criterion). The survey was advertised on social media platforms (e.g., Twitter and LinkedIn) and within online coaching communities (e.g., Basketball England's Hive platform, Basketball England's Talent Pathway WhatsApp group, and a WhatsApp group for sports coaching professionals located worldwide). The survey consisted of twelve questions devised by the first author (Table 4.). These questions included the country where the coaches were based, the sex and age group of players coached, and the number of practice sessions delivered. In addition, questions designed to assess the coaches' beliefs relating to non-basketball specific FMS were included, with open ended questions utilized to determine differences and commonalities between coaches' perceptions of FMS as they pertain to youth basketball development. Informed consent was included within the online survey and was obtained by all respondents.

Table 4. Coaching survey questions

Question		Additional information	Answer format
1.	Please state the country where you are located	-	Open-ended
2.	Please state the age group of the players that you predominantly currently coach	Example: under 13s	Open-ended
3.	Please state the sex of the players	-	Check boxes: male; female
4.	Please provide an approximation of coaching sessions per week and total time delivering supervised coaching sessions to the players	Number of sessions per week followed by number of coaching hours per week	Open-ended
5.	Briefly describe your understanding of what fundamental movement skills are	-	Open-ended
6.	Do you include non-basketball specific exercises / activities in the warm-up ahead of main practice content?	Activities that do not involve basketball specific actions	Multiple choice: yes; no; or sometimes
7.	Would you feel confident to deliver non-basketball specific warm-up exercises that target general athleticism?	-	Check boxes, yes or no
8.	Do you believe there would be value in including general athletic exercises into your coaching session?	-	Multiple choice: yes; no; maybe
9.	If you answered no to the previous question, please provide a brief explanation why you provided this answer	-	Open-ended
10.	Please indicate if you include any of the following athletic movement patterns within any part of your basketball coaching session	Please tick boxes for athletic movement patterns included in your basketball session	Checkboxes: squat; lunge; hip-hinge; landing technique; pushing; pulling; bridging
11.	If you answered yes to any of the exercises listed in the previous question, please indicate an approximate frequency per week that the players are requested to perform them	This can include as part of a game day warm up as well as within practice sessions	Multiple choice: once per week; twice per week; three times per week; four or more times per week
12	How proficient would you rate the players to be at performing these athletic movement patterns with respect to control and stability?	-	Multiple choice: very; fairly; not

A total of 92 youth basketball coaches responded to the surveys, with respondents providing responses to all survey items. However, 11 of the respondents were coaching basketball squads that were deemed not to be youth level (under 19 and above), and two respondents were found to have unintentionally submitted the survey twice. Therefore, each of these cases were removed and excluded from data analysis. From the remaining 79 coaches, a total of 58 were based in the United Kingdom (UK), representing the majority. Other countries included: Spain (8); the United States of America (USA) (5); Canada (2); and single respondents from Belgium, Finland, Indonesia, Jamaica, South Africa, and Qatar.

The age groups worked with by the coaches spanned age groups from under 10 years of age up to under 18. Within this, eleven of the respondents coached multiple age groups, a practice that appeared across the different countries where the coaches were based (Canada, Jamaica, Spain, Qatar, UK, USA). In terms of the gender of the players coached, 19 of the respondents coached exclusively females, 46 coached exclusively males, and 14 coached across both sexes.

4.3.1 Analysis

Data was analysed using a mixed methods approach loosely inspired by realist evaluation methods developed by Pawson & Tilley [440] where we sought to focus on the mechanisms, context, and outcomes that mediated the implementation of FMS and non-specific movement skills by coaches in relation to their practice. Firstly, to assess outcomes (i.e., the uptake of FMS and non-movement skills) we conducted and reported the means and frequencies associated with the forced response questions to the survey. To explore how mechanisms (i.e., what drove people to implement FMS and non-movement skills) were mediated by context (i.e., the practicalities of coaching and the coaches' environment) we analysed open ended responses (questions five and nine) guided by reflexive thematic analysis techniques [441–444]. Data were categorised into subthemes related to the commonalities that existed within the responses to each of the questions [442–444].

To code the data, using survey responses that were collated within Microsoft Excel (Excel version 2103), passages of text were firstly coded using an open (or initial meaning code) and secondly an axial (or categorisation of open codes) coding scheme [443]. For instance, the claim "Balance of priorities to cover including the mental, technical and tactical needs of the athletes. These are developed through S&C sessions" which was initially coded as "context - balance of priorities". After similar statements related to the theme "balance of priorities" was open coded, some text would then be categorised a second time to further classify the statement. In this example, the statement would also be coded under the axial theme of "context - time management".

4.3.2 Considerations of Reliability and Validity

Consistent with a mixed methods approach inspired by Pawson and Tilley's [440] method and theory of realist evaluation, validity and quality were guided by ontological assumptions of critical realism [445,446] that balanced considerations related to truth being both knowable but also subject to interpretation and context. Specifically, we used the following criteria to reflexively guide our decisions: We assessed the topic's worthiness (*What are coaches' perceptions of FMS?* And *how are these perceptions being used to inform practice and pedagogical knowledge*?) and the importance and significance of the work to the broader scholarly field (will this research address a gap in the literature and build upon applied and theoretical understandings of FMS and sport pedagogy?) [447,448]. A rigorous account of the data was produced (is the data nuanced, and does it provide meaningful insights?), which was also transparent in relation to how the conclusions were drawn (is the research clearly described and did the purpose, methods, and findings align?).

4.4 Results

4.4.1 Descriptive Statistics

When participants were asked questions related to outcomes “do you include non-basketball specific exercises/activities in the warm-up ahead of main practice content?”, 58 of the 79 coaches responded “yes”, while 17 responded “sometimes” and four coaches “no”. In response to the question, “would you feel confident to deliver non-basketball specific warm up exercises that target general athleticism?” 75 coaches responded “yes”, and four coaches responded “no”. There were 76 coaches who responded “yes” to the question, “do you believe there would be value in including general athletic exercises into your coaching session?” and three coaches responded with the answer “maybe”. In terms of the number of exposures to non-specific exercises (squat; lunge; hip hinge; landing technique; pushing; bridging (or ‘plank’ variations), 20 coaches’ response was once per week, 30 coaches’ response was twice per week, 17 coaches responded three times per week, and 12 coaches responded four or more times per week. In response to question 10, where coaches were to indicate which athletic movement patterns they included from the choices provided, the number of responses for the inclusion of the squat were: n=70 (89%); for the lunge: n=5656 (71%), for landing technique: n=43 (54%); for pushing patterns=41 (52%); for the hip-hinge: 39 (49%); for bridging or plank activities; and N=34 (43%) for pulling patterns.

When asked "how proficient would you rate the players to be at performing these athletic movement patterns with respect to control and stability", 14 coaches' response was "very"; 57 coaches responded with "fairly"; and 8 responded with "not". Relating to basketball coaching frequency with respective squads, there were 20 ambiguous responses which were removed from the analysis for this question. In addition, due to working with players as part of a national squad, two of the reported only delivering supervised coaching sessions with their respective squads once per month and were also removed from the analysis for this question. The median number of sessions delivered per week was reported as two, while the minimum number was one and the maximum was nine. For session duration, from 55 respondents, the median was 90-minutes, with a maximum reported duration of 170-minutes and a minimum of 45-minutes.

4.4.2 Qualitative findings

Analysis of the open-ended qualitative responses indicate that contextual concerns related to professional knowledge and coaching cultures (see for example: Hammond et al. [449]) impacted their ability to improve FMS,

> *"I coach basketball not S&C, S&C should be given its own specific sessions"* (Coach Gallagher).

"There are lots of non-basketball specific skills that would add value to individual players to enhance and improve performance and athleticism" (Coach Arthurs).

> *"I answered yes to all questions, but I would also state that I don't have a concrete understanding of said movements. I believe in the concept. I more so follow experts I trust like Alan Stein and Brian McCormick to guide me"* (Coach White).

In the present study, the statement from Coach Gallagher suggests that they regard such content as equivalent to S&C, which not only presents a narrow view FMS and its value, but also suggests a denial of responsibility for wider development of youth players. Furthermore, the results for the proportions of athletic skills exercises included within the coaches' practices are suggestive of a disregard for the development of broad FMS.

The lunge and squat patterns were the most widely reported exercises and were deemed to have greater relevance to basketball-related activities. Nevertheless, other responses contributed to the emergence of the subtheme independent entity, and included the following two responses:

> *"Balance of priorities to cover including the mental, technical and tactical needs of the athletes. These are developed through S&C sessions"* (Coach McCarroll).

> *"I do not lead warmups, my role as a coach is more of technical/analytical in nature"* (Coach Bell).

The meaning established from the responses of coaches McCarroll and Bell is one which highlights a potential lack of appreciation for the intertwining nature of movement and coordinative dynamics [450]. While Coach McCarroll's and Coach Bell's perspectives are not deliberately harmful, arguably they are deflecting their responsibility for enriching the athletic development of their players and safeguarding their health and welfare (i.e., from an injury prevention perspective).

In contrast, the subtheme non-specific and basketball specific movement skill interdependency highlighted how some coaches considered FMS to not be distinguished from basketball specific fundamental movement skills [438]. This meant that some of the coaches dismissed the need to emphasise FMS and apply the same pedagogical approach across all movement skills. This is somewhat reinforced by one coach who stated that: "….to elaborate most of these activities will be done with some sort of basketball incorporated" (Coach Ashcroft). While such interactivity of FMS and sports skills is suggestive of an appreciation of the complimentary nature of all motor skills, coaches may also be ignoring the need incorporate FMS in isolation as well as in context [7]. In relation to this, the broader development of the youth basketball players under their charge, including physical capabilities that underpin basketball-specific performance may go underdeveloped, which may have implications to their development of adaptable skills for use within the sports-specific context [262]. Overall, coaches who aligned with the subtheme non-specific and basketball specific movement skill interdependency are likely to include FMS only haphazardly as part of sports-specific drills and exercises and thus defeating the purpose of incorporating FMS in the first place.

When reasons for not including non-basketball specific FMS in practices and the coaches' descriptions of FMS themes were compared, we found a lack of consensus and which, in turn, may unintentionally lead to an undervaluing of their importance. For example, the child focused subtheme intimates that FMS are exclusively children's activities, as one coach described:

"Basic movements that children carry out. Throwing, catching, running etc." (Coach Kelly)

Similarly, another coach responded with:

"The motor skills of a children [sic] and mechanics" (Coach Jones)

These descriptions from Coach Kelly and Coach Jones, while not incorrect, could be interpreted as somewhat limiting. Such limiting notions are reenforced by Coaches' Weller and Meighan:

"Shooting, handling, passing, defence and rebound" (Coach Weller).

"The base of the basketball game, there are several technical fundamentals aspects to be teach [sic]" (Coach Meighan).

The responses from Coaches' Weller and Meighan highlight a limited appreciation of FMS and its necessary role in implementing a holistic approach to youth athlete development [93]. Importantly, these views were not representative of all coaches in the survey. The subthemes, skills for general function, foundation movements, and athletic performance related, were more indicative of the notion that non-specific FMS can provide important foundations for sports-specific skills to be built upon:

"FMS are the basic or primary movements that all other sport movements or movements can be built upon" (Coach Starkey).

"A performers [sic] ability to carry out functional and fundamental movements in a variety of contexts and the [sic] in a basketball context apply to enable skills development" (Coach Archer).

In sum, our qualitative findings consistent with realist evaluation perspectives suggests coaches' implementation of FMS training techniques within their practices are constrained by contextual factors related to professional cultures and knowledge [449,451]. While coaches may appreciate the value of FMS in developing favourable outcomes (e.g., basketball-specific skills) there is a need to think about how coaches can be better supported in context to implement and achieve outcomes and benefits (e.g., injury mitigation, and improved movement vocabulary) associated with the implementation of FMS. In addition to the athletic performance related subtheme, it appears that these coaches are cognisant, to some degree, of the importance of FMS in the development of basketball players. However, the lack of consistency in the coaches' responses within this overarching theme, further highlights the need to improve coaching knowledge.

4.5 Discussion

The findings of this study that context mediates enactment of behaviour mechanisms appear to be consistent with other recent studies [36,437] and the findings related to realist evaluation [446,452] and policy enactment studies in physical education and sport pedagogy [449,451,453]. Owoeye et al. [36] found coaches were inclined to remove strength and balance related tasks in favour of exercises deemed to be more relevant to basketball performance. Similar findings were reflected in the study by Räisänen et al. [437] which investigated the use of NMT-based warm ups by youth basketball coaches, finding that 48% of coaches spent 10-minutes of less on the warm-up component in their practices. Therefore, it is important not to understate the impact of socialisation [454–456] and contextual professional cultures (e.g., Hammond et al. [449]; O'Gorman et al. [451]) in prompting coaches to hold sports-specificity in higher regard than broader aspects of player development as they attempt to implement initiatives such as FMS and non-sport skills into their practice.

However, problems associated with coaches' perceptions have been previously highlighted in the study by Jukic et al. [427] into youth soccer players. In their study, Jukic and colleagues found FMS to be more important in distinguishing player levels of performance compared to coaches' subjective evaluations of their performances, highlighting the existence of disparities between coaches' perceptions and objective markers of performance capabilities. Indeed, coaches' decision making regarding talent identification has recently been found to be based mainly upon tacit knowledge and instinct in place of valid criterion [457]. Moreover, it demonstrates that, again contextual dimensions related to coaching knowledge and dispositions are tilted towards SSS development potentially at the cost of long-term development and player welfare. The literature [425,430,458] reveals, for instance, that single sport specialisation is an outcome associated with limited motor skill development, risk of injury, and burnout syndrome [93]. In youth basketball players, Leppänen et al. [459] found a high prevalence of overuse injury to the knee among both males and females. Therefore, any notion of non-sports specific movement skill training as a separate training form may be deemed as problematic for the long-term health and development of youth basketball players [89,165,425].

Collectively our findings appear to highlight a relative disregard for a holistic approach to the development of youth players in favour of talent identification [10,460,461], suggesting that the education of youth basketball coaches may be a contributing factor. Indeed, education regarding basketball-specific injury prevention was suggested to be an area to address in the study by Räisänen et al. [426], in response to their findings that coaches 67% of the coaches surveyed expected players to experience injury during the next season. Moreover, in a study by Saunders et al. [462], youth netball coaches identified educational resources as an importance factor in NMT programme implementation. Despite identifying restricted time and programme length as barriers, the majority of the coaches believed it was effective in improving athleticism and reducing injury risk [462]. However, it appears that such educational strategies are devoid of the presentation of alternative perspectives on the importance of FMS development, such as increased adaptability of SSS within sports specific contexts, which may be the resultant of concomitantly developed FMS and SSS [262]. Nonetheless, collectively, the studies by Räisänen et al. [426] and Saunders et al. [462] studies, in addition to the findings in the present study, highlight the potential requirement for improved coach education to underline the importance of FMS development to underpin the safe and effective journey of the basketball athlete through the difficult period of adolescent biological maturation. However, as a discipline, sports science, has been previously implicated in the creation of barriers through the overuse of jargon, and for the lack of dissemination of relevant information to coaches [463]. In light of this, it may be that a more clearly defined rationale for the inclusion of FMS is necessary for youth basketball coaches to place a greater emphasis on their development within practices in order to make such coach education interventions as contextually relevant as possible (cf. Cassidy et al. [464]; Cope et al. [465]; Cushion et al. [466]; Tinning, [467].

Based upon the results of this study, it is recommended that national sports organisations and other bodies responsible for coach education improve their rationale for the inclusion of FMS, ensuring its purpose is clear, and elaborated upon more greatly regarding its place in the long-term development of youth basketball players. In place of a dichotomised perspective of FMS and basketball, coaches need to shift to emphasise the complimentary pairing of mutually-important skills that better account for the complexity of skilled action in basketball

[438,468,469], as well as related reductions in risk factors for injury in youth athletes [36,165]. Sport developers might want to explore the adoption of degeneracy and the functional role of movement variability [351] within coach education programmes, such that some of the concepts explored thus far in thus work can be implemented.

Degeneracy represents the ability of an individual to vary how a skill is executed by adapting their coordinative patterns to meet the intended goal of the task [351]. Moreover, expert performers are understood to rely less on a fixed movement strategy, and instead are able to apply different coordinative movement solutions to meet the requirements of a given task [350]. Accordingly, given that functional variability is understood to occur in skilled movement [340], and the highly variable conditions that characterise game-based sports such as basketball, degeneracy of the nervous system is an important feature of skilled performance that coaches must consider in their practice [350].

From a motor skill development perspective, the Athletic Skills Model [31], advocates for the development of FMS to enhance the acquisition of sports specific skills, although future studies could explore the concept of degeneracy as a way to better represent the interdependency of FMS and sports skills. Intertwining ideas from degeneracy encourages a move away from the dichotomising of FMS and sports-specific skill development, and instead encourages the need to emphasise these important skills' development with a level of isolated focus so that they receive adequate attention to be appropriately developed. Moreover, the notion of a limited FMS as a proficiency barrier to the acquisition of basketball specific skills may steer coaches to incorporate more focused attention to the pedagogical approaches applied.

A limitation of this study is that coaches were asked to describe their practice in relation to the implementation of FMS and non-sport skills. Thus, it must be emphasised that only the experiences of coaching from perspectives of the coaches themselves were explored and assumptions cannot be made that the participants have any depth of awareness of their own practice [470,471]. Therefore, it is recommended that future research is required to explore the implementation of FMS interventions in specific contexts (clubs, leagues, countries, national associations) to better understand the multiple dimensions of resistance, or barriers, to the implementation of integrated policies in coaching practice. While the configuration of sport delivery (organisation, policy, and funding) is unique to each country, what was striking from the results of the current study was that coaches were facing similar dilemmas in different locations in a diverse international sample and, therefore, this study could provide a springboard for a more focused realist evaluation of the implementation of FMS skills in the future.

While this study is not statistically generalisable, other scholars and policymakers may be able to glean crucial insights and following [472], when our read in conjunction with that of others, generalisability might be grasped on the basis of recognition of similarities and differences to which other social science pedagogues familiar with the motor learning work cited (e.g., O'Sullivan et al. [314]; Renshaw & Chow, [473]; Young et al. [474]). In addition, there are transferable insights and generalisability where others can infer or translate our findings to other contexts: such as Physical Education (cf. Haegele, [475]; Richards et al. [454]; Richards & Templin, [455]; Wright et al. [456]) or in other areas of coaching policy interventions (cf. Hammond et al. [449]; O'Gorman et al. [451])

In sum, the importance of FMS has been well documented within youth development related literature [14,18,370]. The results of the present study show that youth basketball coaches have a diverse comprehension of what FMS represent and, despite highlighting an appreciation of their importance as well as indicating confidence in including athletic movement skills within their warm-up protocols, there appears to be barriers to their inclusion in modern basketball practices. However, while discourse around the health and well-being of the developing players should provide sufficient rationale to consistently incorporate FMS within practices, it appears that a more relatable, basketball-specific, layer should be added. The concept of degeneracy may provide the important link between FMS development and basketball-specific performance.

Chapter 5

Parkour-Based Activities in the Athletic Development of Youth Basketball Players

Citation

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Abstract

While ideas from athletic development models have been adopted and integrated across different sports, issues related to early specialisation, such as increased risk of injury and burnout, are still common. Although some benefits may be associated with early sport specialization, sports sampling is purported to be a more effective approach to the long-term health and wellbeing of children. Furthermore, the concept of developing what are commonly referred to as FMS is central to the rationale for delaying single sports specialisation. However, in place of sports sampling, it appears that the practice of S&C has become a driving force behind developmental models for youth athletes, highlighted by the growing body of literature regarding youth athletic development training. In this perspective piece, we explore how conventional S&C practice may insufficiently develop FMS because typically, it only emphasises a narrow range of foundational exercises that serve a limited role towards the development of action capabilities in youth athletic populations. We further discuss how this approach may limit the transferability of physical qualities, such as muscular strength, to sports-specific tasks. Through an ecological dynamics lens, and using basketball as an example, we explore the potential for parkour-based activity within the LTAD of youth basketball players. We propose parkour as a training modality to not only encourage movement diversity and adaptability, but also as part of an advanced strength training strategy for the transfer of conventional S&C training.

5.1 Introduction

The concept of developing basic movement skills to provide a foundation for more advanced and specialised forms of movement is not new [18]. However, a concern in the development of youth in sports has been the lack of emphasis on generalised skills and FMS with far greater attention being allocated to SSS [10,90,425]. Although alternative terms exist (e.g., foundational movement skills, functional movement skills, and basic movement skills), typically, FMS encompasses locomotor (e.g., running and jumping) and object control (e.g., catching, throwing, and kicking) [6,7]. Accordingly, FMS are considered foundational for the development of SSS, which if left undeveloped may limit future performance [16,426,427]. Indeed, the development of FMS ahead of specific sports skills is promoted within the LTAD model [83] discussed elsewhere in this work and which has served as an influential framework for the training of young athletes in sporting organisations for over two decades [10,81,476].

Through the development of FMS as well as participation in multiple sports-related activities during childhood, the premise of the LTAD model is to avoid early specialisation and the associated risks relating to injury and burnout [9,38,476]. By emphasising the development of FMS, motor control and movement quality may be enhanced across a far broader repertoire of movements that are pertinent to sport-specific performance [397,433]. In turn, such outcomes could contribute to a reduction in risk factors for injury [397] However, despite recognition by sports organisations of the need for an athletic development strategy, the prevalence of injuries in youth sports, such as soccer and basketball, remains high [e.g., 88,96,473]. While the original intention of the LTAD model was to be used as a framework for sports organisations to adapt and implement to suit their specific needs [178], it has been argued that the development of FMS and general physical qualities remains marginalised in favour of sports-specific training [10,478].

On this, a potential problem relates to some of the debate with respect to FMS [e.g., 7,18,30]. Youth-level basketball coaches have been found to have differing interpretations of FMS, as well as varying ideas as to whom might be responsible for their development within a team operation. Consequently, sports organisations may have become increasingly reliant on their S&C function, and the wider field of S&C in general, to develop FMS and general physical qualities. For example, within Basketball England's version of the LTAD model, the *Player Development Framework*, the S&C domain is responsible for the development of "all round quality of movement literacy". In relation to this, a meta-analysis by Collins et al. [179] found that resistance training, which targets muscular strength, positively impacts FMS through neural adaptations (e.g., motor unit recruitment and firing). However, despite the benefits of youth-based S&C training, which includes reducing risk factors for injury and life-long engagement in physical activity [e.g., 475–477], conventional youth-based S&C practices may lead to the development of movement skills with limited relevance outside of the S&C domain and, thus, could be inappropriate or the modern basketball athlete. Exemplifying this, the development of *athletic movement skills*, such as the overhead squat, hip hinge and lunge patterns [261], are limited to fixed, closed-chain movement patterns, which do not reflect the open-skill movements that characterise basketball-specific actions. Consequently, FMS may not be developed with sufficient depth and diversity to provide the underpinning movement capabilities for SSS development [482,483].

A potential strategy to enrich young athletes' FMS education is the implementation of parkour-related activities [34,37]. Parkour is an acrobatic sport incorporating a broad range of movement skills and motor abilities, which has been proposed as a potentially beneficial activity to develop FMS and general athletic abilities for youth team sports [31,34,37].

