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CAIO GARBO MIGUEL

**LONGITUDINAL ASSOCIATION BETWEEN MAXIMAL SHORT-TERM AND
INTERMITTENT LONG-TERM PERFORMANCES IN YOUNG BASKETBALL
PLAYERS**

Florianópolis

2025

Caio Garbo Miguel

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Orientador(a): Prof. Doutor Humberto Moreira Carvalho

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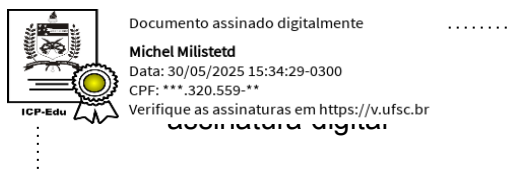
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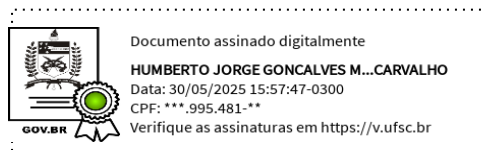
Professor Doutor Humberto Moreira Carvalho
Universidade Federal de Santa Catarina, Brasil

Professor Doutor Ricardo Teixeira Quinaud
Universidade do Extremo Sul Catarinense, Brasil

Professora Doutora Daniele Detanico
Universidade Federal de Santa Catarina, Brasil



Coordenação do Programa de Pós-Graduação



Professor Doutor Humberto Moreira Carvalho Orientador(a)

Florianópolis, 2025

Este trabalho é dedicado a todas as pessoas
que fizeram parte da minha formação acadêmica,
profissional e pessoal ao longo de toda minha vida

RESUMO EXPANDIDO

INTRODUÇÃO

A participação esportiva de jovens geralmente é vista como positiva, entretanto os programas esportivos em sua maioria estão focados no desenvolvimento até a expertise e no nível adulto de elite. Isto faz com que estes programas sejam muitas vezes seletivos e excludentes, se tornando um tema complexo. Jovens atletas que integram o sistema competitivo estão passando por um período de crescimento e desenvolvimento biológico. O crescimento é um processo que envolve o aumento no tamanho da estatura, da massa corporal e óssea. Já a maturação é um processo interno e fisiológico que envolve os tecidos, órgãos e seus sistemas além das composições bioquímicas e suas funções. As grandes diferenças entre sexos começam a se tornar mais evidentes a partir do final da infância e início da adolescência. O Basquetebol por sua vez é uma modalidade onde as dimensões corporais e as capacidades funcionais podem proporcionar vantagens no jogo, especialmente em relação a jovens atletas, uma vez que o processo de crescimento e desenvolvimento não ocorrem de maneira homogênea para todos os indivíduos. As características dos padrões de movimento observados no basquete se dão por ações curtas, intensas e intermitentes como salto, sprint, mudanças de direção (agilidade) e deslocamentos frontais e laterais, ao longo do jogo. Tais movimentos são relacionados principalmente com o sistema anaeróbio, entretanto devido ao tempo de jogo e principalmente pela limitação do atleta realizar estes movimentos de maneira repetida e continua (recuperação) o sistema aeróbio possui uma grande influência no desempenho físico ao longo do jogo. Testes e avaliações físicas surgem como uma maneira de avaliar e mensurar as capacidades físicas dos atletas, entretanto avaliações transversais são limitadas para caracterizar o desenvolvimento um jovem atleta, uma vez que como já dito anteriormente estes estão passando por um processo de constante mudanças e variações. Por isso se faz importante levar em consideração a característica multifacetada dos padrões de movimentos específicos do basquetebol e entender que este processo ocorre de maneira continua sendo necessário avaliá-lo de maneira longitudinal até o atleta atingir a fase adulta.

OBJETIVOS

O presente estudo teve como objetivos principal investigar e explorar o desenvolvimento longitudinal de jovens atletas considerando as dimensões corporais e capacidades físicas, sendo dividido em dois objetivos específicos: (i) descrever as variações no crescimento e no desenvolvimento das capacidades físicas em jovens atletas femininos e masculinos; (ii) estudar as relações longitudinais entre os indicadores de capacidade física em jovens atletas de basquetebol do sexo masculino, ajustado pela influência das dimensões corporais.

METODOLOGIA

Este estudo considerou duas amostras diferentes. No primeiro estudo a amostra consistiu em medidas repetidas coletadas de 92 jovens jogadores de basquete, dos quais 47 eram do sexo feminino e 45 do masculino (11,7 a 16,3 anos). Da amostra total, 10 jogadores completaram seis observações, 18 jogadores completaram cinco

observações, 27 jogadores completaram quatro observações, 17 jogadores completaram três observações e 20 jogadores completaram duas observações com um total de 349 medições levadas em consideração. Já no segundo estudo medidas repetidas coletadas de 45 jogadores adolescentes de basquete do sexo masculino (8,8 e 17,7 anos). Da amostra total, um jogador completou seis observações, 3 jogadores completaram cinco observações, 16 jogadores completaram quatro observações, 14 jogadores completaram três observações e 11 jogadores completaram duas observações. Um total de 146 medições foram levadas em consideração. Para ambos os estudos as amostras foram coletadas de dois diferentes contextos (I) São Paulo: coletadas de quatro clubes diferentes, que disputaram competições oficiais promovidas pela federação paulista de basquetebol (FPB). Essa amostra foi coletada de 2015 a 2018 com observações no início, meio e final da temporada e (II) Santa Catarina. coletada de quatro clubes diferentes, que disputaram competições oficiais promovidas pela federação catarinense de basquetebol (FCB) e equipes de nível estadual. Foram coletadas medidas antropométricas (massa corporal e estatura) e capacidades funcionais de (i) salto através do counter movement jump (CMJ), (ii) agilidade através do line drill test (LD) e (iii) capacidade aeróbia através do yo-yo IR1. No primeiro estudo aplicou-se uma curva básica de modelo de crescimento polinomial de dois níveis para avaliar as mudanças no desenvolvimento de jovens jogadores de basquete em relação à sua idade cronológica, enquanto no segundo estudo utilizou-se Modelagem hierárquica com métodos bayesianos para descrever e avaliar a relação longitudinal entre os resultados de aptidão física

RESULTADOS E DISCUSSÃO

Existe uma diferença no crescimento entre jogadores do sexo masculino e feminino, entretanto para ambos os sexos há uma similaridade na característica de crescimento dos jovens atletas de basquetebol brasileiros com o observado em jovens atletas de basquetebol de outros contextos. Ao longo do crescimento ocorre uma melhora no desempenho de esforços máximos de curta duração para ambos os sexos. Durante o período pré-pubertário há uma forte relação entre os desempenhos nos testes de salto e de agilidade, entretanto essa relação vai diminuindo com o passar do período pubertário. O grupo feminino atinge a estabilidade de desenvolvimento nos desempenhos de esforços máximos de curta duração antes do masculino, sendo observado o mesmo padrão de desenvolvimento para a capacidade aeróbia, entretanto este parece continuar a se desenvolver mesmo após o período pubertário analisado neste estudo. Mas atletas do sexo feminino com maior massa corporal possuíram pior desempenho nos testes de esforço máximo, entretanto essa relação diminui com o passar dos anos ao se aproximar do estado de maturação adulto. Em relação ao desempenho no teste aeróbio, a massa corporal parece não ter influência, independente de sexo.

CONSIDERAÇÕES FINAIS

Com o intuito de minimizar os erros nos processos de seleção e identificação de talentos, é necessário entender por parte dos envolvidos neste processo as nuances entre sexo, idade, crescimento, desenvolvimento e maturação. Em relação as características de jovens atletas masculino e feminino é necessário entender que há diferenças entre os períodos de crescimento e a intensidade que eles ocorrem, sendo necessário a adaptação do treino a característica de cada gênero ao invés da generalização muitas vezes baseada apenas no sexo masculino. O desempenho no período pré-pubertário ou pubertário não necessariamente vai ser refletido no período

pós-pubertário ou adulto, uma vez que atletas que tenham um desenvolvimento precoce tendem a desempenhar melhor as ações do jogo naquele momento. Tais observações são feitas também em relação aos efeitos da massa corporal e sua influência no desempenho físico, especialmente durante e após o período da adolescência, onde acontece os principais ganhos nas capacidades físicas e aumento das características antropométricas. Após este período as diferenças entre os desempenhos em diferentes testes começam a se tornar mais evidentes e a influência do treino na melhora e especialização dos movimentos específicos do jogo de basquete começam a ficar evidenciadas. Em relação a interpretação das avaliações dos testes físicos e das características antropométricas é importante ressaltar que avaliações e interpretações transversais em relação a jovens atletas são limitadas, uma vez que esta população está em constante mudança e variação ao longo do período pubertário. Treinadores, dirigentes e os demais envolvidos no processo de desenvolvimento de jovens atletas devem levar em consideração os múltiplos fatores que influenciam no caminho de jovens atletas até o nível adulto, a fim de favorecer o potencial desempenho futuro destes atletas, tornando assim o contexto esportivo mais saudável e igualitário para todos.

Palavras-chave: Jovens atletas; Crescimento e desenvolvimento e capacidades físicas e características antropométricas

ABSTRACT

Youth sports participation is generally seen as positive. Sports programs are often focused on development to expertise and elite adult level. Hence youth sports is often highly selective and exclusive, becoming a complex issue as the myriad of factors influence young athletes' performance and development across pubertal growth. Substantial changes in size, composition and function with substantial between-individual variation are present across adolescence. Basketball is a sport in which body dimensions and physical fitness can provide advantages in the game. The movement patterns in basketball are characterized by short, high-intensity and intermittent efforts relying on anaerobic pathways. However, given the game duration the aerobic system also has a great influence on the athletes' performance. Due to between-individuals variation and changes across adolescence, cross-sectional measurements are limited to interpret the development of physical fitness of a young athlete. Longitudinal designs are required to provide a more complete understanding of the young athletes' development. In this study we investigated the longitudinal development of body size and physical fitness of young basketball players, specifically considering: (i) described the variations in growth and physical fitness development across adolescence in female and male basketball players; (ii) examined the longitudinal relationships between physical fitness indicators in young male basketball athletes, adjusted for the influence of body dimensions. This study considered two different samples. In the first study, the sample consisted of repeated measures collected from 92 young basketball players, 47 of whom were female and 45 male (11.7 to 16.3 years). In the second study, repeated measurements were taken from 45 adolescent male basketball players (8.8 to 17.7 years). Anthropometric measurements were taken (body mass and height) and functional capacities of (i) vertical jump using the counter movement jump (CMJ), (ii) agility using the line drill test (LD) and (iii) aerobic capacity using the yo-yo IR1. In the first study, a basic two-level polynomial growth model curve was applied to evaluate changes in the development of young basketball players in relation to their chronological age, while the second study used hierarchical modeling with Bayesian methods to describe the longitudinal relationship between physical fitness results. We observed variation in the growth patterns in stature and body mass between female and male athletes. Throughout adolescence, there was substantial improvement in the physical fitness indicators of maximal efforts with short duration for both female and male athletes. During the pre-pubertal period there was a stronger relationship between performance in the jumping and agility tests, but this relationship decreased substantially with age, becoming trivial as players were closer to the end of adolescence. On average, the female athletes attained a plateau of development in short-term maximal effort performance before the male athletes. A similar pattern was observed for the development is observed for aerobic performance, although this seems to continue to develop even after the pubertal period considered in this study. To minimize errors in the process of selection and talent identification, it is necessary to understand the nuances between sex, age, growth, development and maturation. Coaches, managers and others involved in the process of developing young athletes should take into account the multiple factors that influence the path of young athletes' development, in order to favor the potential future performance of these athletes, thus making the sporting context healthier and more equal for all.

Keywords: Young athletes; Growth and development and physical capacities and anthropometric characteristics

FIGURE LIST

<u>Figure 1</u> Posterior predictions of pubertal growth changes for stature and body mass in young female (panel a and c for stature and body mass, respectively) and male (panel b and d for stature and body mass, respectively) basketball players.	39
<u>Figure 2</u> Posterior predictions of developmental changes for the CMJ performance in young female and male basketball players.	41
<u>Figure 3</u> Posterior predictions of developmental changes for the Yo-yo intermittent recovery level 1 test in young female and male basketball players.	42
<u>Figure 4:</u> Posterior predictions of developmental changes for the Line-drill test in young male and female basketball players.	44
<u>Figure 5:</u> Longitudinal relationships between line-drill performance and vertical jump performance (Panel A) in young male basketball players across adolescence, adjusted for within- and between- player variations in body size (Panel B).	56
<u>Figure 6:</u> Longitudinal relationships between line-drill performance and Yo-Yo Intermittent Re-covery Test Level 1 performance (Panel A) in young male basketball players across adolescence, adjusted for within- and between-player variations in body size (Panel B)	57
<u>Figure 7:</u> Longitudinal relationships between vertical jump performance and Yo-Yo Intermittent Recovery Test Level 1 performance (Panel A) in young male basketball players across adolescence, adjusted for within- and between-player variations in body size (Panel B)	58

TABLE LIST

<u>Table 1: Characteristics of the sample at the study baseline.....</u>	38
<u>Table 2: Characteristics of the sample at study baseline.....</u>	54

ABBREVIATIONS

LD - Line Drill

CMJ - Counter Movement Jump

PHV - Peak Height Velocity

SUMÁRIO

1 INTRODUCTION	16
1.1 PURPOSE	21
2 METHODOLOGICAL CONSIDERATIONS.....	23
2.2 MEASURES AND DATA QUALITY	24
2.2.1 Anthropometric Measures	24
2.2.2 Physical Fitness Assessment	24
3 DEVELOPMENTAL CHANGES IN THE PHYSICAL FITNESS OF YOUNG FEMALE AND MALE BASKETBALL PLAYERS: A BAYESIAN ANALYSIS	27
3.1 INTRODUCTION	27
3.2 METHODS	28
3.3 RESULTS	31
3.4 DISCUSSION	37
4. LONGITUDINAL RELATIVE INTERRELATIONSHIPS AMONG PHYSICAL FITNESS INDICATORS IN YOUNG MALE BASKETBALL PLAYERS	43
4.1 INTRODUCTION	43
4.2 METHODS	44
4.3 RESULTS	48
4.4 DISCUSSION	53
5 FINALCONSIDERATIONS	55

PUBLICATIONS

The results presented in this dissertation are accepted or is in final project for submission

Miguel CG, Soares AL, Lima AB, Karasiak FC, Galvão LG, Leonardi TJ, et al. Developmental changes in the physical fitness of young female and male basketball players: a Bayesian analysis. J Sports Med Phys Fitness. accepted for publication

Miguel CG, Soares AL, Lima AB, Karasiak FC, Galvão LG, Leonardi TJ, et al. Longitudinal relative interrelationships among physical fitness indicators in young male basketball players. Working paper

1 INTRODUCTION

Youth participation in sports is perceived as positive for youth development, including positive social interactions, improvement in physical health, and the development of self-identity and self-esteem (1). However, youth sports programs are generally focused on expertise development and attainment of elite adult level. Consequently, youth sports programs are highly selective, as only a minority attains adult levels, particularly higher levels of performance within a sport (2). Given the focus on expertise development, youth sport programs often assume that early deliberate exposure to sport-specific practice and competition is essential to the development of the youth athlete. However, there is limited evidence supporting many of the assumptions considered in youth sports contexts (3).

Youth sport is a complex topic, as the athletes are going through a significant developmental change. Externally, the growth process, with increases in size, physique and body composition and internally, the maturation process, with changes in the bodily systems and in the timing and tempo. Timing refers to when a specific event occurs, and the tempo refers to at which rate that event occurs (4). These processes are interrelated and influence each other and can have an impact on the physical performance of youth athletes. The growth and maturation can occur differently in each chronological age (CA) and varies between individuals. Human growth is a physical and quantitative process that involves an increase in the size and mass of the body, such as bone elongation, muscle mass increase, and weight gain. Growth primarily occurs during childhood and adolescence, but it can also continue, although at a slower rate, into early adulthood. On the other hand, the maturation process is a more complex and difficult process to define than growth. It occurs in all tissues, organs, organ systems and affects all biochemical compositions, and its functions. In general, there are three types of maturation; (I) sexual, which is the functional reproductive capacity, (II) skeletal, the ossification to the adult skeleton and (III) neuroendocrine, which plays an important role in the sexual, skeletal and somatic maturation. In summary, maturation is the process to attain the mature state (1). In the final stages of childhood and the early stages of adolescence (start of the development of puberty) there is much more variability intra and inter individual. In this period there is an improvement in strength and motor skills, but the pattern of improvement is different according to the task (1). Adolescence is the most significant period of growth

and changes in size, body mass, and physiological capacity and is the period where the biological differences between sex starts to appear (2).

Somatic growth occurs until the individual reaches the adult phase, with a rapid growth in stature in infancy and early childhood leveling off in middle childhood and having a rapid spurt in adolescence (10 years for girls and 12 years for boys) and reaching the peak high velocity generally at 12 years for girls and 14 years for boys, slowing and stabilizing in the adult age. This pattern of growth is observed in others body dimensions and body mass (3). The body mass growth spurt occurs slightly later than the height growth (4).

In general, there is a small sex differences in childhood, with a linear increase in boys up to 13-14 years of age and a great acceleration in the adolescent spurt (4). In girls, the same linear increase is seen, although there is a stabilization of the strength increase, even in the adolescent spurt, at 16 to 17 years. The growth literature usually stops at the age of 18, but strength can increase until the age of 30, especially in boys (1).

About the development capacities of the anaerobic system, such as jumps, speed and agility, it's seen a pattern of performance and development as a youth. There is an increase in performance in early childhood (from 5 years old), with a little difference between boys and girls at this age, nonetheless this difference increases abruptly in adolescence, with the girls, in general, stabilizing earlier than the boys (1).

The aerobic fitness is the capacity to deliver oxygen to the muscle through the cardiovascular system to sustain the muscle during an exercise (5). The VO₂ max is the highest rate that oxygen is consumed during an exercise, and it is used to access the aerobic power (1, 5, 6). In general, aerobic power, as indexed with the VO₂ max, increases with the growth and maturation process. Boys typically exhibit a progressive increase in aerobic power up to the age of 16, while girls typically reach a peak in aerobic power between the ages of 13 and 14 (1, 5, 6). The VO₂ max is influenced especially by a variety of factors as muscle mass and body dimensions (1, 5, 6), age, sex, maturity status and physiological and biochemical characteristics.

In addition to the quantitative changes in the athlete body dimensions, the qualitative changes (i.e. capacities to perform those actions beside body size or dimension) are also significant factors of performance in a basketball game (1). These qualitative changes results from deliberate practice and training (7), as there is difference in physical fitness between athletes and non-athletes with the same

chronological age (8). Although there is a lack in the literature of how much the growth and maturation process and the training affect the physical development of youth athletes and how they interact (9). Regarding the body dimensions, training does not appear to have an impact on stature growth. Individuals tend to participate in sports that are best suited for their stature. Basketball is a suitable sport for taller individuals, while gymnastics is better suited for shorter individuals. While training may offer benefits in terms of enhancing bone density, which is a critical factor in determining bone mineral status during adulthood, further research is necessary to elucidate these benefits. Conversely body mass can be influenced by regular training, resulting in changes in body composition. The training will result in a decrease in fatness and an increase in fat-free mass. Nonetheless, it is difficult to precise the real effect of the training in these gains, since adolescence is a period that the fat-free mass almost double in boys, even if not athletes (4).

The development of motor abilities, such as muscular strength and aerobics and anaerobic fitness, is influenced by numerous factors. These include growth and maturational status, training history, physiological experiences, and genetics. The nervous system plays a pivotal role in motor skill execution. The establishment of fundamental movement patterns (general skills) occurs during the developmental period between the ages of 6 and 8, with early childhood representing the most receptive phase for both learning and adaptation. The period of late childhood is characterized by the emergence of specific motor and sports skills. The efficacy of this improvement is contingent upon the implementation of appropriate tasks by qualified coaches who possess a comprehensive understanding of the underlying mechanisms. A similar rationale underlies resistance training, particularly in the context of strength training for youth athletes. Evidence regarding the influence of anaerobic fitness and training in youth athletes is inconclusive; however, it appears to be influenced by training, growth and maturation. Athletic youths have been shown to exhibit superior anaerobic fitness compared to non-athletic peers (10) and the pubertal phase appears to be a critical period on the development, due to changes in size and hormones. The ability to perform repeated anaerobic actions is related to the capacity to resist fatigue, with the aerobic system the primary support about that ability. The aerobic system has more studies evaluating the training and the development in youth athletes. In this case, early childhood tends to perform worse in aerobic tests independent of the training status, having an improvement with the training and as the ages go on. The

factor that trained youth athletes have a great range in the improvement of aerobic fitness using the same training protocols highlights the influence of several factors on the development of this characteristic, especially the growth and maturation (4).

Body size and physical and physiological abilities play an important role in determining success in basketball (2, 11) especially at a young age (9). Changes during youth growth and development process affect the ability to perform basketball-specific actions (1) and players that have an early maturation or was born in the first or second quarters of the year, normally being higher than their colleagues had a better individual or team performance in youth ages. Those results are observed not only in basketball but on other modalities such as soccer (12, 13), rugby (14) and volley (15). Therefore, an understanding of sport movement patterns is necessary when evaluating young athletes, especially when it is well known that the maturation process does not occur at the same rate in all individuals, even those who share the same chronological age (2).

Basketball is a team sport and have energy demand of both energy pathways (16). The main function of the energy pathways is to supply energy to the muscles through the supply of adenosine triphosphate (ATP) (17). Nonetheless this supply can be provided through distinct systems (anaerobic and aerobic) and despite their differences, they manage to operate together to supply energy to the muscles (18). The supply route utilized it would depend on the intensity of the work and its duration (77). The anaerobic energy system comprises two distinct pathways, and its development has been associated with differences in competitive level among adult basketball players (19, 20). This occurs due to the predominance of movement patterns characterized by short, intense, and intermittent efforts, such as sprinting, jumping, shuffling, and changing direction across a basketball game. The anaerobic alactic involves the splitting of the phosphocreatine (PCr) to generate ATP and is stored in the cell, providing immediate energy, mostly used for high intensity and explosive exercises. The lactic anaerobic pathway involves the breakdown of carbohydrate, through glycolysis, resulting in muscle glycogen, then pyruvic acid and then lactic acid (21).

Despite the predominance of the anaerobic energy supply across a basketball match, the duration of the game limits the ability to perform high-intensity efforts for the entire duration of the game. Hence, the aerobic metabolic pathways are important, allowing the optimal recovery during the game to sustain the sport-specific effort being

important to consider in the athletes athletic development (22). Aerobic or oxidative metabolism involves the combustion of carbohydrates and fats and happens in the presence of oxygen (18).

Once the basketball characteristics relies on different energy pathways having a variance in the use of these pathways across a basketball match and its development across the growth phase, it is important to evaluate the main actions that occur in the game, using the most appropriate methods. Agility is one of the most common capacities in a basketball game. A basketball athlete can make 1,000 changes of movement patterns and change of direction in a single match (19). Due to its capacity to reproduce the intermittent characteristics of the game the line drill (LD) test has been a reliable measure to evaluate anaerobic performance. Furthermore, the test has been demonstrated to be both valid and reliable when compared to the Wingate Anaerobic Test, which is commonly considered the reference for anaerobic tests (20). Another advantage of the LD test is that it is commonly used by trainers and coaches in their training, which makes it simpler to apply (22, 23). Vertical jump is an essential motor skill ability and indicator of performance in many sports (23). In a basketball match, an athlete can perform approximately 46 vertical jumps per game (19, 24) being crucial to access the lower limbs power output for jumping. The Counter Movement Jump (CMJ) has been utilized to assess the lower limbs power due to its reliability across various age groups (25, 26) and the facilities for practical application.

As said before the aerobic fitness is a crucial factor in the performance of team sports athletes and plays a significant role in the generation and maintenance of the power output required for high-intensity actions, as well as in the recovery process (27). The majority activities of basketball players occur at moderate to low intensities, 29,2% and 25,2% respectively (28) being dependent on the aerobic pathway (20). The Yo-Yo IR1 test has been widely used as predictor of aerobic capacity due to its reliability and validity in team and intermittent sports (29). In the context of basketball, the yo-yo IR1 test has been a reliable predictor of physical game performance (28).

The interpretation of the physical fitness development of young athletes should take into account that basketball-specific has a multifaceted movement pattern (3, 30) and the data, specially about longitudinal studies with youth basketball players is limited at best (31-33). The few studies with this subject are focused on male basketball players (35), where in this meta-analysis there was only one identified longitudinal study with basketball female athletes. Miss-interpretation and generalization with

physical fitness and anthropometric characteristics in female athletes is a concern due to sexual dimorphism, specifically the differences in timing and tempo of biological maturation (35). Studies regarding male basketball athletes and growth and development are limited (36).