Obtaining transferable athletic capabilities through the implementation of parkour derives from the aforementioned concept of *donor sports*, which are purported to develop and facilitate the transfer of general movement skills and physical qualities to actions typically performed in a *target sport* [31,484]. Given that basketball is characterised by similarly dynamic multidirectional movements [44], youth basketball players through this activity could benefit from the running, jumping, vaulting, and climbing activities that characterise parkour [485].

Thus, in this perspective article, we explore the potential for parkour as a donor sport for the development of youth basketball players. In the next sections, we discuss the role of conventional youth-based S&C practice and its limitations, and present alternative perspectives on the development of movement capabilities through an ecological dynamics lens. It is through this lens that we propose parkour as a donor sport for the development of FMS, as well as forming a strategy to facilitate transfer of skills to basketball performance.

5.2 The Role of Strength and Conditioning in LTAD

A body of research [e.g., 373,394,409,410] has demonstrated the efficacy of NMT on reducing risk factors for injury in youth populations. Furthermore, other forms of S&C training in youth populations are also supported empirically [170,248,486]. This includes evidence of windows of trainability for strength, speed, and the stretch shortening cycle [170,248,486]. Collectively, this has resulted in the publication of position papers, such as the *National Strength and Conditioning Association's* position statement, and the *British Journal of Sports Medicine's* position statement on youth resistance training, both of which recommend the concurrent development of muscular strength and movement skills in children and adolescents [487,488]. Therefore, the role of S&C within the LTAD strategies of sports organisations should be regarded as highly important in reducing risk factors for injury as well as increasing physical performance capabilities [38,479,480]

Notwithstanding the discussed benefits of S&C training, a concern relating to the conventional approach to youth-based S&C is the lack of representative movement dynamics for team sports, such as basketball. Indeed, when considered in the context of "open-skill" games that require decision making and a vast array of movement dynamics [262], athletic movement skills may not sufficiently reflect those particular requirements. To illustrate this, in basketball, offensive players require a large repertoire of action capabilities to evade their opponents, as do defending players who are required to react to the movements of their opponents [44]. Accordingly, it has been argued that to be effective, S&C programmes for basketball players need to better represent the diversity of movement demands of the sport [489]. This contention may also include plyometric exercise, which provides a stimulus to improve jumping, sprinting, and change of direction movement capabilities through enhancement of the stretch-shortening cycle [490,491], amongst other mechanisms [392]. Although these physical qualities are specific to basketball [491], it has been argued that strength-related qualities of agility performance are considered potentially less important than the perceptual and decision making components [483]. Moreover, youth guidelines relating to the prescription of plyometric exercise appear to limit the scope for movement diversity by placing an emphasis on technical proficiency in exercises such as "in-place hops" ahead of progression to more elaborate jumping variations in an effort to push an athlete towards the boundaries of their threshold of capability [492]. While the safety of young athletes is of paramount importance, the often restrictive, formulaic guidelines for plyometric training in youth athletes may serve simply to discourage creative exploration and development of jumping skills that are more characteristic of sports, such as basketball.

Without devaluing the importance of conventional S&C training, it may be that despite its emphasis on developing broad FMS within the LTAD framework, there is scope to encourage a wider array of movement capabilities. Therefore, it is proposed that the S&C domain further permeates the development of youth athletes by more thoroughly accounting for the decision-making demands and diverse array of movement dynamics that characterise skilled motor performance in sports such as basketball. Accordingly, we consider the merit in adopting an ecological dynamics approach to motor learning.

5.3 Adopting an Ecological Dynamics Perspective

The ecological dynamics framework is formed from both ecological psychology and dynamics systems theory [313,314]. Through the ecological psychology lens, information perceived in a performer's environment determines the parameters that dictate how a particular skill is performed [323]. The opportunities for action that an individual perceives within their environment represents what is termed the *affordance landscape* [236,326,327]. For example, a basketball player preparing to shoot will perceive information relating to the proximity of the defensive player, their own specific location on the court, and perhaps the time left on the shot clock. Collectively, this information will influence the dynamics of the shot with respect to its kinetics and kinematics [341]. In a second example, a player in possession of the ball may detect the space between defenders as an opportunity to dribble and *drive* through to advance towards the basket in an effort to score. In this example, based upon a defender's positioning, the attacking player has different action possibilities (affordances) in relation to the direction they may drive [493]. Thus, perception of the environment and the subsequent action are considered to be coupled and must be considered in tandem to facilitate a movement by the athlete that maximises the chance of success (i.e. achieving a score) [262].

Within the domain of ecological dynamics, in place of fixed movement patterns, the ever-changing nature of information from the environment requires adaptability from the performer to coordinate the appropriate action [313,494]. In contrast to fixed movement patterns, muscle synergies, which represent neural organisations, enable a vast array of adaptable movement possibilities [296,323,334]. This is particularly pertinent to how adjustments to ongoing movement skills occur in response to incidental perturbations (e.g., unexpected changes to surfaces) [239,262]. Contributing to the vast array of action capabilities is the combination of anatomical characteristics, learned coordinative patterns and changes to physical output (e.g., force production and stretch-shortening properties), which form what is termed, from an ecological dynamics perspective, as an individual's 'effectivities' [317,495]. Importantly, properties that form effectivities are continually altered across developmental stages of growth and maturation due to naturally occurring physical and biological changes, including hormonal profiles, increased body mass and stature [428], in turn necessitating the continual exploration of the affordance landscape with respect to an individual's action capabilities.

5.4 The Potential of Parkour for Improved Movement Capabilities

Despite popular media portraying Parkour as an "extreme" sport consisting of highly advanced stunts that pose a high risk of serious injury, such as jumping from buildings, or between train carriages [34], expert Traceurs have highlight how contemporary parkour consists of a range of events (e.g., speed runs, freestyle running) which can be performed both in indoor and outdoor environments [37]. Hence, Parkour is characterised by a variety of movements utilised to navigate obstacles and is practiced in various forms and contexts that do not conform to the dangerous characterisation portrayed by popular media [356]. The potential of parkour to support FMS development is based upon the concept of donor sports, which is derived from the aforementioned ASM [31]. The ASM, which adopts an ecological dynamics perspective, purports that exposure to activities that share common characteristics (e.g., skills and abilities) can be transferred or "donated" to a target sport [34,313]. Parkour presents a multitude of different ways of moving based upon a performer's perception of their surroundings, and promotes the necessary creativity to navigate gaps and obstacles with poise and confidence [313,356]. Given these characteristics, Strafford et al. [34] propose that the incorporation of parkour-related activities could provide a platform for youth athletes to develop FMS that could be transferred to other sports. For example, the use of obstacles, termed *speed-runs*, which require a participant to navigate a course as quickly as possible, can be used to encourage transferable agility skills that can be utilised in a variety of sporting contexts [235]. Indeed, irrespective of the target sport, exposure to parkour-based activities, such as speed-runs, may be particularly pertinent during the pre-PHV, which is regarded as a potential period of sensitivity for developing FMS due to high levels of neural plasticity [181,234]. However, for the purposes of *fine tune* existing neural pathways and muscle synergies, and to take advantage of the high-levels of neural plasticity retained in adolescence (~13 years of age and above) [181,496], parkour-based activities may continue to play an important role in athletic development as a child physically matures.

Although currently, evidence directly examining the benefits of Parkour training on basketball is limited, significant correlations between performance tests typically used in basketball (e.g., vertical jump and T-test) and performance in a parkour speed-run has been demonstrated [235]. Furthermore, Abellán-Aynés and Alacid [497] present Parkour as an effective training method for developing agility, horizontal, and vertical jump abilities. Alongside jumping and agility, Parkour training interventions have also demonstrated improved cardiorespiratory fitness with increases in peak oxygen uptake, oxygen uptake at anaerobic threshold, heart rate at anaerobic threshold and running speed at anaerobic threshold [498].

Regarding basketball, owing to similarities between actions, parkour-based activities may also be considered for their potential as a donor for the specific development of action capabilities in youth players. For example, in parkour, the *tic tac* action, which is characterised by pushing off of a wall with the ball of the foot to gain height [499], requires spatial orientation and use of perceptual information from the foot contact to determine the subsequent phase of the movement [34]. Therefore, this action may present developing basketball players with the opportunity to explore their capabilities to decelerate, propel, land and then, move in a new direction, much in the way that they might have to do in a competitive game. Indeed, such a movement ostensibly seems to exhibit similar characteristics to the type of jumps that are used within a game of basketball, with few examples seemingly resembling the type of movements that are typically undertaken in S&C training programmes, such as CMJs and DJs. Furthermore, through what has been termed "synergistic adaptation", the introduction of strength training to youth basketball players could augment changes to force production that naturally occur as a result of growth and maturation [168,249]. In turn, this might alter a players' effectivities (force capabilities), which necessitates the continued exploration of the affordance landscape with respect to their action capabilities, one of which may be an ability to exert force rapidly. To illustrate this, the use of plyometric training, which has been found to enhance the jumping capabilities of the youth basketball players [500], logically, enables players to express improved jumping capabilities within the game.; for example, the execution of rebounding to gain possession of the ball. Rebounding involves an offensive or defensive player aerially competing for possession after a missed shot attempt. However, depending upon the specific scenario that the player is presented with, they may be required to one of a variety of differing jumping actions to successfully defeat their opponent and rebound the ball [501]. Accordingly, despite a player's enhanced force characteristics achieved through conventional S&C training, in the absence them electing to explore their jump action capabilities beyond a traditionally applied plyometric regimen, there may be a limited transfer of adaptations from training to sport-specific contexts. Considering this, Parkour-based actions need not be so advanced that they exceed the affordances identified in one's movement landscape. However, through the introduction of variability to the training stimulus, such Parkour-based actions remain effective to *recalibrate* the mapping of the contributing units to the execution of a particular movement skill [312].

Although it may be argued that basketball-specific practice would better facilitate the transfer of improved force-related capabilities to performance in the sport, problematically, the greater levels of specificity that basketball practice presents, may provide cognitive and decision-making demands that are too high [502]. Therefore, youth players may fail to sufficiently explore the affordance landscape in relation their altered physical capabilities. This is not to appear contradictory to the premises of ecological dynamics with regard to the coupling of perception and action; instead it distinguishes between the effectivities (those impacted by S&C) of the individual player, and the more complex environment that represents the sport in question that is being trained for [503]. In this regard, affordances are both objective, for example, the properties of a given playing surface; and subjective, which relate to an individual's perception of their own physical and decision-making capabilities [292]. With reference to subjective properties, the detection of affordances therefore relates to an athlete's current effectivities [428,495]. Where the properties of effectivities are enhanced through conventional S&C training, Parkour movement training is proposed to sit between conventional S&C training and that of basketball-specific training, essentially retaining elements of both activities. However, as with any training modality, caution should be exercised to avoid excessive workloads being placed upon youth athletes, especially in the form of repetitive movement patterns that replicate the negative consequences of early specialisation [459]. Notwithstanding this, when programmed appropriately, theoretically, the inclusion of parkour-based activities could enable the youth basketball player to better perceive their action capabilities and detect new affordances that are transferable to their sport for performance enhancement purposes.

5.5 Application as an Advanced Strength Training Strategy

An important consideration in the development of adolescent basketball players is that the number of basketball specific practice hours will generally increase in comparison to the amount of time spent in other physical activities [504]. Therefore, the inclusion of parkour activities could be dependent on the constraints of time. Accordingly, at this stage of development, the use of parkour activities might form part of a more advanced strength training strategy thus necessitating a more thoughtful and individually tailored approach to programming. Regarding this, Parkour-based activities should be considered for use by S&C coaches alongside an evaluation of the specific sporting action being targeted.

To account for time constraints, Parkour activities could theoretically be embedded within an S&C programme. For example, this could take the form of a traditionally used complex training regimen, with parkour actions performed concurrently within the same training session as conventional S&C training exercises. Complex training has previously been shown to be an effective method to improve sprint and vertical jump performance in young (<20 years) basketball players [301,302]. Commonly, this training method requires athletes to perform a strength-oriented exercise, such as a barbell back squat, followed by a plyometric-oriented exercise that shares similar movement mechanics, therefore providing a potentiating effect on the subsequent exercise [301]. Where the paired exercise in this example would typically include a jumping exercise, such as a CMJ [302], vaulting activities or TT actions could be included in its place, or in combination, through alternating sets of varying exercises. With regard to the latter, players may be to utilise the post-activation potentiation response occurring in response to the strength-oriented exercise, enabling them to explore the affordance landscape under conditions of augmented neural contribution [302]. Moreover, the varied jumping patterns could present players with more varied landing challenges than those in conventional complex training, which may better prepare players for the more specific scenarios encountered within their sport. While, currently, no known loading parameters exit for parkour-based actions, it would appear prudent to follow the guidelines for contacts that are typical of plyometric and complex training regimens. However, further research is required to validate these suppositions.

5.6 Safety Precautions

Parkour UK, the governing body for Parkour in the United Kingdom, has developed its own risk-benefit assessment and provides standards relating to equipment and codes of practice for the sport. However, its growing popularity is illustrated by the emergence of YouTube videos displaying high-risk manoeuvres in urban settings [485]. Therefore, where parkour actions are being considered within the athletic development programmes of young athletes, the risk/benefit profile of the activity should be considered, with an explicit emphasis placed on performing Parkour techniques safely. Moreover, when introduced, it should be stressed to young athletes that Parkour activities are to be performed in supervised sessions only such that technical competence can be monitored by qualified coaches who are well versed in the diversity of skilled movements required to succeed in the sport of basketball.

5.7 Concluding remarks

Given the S&C domain's influence on the athletic development practices adopted by coaches for the performance enhancement of youth athletic populations, it is proposed here that the S&C field expands its influence to capture both the decision-making and movement dynamic properties that may better represent the demands imposed upon players of basketball at the youth level, particularly those talent-identified athletes who require sequential improvement in physical performance with a view to attaining professional status. While the efficacy of conventional S&C is not in question for the purposes that it was originally intended to be used for, it is argued here that through the adoption of concepts from the ecological dynamics' framework, the S&C domain might become better equipped to instil in children and adolescents, the diverse and adaptable movement capabilities to develop in, and excel at, their chosen sport. Crucially, this would facilitate the development of the perceptual aspects of performance, alongside the interdependency of environmental and movement dynamics. From this perspective, the implementation of Parkour as a donor sport for youth basketball players might enrich their action capabilities and facilitate the transfer of conventional forms of S&C to basketball performance.

Chapter 6

A comparison of maximal acceleration between the "tic-tac" parkour action, drop jump and lay-up shot in youth basketball players: A preliminary study towards the donor sport concept.

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Abstract

The aim of this cross-sectional study was to compare acceleration outputs of the parkour-style "tic tac" action, with the drop jump and the lay-up shot, in youth basketball players. A total of 25 participants (17 males, 13.80 ± 1.30 years of age; and 8 females, 15.00 ± 0.80 years of age) completed three trials of each action while wearing a single inertial motion capture unit with a sampling frequency of 200 Hz, positioned at the lumbar spine. All data was captured in a single session, using the same test order across all participants. Maximum resultant acceleration was calculated from the raw data for each action. Using sex and maturation status as covariates, data were analysed using a Bayesian one-way repeated measures ANCOVA. Results revealed the jump + sex model to be the best fitting ($BF_{10} = 9.22 \times 10^5$). Post hoc comparisons revealed that the tic tac produced greater maximal acceleration than the drop jump and the lay-up. These findings provide a biomechanical basis for the potential use of the parkour tic tac as an activity that could be used within the athletic development of youth basketball players.

6.1 Introduction

Within youth athletic development models (e.g., the Long-term Athlete Development model and Youth Physical Development model), an emphasis is often placed on the fundamental movement skills and the enhancement of physical capabilities (e.g., strength, speed, agility) required for participation in organised sports [10,32,33]. Classically, fundamental movement skills represent skills related to locomotion (e.g., running, skipping, galloping), object manipulation (e.g., striking, catching, kicking), and balance [7,262]. The development of fundamental movement skills is typically recommended in pre-adolescents who, ahead of peak height velocity, are understood to acquire motor skills more readily than older youth due to higher levels of brain and nervous system plasticity [11,181,505]. Accordingly, the years preceding adulthood have been referred to as a golden period of motor learning [181,182]. Moreover, training to enhance different physical capabilities has been recommended to coincide with stages of maturation to augment the natural changes occurring in the growing bodies of young athletes [13,156,171]. However, within sports such as basketball, the adoption and implementation of these broader youth athletic development strategies may be overlooked by coaches in favour of sports-specific practice [36,478].

In contrast to the LTAD and YPD models, the more recently conceived ASM by Wormhoudt et al. [31] presents a pedagogical approach to athletic development that is based upon concepts from the ecological dynamics framework. Ecological dynamics is an integrated theoretical framework that combines ecological psychology with dynamical systems theory in the study of human behaviour [314]. Accordingly, the ecological dynamics framework views motor skill performance as the resultant outcome of the fluid interaction between the individual performer, the specific motor task, and the environment within which the task is performed [494,503].

One of the tenets of the ASM is the notion of so-called "donor sports" [31]. Donor sports are theorised to *donate* action capabilities to a *target sport* through the repeated utilisation of transferable physical skills and perception-action capabilities [34,506]. Through the ecological dynamics lens, the performer perceives their surrounding environment in terms of their ability to act within it, accounting for both the different environmental properties (e.g., surface, dimensions, objects) as well as the performer's current action capabilities (e.g., skills, physical capabilities) [507]. Accordingly, the donor sport concept offers an attractive strategy to develop broad both fundamental movement skills and physical characteristics in a way that the performer can utilise within their chosen sport.

Based upon the donor sports concept, the use of parkour-style training activities has been proposed as a method of developing movement skills and physical capabilities (e.g., agility) that may be transferable to team sports [31,34]. Most pertinently, based upon traditional motor skill definitions, parkour-based actions may be considered to be relatively open and outcome-oriented, with an emphasis on efficiency of movement over fixed technical models [498,508]. Although not without barriers to implementation (e.g., coach education requirements), parkour could serve as an alternative means of physical preparation for other sports [355,358]. This might be particularly apt in sports at the youth level where, despite widespread understanding of the importance of a long-term strategy for physical development, due to time constraints, there is likely a greater emphasis placed on sports-specific training over the development of broader athletic capabilities, which includes the development of fundamental movement skills [10].

Notwithstanding the potential implications of early single-sport specialisation (e.g., injury risk and burnout [165,509], there is a necessity to acknowledge that for continued progression within a sport, eventual specialisation is required and inevitable for those who might have a preference for success over participation [110,510]. This is likely a key consideration within performance pathways where practice and training time is often constrained, or in training camp environments that are building towards a key competition [36,511]. Indeed, the perceived relevance of an activity appears to be an important consideration in promoting compliance with implementation among coaches [36]. Accordingly, coaches may be less likely to adhere to so-called "non-specific" training methods with their athletes [36].

The concept of training specificity, which implies that training content aligns with the specific demands of performance [512], is considered to be of paramount importance in the development of physical performance standards in youth athletes [513,514]. Within the strength and conditioning field, the concept of *dynamic correspondence* has provided a basis for determining the degree of specificity of a training exercise according to its compliance to one or more of five specific criteria that relate to the kinetics and kinematics of sports-specific skilled actions [252,514]. These include the amplitude and direction of movements; accentuated regions of force production; dynamics of effort; rate and time of maximum force production; and regime of muscular work. Improvement made in a given training exercise that translates to improved sports-specific performance is therefore representative of the transfer of training [253]. An example of this is the programming of high-intensity plyometric exercises, such as bounding, to elicit changes in muscle-tendon properties of the lower limb to improve sprinting capabilities [515].

Contemporary ideas regarding training specificity have extended beyond the purely biomechanical parameters of a training exercise [34,516]. Within the S&C field, for example, the notion of *coordinative overload* has been purported to be more representative of motor behaviour and skilled performance compared to more traditional forms of overload (e.g., Weightlifting- and Powerlifting-based exercises) [516,517]. Similarly to the donor sport concept, the notion of coordinative overload is aligned to the ecological dynamics framework and, in contrast to reductionist approaches, is considered a more integrative mechanism for skill development and performance [503,516]. Owing to its acrobatic characteristics, which combine balance, coordination, muscular strength and timing to traverse different obstacles, gaps and surfaces, parkour has been suggested to be a donor sport that can increase the athletic capabilities of youth basketball players. Basketball is a sport that is characterised by high frequencies of jumping and change of direction actions [1,518]. However, within basketball, execution of actions such as the lay-up shot, which combines various different movements into one specific skill, are considered complex to execute [330]. For example, the shooting player must dribble to avoid defensive players, and then jump to put the ball through the basket [519]. With physical preparation programmes of basketball players having been previously criticised for not being representative of the specific movement requirements of the sport [489], the movement diversity and open-skill nature that characterises parkour actions may be more representative of the movement complexities observed in basketball than exercises that are typically utilised within S&C practice.

The Parkour TT jump has been identified as an activity that may contribute to the development of agility [355] and has been proposed as an activity that could donate action capabilities to youth basketball players as part of the athletic development strategy [520]. The TT requires an individual to leap towards a vertically oriented surface with one leg and push off the surface using the nearest foot into a new direction before landing back on the ground. Therefore, the TT is a jumping action that includes a multi-directional element. Although the underpinning rationale for the TT is currently limited to theorised supposition, the running-based nature of the TT jump would appear to be relevant to basketball skills, for example, the lay-up (LU) shot, which is also regarded as a running-based jump [521]. In collegiate players, jump height and jumping index (jump height/contact time) in the LU shot have previously been found to be significantly higher than those for the conventional CMJ and repeated single-leg and double-leg jumps in place [519]. Elsewhere, significant correlations have been observed between the LU shot and CMJ, whilst larger significant correlations were revealed between the LU shot and the maximal running vertical jump, suggesting of greater levels of specificity in the running-based jump [521]. Therefore, while the TT action is not identical to the LU, based upon the donor sport concept, its apparent face validity to the conditions under which the LU is executed, coupled with its relative simplicity to implement, may serve to encourage coaches to utilise it as an alternative athletic development activity.

Although detailed examination of the donor sport concept requires intervention studies, it is also necessary to determine relevant predictor and outcome variables (e.g., biomechanical parameters) to be utilised within such studies. In addition, where the notion of donor sports is relatively novel and the transfer of parkour training in relation to perception-action coupling is currently limited to theory, quantification of biomechanical parameters relating to the TT and LU shot would contribute to an understanding of potential mechanisms for the transfer of training for comparison with traditional training methods. However, perhaps owing to challenges in objectively quantifying parkour-based actions, there is limited empirical evidence on the biomechanical parameters associated with such movement patterns. While evidence exists (e.g., Hernández et al [490]) to support the use of conventional plyometric exercises, such as the drop jump (DJ), to improve physical capabilities in youth basketball players, it has yet to be clarified how a parkour-based activity, such as the TT jump, could benefit the development of truly sport-specific action capabilities in youth basketball players.

The aim of this exploratory study was to compare maximum acceleration outputs of the parkour-style TT action, with the DJ and the LU shot, in youth basketball players. It was hypothesised that the TT and the DJ would display higher maximum acceleration values than the LU. In addition, owing to the running-based nature of the TT action, it was further hypothesised that the TT would result in larger maximum acceleration values compared to the DJ.