Longitudinal studies are important, providing a more complete approach of the growth and maturation, once is a continuous and long way term process and gives important insights into the development of physical fitness in youth athletes (37, 38). Although the importance of longitudinal studies, application in the sport contexts is challenging. Participant attrition, the hierarchical and selective nature of youth sports programs and competitions, the data collected often exhibit complex structures and youth restrictions observations within and between competitive seasons are a complication factor of this study design. Therefore, mixed longitudinal designs are an available option (39). These designs allow for the collection of incomplete and shorter-term repeated measures over the study period. By fitting advanced statistical models that account for the complexity of the data and model assumptions, researchers can derive meaningful descriptions of developmental trends. In particular, multilevel modeling within a fully Bayesian framework provides a powerful and flexible method for dealing effectively with such data (40, 41). Bayesian methods consider parameters as random variables, integrating sample data with prior distribution information to estimate a posterior probability distribution that captures the uncertainty regarding the degree to which the parameters are known based on the data (40, 41). To unfamiliar readers with bayesian methods, significance tests are not considered. Bayesian methods focus on the relative confidence in different models and parameters values, estimation and predictions and assessment of the validation of model predictions (42). Bayesian methods was allows a direct probabilistic interpretation of the uncertainty intervals and posterior probabilities, relevant in sport science, where interests often lie in estimating small effects (41)

1.1 PURPOSE

The process to attain the elite level is difficult and depends not only on the athlete. The process is selective and exclusive. Youth sports performance and success are highly influenced by physical fitness and anthropometric characteristics; thus, the growth and maturation process have a great impact on it. Concerns about this theme

occur when coaches and/or managers evaluate an athlete, not taking into account the maturational status of the individual.

The main objective of this study is to investigate and explore the longitudinal development of young athletes body dimensions and physical fitness in youth basketball players. To attain that purpose, we divided it into two specific studies.

The first study we described the developmental changes in growth and physical fitness in young basketball players throughout adolescence, specifically, we examined the sex-related variations in the developmental changes of physical fitness among Brazilian young basketball players. The second study examined the longitudinal relationships between physical fitness indicators in young male basketball players across adolescence, adjusting for the influence of body size. Both studies take advantage of repeated measures collected at different periods of the season and across multiple years, assessing the body size (stature and body mass) and the performance in physical fitness tests. Both studies ranged from 11 to 19 years old, with the first evaluating male and female basketball players as the second one we attained only to male basketball players.

The available data in this study allows a deeper understanding in the youth development process, contributing to coaches and relevant stakeholders with practical applications, minimizing the naive interpretations in the identification and development of young basketball players, including in the context of talent development.

2 METHODOLOGICAL CONSIDERATIONS

This study, as other published works (33-38, as others) are part of the project “Percursos de formação desportiva em jovem atleta: análise multidimensional “, that aims to (i) characterize the anthropometric growth and development and the physical capacities in youth sports participation; (ii) study the influence of the training context (iii) study the changes in functional performance caused by the deliberate practice; (iv) study the biological determinants and practical context of the injury in youth athletes; (v) investigate discriminant variables in the course the sports excellence.

2.1 Participants and study design

This study considered data from surveys with repeated measures data collected from competitive seasons from 2015 to 2024 in youth basketball. The sample was collected from two different context (I) São Paulo: collected from four different clubs, which played official competitions promoted by federação paulista de basquetebol (FPB). Those sample was collected from 2015 to 2018 with observations in early, mid and end of the season and (II) Santa Catarina.collected from four different clubs, that played official competitions promoted by federação catarinense de basquetebol (FCB) and state level teams. Those samples were collected from 2018 to 2024 with observations in early and end of the season. It should be noted that data collection was not possible between March 2020 and February 2022 due to the implementation of social isolation measures in response to the global pandemic context caused by the SARS-CoV-2 virus.

All players were engaged in formal youth basketball training programs and trained at least three times a week (1.5 – 2.5 hours/training day), playing a match most of the weekends over a 9- month competitive season. No players reported moderate or more severe injuries during 6- months before the testing. Players were from five age categories (under-11, under-12, under-13, under-15 and under-17), according to their birth date to the respective year of assessment (for example, a player who would complete 13 years was classified as under-13, while a player who would complete 14 years in the same season was classified as under-15). Clubs' programs run traditionally from February to July and August to November, completing nine months each season. Data were collected at each basketball club facility.

Players and their parents or legal guardians were informed of the nature of the study, the participation was voluntary, and they could withdraw from the study at any

time. The study was approved by the Research Ethics Committee of the Federal University of Santa Catarina and by the Research Ethics Committee of the University of Campinas. Both athletes and their legal guardians provided written informed consent.

2.2 MEASURES AND DATA QUALITY

2.2.1 Anthropometric Measures

The measure was taken by a single experienced observer following standardized procedures. Body mass was measured with a calibrated portable balance (Seca model 770, Hanover, MD, USA) to the nearest 0,1 kg. Stature was measured with a portable stadiometer (Seca model 206, Hanover, MD, USA) to the nearest 0,1 cm. Based on repeated-measures, stature reliability was verified and established with a perfect correlation between measures and a typical error of measurement 0,18 cm (95% confidence interval 0,12 to 0,40).

2.2.2 Physical Fitness Assessment

To assess the basketball-specific physical fitness levels it was used three tests, two for the anaerobic condition (CMJ and LD) and one for aerobic capacity (Yo-Yo IR1).

The CMJ consists in a vertical jump where the individual starts in a upright position with their hands in the hip, squatting as convenient to perform the highest jump possible. The player performs three jumps in a row, with the best mark being considered. The test is used by coaches to measure basketball specific-performance due to its similarity with the actions in the game and its reliability and validity (8).

The other test to assess anaerobic capacity is the LD test. This drill is very used by coaches in the team routine facilitating the familiarity by the athletes and having validity and reliability. The test consists in a progressive, high-intensity shuttle running in a regular basketball court including seven changes of direction after increasing sprint distances: base line to free throw line (5.8m), base line to half court line (14.0m), base line to other side free throw line (22.2m) and base line to base line (28.0 m), totalizing 140m (22).

To evaluate the aerobic capacity the Yo-Yo intermittent recovery test level 1 consists of repeated 2 x 20-m runs back and forth between the starting, turning, and

finishing line at a progressively increased speed controlled by audio bleeps from a tape recorder. Between each running bout, the subjects have a 10-s active rest period. When the subjects have failed twice to reach the finishing line in time, the distance covered is recorded in meters and represents the test result. The test has been demonstrated to be valid and reliable in youth basketball (29).

3 DEVELOPMENTAL CHANGES IN THE PHYSICAL FITNESS OF YOUNG FEMALE AND MALE BASKETBALL PLAYERS: A BAYESIAN ANALYSIS

3.1 INTRODUCTION

Movement patterns in basketball are performed at near-maximal intensities that involve short, intermittent efforts that require rapid changes in movement that rely on anaerobic energy systems (8). Nevertheless, the majority of playing time is devoted to low- to moderate-intensity activities that rely on aerobic energy pathways and may have more importance on recovery from repeated bursts of high-intensity intermittent efforts (41-43). Overall, basketball players are expected to exhibit the ability to sustain fatigue while performing repeated high-intensity activities, including sprinting, agility, upper-body and lower-body muscular strength throughout the game (43, 44). Basketball activity demands vary by level of play, playing position, gender, and experience level, but a consistent pattern of physiological demands is evident given the nature of the exertion (43). Therefore, the interpretation of the physical fitness development of young athletes should take into account the basketball-specific multifaceted movement patterns (7, 31)

There is still a lack of data on the physiological performance development of young athletes (33). There is also limited data in youth basketball (30, 34, 35). Interpretations in young basketball players are mostly based on cross-sectional data from male samples (30, 36). However, the development of young basketball players has specific nuances that affect the development and selection of young players (37). In particular, research suggests that attributes such as stature and physical fitness play a significant role in the selection of young basketball players (38). As a result, extrapolation from the available cross-sectional data on physical fitness development in young athletes to the context of youth basketball is limited at best.

On the other hand, the limited longitudinal data in youth sports are mostly based on male data, with insufficient attention paid to female athletes (33, 45). Interpretations of physical fitness in young female athletes warrant caution in light of sexual dimorphism (33, 46), and the large differences between girls in the timing and tempo of biological maturation and primary sex differences (47). Thus, interpretations that account for sex differences in growth and physical fitness in young athletes may provide deeper support for training and performance guidelines in youth sports.

Longitudinal studies provide valuable insights into the development of physical fitness in adolescent athletes (48, 49). However, longitudinal studies in applied sport contexts are challenging (39).

Due to factors such as participant attrition and the hierarchical and selective nature of youth sports programs and competitions, the data collected often exhibits complex structures, including imbalanced sample sizes, missing data, irregular measurement intervals, and variability between and among athletes. Limitations within youth basketball contexts can restrict observations within and between competitive seasons, complicating efforts to cover the intended multi-year span of the study. Therefore, mixed longitudinal designs are an available option (39). These designs allow for the collection of incomplete and shorter-term repeated measures over the study period. By fitting advanced statistical models that account for the complexity of the data and model assumptions, researchers can derive meaningful descriptions of developmental trends. In particular, multilevel modeling within a fully Bayesian framework provides a powerful and flexible method for dealing effectively with such data (40, 42).

In this study, we described the developmental changes in growth and physical fitness in young basketball players throughout adolescence. Specifically, using a fully Bayesian framework, we examined sex differences in developmental changes in physical fitness in young Brazilian basketball players.

3.2 METHODS

Study design and sample

This study considered data from repeated-measures surveys collected during the competitive seasons of 2015 and 2024 in youth basketball. It should be noted that data collection was not possible between March 2020 and February 2022 due to the implementation of social isolation measures in response to the global pandemic context caused by the SARS-CoV-2 virus.

The sample consisted of repeated measures collected from 92 youth basketball players, of whom 47 were female and 45 were male. In this study, repeated measures were considered across competitive seasons of players from under-11, under-13, under-15, under-17, and under-19 teams at the pre-season (February/March), mid-season (July/August), and end-season (November/December) points. The minimum age range for players included in the repeated measures was set

at one year. Therefore, we considered data from at least one year for each athlete. The players were assessed and evaluated within a one-week period during each observation interval. From the total sample, 10 players completed six observations, 18 players completed five observations, 27 players completed four observations, 17 players completed three observations, and 20 players completed two observations. Consequently, a total of 349 measurements were taken into consideration.

The players were engaged in youth basketball training programs and competed in the state-level competition, which was supervised by the local federation (São Paulo and Santa Catarina). The São Paulo competition was promoted by the Federação Paulista de Basketball, while the Santa Catarina competition was promoted by the Federação Catarinense de Basketball. All participants engaged in training a minimum of three times per week, with each practice lasting between 1.5 and 2.5 hours. Additionally, they competed in a match on the majority of weekends throughout the nine-month competitive season. The data were collected at each basketball club facility. No players reported experiencing moderate or more severe injuries during the six-month period preceding the testing phase.

The study was approved by the senior author's university research ethics committee. Athletes and their parents or legal guardians provided written informed consent after being informed of the nature of the study. They were also informed that participation was voluntary and that they could withdraw from the study at any time. All measurements were conducted in accordance with the ethical standards set forth in the Helsinki Declaration.

Procedures

Chronological age was considered the nearest 0.1 years by subtracting a birth date from the testing date. We considered anthropometry measurements taken by a single experienced observer following standardized procedures, including stature and body mass. Intra-observer technical measurement errors were 0.25 cm for stature and 0.42 kg for body mass (7).

Vertical Jump: We used the vertical jump with the CMJ to measure the lower-limb explosive strength (50). Each jump's height (cm) was measured using an optical measurement system (Optojump, Microgate, Italy). Players started from an upright standing position and were instructed to begin the jump with a downward movement, immediately followed by a concentric upward movement, resulting in a maximal vertical

jump. During jumping, hands were held on the hips during all jumping phases. Three trials were given with a 30 s rest. The height of the best CMJ was retained to the nearest centimeter. Details about reliability estimates (30, 51).

Line-drill test: In the Line-drill protocol (20, 22, 23, 52), players ran 140 m as fast as possible in the form of four consecutive shuttle sprints of 5.8, 14.0, 22.2 and 28.0 m within a regulation basketball court. Players began the test 1 m behind the baseline of the basketball court. The time was measured using either a video recorder (recording rate of 120 fps) (Sony, Tokyo, Japan) or a pair of photoelectric cells (Multisprint System, Hidrofit, Brazil) aligned with the baseline used as reference for the beginning and end of the test. Time was recorded in seconds. When time was recorded by video, the analysis of players crossing the reference baseline with available video analysis was made using the software Kinovea – 0.8.15 (<http://www.kinovea.org>). Verbal encouragement for an all-out effort was given throughout the test. Agreement between measurement methods was near perfect and detailed elsewhere (22, 23, 53).