6.2 Methods

6.2.1 Experimental Approach to the Problem

A cross-sectional study design was used to compare accelerations between the TT, DJ, and LU actions. All participants were required to take part in two testing sessions separated by seven days, the first of which served as a familiarisation, and the second as data collection. Following the collection of anthropometric measures (mass, height, and sitting height) using medical grade digital scales and stadiometer (Seca, Birmingham, United Kingdom), on both days, participants were required to complete a standardised warm-up that was based upon the *Starting 5* (www.basketballengland.co.uk), a neuromuscular training warm-up devised by the national governing body, Basketball England. In brief, this included pulse raiser activities involving basketball dribbling, athletic movement skills (e.g., squat, lunge, and hinge patterns), and low intensity jumping and landing exercises.

Participants were then required to perform the three actions of interest while wearing a single inertial motion capture system (MyoMOTION 3D Motion Capture System, Noraxon Arizona, USA) with a sampling frequency of 200 Hz and based upon the sensor frame of reference. Output measures from the unit were recorded in milli-gravity (mg) and each trial was recorded separately. For each participant, the unit was positioned at the lumbar spine, above the pelvis at the L5 vertebral disc. All warm-up activities and testing procedures were led by the first author who is an accredited strength and conditioning coach (UKSCA).

6.2.2 Participants

Using convenience sampling, male and female youth basketball players were recruited from a junior-level club consented to take part in the cross-sectional study. To increase the homogeneity of the population sample, participants were recruited using convenience sampling from under 14s and under 16s age groups for both males and females. Based upon inclusion criteria relating to age range, a basketball playing history of at least one year, and being free of injury that resulted in absence from playing during the six months leading up to the study, a total of 27 males (mean age 14.5 ± 1.09 years) and 12 females (mean age 14.88 years ± 1.19 years) were initially included in the study. However, because of the absence of familiarisation testing, a total of 25 participants (17 males and 8 females) were included in the final analysis. To estimate participant maturity status, anthropometric measures were entered into a sex-specific equation to predict maturity offset [149]:

Girls: Maturity Offset (years) = -9.376 + (0.0001882 x (leg length x sitting height)) + (0.0022 x (age x leg length)) + (0.005841 x (age x sitting height)) – (0.002658 x (age x mass)) + (0.07693 x (mass by stature ratio x 100));

and

Boys: Maturity offset (years) = -9.236 + (0.0002708 x (leg length x sitting height)) + (-0.001663 x (age x leg length)) + (0.007216 x (age x sitting height)) + (0.02292 x (mass by stature ratio x 100)).

Following Peña-González [522], participants estimated to be > 6 months from peak height velocity (PHV) were defined as pre-PHV, while those estimated to be > 6 months after PHV were defined as post-PHV. Participants estimated to be within six months on either side of PHV were defined as circa-PHV. Within the male cohort, the estimations for maturity status revealed three individuals to be pre-PHV, four to be circa-PHV and one to be post-PHV. Within the female cohort, all participants were classified as post-PHV. Descriptive data for all participants are reported in Table 1. All experimental procedures and risks were explained fully, both verbally and in writing. Written consent and assent were obtained from the children and their parents/guardians. Ethical approval of the study was granted by the institutional research ethics committee of the authors' university and in accordance with the latest version of the Declaration of Helsinki.

Table 5. Average physical characteristics of the participants and maturity offset estimation by sex.

Sex	Chronological age (years)	Height (cm)	Sitting height (cm)	Leg length (cm)	Mass (kg)	Maturity offset estimation (years)
Male	14.14 ± 1.13	168.30 ± 8.11	83.31 ± 4.50	84.99 ± 4.70	58.45 ± 9.81	-0.01 ± 0.94
Female	14.95 ± 0.89	160.21 ± 9.21	78.71 ± 5.66	78.90 ± 5.30	58.49 ± 16.83	1.85 ± 0.84

6.2.3 Procedures

Firstly, participants completed the DJ, using the technique previously described in the literature (Pauli et al., 2016; Ramirez-Campillo, Moran, et al., 2019). From a standardised box height of 30 cm, which was judged by the lead author to be appropriate across all participants, participants were required to initiate the DJ from an upright position with their toes aligned to the box's edge. From this position, participants were instructed to drop to the floor and, upon ground contact, to *"jump as high as possible as quickly as possible*". Following three practice jumps, participants were required to complete three DJ trials separated by ~20 seconds. Any participants not able to perform the drop jump using the specified technique, as judged by the first author, were removed from the analysis. Specifically, data from participants not dropping appropriately from the box's edge, and participants not being able to generate a fast take-off, were removed from the analysis.

Following the DJ trials, participants completed the parkour-style TT action against a 'Reversaboard' (Eveque Leisure Equipment Ltd, Cheshire, England), constructed of solid plywood and specifically designed to be placed against a wall for indoor athletic activities. Using their preferred 'pushing' leg, participants were required to start from a standardised position measured at 45° and 3 m from the position of the Reversaboard, from where they were instructed to use approach steps towards the board and then propel from the ground to the board before pushing off from the board with the ball of their foot to gain "as much height and distance as possible", before landing back on the floor (figure 8). Participants were instructed to gain as much height and distance from the board as possible. A total of three trials separated by ~20 seconds were recorded for analysis.

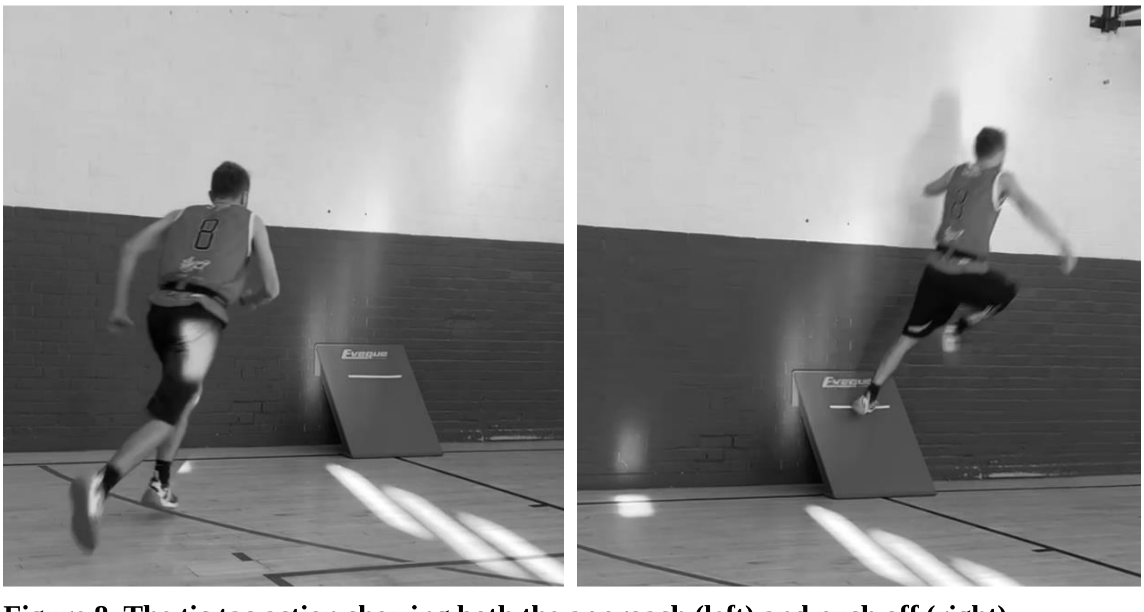

Figure 8. The tic tac action showing both the approach (left) and push off (right) components.

Finally, using a ball size appropriate to their respective age group (size 6-7) participants were required to complete three LU shots, using their preferred shooting side, which corresponded with the preferred take-off limb utilised in the TT. For each trial, the starting position was similarly standardised to the TT, with a 45° and 3-m starting line measured from underneath the basketball hoop. Participants were instructed to execute a LU shot "*as they would in a typical basketball practice"* though the outcome of the shot was not recorded. Each LU trial was separated by ~20 seconds.

6.2.4 Data Analysis

Raw data for each trial for the three jumping actions were extracted and initially processed using Microsoft Excel (Microsoft Office, 2023). Data for all jumps and respective trials was filtered with 4th order low-pass Butterworth filter with a cut-off frequency of 50 Hz [526]. To account for the accelerometer unit being calibrated to the device's reference frame, the sum-vector was calculated (equation 1) to provide the maximum resultant acceleration (a_g). These values were also converted from mg to g for subsequent analyses.

$$a_g = \sqrt{((x^2) + (y^2) + (z^2))} \qquad \text{(equation 2)}$$

[527]

To assess reliability, values for absolute intraclass correlation coefficients (ICC) were calculated using the statistical analysis package, R Studio, version 2024.04.2 (Boston, MA, USA). Statistical analysis was then undertaken using the statistical analysis software, JASP, version 0.18.3.0 (Amsterdam, Netherlands). All measures were tested for normality using the Shapiro-Wilk test. For data found to be normally distributed, separate Bayesian one-way repeated measures ANCOVA tests were used to evaluate the effects of action on $a_{g,}$ using sex and maturation status as covariates. Accordingly, the null hypothesis was that there would not be strong evidence for differences in maximum acceleration between the jumping actions, while the alternative was that there would be strong evidence of differences in favour of the TT. Where strong evidence of differences was revealed, post-hoc comparisons were performed using Bayes factor comparisons to identify which jumping actions these differences belonged to. In accordance with Andraszewicz et al. [528], the Bayes factor was interpreted in terms of discrete categories of evidential strength.

Further, to provide a practical appreciation of the results, between-action effects sizes (ES) for a_g were calculated using a pooled standard deviation for males and females and interpreted as 'small', 'medium', and 'large' in accordance with Cohen's *d* guidelines [529].

6.3 Results

The absolute ICC values across trials were found to be 0.78 for the TT indicating good reliability, and 0.71 for both the DJ and the LU, indicating moderate reliability. Mean values for a_g are displayed in Figure 9. The results of the Bayesian one-way repeated measures ANCOVA tests for a_g (Table 6) revealed extreme ($BF_{10} > 100$) evidence for all models that included the jump test when compared to the Null model. The jump test + sex model was found to be the best fitting. However, despite the BF_M being found to be four times more likely than the second-best model (the jump test alone), the analysis of the effects of sex as a predictor did not reveal conclusive evidence to support its inclusion or exclusion. The Bayes Factors for maturation status showed anecdotal evidence against an inclusion effect ($BF_{10} = < 1.00$). The effects of the different predictor variables and 95% credible intervals are displayed in Table 7. The TT was found to have a positive effect on the model compared with the DJ, which was found not to have an effect, and the LU that revealed a negative effect. The post hoc comparisons revealed that the TT produced greater acceleration than the DJ and LU, while the DJ produced greater acceleration compared to the LU (Table 8).

In the ES analyses (Table 9), a large ES was found between a_g for the TT and the DJ, and between the TT and the LU in the male cohort. The comparison between the DJ and the LU in the male cohort also revealed a large ES. Similarly, in the female cohort, a large ES was found between the TT and the DJ, and the TT compared to the LU a_g values. In contrast to the male cohort, however, the ES between the DJ and LU was small.

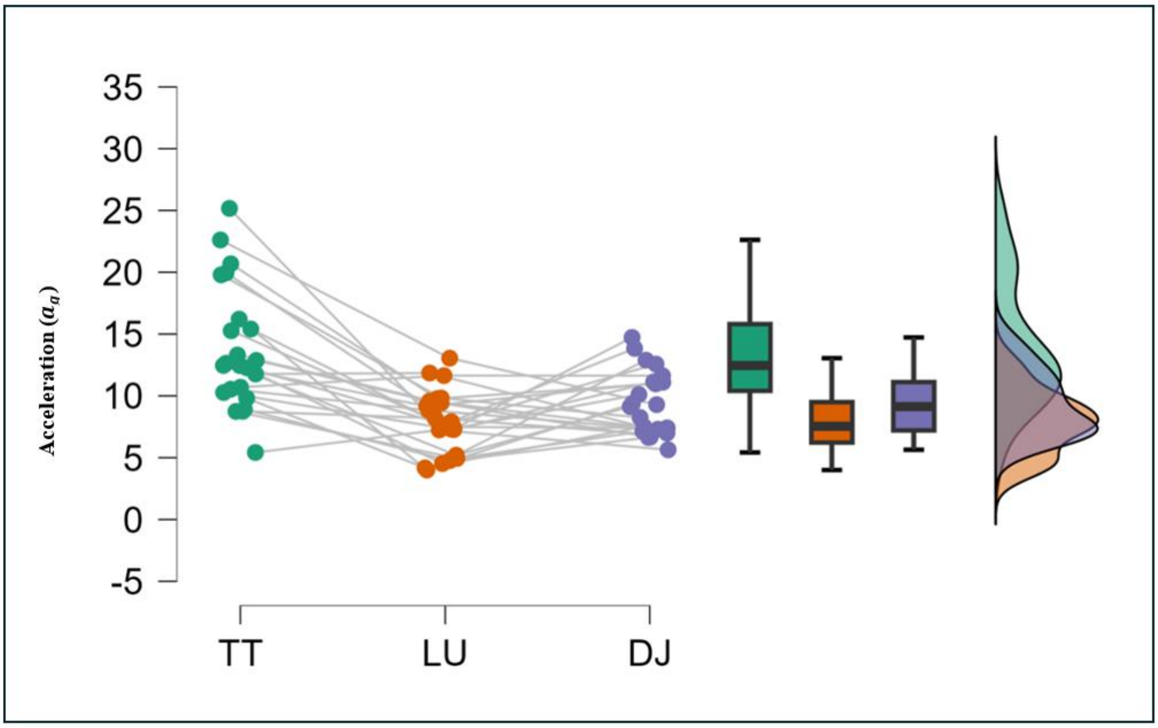

Figure 9. Raincloud plots showing descriptive a_g values for each jumping action.

Table 6. Bayesian ANCOVA model comparison

Models	P(M)	P(M|data)	BF_M	BF_{10}
Null model	0.125	4.306×10^{-7}	3.014×10^{-6}	1.000
Test + Sex	0.125	0.397	4.611	922243.821
Test	0.125	0.276	2.675	642069.579
Test + Sex + Maturation Status	0.125	0.177	1.501	410014.181
Test + Maturation Status	0.125	0.150	1.234	348051.822
Sex	0.125	4.084×10^{-7}	2.859×10^{-6}	0.949
Maturation Status	0.125	2.297×10^{-7}	1.608×10^{-6}	0.534
Sex + Maturation Status	0.125	1.615×10^{-7}	1.130×10^{-6}	0.375

Note. All models include subject, and random slopes for all repeated measures factors. P (M) = Prior model probability; P(M|data) = Posterior model probability; BF_M = Posterior model odds; Bayes factor compared to the null model.

Table 7. Model averaged posterior summary displaying mean values for the effects of the model against the reference with standard deviations (SD) and 95% credible intervals.

				95% Credible Interval	
Variable	Level	Mean	SD	Lower	Upper
Intercept		10.311	0.568	9.148	11.428
Test	TT	3.231	0.521	2.172	4.238
	LU	-2.301	0.508	-3.349	-1.279
	DJ	-0.930	0.495	-1.916	0.041
Sex		-1.719	1.174	-4.131	0.540
Maturation Status		-0.226	0.810	-1.833	1.424

Table 8. Post hoc comparisons.

		Prior Odds	Posterior Odds	$BF_{01, U}$
TT	LU	1.702	5.525×10^{-4}	3.246×10^{-4}
	DJ	1.702	0.002	0.001
LU	DJ	1.702	1.647	0.968

Note. The posterior odds have been corrected for multiple testing by fixing to 0.5 the prior probability that the null hypothesis holds across all comparisons. Individual comparisons are based on the default t-test with a Cauchy (0, r = 1/sqrt(2)) prior. The "U" in the Bayes factor denotes that it is uncorrected.

Table 9. Cohen's d ES comparisons of maximum a_g according to action (0.2 = small effect; 0.5 = moderate effect; 0.8 = large effect).

	Cohen's *d*		
	TT vs. DJ	TT vs. LU	DJ vs. LU
Male	1.05	1.87	0.81
Female	1.00	1.00	0.12

6.4 Discussion

The purpose of this study was to evaluate maximum acceleration in the parkour-style TT jump and DJ compared to the basketball LU shot in youth basketball players and determine the potential utilisation of the TT as a specific-training exercise. The TT was found to produce higher maximum propulsive acceleration compared to the DJ and the LU, which was observed irrespective of sex or maturational status. Considering these findings, this study indicates that the TT may be utilised by both male and female youth-level basketball players to express maximal propulsive acceleration. This was further highlighted by large ES values revealed between the TT and the other two jumping-based actions. Accordingly, this study provides evidence towards the integration of parkour-based actions in the youth athletic development training of youth basketball players.

Despite the long-term strategy for the physical development of young athletes emphasising the development of broad athletic capabilities, the perceived relevance of the training activities by coaches remains important [36,478]. Moreover, conventional strength and conditioning training approaches have been questioned for not being representative of the demands of basketball (e.g., the actions that occur in the frontal plane) [489]. However, contemporary strength and conditioning concepts, such as coordinative overload and those based on the ecological dynamics framework, are purported to be more representative of motor behaviour and skilled performance compared to the traditional forms of mechanical overload [516,517].

From the ecological dynamics perspective, parkour has been proposed as a donor sport for the athletic development of youth athletes in team sports, such as basketball [34]. Through this lens, the use of parkour-style activities, such as the TT, have been purported to benefit the athletic development of young team sports athletes, particularly in relation to agility-related qualities [34,355]. In particular, through the ecological dynamics lens, the human body is regarded as a complex dynamical system and motor skills are considered to emerge out of the interaction between the constraints of the performer's capabilities, the specific motor task, and the surrounding environment [494,507].

Within sports-specific contexts, such as basketball, interacting task and environmental constraints dictate that players must be capable of producing diverse and adaptable skills and movement patterns [530]. Accordingly, the multi-directional nature of the TT jump may contribute to improved acceleration in multiple planes of motion, therefore facilitating greater transfer of training to the 'open skill' context of basketball whereby skills are performed with a degree of unpredictability [329]. Indeed, the TT has been previously suggested as an exercise to target athletic capabilities relating to the coupling of movements at various speeds [355]. Such characteristics appear to relate to basketball shooting, which has previously been shown to correlate with both countermovement jump and change of direction capabilities [531]. It is plausible, therefore, that these findings would extend to the LU shot, which requires the execution of a specific pattern of footwork combined with a subsequent jump to the basket [532,533].

However, when considering our results from an ecological dynamics perspective, it is also important to acknowledge that in a complex dynamical system the observed ES magnitudes in comparisons between the different actions may not necessarily transfer in a linear fashion, especially when considering the complex nature of a skill such as the LU when executed within the context of a basketball game. Such non-linear effects have been previously highlighted in a study by Arede et al. [530] which, following a 10-week strength training programme revealed a large effect size for the observed pre-post differences in peak acceleration displayed by youth players within a simulated basketball game. However, despite utilising the training intervention targeting optimal power output using a loaded back squat, the observed effect size for the pre-post CMJ was small. Accordingly, the larger effect size values observed for the TT may not necessarily correspond to basketball-specific performance of the LU when executed within game-specific conditions.

Of further consideration, from a perception-action perspective, the use of the ball within the LU shot may have also altered the dynamics of the action, with potential implications for the levels of acceleration produced. Indeed, the inclusion of a ball catching task in the execution of the single leg DJ has been found to increase movement variability in youth basketball players, though the condition did not alter jump height or ground contact time in comparison to the no ball condition [535]. Therefore, it is possible that the perceptual differences between the jumping actions would have some bearing on the degree of transfer being the motor tasks. Nonetheless, the findings of this study provide an objective basis for further investigation of the TT as an action that could donate to the development of athletic capabilities of youth basketball players.

Contemporary perspectives aside, within the field of strength and conditioning, the application of mechanical overload is understood to be necessary to elicit training adaptations that can enhance sport performance [517]. Whilst this may not necessarily be of primary concern in the athletic development of youth populations, exercises that possess a high degree of sports-specificity may be more willingly implemented and adhered to by basketball coaches compared with exercises that are considered less specific [36,478]. Accordingly, due to the movement characteristics of the TT (e.g., combined running and multi-directional jumping), coaches of youth basketball players may be more likely to implement the exercise within their practice.

However, from a classical strength and conditioning training perspective, for adaptations to training to be successfully transferred to sports performance, those adaptations must exhibit a high degree of mechanical specificity to the target activity [252,253]. In accordance with the principle of dynamic correspondence, however, to be considered specific, an exercise is only required to overload to one to two of its five biomechanical-based criteria associated with the target activity [252,536]. Accordingly, rather than overloading of an entire movement skill, the training activity is considered to target "local specificity" [517]. Given that the LU has been previously shown to relate to speed and strength qualities [519,537], it is reasonable to infer that because the maximum propulsive acceleration observed in both the TT and the DJ exceeded that displayed in the LU, the utilisation of either jump as a training exercise could provide a greater mechanical overload to the muscles of the lower limb in relation to the production of propulsive acceleration for the jumping element of the LU. Moreover, based upon the dynamic correspondence concept, the larger magnitudes of acceleration in the TT and DJ appear to conform to the rate and time of maximum force production criterion [536]. However, the multi-directional characteristics of the TT would suggest that it may overload the capabilities to produce propulsive acceleration in different planes of motion to a greater extent than the DJ, the latter of which is typically utilised to improve impulse in the vertical plane [538]. Although our results are limited to accelerometery data, given that acceleration is representative of the rate of change in velocity, and is proportional to force, it is plausible that both jump actions could be utilised to enhance the required motor qualities relating to rate and time of maximum force production. Accordingly, both the TT and DJ can be considered to possess some degree of specificity to the LU shot.

From a motor learning perspective, the apparent effectiveness of the TT over the DJ following a single familiarisation session, is also of pertinence to its potential adoption within the coaching practices of coaches of youth basketball players. Certainly, the larger acceleration observed in the TT versus the DJ suggests that the TT may be a practical and more time-efficient activity to include in the athletic development programmes of youth basketball players compared to the DJ. Indeed, within talent pathways and youth sports, time-efficiency of training activities is imperative, with the greatest proportion of dedicated training being allocated to sports-specific development [88,116]. Moreover, the relative simplicity of the TT action coupled with the limited requirement of training equipment, would enable the activity to be implemented within typical basketball playing environments as part of the warm-up. This is of importance in the context of motor learning in youth populations who are considered to develop motor skills more readily due to high capacity for neural plasticity [181]. Accordingly, during what is termed a golden period of motor learning [505], it is suggested that the development of broad and diverse fundamental movement skills should be emphasised to equip youth with greater movement capabilities rather than limiting skill development to a single sport [165].

However, where coaches of youth basketball players have been found to be reluctant to implement athletic development-based activities within their practices, due to time constraints [36], the TT might present a time efficient and effective activity that can be utilised to contribute to the development of broader movement skill and athletic capabilities. Indeed, given that both the DJ and TT were novel actions for the participants, the differences found in output measures indicate that the TT may have been executed more effectively than the DJ and with little time necessary for motor learning. However, this would need to be confirmed through further investigations including longer skill development periods involving the TT and DJ, and through intervention studies examining the training effects of these actions.

To add further context to our findings, the observed differences in accelerations between the TT and the DJ are not surprising given the lower magnitude of ground reaction force likely experienced in the contact phase of the TT and corresponding demands on the musculature of the lower limb. Execution of the DJ requires the athlete to decelerate their body mass by generating eccentric force before re-orientating as rapidly as possible in an upward direction [524,539]. Unlike the DJ, which generates a high-ground reaction force due to the full mass of the individual falling under gravity, the TT action involves a lateral change of direction that requires a lower magnitude of ground reaction force [540].