Yo-yo intermittent recovery level 1 test (yo-yo IR1): The yo-yo IR1 protocol (65) is based on repeated 2 x 20-m runs back and forth between the starting, turning, and finishing line at a progressively increased speed controlled by audio bleeps from a tape recorder. The athletes have a 10-s active rest period between each bout, jogging in a distance of 2 x 5-m. Players ran until they were not able to maintain the required speed; the test was completed when athletes failed twice to reach the finishing line in time. Covered distance was measured in meters. Details about the reliability estimates are available elsewhere (30, 53).

Statistical analysis

We applied a basic two-level polynomial growth model curve (55) to assess the developmental changes in young basketball players relative to their chronological age. In line with previous models used in our research (7), our model describes each player's successive measurements over time, characterizing their individual changes at each measurement point (level 1) and variations in trajectories between players (level 2). Given that the study involved a mixed-longitudinal design spanning adolescence, we considered time (i.e., chronological age) coefficients up to the cubic terms. Furthermore, to account for potential sex-associated variation, we introduced sex (binary variable: female, male) as a population-level effect. We allowed for the

possibility of sex-based differences in player responses at level 2. Furthermore, we examined interaction terms between sex and age to determine whether the trends of change in the outcomes varied between male and female basketball players. Finally, we examined the influence of between-player variation in body dimensions associated to body size on physical fitness (28,32). Furthermore, we considered interaction terms between sex and body size (stature and body mass) to assess whether the trends of body size influence on performance varied between female and male players. For interpretative convenience when considering partitioning the influence of body mass and to speed up computation, we standardized the outcomes by subtracting the sample mean and dividing by two sample standard deviations.

Given the potential for noise in physical fitness measures and the presence of imbalanced repeated measures data, we exercised caution in our interpretations. Hence, we used weakly informative priors to regularize our estimates. We used multivariate normal priors (0,2) for the population-level parameter (i.e., intercept and slopes) and exponential (1) priors for the group-level parameters.

We used leave-one-out cross-validation (LOO-CV) and posterior predictive checks to compare our models (67, 56). Additionally, residual plots were examined to assess whether the models produced size-independent outcomes, given the potential influence of body mass on the outcomes. For each model, four chains were run for 3,000 iterations, with a warm-up length of 1,000 iterations. This was sufficient to achieve convergence and obtain a reasonable effective sample size. The models were fitted using the R statistical language (58) with the brms package (59), which calls Stan (60). The model predictions were extracted using the tidybayes package (61) and visualized using the ggplot2 package (62). The data and code necessary to reproduce the analyses and figures are available in a repository at <https://osf.io/y43gf/>.

3.3 RESULTS

Characteristics of the sample at the study baseline, as reference for description, are summarized in Table 1.

Table 1: Characteristics of the sample at the study baseline.

	Female	Male
Chronological age, year	13.7 (1.6)	14.0 (2.3)
Stature, cm	163.8 (6.7)	171.0 (15.1)
Body mass, kg	58.4 (10.7)	61.6 (15.8)
CMJ, cm	24.8 (3.4)	32.5 (8.0)
Line-drill test, s	35.91 (2.16)	32.73 (3.30)
Yo-yo intermittent recovery level 1 test, m	440 (158)	1223 (486)

Figure 1 shows the stature and body mass of the basketball players in our sample grouped by gender. The corresponding Bayesian multilevel models for body dimensions from which the posterior samples were derived are summarized in Table 1.

Figure 2 provides a visual representation of the posterior predictions and 67% uncertainty intervals (equivalent to approximately one standard deviation) for CMJ aligned by chronological age and adjusted for the influence of body mass in young female and male Brazilian basketball players. The model-based predictions indicated an increase in vertical jump height during adolescence for both female and male players. The increase in vertical jump was more pronounced in male players. The non-linear shape indicated a potential plateau in performance at

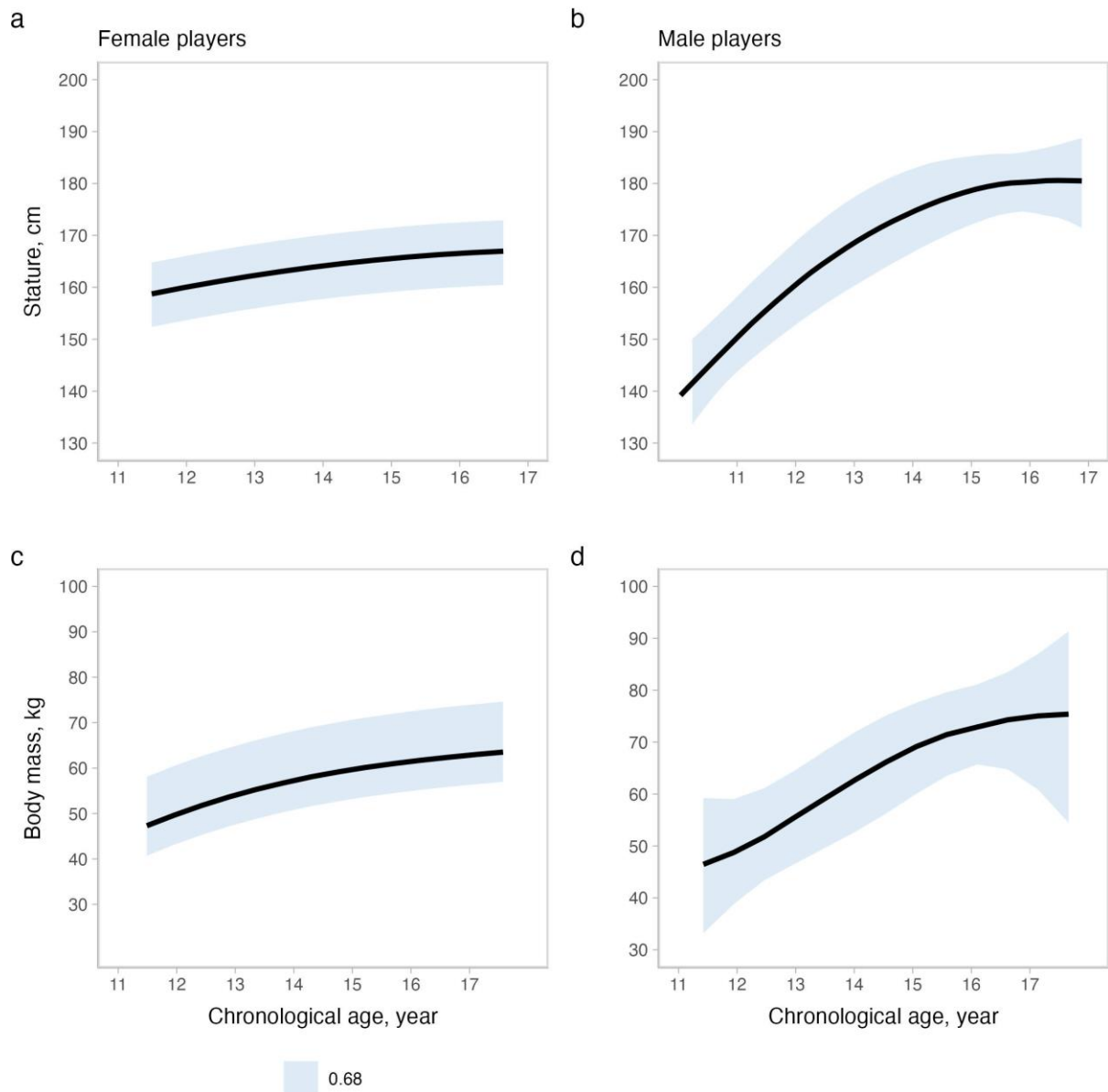


Figure 1 Posterior predictions of pubertal growth changes for stature and body mass in young female (panel a and c for stature and body mass, respectively) and male (panel b and d for stature and body mass, respectively) basketball players.

approximately between 14 and 15 years of age for females, followed by a subsequent stabilization. In male players, the rate of improvement per year appeared to become slower at approximately 16 years of age. There was small influence of stature and body mass on CMJ performance for female players ($\beta_{stature} = 0.22$ 68% credible interval: 0.11 to 0.33; $\beta_{mass} = -0.25$ 68% credible interval: -0.37 to -0.13). For males on the other hand, the positive interaction term ($\beta_{mass \times male} = 0.41$, 68% credible interval: 0.27 to 0.53) indicates a substantial positive relative contribution of body mass to vertical jump performance. Furthermore, the considerable between-

player variation ($\sigma_{mass} = 0.64$, 68% credible interval: 0.50 to 0.77) and the negative covariance between body mass and age ($\rho_{\sigma_{mass}\sigma_{age}} = -0.84$, 68% credible interval: -0.94 to -0.75) suggest that the relative contribution of body mass to vertical jump performance development decreased with age.

With respect to the LD test (Figure 3), the alignment of performance by chronological age revealed non-linear trends in our model-based predictions. In particular, substantial differences were observed between female and male players. The trend of improving performance (lower times indicate better performance) was more pronounced for male players. Improvements in the line-drill test performance began to plateau approximately between 13 and 14 years of age for female players, with performance then stabilizing. In male players, the rate of improvement per year appeared to become slower at approximately 15 years of age. There was substantial variation in the LD test associated with body mass ($\beta_{mass} = 0.33$, 68% credible interval 0.23 to 0.44). However, the magnitude of the negative interaction term ($\beta_{mass \times male} = -0.36$, 68% credible interval: -0.51 to -0.21) indicate that the negative influence of body mass in line-drill test performance was mainly for female players. There was no substantial effect of stature on the development of the line-drill test performance. Furthermore, the negative covariance between body mass and age ($\rho_{\sigma_{mass}\sigma_{age}} = -0.50$, 68% credible interval: -0.79 to -0.21) suggest that the influence of body mass on performance development in the LD test decreases with age.

There was substantial variation in the rate of development of intermittent endurance between female and male. An almost linear trend was observed when raw yo-yo IR1 when performance was modeled by chronological age. However, the non-linear trend became clear when intermittent endurance development was adjusted for body size in the model (Figure 4), in particular for female players. There was a small negative effect of body mass on the development of intermittent endurance performance associated with body mass was small ($\beta_{mass} = -0.16$ 68% credible interval: -0.25 to -0.07). These non-linear trends indicated a positive development in intermittent endurance performance throughout adolescence.

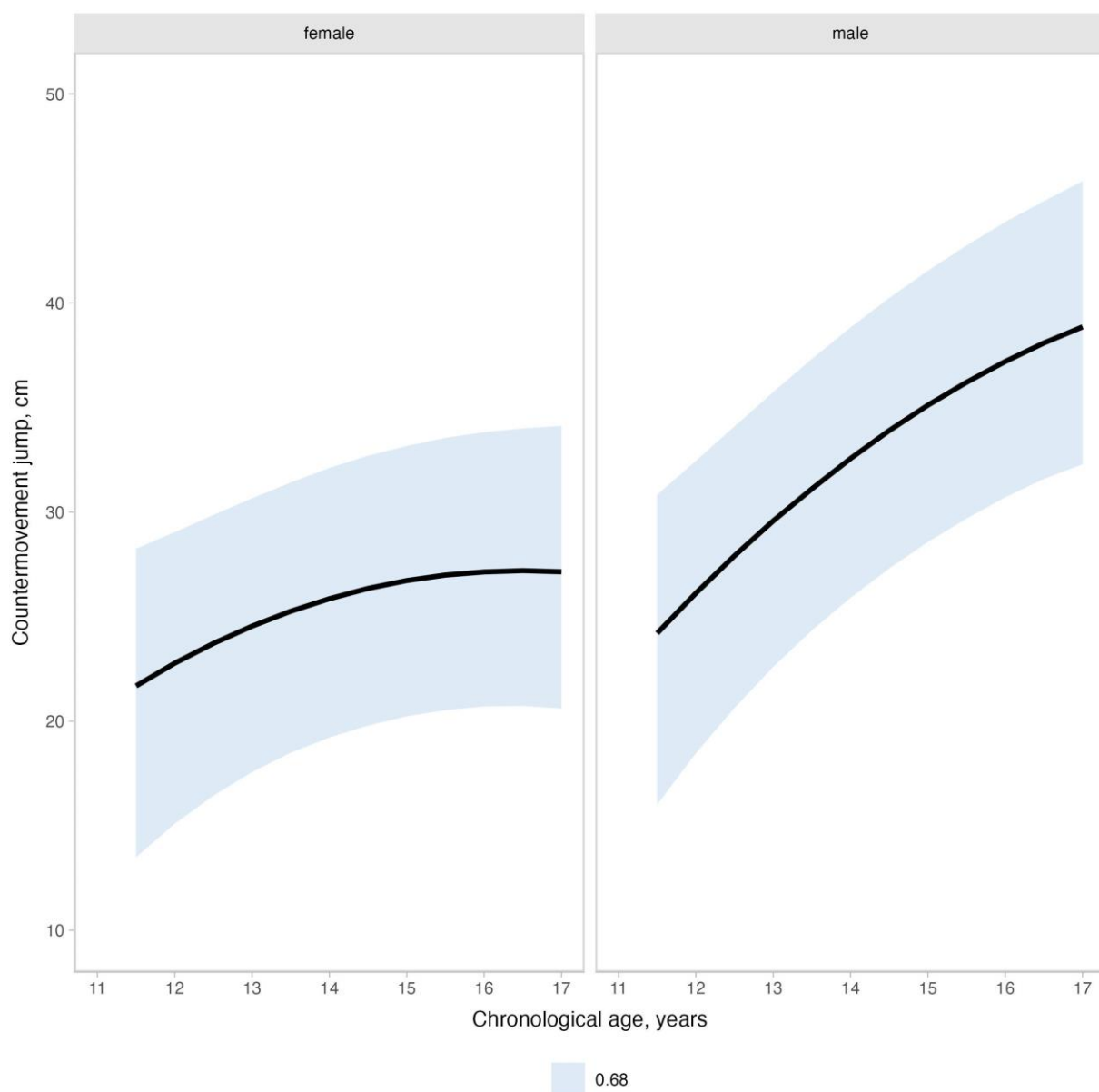


Figure 2 Posterior predictions of developmental changes for the CMJ performance in young female and male basketball players.