However, another explanation for the *Peak* a_g values resulting from the DJ might relate to the drop height that was fixed at 30 cm for all participants, regardless of body size, athletic capability, or sex. Ground contact time and subsequent jump heights have previously been found to be influenced by the drop height [541,542]. In general, drop heights are typically between twenty and fifty centimetres, with the larger heights presenting increased ground reaction forces and, in turn, greater eccentric demand on the muscles of the lower limb [540,543,544]. Of pertinence, compared to adults, youths' musculotendinous tissue is more pliable and this can reduce the efficiency with which they utilise the stretch-shortening cycle [545,546]. Therefore, in the absence of measures of ground contact times, the fixed thirty-centimetre drop used in our study was deemed to be appropriate to the cross-sectional design, and age range and sex of the participants. Indeed, this was further vindicated by our finding that the maturation status of the participants did not appear to have any significant effect. On this basis, the TT may be regarded as an activity that may be of benefit to youth basketball players, irrespective of their age or maturity status. Furthermore, with inconclusive evidence for an effect of sex in the results, despite differences that emerge between males and females at the onset of puberty, the TT may be beneficial across all youth basketball players.

Caution must be exercised regarding the small number of female participants included in our study and all of who were estimated to be post-PHV, our results appear interesting when considered against studies that have investigated the effects of plyometric exercises across different stages of maturation [e.g., 388,482]. Such studies have revealed the effectiveness of plyometric training to vary based upon stage of maturation, which differs between males and females. For example, plyometric exercise has been found to be more effective in younger females (< 15 years of age), potentially owing to increased levels of fat mass in post-pubescent girls [486]. In contrast, males have been found to benefit from plyometric training to a greater extent in both pre- and post-PHV periods, with post-PHV trainability suggested to be related to greater force capabilities owing to increased muscle tissue [392]. Our findings, however, suggest that the TT may be an activity that enables adolescent females to express of greater propulsive acceleration than the DJ which, in turn, may be utilised as an exercise to increase propulsive outputs.

Although our findings provide some interesting insights relating to the use of the parkour-style TT action, there are important limitations to consider. Firstly, our study compared the acceleration between jumps without addressing ground reaction force produced in the three jumping actions. The inclusion of ground reaction force would have provided greater insights into the kinetic differences between the TT, DJ, and LU, which would have also accounted for ground contact time and impulse. Secondly, optimal jump height, using the reactive strength index to account for differences in eccentric capabilities, may have elicited different outcomes with respect to the DJ. Thirdly, measures of the LU skill both with and without a ball, may have provided valuable comparisons of acceleration outputs without the constraints imposed by the executing the basketball shot. Finally, the use of the Mirwald equation, whilst widely utilised within the youth-related research literature, provided only an estimate of maturity offset. Therefore, the maturity status of the participants within our study may have differed based upon the standard errors of the equation.

Conclusions

Training specificity and the transfer of training exercises is a central consideration in the preparation of athletes. However, this is also somewhat at odds with the long-term aims of the athletic development strategy of youth athletes, where the enhancement of FMS and general physical capabilities is typically recommended over highly specialised and specific training activities. In the context of the principle of dynamic correspondence, the greater maximal propulsive acceleration observed in the TT indicate that it may provide specific overload to acceleration capabilities which may be beneficial to the LU shot. From an ecological dynamics standpoint, where parkour has been proposed as a donor sport for the athletic development of youth team sport athletes that might benefit agility, the use of the TT may present young basketball players with a multi-directional jumping action that is more representative of the dynamics of basketball-specific actions, such as the LU shot, which occur with a high degree of unpredictability and variability. In addition, the TT may represent an exercise that requires little practice by youth players for them to express large acceleration outputs. In turn, the TT may be more readily adopted by youth basketball coaches, thereby contributing to the development of a broad range of movement skills and enhancing physical capabilities in line with athletic development models

Chapter 7

Beyond athletic development: the effects of Parkour-based versus conventional neuromuscular exercises in pre-adolescent basketball players

Citation

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Abstract

The purpose of this study was to compare the effects of a Parkour-based warm-up to a conventional NMT warm-up on the athletic capabilities of youth basketball players. This was examined through two arms: In Investigation 1, the aims were to measure the effects of the two warm-ups on physical measures of athletic performance in pre-adolescent basketball players. Following this, using post-intervention semi-structured interviews, Investigation 2 aimed to gain insights from the players in relation to the perceived benefits of the two warm-up protocols. Pre-adolescent children were recruited from two youth level basketball teams. Participants from one club were randomly assigned to either a conventional NMT warm-up group or a parkour warm-up group, while a control group was formed of participants from a second club to avoid potential contamination of the participant pool. Participants of both experimental groups were required to complete a 15-minute warm-up, once per week, before their regular basketball practice, over an 8-week period. For both groups, the coach adopted the same pedagogical approach, utilising a guided discovery strategy. Baseline to follow-up measures of overhead squat performance, countermovement jump, and 10-metre sprint speed were recorded in all three groups. Additionally, baseline to follow-up measures were recorded for a timed parkour-based obstacle course for the two experimental groups. No significant between-group differences ($p > .05$) were found between pre- and post-test measures. However, analysis using Cohen's *d* effect sizes revealed improvements in both intervention groups versus the control group. Following the intervention, participants from both experimental groups were also invited to take part in a post-intervention semi-structured interview to discuss their experiences of the programme. The thematic analysis of these semi-structured interviews revealed three higher order themes: *Enjoyment; Physical literacy;* and *Docility*; of which the two former themes appear to align to constructs relating to the wider concept of physical literacy. In summary, both warm-ups were found to be equally effective. However, to improve

athleticism, the results of this study highlight that less structured and more diverse movement skills than are typical of conventional NMT warm-ups can be included. Specifically, the results of this investigation provide evidence that advocates for warm-ups that include parkour-related activities to develop athletic capabilities and to simultaneously evoke a sense of enjoyment, fun, and purpose. The benefit of such activities may extend beyond athletic development and, more broadly, contribute to the development of physical literacy.

7.1 Introduction

Experts argue that participation in youth sports such as basketball is a healthy activity for youngsters [17,96]. Youth sports (under the right conditions) are effective in developing what Whitehead [368,547] has described as *physical literacy* (PL). Young et al. [548,549] draw on the International Physical Literacy Association's definition, which states PL to be "the motivation, confidence, physical competence, knowledge and understanding to value and take responsibility for engagement in physical activities for life" (International Physical Literacy Association [IPLA], 2017). Young and colleagues highlight that Whitehead [550] drew on existential and embodied phenomenological theories to define PL "as a holistic concept which focuses on developing the whole person; mind and body as one," (p. 948) [548,549].

Although engagement in youth sports may contribute to the development of PL, early specialisation (which is defined as year-round participation and competition within a single sport [89,551]) may lead to the underdevelopment of FMS [33,38,88,552]. Commonly, FMS include object manipulation, locomotor capabilities and balance, and are considered to be the building blocks for more advanced athletic movements, such as kicking, throwing and striking skills, and advanced techniques within sports [6,7,18,180]. Thus a youngster who is engaged in organised sport might not exhibit competency in the FMS that underpin SSS [552,553]. Moreover, owing to the strong reported associations between child motor competence in movement skills and levels of self-confidence, where the possession of FMS is considered integral to PL [549,554,555], early specialisation may impede PL development.

Despite the purported issues relating to early specialisation, some researchers argue that these issues are overly simplistic [549,553] and not fully understood [556]. However, in response to the perceived threat of early specialisation, National Governing Bodies (NGBs) have developed numerous NMT programmatic interventions (e.g., the FIFA 11+, Basketball England's Starting 5, and the English Rugby Union's Activate). Typically, NMT programmes comprise a range of FMS, balance, stability, and muscle strengthening exercises to prepare young athletes for the rigours of their sport [393,557,558]. Furthermore, to encourage their implementation, the aforementioned NMT programmes have been devised to be conveniently integrated within the warm-up to regular sports training, requiring only ~20 minutes to complete, thus ensuring athlete compliance and making them relatively time-efficient to execute [36,414]. Such programmes have been found to enhance athletic capabilities and to address factors that are associated with injury incidence [393,414,505,559]. Consequently, the warm-up period is considered to be a valuable opportunity to integrate S&C-based training activities, such as NMT programmes, as an athletic development strategy [415].

In addition to enhancing athletic capabilities in youth athletes, the efficacy of NMT programmes may also relate to the variability of movement patterns presented within such programmes. Accordingly, the performance of varied movement patterns reduces the persistent mechanical stress on the same soft-tissue structures through repeated exposure to SSS, while concomitantly developing a greater breadth of FMS in the process [95,102]. Indeed, owing to their high levels of neural plasticity – especially during pre-adolescence, youth athletes who are exposed to NMT stimuli may develop motor control more readily [181,505]. Notably, the highly individualised patterns of growth and physical development in youth populations reflect complex and dynamic systems. Consequently, the learning of motor skills and the enhancement of physical capabilities become a non-linear process [560]. Accordingly, it may be difficult to detect enhanced performance capabilities that have occurred in response to a training stimulus [375]. Nonetheless, in place of a rigidly prescribed NMT-programme that might limit the breadth of movement skills developed, less structured forms of movement training (as is often emphasised for youngsters within athletic development models [17,37,38]) may be more effective for the learning and development of diverse and adaptable movement skills. One such activity that may inherently provide exposure to a richer breadth of movement skills through its low structured, guided-discovery coaching approach, is Parkour [34].

Previously, Parkour has been proposed as an activity to develop FMS and athletic capabilities that can be transferred to SSS [34,37]. Indeed, there appears to have been an increase in the amount of S&C coaches using Parkour-based concepts with young athletes to develop movement skills for their sports [354]. Often, these coaches have cited the importance of activities being less structured than conventional S&C training forms, as well as being more mentally engaging for young athletes to participate in. In this regard, typically, parkour adopts a guided discovery approach to learning that is self-paced and enables the participant to explore their capabilities in the absence of strict technical models that could potentially impede learning [34,561]. Of further relevance, recently, significant associations have been identified between performance in the agility T-test, standing long jump and CMJ, and higher performance in a parkour obstacle course [235]. Accordingly, Parkour has been suggested to be a potentially efficacious, yet still unproven, way to develop transferable movement skills for youth athletes to exhibit in their sports, potentially improving performance [520]. However, to date no research has examined this theory empirically. Accordingly, the purpose of this study was to compare the effects of a Parkour-based warm-up to a conventional NMT warm-up on athletic performance measures in youth basketball players, implemented using a low-structured, guided discovery coaching approach. This was examined through two arms: In Investigation 1, the aims were to measure the effects of two warm-up protocols on physical measures of athletic performance in prepubescent basketball players. It was hypothesised that there would be no differences in outcome measures in response to the respective NMT protocols. Due to the novel concept of using Parkour-based activities within a warm-up protocol, using post-intervention semi-structured interviews, Investigation 2 aimed to gain insights from the players in relation to their observations and perceptions of the two warm-ups.

7.2 Materials and methods

7.2.1 Participants

A total of 34 youth (20 males; 14 females) basketball players (mean age 11.4 ± 0.67 years) consented to participate in the study across an 8-week intervention period using convenience sampling. To increase the homogeneity of the population sample [562], participants were recruited using convenience sampling from four (2 boys' teams and 2 girls' teams) youth basketball teams (under 12 years of age between the months of January and December) from two clubs registered and affiliated with the NGB, Basketball England. Participants from one club were randomly assigned to either a conventional NMT warm-up group or a Parkour warm-up group. To prevent cross-group contamination, the control group was recruited from a second club, unaffiliated with that which provided the experimental groups. For inclusion in the study, all participants were to be classified as pre-PHV, based upon the prediction equations by Mirwald et al. [149] (<- -0.5 years from PHV), have at least one year's basketball playing experience, and be free from musculoskeletal injury. Participants that were identified as being > 0.5 years from PHV were excluded from the study. Other exclusion criteria included participant absence from one of the testing sessions, and absence from three or more of the training sessions. All experimental procedures and risks were explained fully, both verbally and in writing. The written consent and assent was obtained from the children and their parents/guardians. Ethical approval of the study was granted by the institutional research ethics committee of the authors university and in accordance with the latest version of the Declaration of Helsinki.

7.2.2 Phase 1 – Quantitative measures and analysis

7.2.2.1 Testing Procedures

All testing was place in gymnasiums across two sites used by the respective basketball clubs for regular practice. Testing took place one week before and one week after the eight-week intervention period and included: anthropometry (height, seated height, mass), overhead squat OHS assessment, CMJ, 10-m sprint and, for the experimental groups only, a Parkour speed-run. To estimate participant maturity status, anthropometric measures were recorded using medical grade digital scales and stadiometer (Seca, Birmingham, United Kingdom) and entered into a sex-specific equation to predict maturity offset [149]:

Girls: Maturity Offset (years) = -9.376 + (0.0001882 x (leg length x sitting height)) + (0.0022 x (age x leg length)) + (0.005841 x (age x sitting height)) – (0.002658 x (age x mass)) + (0.07693 x (mass by stature ratio x 100));

and

Boys: Maturity offset (years) = -9.236 + (0.0002708 x (leg length x sitting height)) + (-0.001663 x (age x leg length)) + (0.007216 x (age x sitting height)) + (0.02292 x (mass by stature ratio x 100)).

For the OHS assessment, participants were instructed to hold a wooden dowel with extended arms above the crown of their head and, while maintaining the OH position, squat as low as possible. Following three warm-up trials, three further repetitions were performed and recorded using the motion analysis system, HumanTrak (Vald Performance, Brisbane, Qld, Australia). The sum of knee flexion angle for both limbs for the OHS were averaged for the three repetitions and used in the analysis.

To measure the CMJ, participants were required to jump with their hands placed upon their hips and instructed to descend to a self-selected angle of knee flexion before immediately jumping as high as possible with a vigorous extension of the lower limbs. Following three warm-up trials, participants performed three experimental test trials on dual portable force platforms (ForceDecks, Vald Performance, Brisbane, Qld, Australia), with at least 20-seconds rest taken between trials. The average of the three jumps were analysed.

For acceleration speed, electronic timing gates were used (Brower Timing Systems, Draper, Utah, USA). Following a standardised warm-up comprising submaximal running efforts over a 10-m distance and two practice trials at maximal intensity, each participant completed three trials with at least 60-seconds of recovery time between trials. Participants began each trial in a *two-point* position, 50 cm behind the first timing gate and were instructed not to countermove ahead of their first step forward, before sprinting as fast as possible through the end-point timing gate. The average of the three trials was used in the analysis.

The speed-run route was designed in accordance with Strafford et al. [37,235] and in collaboration with an experienced Parkour coach and athlete. In brief, this included a series of obstacles (gymnastics vaulting boxes and benches) and open spaces set out within a gymnasium. The participants were required to navigate the course in the quickest way possible and were timed using timing gates positioned at the start and end points of the outline course. Following two practice trials, each participant completed three trials with at least two minutes of recovery time between each, the best of the three trials being used in the analysis. A familiarisation session of the speed-run test was executed one week prior to the pre-intervention testing with that data used against the pre-intervention measures to determine intra-class reliability (ICC).

7.2.2.2 Training Interventions

Participants of both experimental groups were required to complete a 15-minute warm-up once per week before their regular basketball practice, across an eight-week timeframe. The warm-up was led by the principal researcher (also a qualified S&C coach) and was conducted in the same school gymnasium located in a separate building to which basketball practice was undertaken. While one group completed their intervention protocol, the other group completed low intensity shooting exercises with their basketball coach. This was portrayed to the players as being to be due to the limited space available in the warm-up area. However, to account for any impact of the shooting exercises, the order by which each group completed the intervention (before or after shooting) was alternated each week to minimise the effects of systematic bias. To ensure the time of the warm-up programmes was matched, a timer was set for 15-minutes and commenced upon the explanation of the first activity/exercise of each of the respective warm-ups.

The details of the included exercises for both warm-ups can be seen in Table 10. For both groups, the coach adopted the same pedagogical approach, utilising a guided discovery strategy that provided limited technical instruction after the initial introduction to the movement skills and activities to be performed. This approach aligned to the typical practice of parkour coaches [561]. In addition to this, to prevent potential tedium in the NMT Group, exercises were ordered differently in both groups across the 8-weeks, though this was administered in a uniform way to standardise the programmes. The control group, who were unaware of the warm-up interventions performed by the two experimental groups, instead continued with their normal basketball practice as well as other typical physical activities they were engaged in.

Table 10. Exercises and activities included within the 15-minute warm-up for the respective experimental groups.

NMT Group (exercises from):	Parkour Group (exercises from):
Body weight squatting	Tic-tac actions
Reverse lunge	Continuous bench vaults
Skipping for height / distance	Vault box jumps / mounts
Countermovement jumps	Vaulting
Drop landings (from toe raise)	Ground-based floor vaults
Accelerations (5-10 metres)	Leaping over benches (on to crash mats)
Ice skater jumps	Rope swings
Hip hinge (single and double leg)	
Short sprint races	
Hopping	
Push up variations	

7.2.2.3 Data Analysis

Within subject coefficient of variation (CV) and average CV measures for each test were determined using the spreadsheet software, Microsoft Excel (Microsoft Office 365). Using the same software, the minimal detectable change (MDC) was also calculated for each of the test measures and according to group. ICC calculation and inferential analyses were performed using the statistical analysis software, IBM SPSS Statistics for Windows, version 28.0. All measures were tested for normality using the Shapiro-Wilk test and for homogeneity using the Levene's test. To evaluate mean differences across the multiple variables, a repeated-measures MANOVA was used to assess differences by group and time between pre- and post-testing for all three groups and across all measures except for the parkour speed-run. For the speed-run, a repeated-measures ANOVA was used to assess differences by group and time.

In addition, due to the low dose application of the warm-up protocols, Cohen's *d* was used to calculate within group effect sizes (ES) for each of the performance measures. The between group ES were also calculated to compare post-intervention measures between the two intervention groups. The ES values were interpreted as 'small', 'medium', and 'large' in accordance with Cohen's guidelines [529]. For further practical understanding of the data, pre-post changes beyond the within-subject coefficient of variation was also calculated for all measures.

7.2.3 Phase 2 Qualitative data and analysis

7.2.3.1 Semi-Structured Interviews

Based upon recommendations by Ponizovsky-Bergelson et al. [563], qualitative interviews were conducted with eight of participants from the two experimental groups in Investigation 1 (four from the NMT group and four from the Parkour group). Semi-structured interviews (Table 5) were used to elicit children's perspectives on the warm-up protocols. Each interview took place in the presence on a parent or guardian via the virtual meeting platform, Microsoft Teams (Redmond, Washington, USA), and the footage was recorded for later transcription. All interviews lasted no more than 30-minutes in duration. Although it has been suggested that face-to-face interviews would have allowed for greater synchronous communication (e.g., social cues of the interviewee, such as body language) than virtual meetings [564,565], due to the COVID-19 pandemic a decision was made to use virtual rather than face to face meetings. Following each interview, the recording was transcribed using the transcription tool, Sonix (San Francisco, USA), after which, the transcriptions were checked for accuracy by the principal researcher.

7.2.3.2 Data Analysis

A thematic analysis was undertaken using the codes developed through three rounds of iterative coding. In addition, inductive analysis techniques were also utilised in the analysis of the transcripts, creating additional codes deemed to be pertinent to the study aims (see for e.g., Fereday and Muir-Cochrane [566]). To code the data, each of the transcripts and text were read and coded against preliminary codes using Excel. Initial meaning codes were then considered before determining the axial coding scheme [443].

7.3 Results

Having been calculated to be approximately classified as either circa- or post-PHV, five participants were removed from the analysis. Additionally, due to low adherence levels (< 6 from a total of 9 exposures), a further three participants' data were removed from the analysis. In addition, one participant was removed due to injury. Therefore, a total of 18 participants who met the inclusion criteria relating to adherence, maturity status, and at least one year of participation in basketball were included in the statistical analyses (Table 11.). In the analysis of the parkour-based speed run, 10 participants were included. The descriptive data for all the participants is reported in Table 12.

Table 11. Descriptive data for participants including group and maturity offset.

Group	Chronological age (years)	Height (cm)	Sitting height (cm)	Leg length (cm)	Mass (kg)	Maturity offset estimation (years)
NMT Group	10.96 ± 0.14	153.00 ± 7.54	75.50 ± 4.32	77.50 ± 4.85	42.45 ± 10.18	-2.20 ± 0.93
Parkour Group	10.76 ± 0.23	148.80 ± 6.83	73.40 ± 2.70	75.40 ± 5.46	40.68 ± 6.74	-2.76 ± 0.37
Control Group	11.96 ± 0.56	158 ± 3.99	80.42 ± 5.14	78.40 ± 5.54	45.53 ± 6.34	-1.49 ± 0.73

Table 12. Descriptive pre- and post-intervention test measures.

Group	OHS knee flexion (˚)				10-m time (s)				CMJ (cm)				Pre-speed-run time (s)			
	Pre	**Post**	**MDC**	**ES**	**Pre**	**Post**	**MDC**	**ES**	**Pre**	**Post**	**MDC**	**ES**	**Pre**	**Post**	**MDC**	**ES**
NMT	119.16 ± 23.57	138.05 ± 27.67	24.08	0.71	2.12 ± 0.19	2.07 ± 0.15	0.23	0.35	21.66 ± 3.83	21.95 ± 3.54	4.41	0.14	9.17 ± 1.07	8.62 ± 0.92	1.32	0.56
Parkour	120.02 ± 30.02	117.59 ± 15.07	31.14	-0.63	2.14 ± 0.10	2.16 ± 0.15	0.11	-0.14	19.08 ± 4.97	19.15 ± 4.72	5.19	0.09	9.87 ± 1.42	9.39 ± 1.19	1.76	0.37
Control	138.21 ± 16.11	127.90 ± 29.64	18.23	-1.12	1.96 ± 0.16	2.02 ± 0.18	0.18	-0.37	22.82 ± 5.97	22.25 ± 4.80	4.80	0.11	-	-	-	-

Means, standard deviations (±), MDCs, and within-group Cohen's *d* ES values are shown for each dependent measure

A high degree of reliability was found between familiarisation scores and the pre-intervention test scores for the speed-run. Based on an absolute agreement, 2-way mixed-effects model, the ICC estimate was .963 with a 95% confidence interval from .600 to .994. The average CV for the familiarisation scores was 6.65%. Within subject variation (CV) values for all pre- and post-intervention tests are displayed in Table 13.

All pre- and post-intervention data was determined to be normally distributed ($p > 0.5$). The repeated-measures MANOVA revealed no significant effects of group on pre-post intervention measures, F (6, 22) = .793[b], $p > .05$, Wilk's $\Lambda = .676$, partial $\eta^2 = .178$. In addition, no significant between subjects effects were observed for time, F (3, 11) = .092[b], $p > .05$, Wilk's $\Lambda = .975$, partial $\eta^2 = .025$. Following this, using partial η^2 to determine effect size, a post-hoc power analysis for between subjects' effects revealed effect size F = 0.312 and statistical power (1- β err prob) to be 0.25.

The repeated measures ANOVA used for the analysis of the parkour-based speed run revealed no significant effects of time x group interaction on completion times, F (1, 9) = .219[b], $p > .05$, Wilk's $\Lambda = .976$, partial $\eta^2 = 0.24$. A post-hoc power analysis revealed the effect size F = 0.562 and statistical power (1- β err prob) to be 0.91.

Table 13. Average pre- and post-intervention coefficient of variation (%) per group.

	OHS Pre-knee flexion angle left	OHS Post-knee flexion angle left	OHS Pre-knee flexion angle right	OHS Post-knee flexion angle right	Pre-10-m	Post-10-m	Pre-CMJ	Post-CMJ	Pre-speed-run time	Post-speed run time
NMT Group	2.49	3.34	1.96	3.24	2.82	2.05	5.86	3.70	3.58	2.85
Parkour Group	1.62	3.91	1.84	3.26	2.50	1.51	3.89	4.82	2.82	1.59
Control Group	3.30	1.85	3.50	3.30	0.95	2.08	4.32	4.04	-	-

In the NMT Group, the within group ES values revealed a medium ES improvement in knee flexion angle in performance of the OHS. In contrast, both the Parkour Group and Control Group displayed reductions in knee flexion angles with medium and large ES, respectively. For the NMT Group, the Cohen's *d* yielded a small ES for the 10-m sprint. In contrast, the Parkour Group and Control Group both displayed increases in 10-m sprint times with small ES though the magnitude of the increase was greater in the Control group. For the CMJ, across each group, the within group ES was found to be small. In the speed-run, a medium ES was revealed for the NMT Group, while the Parkour Group displayed a small ES for their pre-post speed-run times. The between-group ES values for the two experimental groups were 0.61 for the 10-m sprint, 0.73 for the speed-run, 0.62 for the CMJ, and 0.98 for the OHS, representing medium to large effects across all measures in favour of the NMT Group. In addition, across measures, no group displayed improved performance beyond the calculated values for MDC.

Figures 10-13 provide individual pre- and post-intervention data across each of the performance measures. Dashed lines have been used to represent individuals showed percentage changes greater than pre-intervention CV, while solid lines have been used to indicate that changes were less than pre-intervention CV.

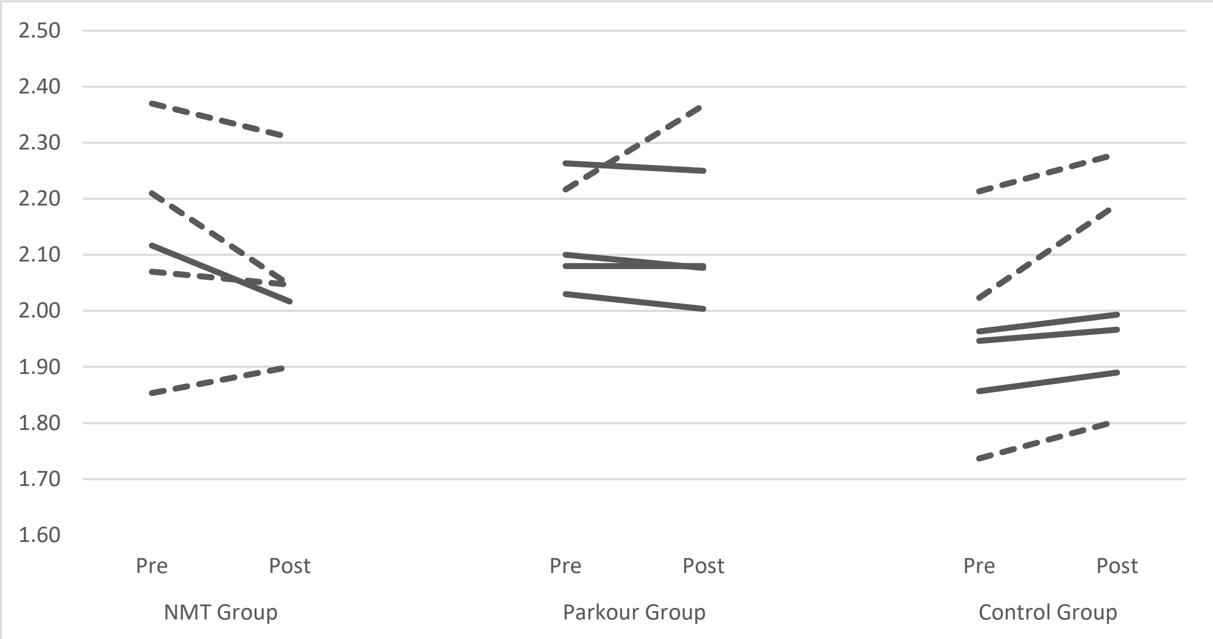

Figure 10. Individual pre-post intervention mean 10-m sprint data. Dashed lines represent % changes > than pre-intervention CV; solid lines represent difference that was not > CV.

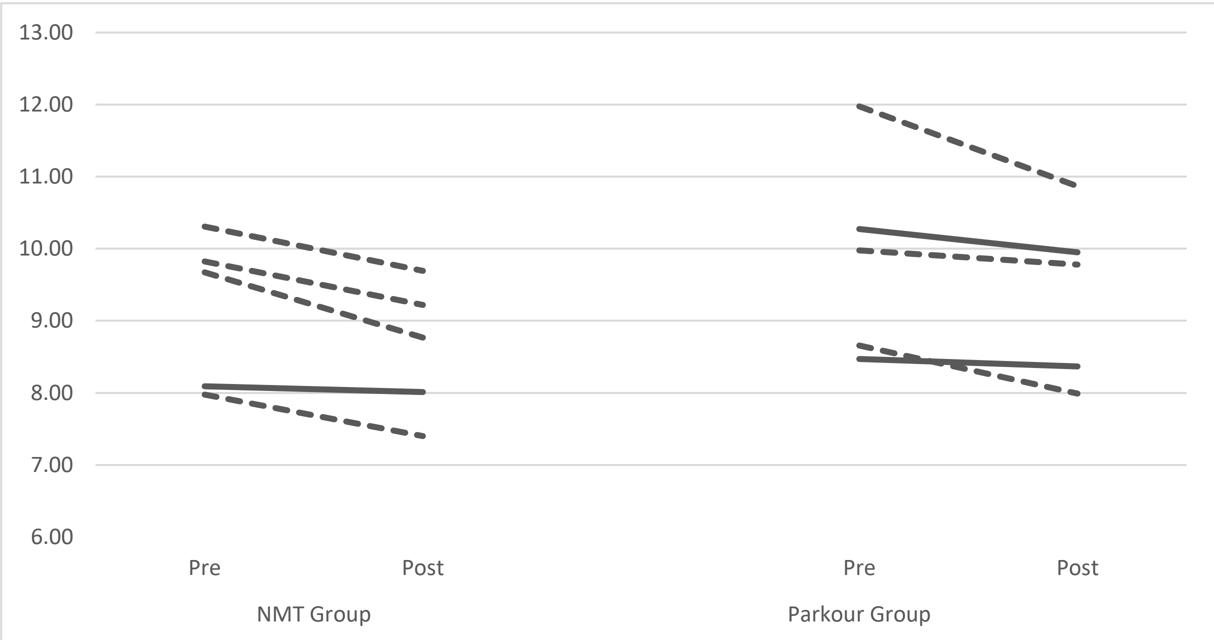

Figure 11. Individual pre-post intervention mean Speed-Run data. Dashed lines represent % changes > than pre-intervention CV; solid lines represent difference that was not > CV.

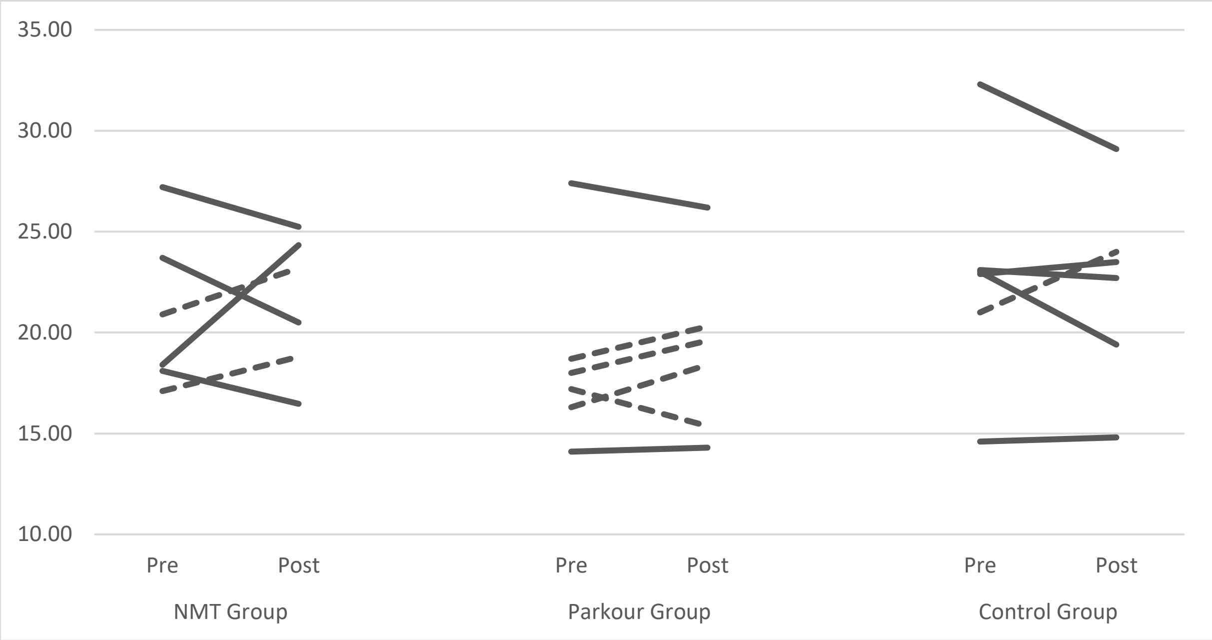

Figure 12. Individual pre-post intervention mean CMJ data. Dashed lines represent % changes > than pre-intervention CV; solid lines represent difference that was not > CV.

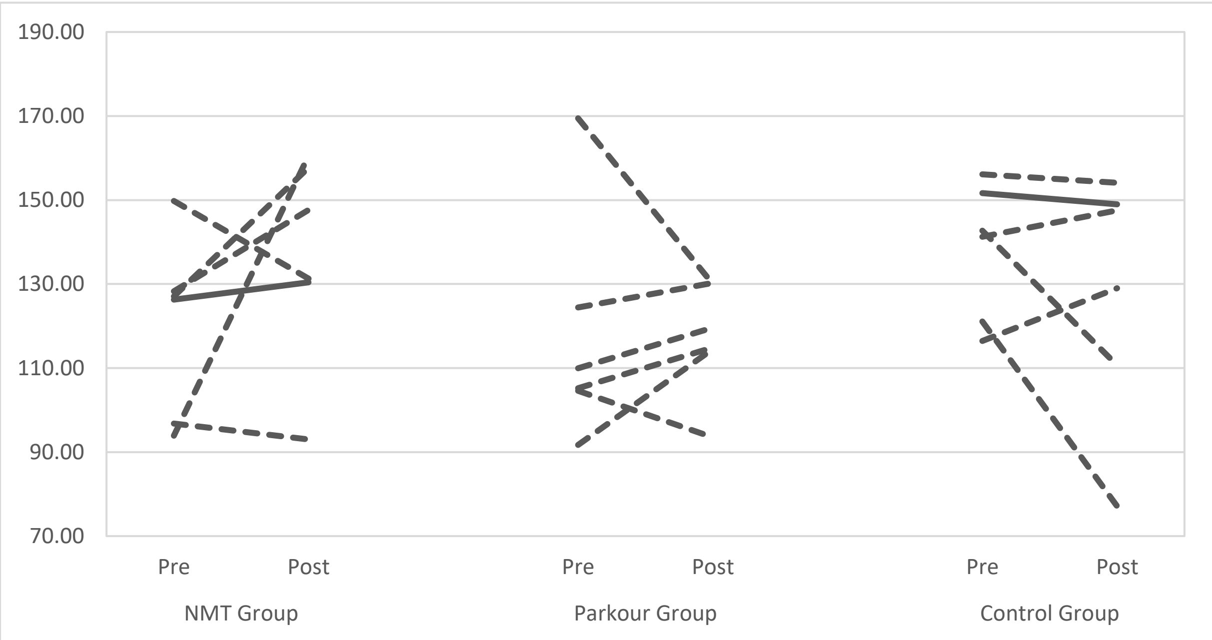

Figure 13. Individual pre-post intervention mean Overhead Squat knee flexion data. Dashed lines represent % changes > than pre-intervention CV; solid lines represent difference that was not > CV.

7.3.1 Qualitative findings

Data were categorised into three higher order themes drawing on data from the young players' responses: enjoyment; physical literacy; and docility. These themes included subthemes that related to the young players' reflections on the value and purpose of the warm-up intervention and perceived benefits on basketball playing performance (see Table 14.).

Table 14. Higher order themes and associated subthemes

Docility	Enjoyment	Physical Literacy
Despair	Free play	Autonomy
Lack of enjoyment	Fun	Confident
Performativity	Getting ready	Critical (of activities prescribed)
Parent	Improvement	Inquiry
	New	Reflection
		Self-awareness
		Specificity

Theme 1 – *Enjoyment*

Most participants indicated that they enjoyed the warm-up activities, irrespective of the experimental group they were assigned to:

> *"Yeah, it's definitely one of the things that I enjoy doing a lot because it's not just like running there and back, but it's including like jumps and then like moving around more rather than going in the straight line there and back."*

With specific reference to parkour-based activities, participants also suggested that they found the warm-up to be fun. One individual commented:

> *"I think honestly, I really like jumping over the things because I found it fun. It was like when and also jumping onto the mat. That was quite fun as well. And obviously the ropes at the end. That was just the fun."*

Similarly, another individual stated:

> *"Yeah, because it was it was [sic] a good time doing it. It was a good part of the day, like, oh year, it's fun."*

Theme 2 – *Physical Literacy*

Improved confidence in relation to movement competency and motor abilities was identified by the participants. In addition, participants displayed critical reflection of the activities prescribed and self-awareness of their movement capabilities. When asked whether the warm-up activities benefitted basketball performance, one participant reflected:

> *"The rope swing? Yeah, I think those might be less applicable to basketball, but they still help upper body strength."*

Another participant responded with:

> *"For me, I think it was like during the sprint. Uh, because that was the bit that helped me the most. And also because because [sic] like it, it was a bit more competitive than most of the other warm ups we did."*

And, another participant stated:

"It helped me like [sic] control my speed levels…I can like [sic] fake it"

Theme 3 – *Docility*

In some of the participants, docility was detected through responses that conveyed an indifferent attitude or appeared to indicate a level of performativity. In response to whether they enjoyed the warm-up activities one individual commented:

"I don't know. I can't think right now that nothing was not fun. I liked it."

Another individual stated:

"Like the obstacle course, all the stuff we did. And, yeah."

7.4 Discussion

The results of the quantitative phase of our study revealed no differences between conventional neuromuscular training exercises and parkour-based actions when utilised within the warm-up protocols of pre-PHV basketball players. In relation to the NMT Group, our findings appear to contradict previous studies that have highlighted the efficacy of NMT-based warm-up programmes [393,414,505,567]. Where typically the purpose of NMT-based warm-ups is to improve neuromuscular control and force related outputs [393], the warm-up interventions used in our study did not elicit these particular adaptations. Due to the high-levels of neural plasticity in pre-PHV populations, athletic development models typically advocate for a wide breadth of movement skills to be developed ahead of the adolescent growth spurt, after which force characteristics may be more readily enhanced through resistance training [88,505]. Thus, where the emphasis here is on breadth of movement skills, the corollary may be a subsequent limited display of athletic capabilities (e.g., CMJ and 10-m sprint speed). Another possible explanation for our results is that the stimulus of the respective warm-ups may not have been sufficient to enhance the physical capabilities of the young players [414]. Considering this, the adopted pedagogical approach may have limited the consistency of stimulus exposure across both warm-up interventions. The guided discovery approach, along with the decision to match the workload by time to better accommodate the parkour-based content, is likely to have reduced the total volume of work in each of the exercises, and, in turn, the magnitude of the stimulus. Guided discovery enables the learner to explore multiple possibilities rather than following a traditional coach-led and narrow technique-based pedagogy [199,568]. However, inherently, this method may require more time for improvements to occur compared to the coach-led approach using direct instruction [569]. Given the lack of training experience and exposure to NMT-based warm-ups by the participants in our study, it is possible that the guided discovery approach limited the development of the skills and athletic capabilities in the two experimental groups. Therefore, though this approach is considered beneficial for long-term development and skill transfer to other activities [568,570], where the aim of the NMT programme is to improve movement skills and enhance general physical qualities, this pedagogical approach may not be optimal for short term development of athletic capabilities. Nonetheless, this delivery approach would appear to align to the wider aims of PL by enabling the young individuals to explore movements and perform skills without the constraints of strict technical models [35].

In addition to the pedagogical delivery strategy, another possible explanation for our results may relate to the frequency of the warm-up exposure being limited to once per week. Typically, studies that have highlighted the efficacy of NMT-based warm-ups have prescribed two exposures per week [e.g., 373,386,524]. Similarly, the duration of the intervention period may have been a contributing factor to our results. A meta-analysis by Faude et al. [393], which observed the effects of NMT injury prevention programmes, found larger effects with >23 training sessions compared to < 23. However, other studies [e.g., 410,524] have observed improved performance in response to only 4-weeks exposure to NMT-based warm-up protocols. However, these studies have exposed participants to three sessions per week, thus reaffirming the importance of training session frequency. Accordingly, the efficacy of relatively short NMT-based warm-up intervention periods may be dependent upon the frequency of exposures. It is likely, therefore, that the single weekly exposure across an 8-week period in our study was not sufficient to lead to significant changes.

Notwithstanding the results of our multivariate analyses, comparisons of within-group ES values for baseline to follow-up measures appeared to demonstrate that some specific adaptations were elicited in response to the stimuli of the respective warm-up programmes. Specifically, there were observed improvements in speed-related measures for the NMT Group, whereas both the Parkour Group and Control Group worsened in their respective 10-m sprint performances, the largest effect of which was found in the control group. In the parkour-based speed-run test, however, while the largest within-group effect size was found for the NMT Group, the Parkour group also showed improvements in performance. In contrast, follow-up measures for the CMJ did not reveal any clear changes, with very small effect sizes observed across all three groups. In the OHS, knee flexion angles were found to improve with moderate effect sizes in the NMT Group. In contrast, knee flexion angles in the OHS were reduced in both the Parkour Group and Control Group. However, as might be expected, irrespective of group, at an individual level, each of the test measures revealed highly mixed results with some participants appearing to either show positive or negative changes greater than their pre-intervention CV. These findings may reflect the complex and dynamic systems of the human body, which, in response to a training stimulus, yield highly individual responses that are not easily detected by typical performance-related measures [375]. Indeed, the notion of the athlete as a complex adaptive system accounts for seemingly unpredictable patterns of development and changes to performance [375]. Moreover, the highly individualised and non-linear patterns of growth and maturation in youth populations creates further complexity and unpredictability to the observed training response [119,236,571]. Thus, despite good levels of pre- and post-test reliability, the observed effect sizes that appeared to be somewhat influenced by outliers (with some participants displaying substantially large differences between pre- and post-intervention measures), was perhaps representative of non-linear development within the pre-adolescent participants in the current study. In addition, these findings highlight the challenges associated with physical testing in empirical studies involving preadolescent youths. These challenges are likely to reflect high levels of intra- and inter-group variability, a situation exacerbated in studies with small sample sizes. In this regard, it has previously been highlighted that in younger athletic populations, there may be increased variability in test performance due to limited physical development [572]. However, it is entirely plausible that any observations of limited physical development are representative of non-linear responses to the applied training stimulus. Notably, however, in accordance with the results for within-group ES, most participants that improved their test measures beyond their pre-intervention CV were in the two experimental groups. Importantly, therefore, based upon the findings, compared with the control group, the two warm-up interventions appeared to provide stimuli that, at the very least, preserved physical fitness qualities, despite being characterised by low volumes and frequencies. Importantly, this is of relevance to youth athletic populations who, through specialisation in a single sport, have been highlighted as being at risk of underdevelopment of movement capabilities and physical development of general fitness qualities [16,236] and, in turn, may be at may greater risk of injury [510,573,574].

Despite both warm-up interventions potentially preserving the young athletes' physical fitness qualities, the medium to large between group ES, taken with the within-group ES difference across groups, appear to suggest that, for certain qualities, the NMT Group's warm-up was more effective than the Parkour-based warm-up. For example, the NMT Group's exposure to acceleration speed is a likely explanation for their improvement in measure for 10-m sprint speed compared to the other groups. This may also account for the observed differences in OHS knee flexion achieved by the NMT Group compared to both the Parkour Group and Control Group. While the OHS was purposefully not included in the NMT Group's warm-up, a bodyweight squat pattern (with arms held in front of the body) was included in each training session. Where the ability to perform a bodyweight squat to a depth of at least 90˚of knee flexion (or thighs parallel to the floor) is considered an indication of movement quality and neuromuscular control and movement skill [237,305], it is likely that exposing the participants to various squat patterns contributed to improvements in the OHS..

Somewhat contradicting to the apparent specific responses to the respective warm-up interventions' content is observed in the Parkour Group's small ES value for the CMJ, despite being characterised by a greater volume of jumping and leaping activities compared to the NMT Group. However, as indicated by the observed changes across the groups against the pre-intervention CV values, there appeared to somewhat similar patterns of improvement in response to the different two warm-up interventions. A plausible explanation, therefore, is that the lack of prescription of exercise repetitions / foot contacts in the Parkour group in comparison to typical NMT-based warm-up programmes that prescribe progressively increasing volumes for each exercise (e.g., FIFA-11+). Indeed, the comparative results for the NMT Group, suggest that the low-structured prescription of exercises that characterised both interventions may have limited the development of jumping-related qualities.

In summary, our quantitative results suggest that 15-minute on NMT-based warm-up interventions, offer some preservative benefits to the physical fitness qualities of pre-PHV athlete group. Moreover, as indicated in the results of the Parkour group's warm-up intervention versus the control, there is potential merit to the incorporation of less conventional activities and exercises with the youth athletic development strategy.

7.4.1 Qualitative research better psycho-social and embodied outcomes consistent with phenomenological definitions of PL

The thematic analysis revealed that the intervention warm-ups aligned with concepts of holistic development of the young basketball players typically emphasised within youth athletic development literature [38,520,552]. Such an approach goes beyond physical training outcomes (e.g., muscular fitness and strength) and includes cognitive training, as well as social interaction and stress management [181]. Accordingly, it has been suggested that for children, the focus of training should be placed on fun-based activities that are geared towards preparatory conditioning [14,181]. Both intervention warm-ups used in the current study appeared to create a sense of enjoyment in the participants, with multiple references to fun made by the interviewed children. This may have related to the pedagogical delivery of the warm-up activities, though it is possible that the novelty of the movement patterns and actions resulted in the feelings of fun experienced by the participants. Of importance, responses from the children that highlighted the notion of fun and enjoyment appeared to be specifically related to the parkour-based activities. This was indicated by responses from the NMT Group that appeared to relate to the speed run test, which required participants to navigate and overcome various obstacles. Therefore, while no significant differences were observed in the physical performance measures between the two experimental groups, the Parkour activities might be a more effective means to create engagement through increased levels of enjoyment.