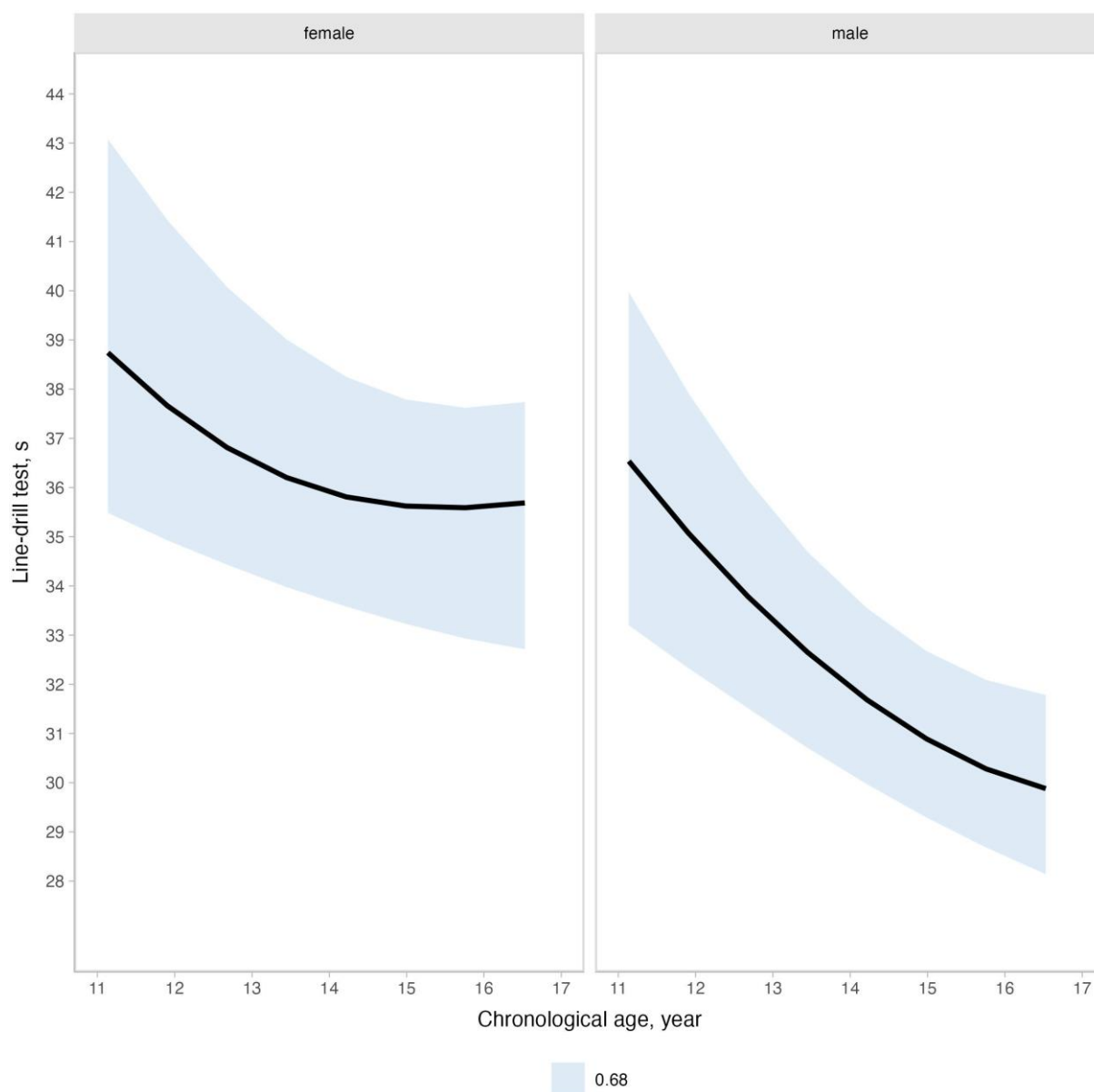


Figure 3 Posterior predictions of developmental changes for the Yo-yo intermittent recovery level 1 test in young female and male basketball players.

Moreover, the model-based prediction indicates that the decreases in the rate of development started to occur at about 15 to 16 years of age for female players. As for male players, the decreases in the rate of development appeared to start occurring at the end of adolescence, at best, or likely occurring after the upper limit for age (17 years) set in our predictions. However, the substantial between-player variation observed in the second-degree age parameter ($\sigma_{age2} = 0.43$, 68% credible interval: 0.27 to 0.58) suggests that an important proportion of players' performance development may tend to flatten out at the end of adolescence. Female players also showed a substantially lower rate of development of intermittent endurance performance compared to male players.

3.4 DISCUSSION

The sex-associated developmental changes in body size and physical fitness of young Brazilian basketball players throughout adolescence were considered in the present study. We summarize the main findings as follows: (i) the trends and rates of development varied substantially between female and male basketball players; (ii) when examined by age for short-term maximal-intensity exercise performance, increases in the development of performance in young female basketball players plateaued at approximately 15 years of age for the vertical jump, and approximately between 13 and 14 years of age for the line-drill test; (iii) male players linear increases in performance last until approximately 16 and 15 years of age for the vertical jump and line-drill test, respectively; (iv) when examined by age, there was an almost linear trend of development with regard to intermittent endurance performance in female and male players, but with female players showing a substantially lower rate of development compared to male players; (v) maximal-intensity exercise performance is lower in female players with larger body size, but this negative effect of size on performance tends to decrease with age; (vi) for male players, maximal-intensity exercise performance increases became associated with age at late adolescence, but

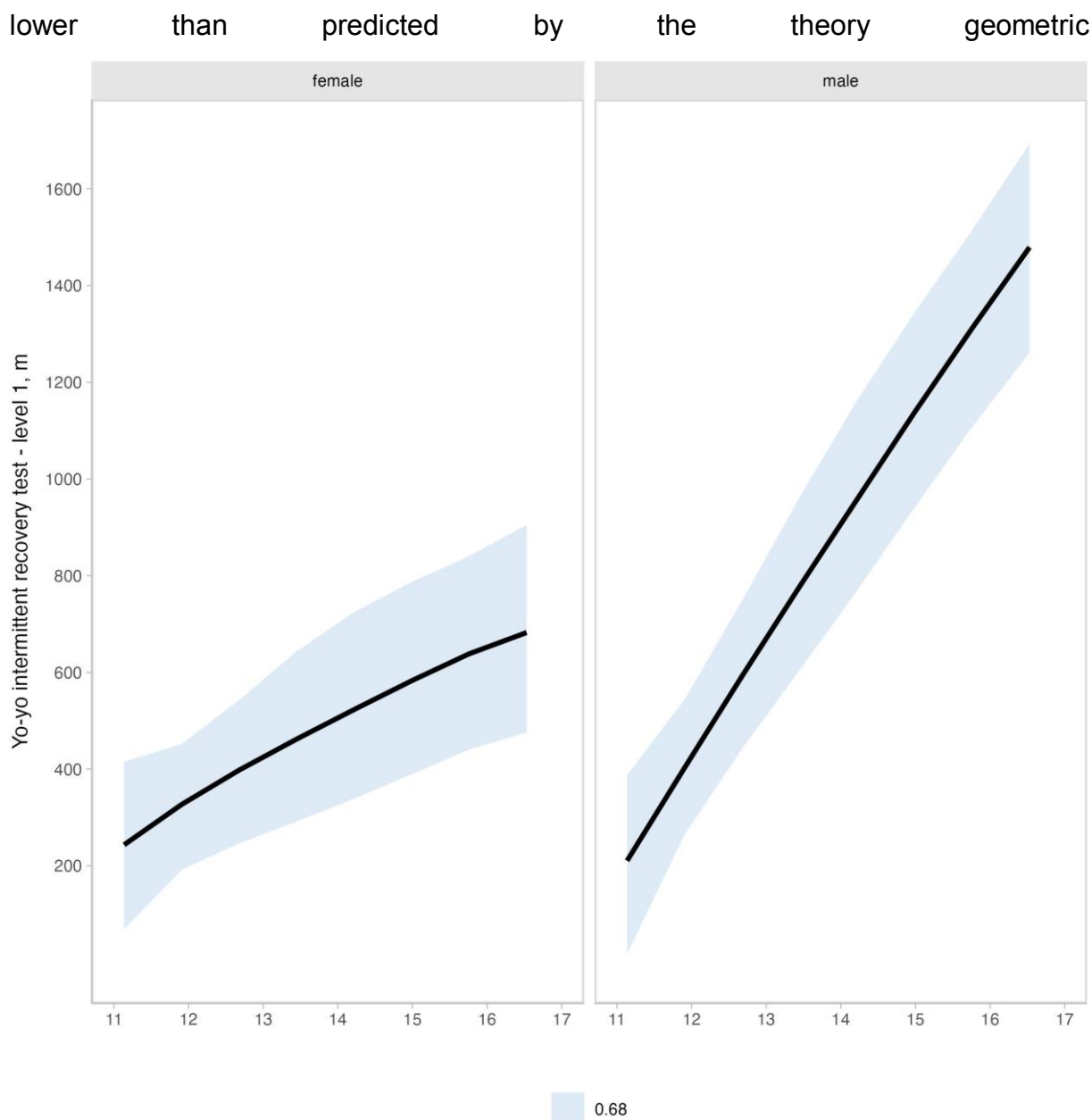


Figure 4: Posterior predictions of developmental changes for the Line-drill test in young male and female basketball players.

similarity: (vii) there was no substantial variation in the development of intermittent endurance performance associated with body size. Adjusting physical fitness development for between-player variation in changes in body size, as a surrogate for active muscle mass, with pubertal growth was essential to clarify sex differences. Overall, the results highlight the asynchronies in body dimensions and physical fitness development between male and female young Brazilian basketball players throughout adolescence.

The growth characteristics of Brazilian adolescent basketball players in the present study sample were similar to cross-sectional observations in youth basketball (63).

Conditional on the data, posterior predictions of longitudinal growth indicate that the female basketball players were, on average, above the 85th percentile of the WHO growth reference (64) until about 12 years of age, and about the 75th percentile thereafter. As for the male basketball players, the posterior predictions of longitudinal growth indicate that the players' stature was, on average, around the 85th percentile reference of the WHO growth references (65). The uncertainty estimates of our predictions suggest the presence of a significant number of very tall young female and male players in youth basketball. The mean masses of female and male Brazilian youth basketball players during adolescence, specific for age and sex, fall between the 50th and 75th percentiles of the US population (65). Comparable data for body mass in the WHO growth references are not available (65). Conditional on the model and data, female players had lower rates of stature growth than male players, likely reflecting maturity-related asynchronies in stature growth. On average, girls experience earlier pubertal growth than boys (66, 67). Also, conditional on the data and model, the present observations suggest that early maturing female players are likely over-represented in youth basketball in early adolescence (36). However, their early stature advantages appear to be attenuated by late adolescence.

The trends of non-linear increases in vertical jump and line-drill performance throughout adolescence were consistent with the limited repeated measures data in youth basketball considering maximal short-term outputs, allowing for variation in the indicators (30, 35, 63, 68, 69). However, most of the available longitudinal data is based on young male basketball players. Our model-based predictions indicate substantial differences in the rate of development of both vertical jump and line-drill test performances, and performance development leveling off. Female players' maximal short-term performance rate of development was lower, and a plateau in improvements was attained earlier than male players. Furthermore, after reaching these peak points of performance development gains became almost negligible.