While the Parkour warm-up group indicated greater levels of enjoyment, both groups appeared to display self-reflection and critical thought in relation to the included activities. In this regard, the responses contributed to the theme PL, which, as a concept, relates to the confidence and physical competence, as well as the knowledge and understanding, to engage in physical activity across the lifespan [366,368,548]. Indeed, confidence appeared as a subtheme within the higher order PL theme. Across both warm-up groups, participants referred to feeling a sense of increased self-confidence. Some individuals referred to specific aspects of their game, for example a participant from the Conventional group stated:

"*I've been more confident in the things that I know...I'm able to do some of these things now rather than before. But now I know I'm able to do it so I can definitely give it a go*".

The above example highlights the wider implications of the warm-up that extend to psychological-based outcomes. In relation to this, PL extends beyond physical capacities and encompasses perception, memory, experience and decision-making [368]. Indeed, the display of self-reflection in the responses of the young basketball players, for example the comments relating to the rope swing's relevance to basketball and another participant's reference to sprint races that "*helped the most*" suggests that they perceived benefits to their own performance capabilities. Such reflection and search for meaning can be considered to relate to the philosophical underpinnings of PL, including existentialism and phenomenology [361,362]. These underpinnings are closely aligned and relate to an individual's experiences and perceptions of the world around them and the meaning that the individual derives [361]. In this regard, the ability of the young basketball player to think about and contextualise the relevance of warm-up activities to basketball performance highlights the occurrence of learning through movement, which is representative of the holistic nature of PL [575]. Potentially, the novelty and explorative nature of the activities, as well as the pedagogical delivery approach, may have provoked the young basketball players to contextualise the meaning of the warm-up, in light of the target activities it is used to support. However, what is not known is whether or not the young players would demonstrate this same level of self-reflection in relation to other athletic development activities not delivered with the same pedagogical approach.

The third and final theme, *docility,* appears to contradict the notion of reflective and critical thinking. A possible explanation for this, however, may have been related to the nature of the semi-structured interviews that were administered. The online medium used to conduct the interviews may have influenced the young players, causing them to appear docile in response to the questions. While online interviews have been suggested to be as effective as in-person interviews [564], interviews in person have been found to result in more words spoken by adolescent respondents [576]. In this regard, the docility may well have been temporary rather than being associated with any deeper meaning. Further possible explanation might relate to the open questions and the interviewer attempting to avoid leading questions and biasing the responses given by the young interviewees themselves. The challenge of interviewing children has been previously discussed by Ponizovsky-Bergleson [563], who suggests that children have a tendency to respond to questions in an obligatory manner. Indeed, within the docility theme, the subtheme, *performivity,* was also identified. In this regard, children appeared to provide answers that they felt the interviewer, or indeed their parents, wished to hear. Strategies to reduce performivity include question request (e.g., "can you explain that to me?"), and encouragement (e.g., statements of approval) [563]. However, it is possible that in online interviews where body language is difficult to determine [576], as well as where there is a need for parental guidance, there may trade-offs between docility and performivity in the participants, representing a potential limitation of the approach.

7.5 Conclusions

Collectively, the results of this investigation suggest that Parkour-based activities may be as effective as conventional NMT exercises in the broader development of pre-adolescent basketball players. These findings highlight the potential benefits of Parkour-related activities which extend beyond the typical aims and objectives of athletic development. Despite the low frequency of exposure, incorporating Parkour-related activities within a low-structured learning environment may, at the very least, preserve athletic capabilities ahead of PHV. Moreover, from a holistic perspective, this approach would appear to contribute to the broader aims of PL, including the development of FMS and qualities of physical fitness (e.g., speed, strength, jumping ability), critical reflection and self-confidence, while evoking a combined sense of enjoyment, fun, and purpose.

Chapter 8

The parkour tic-tac action versus the drop jump as part of a complex training programme for talented youth basketball players

Citation

Williams MD, Liew B, Castro F, Davy G, Moran J. A Comparison of Maximal Acceleration Between the “Tic Tac” Parkour Action, Drop Jump, and Lay-Up Shot in Youth Basketball Players: A Preliminary Study Toward the Donor Sport Concept. J Mot Learn Dev. 2024;1–20.

8.1 Abstract

The aim of this study was to examine the effects of two different complex training protocols on measures of physical performance in highly trained youth basketball players. Fourteen talented adolescent basketball players completed twice weekly sessions, performing one of two different 8-week complex training protocols (Drop Jump group, n = 7; Tic-tac group, n = 7) comprised of 1-3 sets of 8-9 exercises. Testing protocols, including jumping tests (CMJ, squat and 10-5 hop jumps), using dual portable force platforms were conducted before and after the intervention period. Also, change-of-direction speed (5-10-5), sprinting (0-20 meters) and muscular strength (isometric midthigh pull) tests were carried out. The intraclass correlation coefficient of within subjects measures was 0.95. A generalised linear mixed model revealed no significant fixed effects for group or time on the performance variables ($p > 0.05$). Random effects for differences between subjects and measurements revealed greater variance to be attributed to measurements. The interindividual response to training showed high variability, contingent on the specific performance outcome. The current findings suggest that the Parkour-based Tic-tac can be included in the S&C program for youth basketball players to enhance sport-specific action capabilities. However, to improve physical performance in young team-sport athletes, it is crucial to address the individual needs of each athlete. This includes acknowledging the highly individualised responses to training stimuli

8.2 Introduction

Strength and conditioning (S&C) training has become an integral component of the development of youth athletes [241,577–579]. This corresponds with a growing body of scientific evidence relating to resistance training in youth populations [38,577], and the publication of position statements, from organisations such as the United Kingdom Strength and Conditioning Association and the National Strength and Conditioning Association, advocating for the benefits of such training in children and adolescents [217,580,581]. Accordingly, within youth athletic development models, such as the YPD model [33], resistance training and other S&C-based activities (e.g., plyometric exercise) have been promoted as a means to enhance the physical capabilities of young athletes to better prepare them for the demands of organised sports [13,14,38].

One of the central aims of athletic development models is to enhance physical fitness qualities. In turn, this helps offset the risks associated with early single-sport specialization, which involves a year-round commitment to a single sport in youth [100,101]. Through exposure to high volumes of intensive training, single sport specialisation is purported to increase the risk of injury [504,582]. Moreover, single sport specialisation may disrupt motor development and limit the learning of broad motor skills and movement capabilities [89]. To mitigate against such concerns, athletic models propose a systematic approach to training that aims to contribute to increased levels of motor competence and neuromuscular capabilities that, in turn, may reduce risk factors for injury [13,32,580]. Within this approach, the use of S&C activities may increase levels of muscular strength and motor skill performance beyond a level that could be achieved through growth and maturation alone [577,583]. Accordingly, there has been an increased implementation of S&C training within youth sports. However, S&C coaches of youth athletes tend to place greater emphasis on developing resistance training competencies over those related to linear speed and agility [241]. Consequently, despite the benefits of resistance training, such training may be limited in terms of the breadth of movement skills to which the developing young athlete is exposed [520].

In addition to the above, the extent to which youth athletes are physically prepared for their sport may not be optimal. For example, in the sport of basketball, which requires high volumes of multidirectional movements and jumping actions, S&C programmes have been suggested to lack of specificity [489]. Specificity is a core principle within S&C training [513,514] though within youth athletic development, training that is more general in nature is typically recommended, with progressions to more advanced training based upon the competency of the individual athlete [250,577]. Nonetheless, for training to adequately prepare youth athletes for the rigours of their chosen sports, the content of the S&C training must be sufficient to account for the specific characteristics of those sports, while also meeting the individual developmental needs of each athlete.

Like adult basketball players, youth players are required to execute repeated high intensity efforts including vertical jumps, short distance sprints and changes of direction on the court [78,584]. Proficiency in such movements has been found to be a differentiating factor between selected and non-selected players for a youth national basketball team [78], therefore, S&C training that targets all the physical capabilities required in basketball would appear necessary for optimal development. However, in accordance with the principle of *specific adaptation to imposed demands* (SAID), which holds that the body will only adapt to the stress being placed upon it [585], high-school basketball players have been found to display specific adaptations in response to different S&C training programmes [586]. For example, participants following a change of direction-focused programme significantly improved performance in a timed 10-m “zig-zag” test but did not significantly improve in measures of vertical jump performance compared to plyometric and strength training groups that did [586]. Accordingly, given the breadth of the physical requirements of basketball, obvious challenges exist for S&C coaches, especially when programming time is a constraint to optimal performance [587,588].

Providing a solution to the above dilemma is the use of “complex training”, which combines heavy loads with lighter loads in two biomechanically similar movement patterns [302,589]. In addition to its time-efficiency, complex training is also understood to create conditions of post-activation potentiation (PAP) for the subsequent exercise which, owing to increased motor neuron excitability, facilitates greater levels of force production [302]. However, while studies [e.g., 29, 31] have shown the complex method to be effective in improving physical characteristics in youth basketball players, the exercises utilised in the “complex pair” appear to be limited to jumps occurring within the sagittal plane, which may not necessarily meet the demands of basketball, a sport which requires high-intensity actions in the frontal plane also [489].

Responses to training programmes in athletic populations may be difficult to detect, especially when the learning of new motor skills is necessary [375]. When aiming to improve skill acquisition and performance, coaches can provide athletes (learners) with clear instructions, such as the optimal technique to use, or they can design learning scenarios that encourage exploration of different movement scenarios [419]. In this regard, training has long been influenced by models rooted in pedagogy and sports psychology, relying on external guidance from coaches to instruct the performer towards a desired technical model [591] . However, more recently, there has been an emergence of models based on dynamic systems and biology [419]. This approach views the learner as a complex biological system composed of different parts that are independent, but which interact with one other. Thus, emphasis is placed primarily on changes in state over time rather than on stable states [592]. Based on these assumptions, parkour that is an activity that requires the performer to travel between two points as quickly and as efficiently as possible, while traversing obstacles and negotiating differing surfaces [34,498], has been proposed as an alternative method for the development of movement capabilities and agility for team sport athletes, including young basketball players [34,37].

Based upon ideas from the ASM by Wormhoudt et al. [31,236], parkour has been suggested to be an effective supplementary activity for young basketball players in promoting diverse movement solutions and aligning more closely with the demands of the unpredictable environments encountered in basketball games. [520]. To date, however, there has been very little scientific evidence to support the donor sport concept meaning that more is required to clarify its effectiveness and programming potential for basketball coaches. In Chapter 7, the use of parkour on the physical capabilities of youth basketball players. In the 8-week intervention study, which compared a parkour-based warm-up with a conventional neuromuscular training-based warm-up, no significant between-group differences were found in the preadolescent participants in test measures that included both vertical jumping and sprinting as well as a timed obstacle course, suggesting that parkour was as effective as typical S&C-based exercises [593]. However, no studies have examined the use of parkour-style activities in adolescent basketball players as part of a structured S&C programme, specially incorporating the use of complex training.

On the basis of such a lack of knowledge with regard to the effectiveness and application of the donor sport concept, the aim of the present study was to examine the effects of two different complex training interventions, implemented within the normal strength and conditioning programme of talented adolescent basketball players, on measures of force, speed, and jumping capabilities. Based upon the results of study four (chapter 6), which demonstrated higher maximal acceleration outputs in the TT compared to the DJ, it was hypothesised that the TT group would show greater levels of improvement in the jumping-based measures than the DJ group.

8.3 Methods

8.3.1 Study Design and Participants

Using a convenience sample, a quasi-experimental intervention study design was used to compare the effects of training complex interventions across an 8-week training period. Male participants were recruited from the same under-18 basketball academy, which is part the talent pathway of Basketball England, the national governing body for English basketball. Players within this structure complete a fulltime basketball programme alongside their studies, that includes at least two structured S&C-based training sessions per week, and a competitive game against other academies across the country. Accordingly, the participants could be defined as *highly trained/national level athletes* based upon the criteria by McKay et al. [594]. To qualify for this classification, in brief, the athletes were required to compete in national leagues and tournaments and be engaged in structured and periodised training. In total, 16 participants were recruited for the study with an average age of 17.2 ± 0.58 years. The mean stature of the participants was 188.00 ± 4.2 cm and mean body mass was 77.86 ± 8.82 kg. All participants had at least six months experience of S&C training. Participants were randomly assigned to either the drop jump (DJ) or the tic-tac (TT) group by another researcher, while the other authors were blind to the composition of the participants groups. All participants provided assent to take part in the study and ethical approval was granted by the institutional research ethics committee of the author's university and in accordance with the latest version of the Declaration of Helsinki.

8.3.2 Training programme

The two training interventions were embedded separately within the two weekly S&C sessions delivered as part of the players' typical training between the months of September and November. These months constitute the first half of the competitive season. Sessions took place on Mondays and Thursdays across the 8-week period. The S&C programmes (Table 15) for both groups were matched for exercises, and prescribed sets and repetition ranges except for the exercise paired with the 'strength exercise' to form the 'complex pair'. The strength exercises utilised in the complex pairs were implemented based on a progression system to ensure safe and effective execution. Specifically, where appropriate, some participants began with the goblet squat and then progressed to the front squat. This strategy ensured that participants received a strength stimulus in the squat pattern while attaining greater skill over the 8-week intervention period. However, for the second strength exercise, the hexagonal bar deadlift, no such progression was necessary Nonetheless, immediately following the strength exercise, the TT group were required to complete a parkour-style tic-tac jumping action, while the DJ group were required to execute the drop jump exercise from a box with a height of 60 cm. The volumes for both intervention jumps were matched across the 8-week period.

To create equivalence in the loads used for the strength exercises within the complex pairs, the autoregulatory progressive resistance exercise (APRE) method was utilised. Previously described by Mann et al. [595], the APRE method provides a parameterised form of autoregulation that enables the individual to adjust training loads to account for their strength capabilities on a given training day. In the present study, the six-repetition maximum (6RM) protocol outlined by Mann et al. [595] was utilised (Table 16), which required the participant to complete four sets of the strength exercise, first performing 10 repetitions at a load approximating 50% of their anticipated 6RM, followed by a set of six repetitions at approximately 75% of 6RM. For their third set, the participant completed as many repetitions as possible (AMRP) using 100% of their anticipated 6RM. The final set of the strength exercise required the participant to complete AMRP with an adjusted load to set three using the adjustment guidelines displayed in Table 16. The same adjustment guidelines were then utilised to determine the initial loads utilised for the subsequent training session, with all volume-load for the exercise being logged by each participant on an online strength training platform. In all other exercises in the programme, loads were self-selected by the participants with guidance from the third author of the study, who was also the strength and conditioning coach supervising the programme delivery.

Table 15. Training programme utilised across the 8-week intervention period. Exercise "B2" determined by the assigned intervention group. *Rear foot elevated.

	Session One	
Exercise Order	**Exercise**	**Prescribed sets x repetitions**
A1	Triple hop	3 x 2 each leg
A2	Band assisted jump	3 x 5
B1	Front / goblet squat	1 x 10, 1 x 6, 1 x AMRAP, 1 x AMRAP
B2	Tic tac or depth jump	4 x 3 each leg
C1	Flat dumbbell press	3 x 8
C2	Chin up	3 x 6
D1	Isometric DB RFE* floating heel lunge	2 x 45 seconds each

D2	Nordic hamstring extension	2 x 5
D3	Dumbbell W to Y	2 x 12

Session Two		
Exercise Order	**Exercise**	**Prescribed sets x repetitions**
A1	Triple hop	3 x 2 each leg
A2	Band assisted jump	3 x 5 each
B1	Hexagon bar deadlift	1 x 10, 1 x 6, 1 x AMRAP, 1 x AMRAP
B2	Tic tac or depth jump	4 x 3 each leg
C1	Landmine ½ kneeling single arm press	3 x 8 each arm
C2	Dumbbell split squat	3 x 10 each leg
D1	Inverted row	2 x 10
D2	Dumbbell staggered stance RDL	2 x 10 each leg

Table 16. Table 16. APRE load adjustments for set 4.

Repetitions for set 3	**Set 4 adjustment (kg)**
6RM routine adjustment	
0-2	-2.5 to -5
3-4	0 to -2.5
5-7	No change
8-12	+2.5 to +5
>13	+5 to +7.5

8.3.3 Testing Procedures

All testing was carried out by the third author and took place within the basketball academy's usual S&C training venue. Testing was administered one week prior and one week post the 8-week intervention period and, on each occasion, across two days. In each instance, the testing took place at a similar time of day (late afternoon). After completion of a standardised warm-up, the participants performed the test battery comprised of a 20-m linear sprint (with splits of 0-5-m, 5-10-m, and 10-20-m), the 5-10-5 *"Pro agility test"*, countermovement jump (CMJ), squat jump (SJ), the 10-5 hop test (HT), and the isometric midthigh pull (IMTP). Anthropometric measures of stature and body mass were also recorded.

The sprint and 5-10-5 change of direction speed tests were both recorded using an electronic timing-gates (Smart Speed, Vald Performance, Brisbane, Qld, Australia). For the 20-m linear sprint, the participants began each trial in a *two-point* position 50-cm behind the first timing gate and were then instructed not to countermove ahead of their first step forward, and to sprint through the end timing gate. Participants performed three trials and the average of the three trials for each of the splits were used in the analysis. For the 5-10-5 test, participants were required to start 50-cm behind the timing gate positioned on the start/finish line. Without a countermovement, participants were instructed not to sprint 5-m to the first line as fast as possible before turning and sprinting in the opposite direction to the far line (10-m away), before turning and sprinting back through the start/finish line. For both linear sprint and 5-10-5 tests, trials were separated by at least two minutes for recovery between efforts.

The CMJ, SJ, HT and IMTP trials were all recorded on dual portable force platforms (ForceDecks, Vald Performance, Brisbane, Qld, Australia). For the CMJ, participants were required to jump with their hands placed upon their hips and instructed to descend to a self-selected countermovement depth before immediately jumping as high as possible. Three trials were completed with at least 20-seconds. Means of jump height (flight time), peak concentric force, relative peak concentric force, and eccentric impulse of the three jumps were used in the analysis.

Similar procedures were used for the SJ, except the participant was required to descend to a self-selected depth where they were required to hold the position for three seconds before jumping as high as possible whilst maintaining their hands being placed on their hips. A total of three SJs were completed with at least 20-seconds between trials and the average of three jumps was analysed. For the HT, following an initial countermovement jump, participants were required complete ankle dominant 10-hops, with the aim of achieving as much height as possible in each hop whilst minimising ground contact time. A total of two trials were completed by each participant with approximately two-minutes between. The reactive strength index (RSI) (calculated by the division of jump height and respective ground contract time) of the best five jumps was used for the analysis.

For the IMTP, a *power rack* setup was utilised, with the barbell set so that it was immovable by the participant. The bar was positioned at a height approximating mid-thigh height of the participant, with a knee angle between 135-145˚, and a hip angle of between 140-150˚. Using lifting straps to reduce the influence of grip strength as a limiting factor, each participant adopted a position with their shoulders slightly in front of the bar and directly over their hands, similar to the second pull of the power clean. After a weighing period of three seconds, with limited pre-tension, each participant was instructed to *"pull as hard and as fast as possible"* against the immovable bar for five seconds. A total of two trials were completed by each participant with a rest period of at least two-minutes between trials. The average of peak force from the two trials was used for the analysis.

8.3.4 Statistical Analysis

Statistical analyses were performed using the statistical analysis software, RStudio for Windows, version 2024.04.02. Volume loads between the two groups were analysed using an independent t-test. In relation to the pre-post physical performance measures, all data were initially tested for normality using the Shapiro-Wilk test and an intraclass correlation coefficient (ICC) was used to assess the reliability of the measurements within-subjects. To evaluate the effects of group and time on the performance measures, a generalised linear mixed model (GLMM) with a Gamma family and a log link function was fitted to the data. The model included random effects for subject and measurement to account for repeated measures and variability across different tests. Following this, R-squared values were computed to evaluate the proportion of variance explained by the fixed and random effects in the model.

In addition, effect size (ES) using pooled standard deviations were calculated to compare both within-group pre- to post-intervention measures and between-group post-intervention measures. In both cases, the ES values were interpreted as 'small', 'medium', and 'large' in accordance with Cohen's guidelines [529].

8.4 Results

Due to unforeseen circumstances, one participant from each of the intervention groups were unable to partake in the post-intervention testing. Therefore, the pre-post data for a total of 14 participants (seven per group) was included in the analysis (table 17). The means of the load-volumes from the 8-week training intervention for the two strength exercises used in the complex training were 24371.50 ± 10426.37 kg for the DJ group, and 30458.88kg ± 7802.64 kg for the TT. The independent t-test did not reveal differences between the two load-volumes to be significant ($p > .05$).

The results of the ICC were 0.995, revealing a high degree of reliability in the within-subject measures. The GLMM revealed no significant fixed effects for the estimated marginal means of group (TT vs. DJ), $p = 0.207$, time (pre vs. post), $p = 0.644$, or the interaction of group * time, $p = 0.594$. The random effects of the model, which accounted for the variance due to differences between subjects and measurements, revealed a variance of 0.01903 (± 0.138) for subject and 5.45898 (± 2.336) for measurements. The marginal R-squared value for the model was 0.001, indicating that < 0.1% of the variance in the data was explained by the fixed effects of group and time. However, the conditional R-squared value was 0.995, indicating that 99.5% of the variance was explained by both the fixed and random effects.

Table 17. Pre- and post-intervention descriptive test results according to group (mean and standard deviation).

	DJ		TT	
	Pre	Post	Pre	Post
CMJ height (cm)	39.69 ± 6.82	37.91 ± 7.11	44.89 ± 9.32	42.47 ± 7.20
CMJ concentric peak force (N)	1870.86 ± 300.20	1839.86 ± 229.80	2040.43 ± 361.31	2077.71 ± 391.86
CMJ relative concentric peak force (N· kg)	24.27 ± 1.91	23.67 ± 1.81	26.17 ± 2.63	26.26 ± 2.39
CMJ eccentric impulse (N·s)	96.24 ± 22.45	95.23 ± 16.67	115.01 ± 31.92	104.89 ± 31.52
SJ height (cm)	35.13 ± 5.93	35.56 ± 7.41	39.09 ± 7.74	37.97 ± 6.60
HJ RSI (m/s)	1.22 ± 0.23	1.11 ± 0.34	1.37 ± 0.53	1.22 ± 0.41
IMTP net peak force (N)	1592.43 ± 598.88	1736.86 ± 451.22	1978.29 ± 416.23	1889.43 ± 409.72
5-10-5 change of direction speed (s)	4.98 ± 0.13	4.98 ± 0.12	5.08 ± 0.19	5.00 ± 0.16
0-10-m sprint (s)	1.80 ± 0.11	1.73 ± 0.06	1.77 ± 0.08	1.77 ± 0.08
10-20-m sprint (s)	1.30 ± 0.05	1.28 ± 0.05	1.28 ± 0.06	1.27 ± 0.06

The within group ES comparisons (Table 18) revealed a small effect between pre-post measures in both intervention groups for CMJ height, which was also reflected in the small ES magnitude between the post-intervention measures. This revealed a smaller decrease in post-intervention jump height in the DJ group compared to the TT. However, the TT group were found to have a post-intervention increase in concentric peak force compared to the DJ group, which displayed a decrease with a medium ES. For the same metric, the within-group ES was revealed to be small for both intervention groups. Relative to body mass, the magnitude of difference in concentric peak force between the two groups was small. Similarly, in the within-group ES analysis, magnitudes of pre-post differences were also revealed to be small. There was a reduction in eccentric deceleration impulse between the two groups which was larger in the TT group though the ES of this difference was determined to be 'small'. The within-group ES magnitudes were also observed to be small for both groups.