The effects of body size on maximal short-term outputs varied between the young female and male players. For female players the effect of body mass on the development of both vertical jump and line-drill test performance was similar. Leaner female players had better short-term performance at early adolescence. However, remaining lean explained a large portion of between-player variation as players became older for vertical jump. On the other hand, heavier male players (as a surrogate of active muscle mass) had better vertical jump at early adolescence. As

young male athletes become older, leaner players have better vertical jump performance. For the line-drill test performance development, heavier female players had worst performance during early adolescence. However, a large portion of between player variation as both female and male players became older for the line-drill test. Overall, the observed accentuated non-linear increases in performance may, in part, be attributed to pubertal growth in body mass, in particular the lean components of free-fat mass, which typically occurs approximately 1 year after the age at peak height velocity (66). Body size had a negative effect on both indicators of maximal short-term performance in female players. These observations might reflect the decrease in relative muscle mass in females as consequence of greater body fat gains of girls by the end of puberty (47). Also, the observed sex-associated variation in the non-linear increases in the present study is consistent with sexual dimorphism in maximal short-term outputs observed in non-pediatric populations (33), allowing for procedures variation. However, the covariance patterns of body mass and age in our models suggest that changes in body size, in particular being lean, with age became more relevant to explain the improvements changes in maximal-short-term performance in both female and male players. This suggests that basketball-specific training effects on muscle mass gains have a significant link to maximal short-term performance improvements after pubertal growth. These observations are consistent with data showing that female adolescent athletes, in particular, are stronger than their less athletic peers (46, 70). Note that our data was insufficient to model the differences between male and female players at higher levels. Hence, our interpretations need to be taken with caution.

The trend of development of intermittent endurance performance was also nonlinear for both female and male basketball players. However, there was substantial variation in the rate of development between female and male players. Allowing for methodological variation, the observed sex-associated variation in the increases in performance development is consistent with sexual dimorphism in aerobic exercise development observed in non-athletic pediatric populations (31, 35, 63). There was a negative association between the increases in intermittent endurance performance and body mass, for both female and male players. These observations contrast with the consistent observations showing a positive effect of body mass on aerobic performance development in non-athletic pediatric populations (63, 64), and in adolescent male basketball players (70). Conditional on the data and models,

predictions suggest that leaner young players have higher intermittent endurance performance, and leaner players. However, the covariance patterns between body mass and age suggest that the effects of body mass on intermittent endurance performance remain stable across adolescence.

The analytical approach used in this study to partition the size-related variation in physical fitness outputs was statistically appropriate, as demonstrated by the near-zero association observed between the model's residuals and the size descriptor, i.e., body mass (refer to Figure 4). We concur with the call to check the validity of modeling assumptions as this remains an important source of bias in physiological assessment in pediatric populations (71, 72). However, it is worth noting that changes in body mass are associated not only with pubertal growth but also with training exposure (33). In our data, we were unable to derive individual growth curves and estimate the age at peak height velocity. Further interpretations of maturity status based on prediction-based equations are not appropriate, as they may be insensitive and young athletes may often be assigned to the wrong maturity status category (73, 86).

The Bayesian hierarchical modeling approach offers a robust and adaptable framework for addressing the common data limitations found in youth sports monitoring. This methodology enables the explicit incorporation of prior knowledge with observed data to update and refine our understanding (40). Hierarchical models, also known as multilevel or mixed-effects models, account for data clustered by individuals (e.g., players) over repeated observations, allowing us to consider irregular measurements over time (74). These models also allow for partial pooling of estimates, guided by the data (i.e., regularization) (75). Given the limited data available in youth basketball and the significance of repeated measures for tracking performance development in young athletes, this study's data enhances our comprehension of their growth during adolescence. Moreover, in line with the growing emphasis on transparency and reproducibility in science, including Sports Sciences (76), we are making our data and codes publicly available to enable replication of our analyses and contribute to the body of open-access data.

In summary, this study provides a comprehensive description and interpretation of the development of pubertal growth and physical fitness across adolescence in female and male basketball players. The present findings highlight that training programs for young basketball players must address the sex-specific aspects of performance, rather than generalizing practices primarily based on information from young male basketball

players. For young athletes, coaches, and stakeholders, it is important to approach expectations of improvements in physical fitness during adolescence cautiously, taking into account the sex-specific patterns observed among young basketball players. Furthermore, the study highlights the importance of adjusting interpretations of physical fitness development to adjust for the influence of body size pubertal changes. The results hold particular relevance for coaches, sports researchers, and individuals involved in the selection and development of youth basketball players. Understanding the developmental trajectories of physical fitness can contribute to more informed decision-making in training and talent development processes.

4. LONGITUDINAL RELATIVE INTERRELATIONSHIPS AMONG PHYSICAL FITNESS INDICATORS IN YOUNG MALE BASKETBALL PLAYERS

4.1 INTRODUCTION

Basketball is a team sport that relies on both aerobic and anaerobic energy pathways, with various movement patterns and intensities (19). The anaerobic movements are characterized by short, intense, and intermittent efforts, such as sprints, jumps, shuffles, and changes of direction (43). The aerobic pathway also plays an important role in performance, as a significant portion of game actions occur at low-to-moderate intensities (19). Additionally, aerobic capacity contributes to the recovery from fatigue caused by intermittent high-intensity movements (32,43). The physiological demands and reliance on energy pathways may vary based on factors such as the level of play, gender, playing position, and age (41-43). Therefore, the interpretation of physical fitness in young basketball players must consider different movement patterns and intensities, especially as these athletes undergo growth and development (7, 77).

Participation in sports is generally seen as beneficial for youth athletes, with youth programs often focusing on skill development and the attainment of elite-level performance. However, these programs tend to be highly selective (78,79). Furthermore, youth athletes experience continuous changes in body dimensions, composition, and bodily systems, including the sexual, skeletal, and neuroendocrine systems (10). These changes, driven by the processes of growth and maturation, can affect performance at various stages (3). These developmental variations are individual-specific and may not align with chronological age, making youth sports even more complex and requiring a cautious approach.

The available data on young athletes remains insufficient (33), particularly with respect to longitudinal data on young basketball players (30,34,35). Longitudinal studies are essential for understanding changes in physical fitness and anthropometric characteristics in young athletes (48,49). However, conducting longitudinal studies in sports contexts presents significant challenges, making the data that is available highly valuable (80). These challenges, such as participant attrition and the hierarchical, selective nature of youth sports programs, frequently lead to complex data structures. These complexities include imbalanced sample sizes, missing data, irregular

measurement intervals, and significant variability both within and between athletes. In youth basketball specifically, these limitations often restrict the ability to gather consistent observations across competitive seasons, further complicating efforts to capture the intended multi-year scope of a study.

To address these challenges, mixed longitudinal designs provide a practical alternative (80). These designs allow for the collection of incomplete and shorter-term repeated measures over the study period. By applying advanced statistical models that account for data complexity and meet model assumptions, researchers can derive meaningful insights into developmental trends. In particular, multilevel modeling within a fully Bayesian framework provides a powerful and flexible approach to effectively handle such data (40, 42).

In this study, we examined the longitudinal relationships between physical fitness indicators in young male basketball players throughout adolescence, adjusting for the influence of body size.

4.2 METHODS

Experimental approach to the problem

We considered data from repeated-measures surveys collected during the competitive seasons from 2015 to and 2024 in youth basketball. The data is based in a mixed-longitudinal design, with data from at least one year of repeated measures for each athlete.

Repeated measures collected from 45 male adolescent basketball players aged 8.8 to 17.7 years at baseline were considered in this study. The repeated measures were collected across 9-month competitive seasons from under-11, under-13, under-15, under-17, and under-19 teams at the pre-season (February/March), mid-season (July/August), and end-season (November/December) points. We set the minimum age range for players included in the repeated measures at one year. The players were assessed and evaluated within a one-week period during each observation interval. From the total sample, one players completed six observations, 3 players completed five observations, 16 players completed four observations, 14 players completed three observations, and 11 players completed two observations. A total of 146 measurements were taken into consideration.

The players were engaged in youth basketball training programs and competed in the state-level competition, supervised by the Federação Catarinense de Basketball

(Santa Catarina Basketball Federation). All participants engaged in training a minimum of three times per week, with each practice lasting between 1.5 and 2.5 hours. Additionally, players competed in a match on the majority of weekends throughout the nine-month competitive season. The data were collected at each club facility. No players reported experiencing moderate or more severe injuries during the six-month period preceding the testing phase.

The study was approved by the senior author's university research ethics committee and measurements were conducted in accordance with the ethical standards set forth in the Helsinki Declaration. Athletes and their parents or legal guardians provided written informed consent after being informed of the nature of the study. Athletes were informed that participation was voluntary and that they could withdraw from the study at any time. All measurements were conducted.

Procedures

Chronological age was considered the nearest 0.1 years by subtracting a birth date from the testing date. We considered anthropometry measurements taken by a single experienced observer following standardized procedures, including stature and body mass. Intra-observer technical measurement errors were 0.25 cm for stature and 0.42 kg for body mass (Soares et al., 2023).

Vertical Jump. We used the vertical jump with the CMJ to measure the lower-limb explosive strength (81). Each jump's height (cm) was measured using an optical measurement system (Optojump, Microgate, Italy). Players started from an upright standing position and were instructed to begin the jump with a downward movement, immediately followed by a concentric upward movement, resulting in a maximal vertical jump. During jumping, hands were held on the hips during all jumping phases. Three trials were given with a 30 s rest. The height of the best CMJ was retained to the nearest centimeter. Details about reliability estimates (30, 51).

Line-drill test. In the Line-drill protocol (20, 22, 52), players ran 140 m as fast as possible in the form of four consecutive shuttle sprints of 5.8, 14.0, 22.2 and 28.0 m within a regulation basketball court. Players began the test 1 m behind the baseline of the basketball court. The time was measured using either a video recorder (recording rate of 120 fps) (Sony, Tokyo, Japan) or a pair of photoelectric cells (Multisprint System, Hidrofit, Brazil) aligned with the baseline used as reference for the beginning and end of the test. Time was recorded in seconds. When time was recorded by video,

the analysis of players crossing the reference baseline with available video analysis was made using the software Kinovea – 0.8.15 (<http://www.kinovea.org>). Verbal encouragement for an all-out effort was given throughout the test. Agreement between measurement methods was near perfect and detailed elsewhere (22, 82).

Yo-yo intermittent recovery level 1 test (yo-yo IR1). The yo-yo IR1 protocol (65) is based on repeated 2 x 20 m runs back and forth between the starting, turning, and finishing line at a progressively increased speed controlled by audio bleeps from a tape recorder. The athletes have a 10-s active rest period between each bout, jogging in a distance of 2 x 5 m. Players ran until they were not able to maintain the required speed; the test was completed when athletes failed twice to reach the finishing line in time. The covered distance was measured in meters. Details about the reliability estimates are available elsewhere (30, 53).

Statistical analysis

We used Bayesian hierarchical modeling to describe evaluate the longitudinal relationship between the a physical fitness outcomes. The general form of our model describes each player's successive measurements over time (i.e., chronological age), characterizing their individual changes at each measurement point (level 1) and variations in trajectories between players (level 2). To explore the relationship between the physical fitness outcomes we included the physical fitness of interest as a predictor, as well as their interaction with age. For interpretative convenience and to speed up computation, we standardized the outcomes by subtracting the sample mean and dividing by the sample standard deviations. The general form of the model, for example with LD as outcome and vertical jump as predictor, was specified as follows:

$$\begin{aligned}
 y_i &\sim \text{Normal}(\mu_i, \sigma) \\
 \mu_i &= \alpha_{i[t]} + \beta_{i[t]}^{age} + \beta_{i[t]}^{jump} + \beta_i^{age \cdot jump} \\
 u_i &\sim \text{MVNormal}(0, \Sigma_u)
 \end{aligned}$$

where y_i is the observed standardized outcome for player i ; μ_i , represents the expected value of y_i for player i , modeled as a linear combination of predictors; $\alpha_{i[t]}$

is the population-level intercept for player i at time t ; $\beta_{i[t]}^{age}$ and $\beta_{i[t]}^{jump}$ are coefficients for the effects of age and vertical jump, respectively that are allowed to vary between player; $\beta^{age \cdot jump}$ is the coefficient for the interaction effect between age and vertical jump. $\alpha_i[t]$, $\beta_{i[t]}^{age}$, and $\beta_{i[t]}^{jump}$ are derived from covariance matrix that describes the variances and covariances of the random effects, with ρ indicating the correlations between the intercept and slopes. The covariance matrix is specified as follows:

$$\begin{pmatrix} \alpha_{i[t]} \\ \beta_{i[t]}^{age} \\ \beta_{i[t]}^{jump} \end{pmatrix} \sim \mathcal{N} \left(\begin{pmatrix} \alpha \\ \beta^{age} \\ \beta^{jump} \end{pmatrix}, \begin{pmatrix} \sigma_\alpha^2 & \sigma_\alpha \sigma^{age} \rho & \sigma_\alpha \sigma^{jump} \rho \\ \sigma^{age} \sigma_\alpha \rho & \sigma_{jump}^2 & \sigma^{age} \sigma^{jump} \rho \\ \sigma^{jump} \sigma_\alpha \rho & \sigma^{jump} \sigma^{age} \rho & \sigma_{jump}^2 \end{pmatrix} \right)$$

We used weakly informative priors to regularize our estimates due to potential noise in physical fitness measures and the presence of imbalanced repeated measures data.

$$\alpha \sim \text{Normal}(0, 2)$$

$$\beta_{i[t]}^{age}, \beta_{i[t]}^{jump}, \beta_i^{age \cdot jump} \sim \text{Normal}(0, 2)$$

$$\sigma_\alpha, \sigma^{age}, \sigma^{jump} \sim \text{Exponential}(1)$$

$$\sigma \sim \text{student-t}(3, 0.25)$$

$$R \sim \text{LKJ}(1)$$

R is the correlation matrix between intercepts and slopes:

$$R = \begin{pmatrix} 1 & \rho_{\alpha, \beta^{age}} & \rho_{\alpha, \beta^{jump}} \\ \rho_{\alpha, \beta^{age}} & 1 & \rho_{\beta^{age}, \beta^{jump}} \\ \rho_{\alpha, \beta^{jump}} & \rho_{\beta^{age}, \beta^{jump}} & 1 \end{pmatrix}$$

Also, we examined the influence of between-player variation in body dimensions on physical fitness (30). In this case we included body mass and stature in our models as predictors and allowed both variables to vary between players at level 2.

We checked our models performance and predictions using leave-one-out cross-validation (LOO- CV) and posterior predictive checks (67, 56). We also examined residual plots to assess whether the models produced size-independent outcomes, given the potential influence of body mass on the outcomes. For each model, four chains were run for 2,000 iterations, with a warm-up length of 1,000 iterations, which was sufficient to achieve convergence and obtain a reasonable effective sample size. Our were fitted models using the R statistical language (58) with the brms package (70), which calls Stan (60). The model predictions were extracted using the tidybayes package (61) and visualized using the ggplot2 package (62). The data presented in this study, and code necessary to reproduce the analyses and figures are available in a repository at <https://osf.io/s52bf/>.

4.3 RESULTS

The characteristics of the sample of male adolescent basketball players at baseline are summarized in Table 2 as a reference for description.

Table 2: Characteristics of the sample at study baseline.

	Average	Standard deviation
Chronological age, year	14.0	2.3
Stature, cm	171.0	15.1
Body mass, kg	61.6	15.8
CMJ, cm	32.5	8.0
Line-drill test, s	32.73	3.30
Yo-yo intermittent recovery level 1 test, m	1227	487

The longitudinal relative relationship between line-drill test performance and vertical jump in young basketball players is displayed in Figure 5. The 68% uncertainty intervals, which are comparable to a standard deviation, capture the variability in the predicted population-level parameters. Model-based predictions indicate that, on

average, at the sample's grand mean age (15.0 years), players who excelled in the line-drill test also tended to demonstrate superior vertical jump performance. The negative population-level age effect indicates that line-drill performance improved with advancing age. Notably, the positive interaction between age and vertical jump performance indicates that during early pubertal growth years, players with higher vertical jump performance were typically among the top performers in the line-drill test. However, as players grew older high vertical jump performers were no longer consistently the best in the line-drill test. When adjusting model predictions to account for within- and between-player variations in body size, the trends in the relative relationships remained consistent. Players with lower body mass demonstrated superior performance in the line-drill test. However, stature did not emerge as a significant determinant of line-drill performance.

The longitudinal relative relationship between line-drill test performance and Yo-Yo Intermittent Recovery Level 1 test performance in young basketball players is presented in Figure 6. On average, players with higher vertical jump performance also had better intermittent endurance. The positive population-level age effect was consistent with previous model when interpreting improvements across adolescence. The positive interaction between age and Yo-Yo intermittent performance indicates that during early pubertal growth years, players with better intermittent endurance were typically among the top performers in the line-drill test. However, this trend reversed during late adolescence, with players excelling in intermittent endurance no longer being the top performers in the line-drill test. Adjusting model predictions for within- and between- player variations in body size revealed that the observed trends in relative relationship between Line-drill test performance and intermittent endurance performance was stronger at the sample's grand mean age (15.0 years).

Lastly, the longitudinal relative relationship between vertical jump and Yo-Yo Intermittent Recovery Level 1 test performance in young basketball players is illustrated in Figure 7. Model-based predictions suggest that, on average, at the grand mean age of the sample (15.0 years), the relative

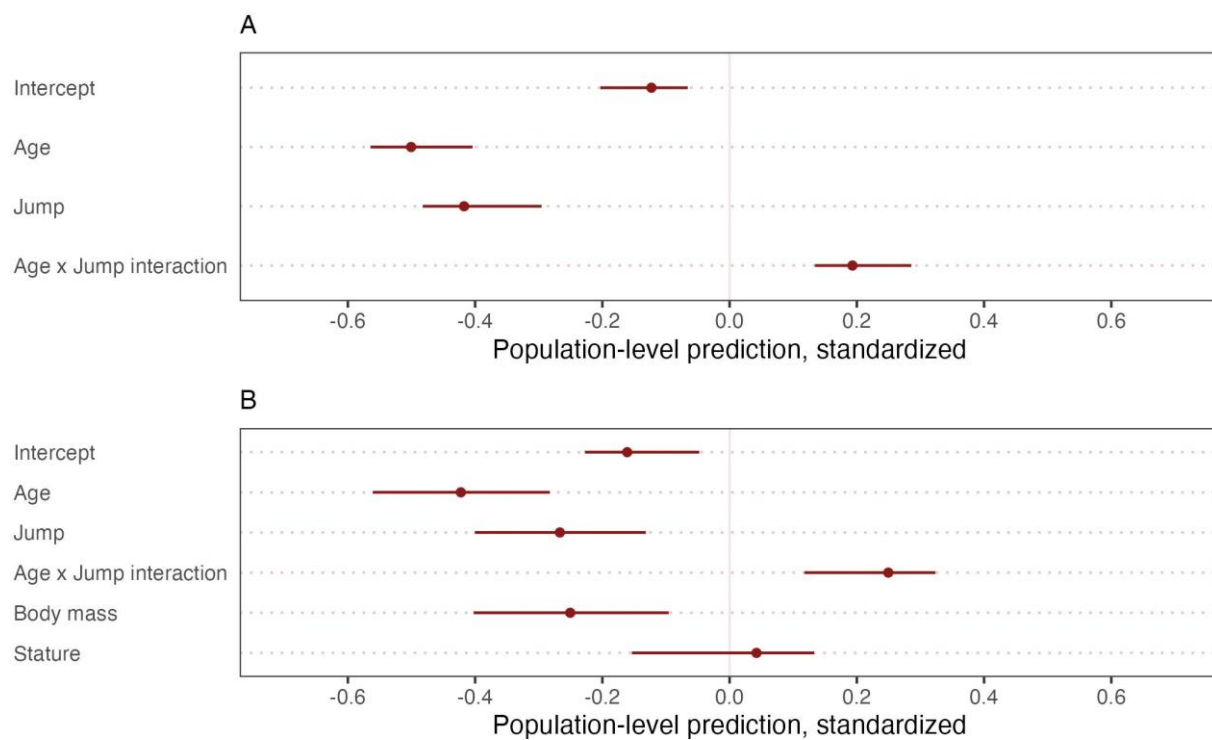
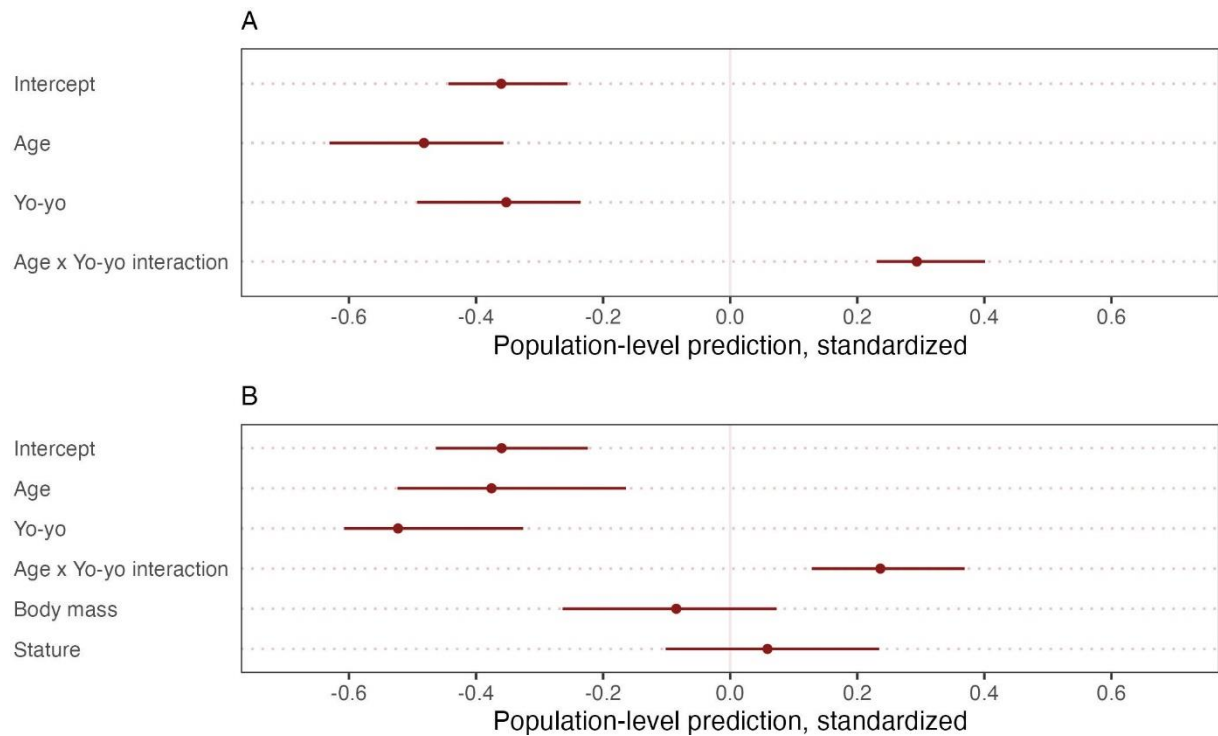


Figure 5: Longitudinal relationships between line-drill performance and vertical jump performance (Panel A) in young male basketball players across adolescence, adjusted for within- and between-player variations in body size (Panel B).



relationship between these two performance measures was modest. The positive population-level age effect indicates that vertical jump performance generally improved with age. However, the negative interaction between age and intermittent endurance performance indicates that during early pubertal growth, players with better vertical jump performance were more likely to demonstrate better intermittent endurance. This relative relationship diminished with advancing age, as players who were better in vertical jump were not consistently among those with the highest intermittent endurance performance.