In the SJ, there was a small difference between pre-post scores, which was also reflected in the small within-group and between-group ES values. The same outcome was also revealed for RSI comparisons for the HJ test. In the IMTP test, there was a medium ES in the pre-post peak vertical force differences between the two groups, with the DJ group displaying an increase compared to the TT group who decreased in this measure. For the same measure, the within-group ES revealed pre-post differences to be small for both the intervention groups, though the magnitude of the effects was larger in the DJ group than was observed for the TT group.

In the sprint test, the DJ group were found to have reduced their 0-10-m time with a large ES magnitude compared to the TT group. The within-group ES revealed pre-post differences to be large for the DJ group whilst, a medium ES value was observed in the TT group. In the results for the 10-20-m split, a small ES revealed for the post-intervention differences in performance between the two groups. However, the within-group ES for the 10-20-m split revealed a large pre-to-post intervention effect for the DJ group and a small effect for the TT group. Finally, for the 5-10-5 change of direction (CoD) speed test, there was a decrease in time in the TT group compared to the DJ group with a small ES magnitude. However, the within-group ES was revealed to be larger for the TT group than the DJ group.

Table 18. Mean pre-post intervention differences and associated within group and between group Cohen's d ES values according to group and physical performance test.

	DJ		TT		
Performance Measure	**Mean**	**ES**	**Mean**	**ES**	**Between group ES**
CMJ height (cm)	-1.77 ± 3.25	0.30	-2.41 ± 3.51	0.27	-0.19
CMJ concentric peak force (N)	-31.00 ± 117.64	0.12	37.29 ± 114	0.24	0.59
CMJ relative concentric peak force (N· kg)	-0.60 ± 1.43	0.19	-0.02 ± 1.97	-0.19	0.34
CMJ eccentric deceleration impulse (N·s)	-1.01 ± 16.58	0.08	-10.13 ± 23.18	0.38	-0.47
Squat jump height (cm)	0.43 ± 2.48	0.12	-1.11 ± 5.74	0.01	-0.35
HJ RSI (m/s)	-0.10 ± 0.25	0.17	-0.15 ± 0.32	0.20	0.15
IMTP net peak force (N)	144.43 ± 393.77	0.47	-88.86 ± 349.34	0.12	0.63
5-10-5 CoD test (s)	-0.01 ± 0.18	0.08	-0.12 ± 0.29	0.45	-0.45
0-10 m sprint (s)	-0.09 ± 0.10	1.03	-0.02 ± 0.08	0.49	0.82
10-20 m sprint (s)	-0.02 ± 0.04	1.12	-0.01 ± 0.03	0.29	0.18

At an individual participant level, comparisons of pre-post intervention scores are displayed in figures 14-21. Across each of the measures, there were varying levels of pre-post changes across both intervention groups, indicating an individual responsiveness to the training stimulus.

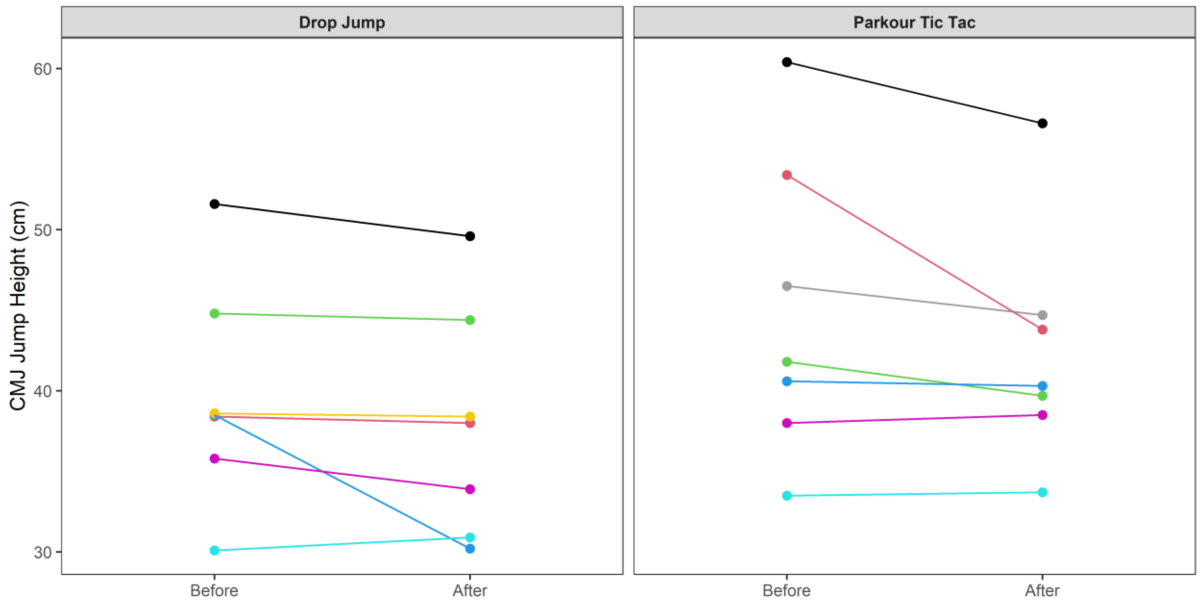

Figure 14. Individual mean pre-post CMJ height (cm) according to intervention group.

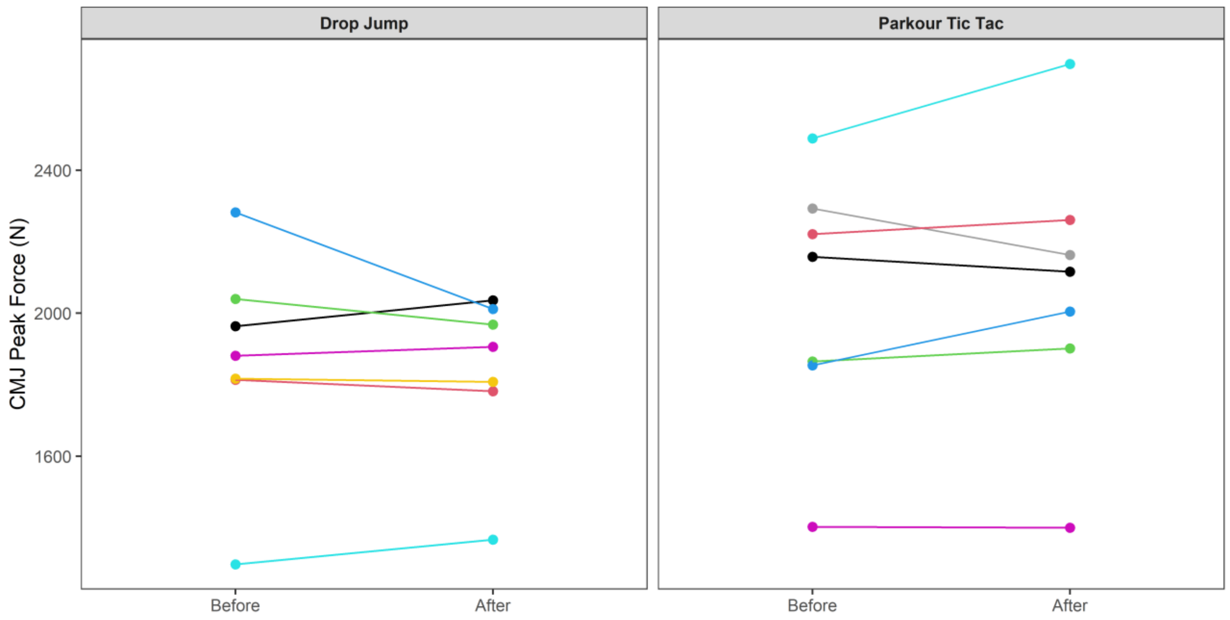

Figure 15. Individual mean concentric peak force (N) measures from participants' pre-post CMJ trials according to intervention group.

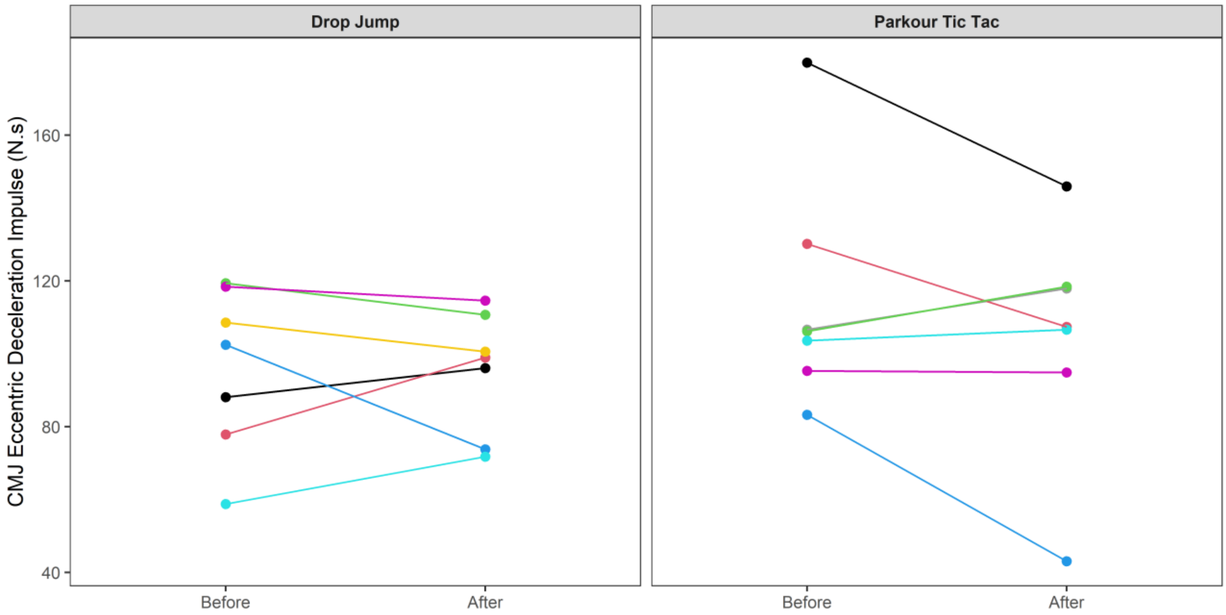

Figure 16. Individual mean eccentric deceleration impulse (N.s) measures from the participants' pre-post CMJ trials according to intervention group.

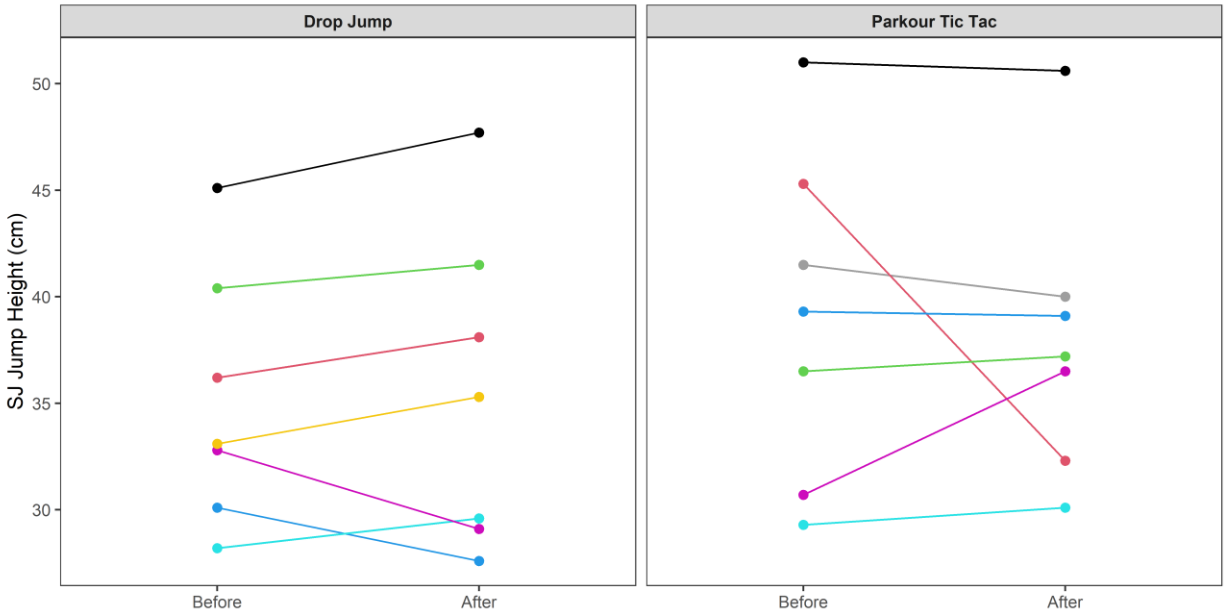

Figure 17. Individual mean pre-post intervention SJ height (cm) according to intervention group.

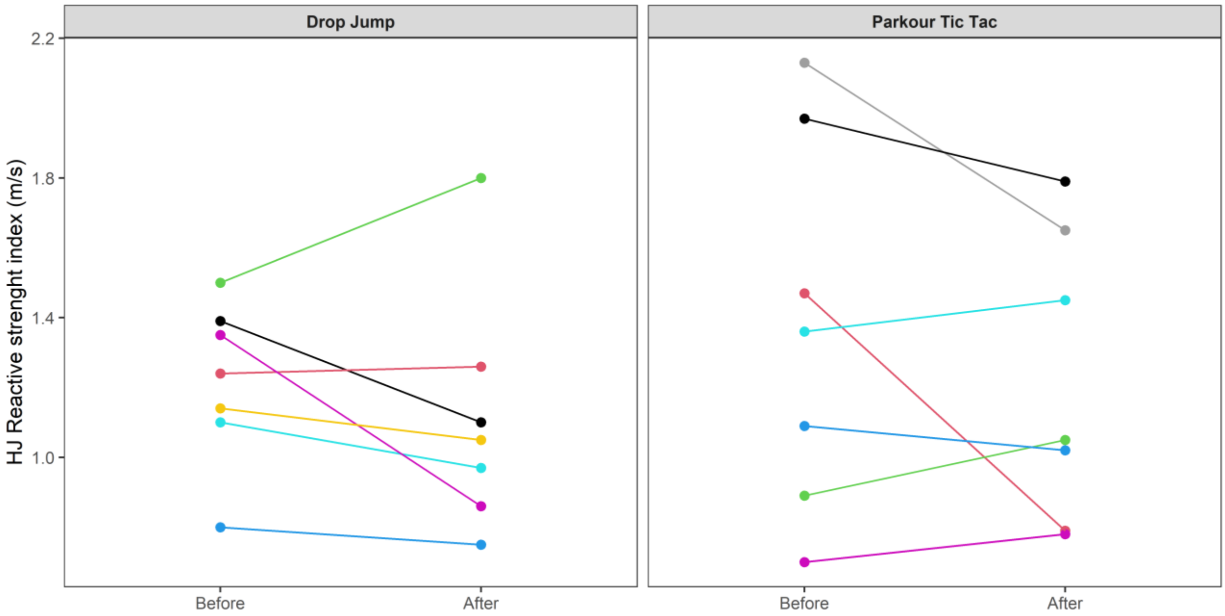

Figure 18. Individual mean pre-post intervention reactive strength index scores (m/s) obtained from HJ 10-to-5 test protocol.

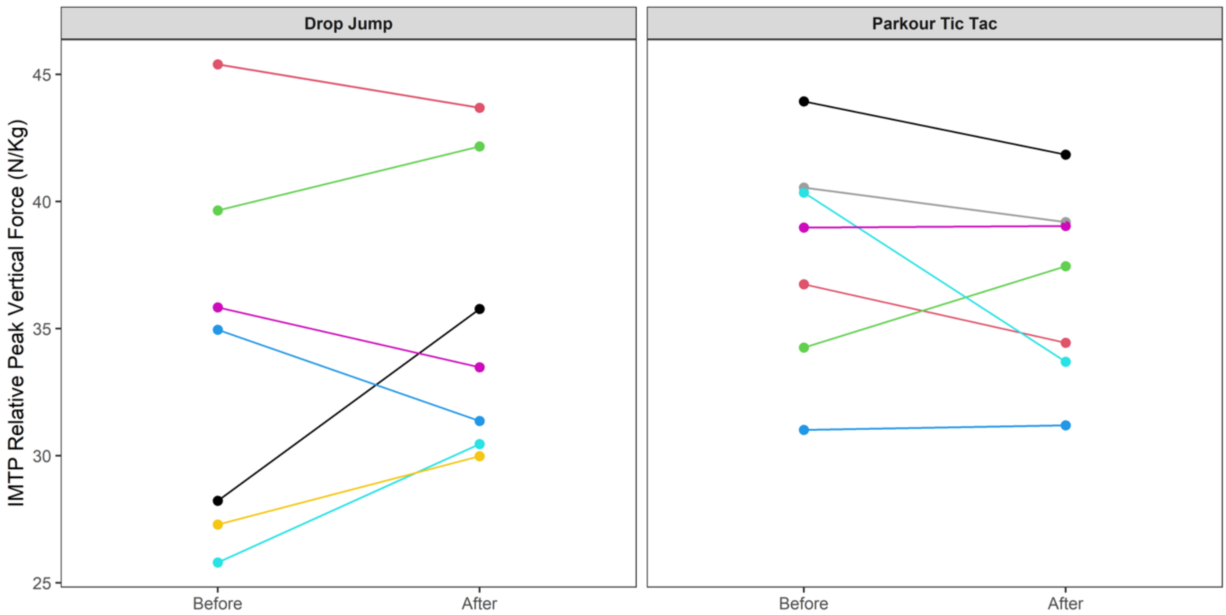

Figure 19. Individual mean pre-post intervention relative peak vertical force derived from the IMTP.

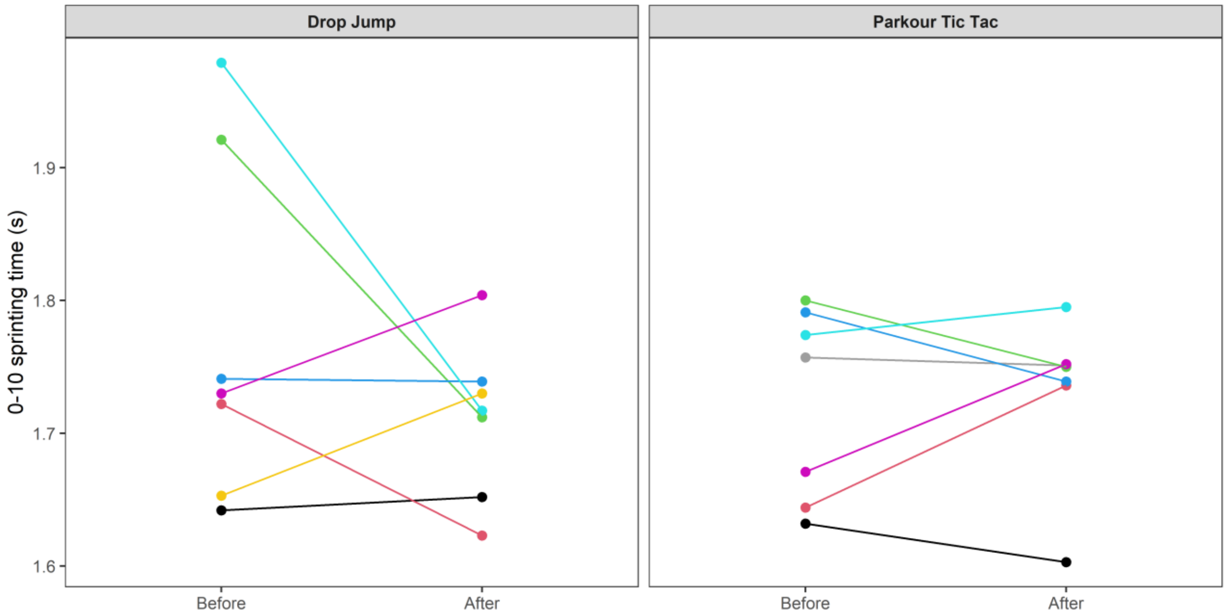

Figure 20. Individual mean pre-post intervention 0-10m sprint times according to intervention group.

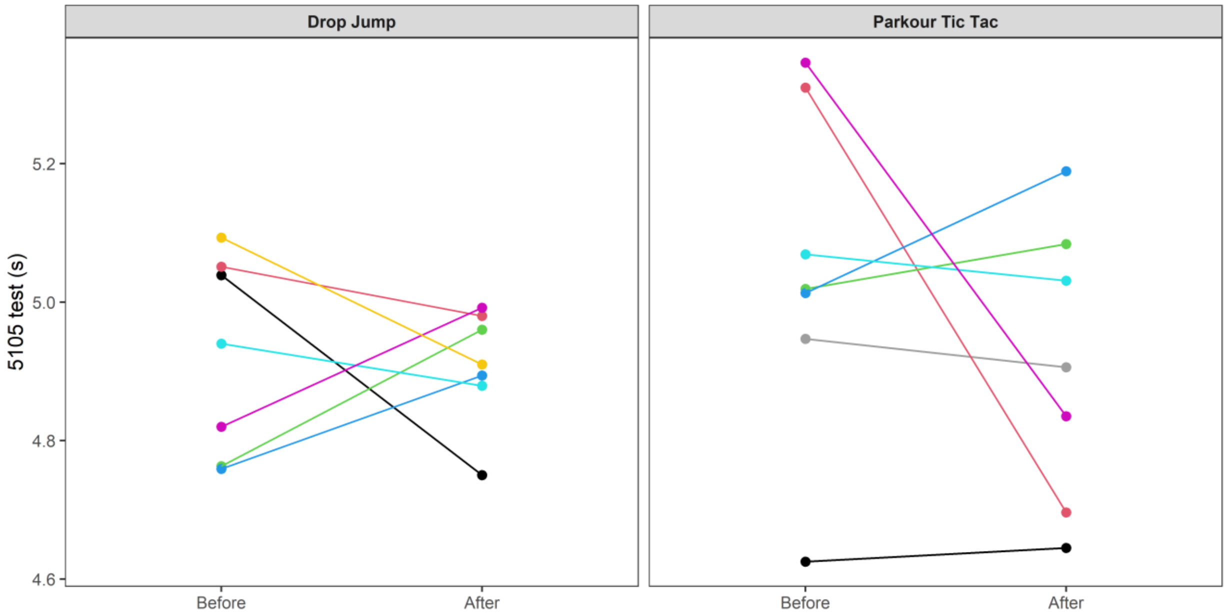

Figure 21. Individual mean pre-post intervention 5-10-5 change-of-direction speed times according to intervention group.