Figure 6: Longitudinal relationships between line-drill performance and Yo-Yo Intermittent Recovery Test Level 1 performance (Panel A) in young male basketball players across adolescence, adjusted for within- and between-player variations in body size (Panel B)

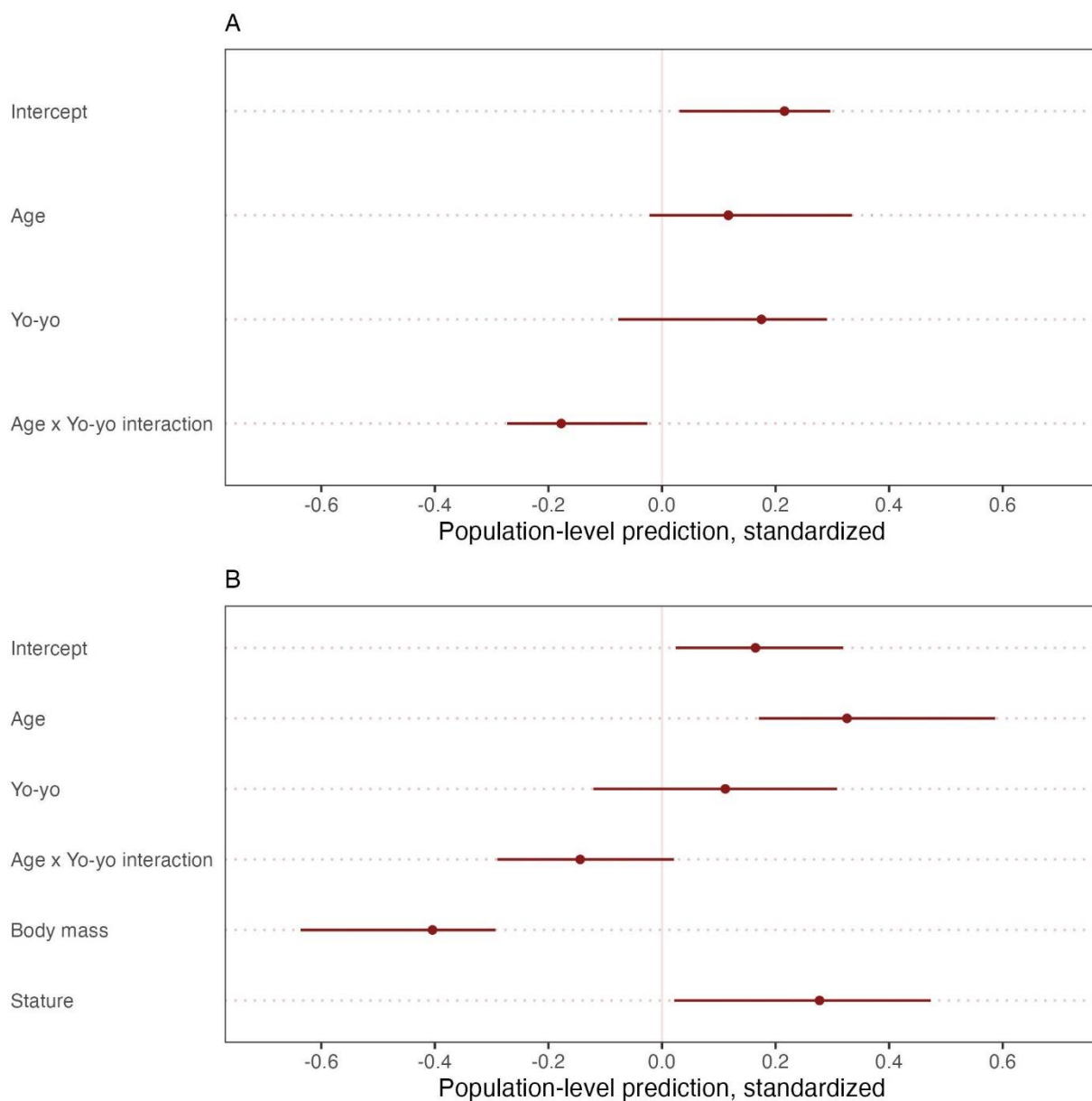


Figure 7: Longitudinal relationships between vertical jump performance and Yo-Yo Intermittent Recovery Test Level 1 performance (Panel A) in young male basketball players across adolescence, adjusted for within- and between-player variations in body size (Panel B)

4.4 DISCUSSION

The relative longitudinal relationships between physical fitness indicators in young male basketball players throughout adolescence were considered. Furthermore, we, adjusted for the potential influence of body size on physical fitness indicators. Overall, during early pubertal years, i.e, before or around peak height velocity, the player who excelled in the line-drill was also the best performer in the vertical jump and intermittent endurance test. However, in late pubertal growth and when adolescents players became mature, the relative relationship between line-drill, jump and intermittent endurance becomes trivial, at best.

As noted in previous observations, the growth characteristics of Brazilian adolescent basketball players in the present study sample were similar to cross-sectional observations in youth basketball (63). In general, our data (83, 84) indicate that players' stature was, on average, about the 85th percentile reference of the WHO growth references (64).

Our linear predictions showed strong association between the line-drill ($\beta_{i[t]}^{age} = -0.7$, (68% uncertainty interval -0.92 to -0.65), vertical jump ($\beta_{i[t]}^{age} = 0.63$, 68% uncertainty interval 0.53 to 0.73) and Yo-Yo Intermittent Recovery Level 1 test performance ($\beta_{i[t]}^{age} = 0.91$, 68% uncertainty interval 0.82 to 1.00) with age. Overall, these parameters describe a substantial improvement of young basketball players physical performance across adolescence. These observations are consistent with the limited repeated measures observations with young athletes (69). For modeling and interpretative convenience, we considered a linear relation to describe the changes of physical fitness with age relations. However, ours and other previous analysis showed that developmental changes of physical fitness in young athletes are mostly non-linear (85).

Our models predictions showed that during early adolescence players who excelled in the line-drill test also tended to demonstrate superior vertical jump performance and intermittent endurance. Overall, our data was consistent with cross-sectional observations with adolescent athletes, in particular, young basketball players (51, 86, 87). However, the interactions between age and physical fitness indicate that as players grew older, those with highest vertical jump performance or intermittent endurance were no longer consistently the best in the line-drill test. Although with smaller magnitude, the trends were similar when interpreting the relative relationships

in the development of vertical jump and intermittent endurance performance. The high relative relationship between physical fitness outcomes in our data may reflect the trend of over-representation of early maturing boys noted in youth basketball (88). Skeletal maturation was noted to be a significant predictor of line-drill and vertical jump performance (88). Therefore, players with advanced maturity status tend to have better performance in maximal-short-term power outputs than on time, or late maturing players at a given chronological age during pubertal growth (88). The present observations suggest that as soon as players became biologically mature, the transient advantages of maturity status in physical fitness performance disappear.

As players get older across adolescence, the metabolic-specific traits of effort became apparent. This suggests the need to consider training specific stimulus for the development of specific efforts and respective metabolic and neuromuscular characteristics. However, it is reasonable to assume that between-player variation in the effort-specific responses may be apparent from early age, but its interpretation masked by between-individual variation in maturity status and body dimensions. In sports where body dimensions are highly valued, such as basketball (37), misinterpretations of young athletes physical fitness performance during early pubertal years are likely a concern (89).

5 FINAL CONSIDERATIONS

Development of youth basketball players

The Brazilian competitive basketball structure is primarily organized by clubs, associations, and federations. The programs of these entities are typically focused on performance and attaining elite levels. Within this structure, sport-specific specialization, deliberate practice, and competition are often considered essential to the athlete's success. While this viewpoint can be perceived as exclusive, it is imperative to acknowledge that coaches must "identify talent" with precision, as any misinterpretation could potentially result in erroneous decisions, particularly in the initial stages of development.

In talent identification body dimension and game performance are the main variables used to classify a talented youth (90). Body dimensions have a large influence on basketball game performance and are related to individual and team success, particularly in youth level. On the other hand, childhood and adolescence are periods of major changes due to growth and maturation process. Despite that process occurring in every individual, the tempo (when it occurs) and timing (rate that occurs) may happen differently in each one, even when the same chronological age. Although this characteristic of the process is well disseminated, youth performance is a very complex theme in general and requires a full approach and understanding of it. The available literature on this topic is scarce and insufficiently addressed, particularly when considering the need for a longitudinal design that accounts for numerous changes over time. As a result, errors in the practical field continue to occur recurrently.

Interrelationships between physical fitness indicators and interpretation of performance

Conditional to our data, our predictions revealed a substantial dimorphism in the rate of development between male and female athletes, both considering when body dimensions and physical capacities. Female athletes typically initiate development and attain full maturity at an earlier age than their male counter parts. However, the rate of this development is greater and more intense in male athletes. This observation is further substantiated by the finding that female athletes typically attain their plateau between the ages of 13 and 15, while male athletes reach this plateau between the ages of 15 and 16, exhibiting superior performance at their peak. With respect to endurance capacity, the present study indicates that neither gender attains the plateau

phase, suggesting that aerobic capacity continues to develop independently of gender beyond the specified age limit (19 years). Concerning the body dimensions of the players, our findings indicate that the stature of the study sample was similar with observations concerning youth basketball players in general. Basketball players are known to have a mean stature that is higher than the general population, particularly among male athletes. It can be hypothesized that early maturation in girls is a factor in their selection in the early phases, once the stature average of that population is classified in the 85th percentile according to the World Health Organization (WHO) until the peak height velocity mean age of 12 years. After that age, the average drops to the 50th percentile. The general observation regarding body mass is consistent with the findings reported in the basketball youth population. However, it should be noted that body mass exerts a direct influence on physical performance. Male athletes who possess a high degree of muscle mass demonstrate superior performance in maximal-intensity efforts, particularly during the adolescence phase, when muscle mass experiences a pronounced increase. Conversely, female athletes with larger body size demonstrate poorer performance in maximal-intensity efforts, with this relationship diminishing over time. While the female population generally exhibits a higher percentage of fat mass, the onset of training in female athletes results in a reduction of fat mass and an increase in muscle mass, leading to enhanced performance in later age groups. The findings of the study indicate a linear increase in physical capacities and their development across the years in both sexes. As previously mentioned, the rate of increase is greater in male athletes, and this increase tends to persist beyond the ages covered in this study. Conversely, the training effects appear to be more immediate and evident in female athletes. In pre-pubertal years, a positive correlation exists between performance in the line-drill test and the vertical jump and endurance test. However, after the pubertal phase, the interactions between age and physical performance undergo a shift, indicating that as players mature, those who demonstrate the highest levels of performance in the vertical jump and endurance tests are no longer necessarily the best in the line-drill test. In general, skeletal maturation serves as a significant predictor of line-drill performance and vertical jump ability. Early matured players tend to demonstrate superior performance in these domains. However, as they approach full maturation, this advantage begins to diminish. In the late stages of the growth process, the effects of training become evident, and the

specific training, movement patterns, and energy pathways utilized have the most influence on the improvement and specialization for the basketball-required actions.

We were not able to determine peak height velocity given our data, but our findings are consistent with longitudinal growth data that relate physical performance with growth and maturation biological markers. The years after peak height velocity tends to have a greater increase in body dimension and in physical performance. The peak gain of body mass tends to occur after the peak height velocity (91). As shown in this study the muscle mass have a positive relation with the performance in short-maximal intensity efforts and the peak development of physical efforts tend to occur right after the peak mass velocity gain, in basketball youth players (92) or in other youth sports athletes (91). In general the peak height velocity phase shows to be the marker for the most intensity biological changes and gains during the pubertal years and these variances slow down as the years go by from the peak height velocity, with the gains in body mass and physical capacities being more associated with the influence of the training.

Practical applications

A substantial disparity exists in the growth and maturation process between sexes, particularly in terms of practical applications. Specifically, male subjects tend to initiate and complete their growth process at later ages, yet they demonstrate a more rapid rate of development in comparison to female subjects. It is imperative for practitioners involved in training and selection processes to acknowledge this distinction and adapt training regimens to address sex-specific differences, rather than relying on generalizations based solely on the characteristics of male basketball players. Further research, incorporating female subjects, is essential to elucidate the nuances that differentiate between the sexes. Furthermore, this study underscores the significance of comprehending and interpreting the physical fitness of young athletes during the developmental phase. It has been observed that early matured players tend to demonstrate superior performance in maximal-intensity efforts; however, this advantage tends to diminish following the pubertal phase. For practical applications, the evidence suggests that specific training for different movement patterns and energy (92) pathways is associated with enhanced physical performance during this period. The body dimensions of young athletes, particularly their body mass, have been shown to influence their performance in maximal-intensity efforts. For male players, a positive

correlation exists between body mass and performance, while for female players, this relationship is negative in the early stages and decreases over time. The importance of strength and resistance training in maximizing muscle mass and reducing fat mass is also highlighted. The available literature suggests a relationship between aerobic performance and body mass, with the development of aerobic capacity being observed to commence later than that of anaerobic capacity and persist beyond the age limit of the study. This suggests the potential for ongoing development of aerobic capacity throughout an individual's athletic career, emphasizing the importance of targeted training regimens.

The present studies make a significant contribution to the extant literature on the theme of youth sports and their specialization and talent identification. These topics have been the focus of extensive research, yet they continue to elude consensus. Youth sports are a multifaceted and complex phenomenon, and biased decisions can lead to adverse consequences that impact not only the clubs and sports themselves, but also the lives of young individuals.

Study limitations and future researches perspective

In light of the study's limitations and the potential for future research collaborations, it is important to consider the challenges associated with employing a comprehensive longitudinal design. In this study, this limitation is seen in the number of observations of each athlete, with a higher number of athletes who have been observed two or three times, compared to athletes four or more measurements. To minimize this factor, the application of this type of study in a well-structured context can be carried out, in order to facilitate the control of the participants and minimize the loss of data throughout the process and even make it possible to carry out complete longitudinal study. Additionally, it would be relevant to consider various contexts, including different levels and settings (e.g., city, country).

Maturation must be appropriately assessed and considered when interpreting the young athletes' development, as it poses a significant challenge when studying male athletes due to the need of invasive or costly methods. However, in the case of female athletes, the onset of menstruation (menarche) can be more readily observed. In conclusion, a more comprehensive study encompassing adult athletes and their relationship with training aspects would provide more detailed information on this subject.

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