8.5 Discussion

The aim of this study was to compare the effects of two different complex training interventions implemented within the normal strength and conditioning programme of talented adolescent basketball players on measures of physical performance. Although no significant differences between the two interventions were revealed, notable differences based on effect size calculations were observed. Most notably, the DJ group improved in the linear sprint measures to a larger extent than the TT group, whilst the TT group displayed greater improvement in COD speed compared to the DJ group. In jump-based measures (CMJ, SJ, and the HJ), differences appeared to be highly varied with ES that were revealed to be small. Only the IMTP test appeared to show any additional distinction between the two intervention groups, with increased force outputs observed in the DJ group only. In addition to these findings, highly individualised responses to the training interventions were observed in both groups. Therefore, while the lack of significant pre-post differences between the two interventions suggests that neither the TT nor the DJ used within complex training were effective in eliciting changes to the physical capabilities of the players, the observed nuances in the findings suggest that the training was effective, though with a high degree of variability.

While these results appear to contrast with other studies [e.g., 45,46] that have investigated the effects of S&C-based training in youth basketball populations and observed significant improvements in performance-related measures, the individualised responses to the training interventions in this study suggest a non-linear pattern of development in physical capabilities among the youth players. This pattern was somewhat reinforced by the high reliability of the performance test measures, with most of the variance relating to differences between subjects. Such individuality in training responses aligns with concepts from the ecological dynamics framework, including non-linear pedagogy and the perspective of the human body as a dynamic and complex system. Accordingly, the ecological dynamics framework articulates that the performance of motor skills is the manifestation of the interaction of individual, task, and environmental constraints, which are ever changing [473]. In contrast to traditional theories for motor learning which are considered to be reductionist, the ecological dynamics framework draws on ecological psychology and dynamical systems theory to account for the complexity of skilled performance [327,494]. From this perspective, the heterogenous results found in our study appear to highlight non-linear responses to the training intervention and indeed the wider S&C programme across the 8-week period. This was further highlighted by some of the participants showing improvements whilst others showed performance decrements, indicating that responsiveness to training was non-linear and highly individualised. This may be particularly pertinent in the case of the exercises within the programme which, for the youth basketball players in this study, may have been utilised movement skills that were relatively novel and therefore less refined.

The individual responses observed in the results of this study demonstrate the human body as a complex biological system. From a dynamical systems perspective, small changes in the performance of a motor task may lead to unpredictable system responses [597]. In relation to the individual performer, skilled action represents the synergetic organisation of the neuromuscular system based upon their morphological and biomechanical constraints [318]. Accordingly, changes to the individual performer's constraints would have implications for motor skill performance. In relation to the findings of the present study, the highly individualised responses observed among the participants may represent the non-linear behaviour and self-organising processes inherent in everyone. These processes are not only a result of the S&C training intervention but, from a dynamical systems perspective, always exist. For example, in response to acute levels of fatigue, the self-organising process will differ accordingly. Such a perspective must also factor in psycho-emotional states, which will further influence the biology of the system both in the short-term and across longer-term training periods, therefore influencing training adaptations [598]. Moreover, as can be observed in the individual responses in our results, in some participants, the training stimuli was effective though for others, it was appeared to be detrimental, further highlighting the complex biology of the human body and the need for individualised training approaches, even in youth level athletes who are typically considered to be highly responsive to S&C-based training [599].

From the perspective of traditional S&C-based training principles, the lack of significant differences resulting from the two interventions was somewhat surprising given the relatively low training experience of the participants. Indeed, in contrast to the SAID principle, which holds that specific adaptations will occur in response to the type of training utilised [517], athletes with a low S&C training age have previously been found to improve performance despite the use of non-task specific exercises [e.g., 27,32]. For example, Latorre Román et al. [590], who also utilised complex training in youth basketball players, observed significant changes across all measures, including sprinting and change of direction speed. In contrast to the current study, however, the participants in the Latorre Román et al. [590] study were pre-PHV, which may have accounted for their responsiveness to the plyometric training. To explain this, the authors suggested that neural adaptations in the prepubertal participants resulting from the plyometric training may have increased the neuromuscular capabilities (e.g., motor unit activation, intermuscular coordination) that are transferable to sprinting and change of direction speed tasks. However, in the meta-analysis by Ramirez-Campillo et al. [491]that looked at the effects of plyometric training on physical fitness capabilities of young basketball players, significant improvements were revealed in older players (>17.15 years of age) compared young players in measures of horizontal jump distance, linear sprint and change of direction times. Concerning the SAID principle, Ramirez-Campillo et al. [491] highlighted that 27 of the 32 studies included in their meta-analysis included a combination of horizontally and vertically oriented jumps, which the authors suggested may have had relevance to the sprinting and change-of-direction speed tests, where horizontal force application is important. Indeed, Moran et al. [600] previously found that horizontally-oriented jumps are superior to vertically-oriented jumps in enhancing horizontal performance, such as short-distance sprinting. Similarly, a study by Gonzalo-Skok et al. [596] revealed specific adaptations in response to the training of specific force vectors. Therefore, it may be that the plyometric-based exercises utilised in the studies included within the meta-analysis by Ramirez-Campillo et al. [491], were more specific to the performance measures than the TT and DJ in the current study.

Despite not reaching statistical significance, the within-group differences observed in the current study indicates that the two interventions may have induced their own unique adaptations. For example, the 0-10 m and 10-20 m sprint times revealed large effects from the DJ intervention compared to the TT, while the TT showed greater within-group effects on the pre- to post-times for the 5-10-5 test compared to the DJ group. In the case of the TT, it is plausible that the intervention may have contributed to improved COD movement skills that benefitted performed in the 5-10-5 test. Although it is likely that the participants' momentum at the point of contact with the angled wall board during the TT was lower compared to their momentum during the changes of direction in the 5-10-5 test, a common strategy for developing COD skills is to practice at low intensities before progressing to high intensities[601,602]. On this basis, the TT may have developed COD skills, including the orientation of body segments to produce a braking impulse followed by a subsequent propulsive force in a new direction. [603]. However, in the absence the lack of a reliable and validated test, with the necessary specificity to measure performance in the TT movement, including kinetic and kinematic variables, the potential mechanism that may have contributed to improved COD performance are unclear.

Another consideration in relation to the lack of observed pre-post changes in the performance measures in our study relates to the complex training method utilised. Typically, complex training combines maximal or near maximal muscle actions to recruit higher threshold motor units ahead of a subsequent plyometric or ballistic exercise [302]. For example, in the previously mentioned study by Latorre Román et al. [590], an isometric half squat was combined with a subsequent plyometric activity, which may have yielded a greater PAP effect than was attained through an isotonic hexagon bar deadlift and goblet / front squat exercises utilised in our study. Although the APRE method was deemed to be appropriate to create equivalence in the training loads of the participants in the current study, who have varying levels of S&C competency and training ages, it may not have been sufficient to ensure sustained recruitment of higher threshold motor units until the penultimate and final sets of the prescribed exercises. Further, with both sets being completed to volitional failure, it is possible that rather than stimulating a PAP effect on the subsequent jumping actions, the two sets of the strength exercises induced levels of fatigue that attenuated the participants' performances in the paired jumps. Recently, reductions in jump height and RSI in the unilateral single leg jump were found to an acute response to fatigue induced by the 30-15 intermittent fitness test in elite female basketball and handball players, aged 14-18 years [604]. Despite the utilisation of the running-based test to induce fatigue, due to repeated acceleration and deceleration phases, coupled with increasing levels of speed at each stage, the 30-15 intermittent running test is understood to place considerable demand on the neuromuscular system [605]. Accordingly, similarities in the neuromuscular demand induced by the APRE protocol and the final stages of the running test are plausible. However, prior to the two sets of the strength exercises completed to failure, irrespective of any PAP effect, two sets of the jumping actions were performed in the absence of such levels of fatigue which, alone, do not appear to have elicited any changes in physical performance. It may be, therefore, that the volume of jumps performed in each session across the 8-week training period was not sufficient to elicit changes to force characteristics of the lower limb that might have led to improved performance in the post-intervention measures. Moreover, it is possible that the magnitude of the training stimulus of the S&C programme was not greater than that experienced by the basketball-specific workloads. Given the players were part of a full-time basketball programme that required them to practice four to six times per week, undertaking one to two competitive games, their associated levels of conditioning, through exposure to high-intensity efforts, including jumping, repeated sprinting, and high-frequency changes of direction, may have warranted a greater training stimulus from the S&C programme. Indeed, the total number of plyometric sessions in a programme has previously been found to have a significant positive effect on jump height in basketball players (53), indicating that the total number of training sessions within our intervention may not have been sufficient to induce such an effect.

In addition to above, a study by Arede et al. [534], which revealed significant improvements in physical performance measures in youth basketball players in response to a 10-week strength training programme, utilised only two exercises (bench press and parallel squats) with training volumes of five sets of five repetitions and loads that optimised power output for each repetition. Accordingly, it is indeed possible that the programme used within the current study included more exercises than was optimal for positive adaptations to occur, meaning that basketball S&C coaches might need to explore a variety of different ways to successfully incorporate elements of parkour into their programming repertoires. Indeed, the supposition here appears to be further vindicated by the lack of significant change across both groups in response to other components of the training programme, particularly in relation to exercises that targeted the lower limb (e.g., the isometric DB RFE floating heel lunge).

To some extent, our results raise questions about the intended purpose of the S&C program in the development of youth athletes. Despite the benefits of S&C-based training and the scientific literature emphasizing its importance within the long-term strategy for young athletes [e.g., 1,23,54] the effectiveness of such training may be hindered when considered against other demands, such as sport-specific training and competition.. Moreover, it may simply constitute the addition of extra work for the young athlete without necessarily providing the intended value. Accordingly, it is a necessary analysis of the purpose of S&C within youth athletic development to better inform talent development processes. Where typically, the purpose of such training is to ensure the appropriate development of the physical capabilities necessary for sport, this must be balanced against the total workloads applied to the athlete and the methods of recovery to optimise adaptations [111].

The ASM, which is a model of athletic development that is based upon concepts from the ecological dynamics framework, aims to develop diverse movement capabilities that are adaptable (as opposed to fixed) and, in accordance with the concept of interacting constraints (individual, task, environment), enable the performer to develop more effectively for the complex demands of sport [31,236]. Based upon ideas these ideas, parkour has been proposed as a method of alternative activity for the athletic development of team sport athletes [34]. The diverse movements that characterise parkour, coupled with the encouragement to explore action capabilities, have contributed to the proposed use of the activity in the athletic development of youth basketball players [593]. However, it is important to also indicate that parkour is a complementary activity to traditional S&C training and the results of this study do not support a reduction in the latter from the regular regimes of youth players. Previously, a study by Williams et al. [593], which compared a parkour-based neuromuscular warm-up to a conventional neuromuscular warm-up in pre-adolescent basketball players, found no significant differences between the groups following the 8-week intervention, although it is possible that a longer study duration may have yielded different results. Nonetheless, despite no significant differences, in a similar fashion to the results of our study, there were clearly positive individual responses to the training interventions, with little ultimate difference in their relative effects. This appears to support the non-linear and complex nature of athletic development in youth populations and the need for S&C practitioners to acknowledge the individuality of each young performer in their programming and long-term preparation strategy.

8.6 Conclusion

The preparation of athletes in the context of team sports involves many challenges, notably the need to develop many aspects simultaneously due to time constraints that can interfere with programming efficiency. Importantly, athletes operate in sometimes unpredictable and chaotic scenarios that place demands on physical movement, spatial awareness and cognitive evaluation of a given scenario. Accordingly, S&C programmes must promote all the capabilities that are required for competitive success in such scenarios. In this way, including strategies that stimulate movement variability, such as parkour, can facilitate the development of adaptable movement capabilities. In addition to other studies that may be carried out in the future to better understand the real effectiveness of this method, with the present results, practitioners are encouraged to adopt alternative strategies, such as the TT movement, that can concurrently target different aspects of physical preparation relevant to the demands of the sport of basketball.

Chapter 9

Conclusion and Summary

9.1 Summary

Based upon the results of the presented work, it may be concluded that a golden period for motor learning may indeed exist pre-PHV, with specific focus on motor tasks requiring neuromuscular control, stability, and balance in the lower limbs during movement. However, this cannot currently be directly attributed to the concept that preadolescence represents the developmental stage where motor learning occurs more steeply. Instead, it may be that, ahead of the growth spurt and the associated changes in stature, body mass, physiology, and biology, motor tasks requiring neuromuscular control, stability, and balance are more easily acquired by the smaller and lighter bodies of younger athletes. In turn, given that neuromuscular control can be considered to encompass movement skills that are classically classified to be *fundamental*, the results of the current work appear to support the notion that FMS should be emphasised in athletic development of youth populations in the years preceding adolescence. Therefore, the current results appear to support the central principles of the LTAD and YPD models of athletic development, both of which highlight a need to develop FMS during middle childhood. Of pertinence to the applied practice of youth coaches, where time is often constrained, it appears possible that the development of FMS and other athletic capabilities may occur through the implementation of NMT programmes, which can be included within the warm-up protocols before commencement of sports-specific practices for sports such as basketball.

While there appears to be efficacy in the implementation of NMT programmes to develop FMS, the results of the presented work suggest that the value placed upon the development of FMS by coaches of youth basketball players is varied. Despite basketball coaches displaying knowledge of FMS, the lack of uptake and implementation within their practice appears to suggest that the responsibility for the development of skills, other than those specific to basketball itself, exists outside of their remit. Accordingly, a different approach is warranted which, based on the current results, could feasibly be the adoption of concepts from the ecological dynamics framework. Such an approach could comprise a less conventional mechanism for athletic development and S&C, one that aligns instead to the ecological dynamics perspective of skilled performance and motor learning. In contrast to typical athletic development activities which have been strongly influenced by the field of S&C, the current results indicate that the use of parkour for the development of FMS and athletic capabilities appears to be as effective as conventional approaches, such as the use of NMT programmes. Through parkour-based exercises, movement capabilities may be developed by the young basketball player, with less emphasis placed on rigid movement patterns and technique. Instead, parkour-based exercises may encourage more diverse and adaptable movement skills, which are likely to be more representative of basketball specific skills. Moreover, if utilised during middle childhood and the years preceding PHV, this may be an effective strategy to develop motor skills and capabilities that are transferable to basketball, whilst simultaneously serving to mitigate against the issues of early single sport specialisation and underdeveloped FMS. Accordingly, parkour-based actions could be implemented by coaches of youth basketball with the dual purpose of athletic development *and* enhancement of basketball-specific capabilities. However, to encourage uptake of this practice, such a strategy would require a change in the discourse within education programmes towards the adoption of concepts from the ecological dynamics framework. Accordingly, the education of coaches with terms and concepts such as ‘representative practice design’, ‘donor sports’, and ‘perception-action coupling’ would feasibly facilitate the development of a coaches’ appreciation for how parkour may improve the basketball-specific performance capabilities of the players under their charge.

The current research also found that the TT may lead to greater transfer of training to the LU shot. Certainly, the findings indicated that the greater maximal acceleration was produced in the tic tac compared to a basketball shot and the conventional drop jump exercise. Furthermore, the results indicated that the TT could be utilised as an exercise within the S&C strategy of adolescent elite level players, with no apparent compromise in performance when compared to more traditional methods of S&C. To increase the transfer of training, S&C practitioners may wish to adopt the parkour action within their programming. However, the results of the current research also highlighted individualised responses to training and, therefore, coaches should also acknowledge and expect non-linearity in the pattern of the anticipated training response. This exists as somewhat of a juxtaposition between the long-term development of talented youth players and the often-constrained time available to develop their physical capabilities. However, the ecological dynamics perspective regards humans as dynamic and complex beings, a lens through which S&C and basketball coaches may be able to appreciate the nuanced responses to training and the importance of an individualised approach to the training of youth players.

Beyond athletic development, frameworks such as the LTAD and YPD models have advocated for a long-term approach as a strategy to develop physical literacy. However, only the ASM, from which the donor sports concept originates, appears to present a plan for the achievement of physical literacy that is aligned to the broader constructs of that concept. The results of the current research suggest that the use of parkour may develop the affective domain as well as the physical capabilities in preadolescent basketball players. Basketball governing bodies and other key stakeholders should consider the broader aims of physical literacy as well as the adoption of the ideas proposed by the ASM, including the donor sport concept and its application of the ecological dynamics framework. Not only could this contribute to improved athletic capabilities in youth basketball players, it might also lead to wider impact on the development of physical literacy of children in general.

9.2 Research Question 1 - Does a golden period for motor learning exist in preadolescent youth?

Regarding motor control and stability, yes. Although maturation status was not measured, based upon the evidence from the meta-analysis in this work, bodyweight-only NMT programmes appear to be more effective in younger, lighter, and shorter youth, indicating that preadolescence may represent a period where FMS and other motor skills may be more readily developed. However, this is not to suggest that more mature youth are not able to successfully develop these motor skills also, only that it may be more challenging and potentially require a larger stimulus than that typical of NMT programmes. Nonetheless, where younger children may more easily develop motor skills such as FMS, it would be logical for this to be regarded as an appropriate period for motor learning development.

9.3 Research Question 2 - Are FMS valued and understood by coaches of youth basketball players?

Yes, in terms of coaches displaying an understanding of FMS and seemingly having knowledge of their value. However, FMS are not necessarily valued to the extent that basketball coaches will implement their development within their own practices. Furthermore, the responsibility for the development of FMS is not regarded as that of the basketball coach which, problematically, may mean that young players are limited in their exposure to motor skills and forms of movement other than those specific to basketball. In turn, and in direct relation to question 1, there may be a missed opportunity to develop motor skills during a period when these can be achieved most easily (i.e. pre-PHV). In turn, issues relating to early specialisation remain unresolved. Collectively, therefore, there is an apparent lack of critical understanding of FMS in coaches of youth basketball players.

9.4 Research Question 3 - Using the ecological dynamics framework and the donor sport concept, can parkour be used to develop FMS in youth basketball players?

Yes. There appears to be no substantive difference between the use of parkour and conventional S&C-based exercises (e.g., those typical of NMT programmes) to develop FMS in this population of players. When implemented in preadolescent players, parkour-based actions may replace typically utilised neuromuscular exercises, exposing young players to movements that are more diverse and open in nature. In relation to question 1, this would facilitate the development of FMS and other non-basketball specific movement capabilities during the period where motor skill development is more easily achieved In older and more mature players, the utilisation of parkour-based actions, such as the TT, may be utilised as part of a more structured S&C training regimen to facilitate the transfer of training to basketball-specific performance (Figure 22). Accordingly, using parkour as a donor sport for youth basketball to develop FMS and athletic capabilities appears entirely feasible; however, coach education would need to adopt concepts from the ecological dynamics framework to appreciate the value of parkour for it to be implemented as a donor sport.

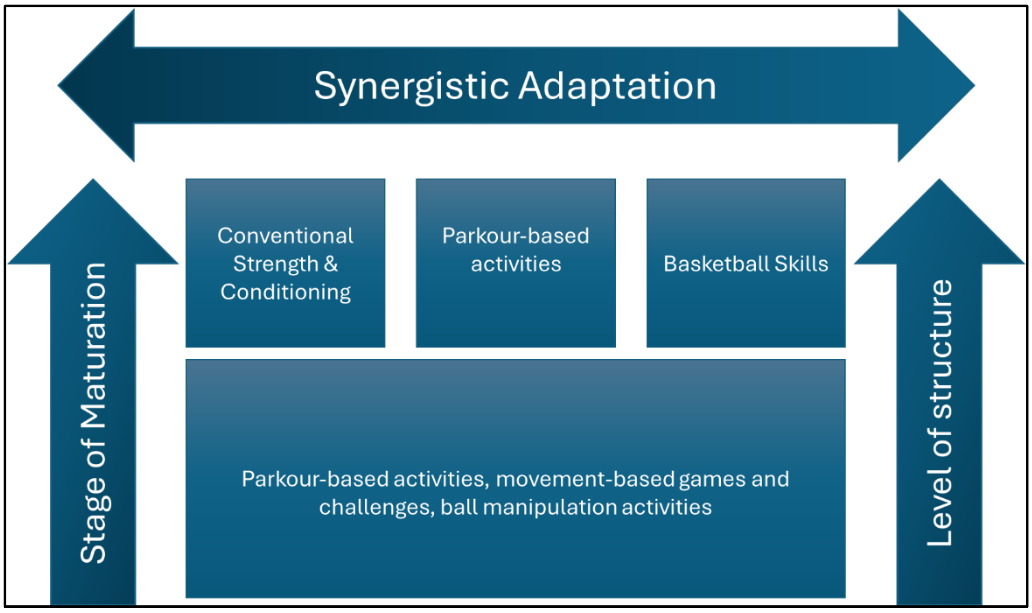

Figure 22. Theorised model of athletic development for youth basketball players, incorporating parkour-based activities.

9.5 Limitations

The research has several limitations could be addressed by future research in this area:

- In the meta-analysis there was high heterogeneity which likely related to the lack of uniformity in the NMT programmes of the included studies.
- In addition to the above, only inferences were made relating to the maturation status of the participants included in the studies, with chronological age, mass, and stature used as a basis for determining the likely biological maturity of the participants of the included studies. However, the studies included in the meta-analysis had not calculated maturity, therefore, limiting the interpretation of the results.
- The survey of basketball coaches did not provide the respondents with prior information relating to FMS and, therefore, could not wholly glean the coaches' thoughts towards the value of FMS and the reasons why the implementation of FMS development was not necessarily deemed to be their responsibility.

- Within the intervention studies, the sample sizes were small, which likely will have had a bearing on the results and potentially limited the wider application of the findings.
- The two intervention studies were limited in both the session time and intervention durations, which may have affected the observed outcomes. Study periods across longer timeframes may well have yielded different findings.
- Due to challenges relating to logistics and recruitment of participants, which was heavily impacted by the COVID-19 Pandemic in 2020, the included studies did not capture perceptual data and was unable to measure the effects of parkour on basketball-specific performance.
- The accelerometer-based study was limited to comparisons of maximum acceleration between the jumping actions. Kinetic and kinematic data capture would have enabled a more comprehensive comparisons between the TT, DJ and LU actions.

9.6 Future Directions

The emphasis within the preceding chapters has been placed on the ecological dynamics framework and the use of parkour to develop movement skills and athleticism that may be "donated" to basketball specific performance in youth players. The results of the current research provide a basis for further investigation examining the effects of the implementation of parkour-based exercises on athletic capabilities of youth basketball players in longitudinal studies. Longer-term intervention studies, that span multiple stages of maturation, could provide important insights relating to the development of movement skill at different stages of maturation, as well as the potential implications of growth and maturation on these skills over time.

It remains limited to theory and indirect evidence that movement skills that are well developed during preadolescence are retained into adolescence due to myelination of neural pathways. Additional empirical research supporting the retention of movement skills from pre-PHV through to post-PHV would provide important evidence for national governing bodies and key stakeholders in youth basketball (e.g., coaches and parents). This evidence would further highlight the importance of a coherent athletic development strategy executed in parallel with the development of technical and tactical playing capabilities. However, another important area of future research towards this outcome is the investigation of the effects parkour on basketball-specific performance of youth players. This is an obvious extension of the current work that is necessary to provide evidence of the donor sport concept with respect to the transfer of perception-action capabilities between parkour and basketball. Studies designed to examine the effects of parkour-based training on the detection of affordances and the utilisation of enhanced action capabilities within basketball-specific scenarios are required to provide direct evidence of the donor sport concept through the ecological dynamics lens. Such work could be highly impactful on the future strategies of organisations responsible for the development of talented youth basketball players, and indeed players of other sports too. The current work may be built upon by other researchers to further investigate the donor sport concept as well as the adoption of the ecological dynamics perspective within the athletic development strategy of youth basketball players.

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