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SAGITTAL STANDING POSTURE AMONG SCHOOL-AGED CHILDREN:

PATTERNS AND THEIR RELATION WITH ANTHROPOMETRICS AND BODY COMPOSITION

FÁBIO ARAÚJO

TESE DE DOUTORAMENTO APRESENTADA

À FACULDADE DE MEDICINA DA UNIVERSIDADE DO PORTO EM

SAÚDE PÚBLICA

Sagittal standing posture among school-aged children: patterns and their relation with anthropometrics and body composition

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Porto | 2017

Dissertação de candidatura ao grau de Doutor apresentada à Faculdade de Medicina da Universidade do Porto

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Ao abrigo do Art.º 8º do Decreto-Lei n.º 388/70, fazem parte desta dissertação as seguintes publicações:

I. Araújo FA, Simões D, Silva P, Alegrete N, Lucas R. Sagittal standing posture and relationships with anthropometrics and body composition during childhood. [Submitted]

II. Araújo FA, Severo M, Alegrete N, Howe LD, Lucas R. Defining Patterns of Sagittal Standing Posture in Girls and Boys of School Age. Phys Ther. 2017;97(2):258-67.

III. Araújo FA, Lucas R, Simpkin AJ, Heron J, Alegrete N, Tilling K, Howe LD, Barros H. Associations of anthropometry since birth with sagittal posture at age seven in a population-based birth cohort: the Generation XXI study. BMJ Open. 2017;7(7): e013412

IV. Araújo FA, Martins A, Alegrete N, Howe LD, Lucas R. A Shared Biomechanical Environment for Bone and Posture Development in Children. Spine J. 2017; 17(10):1426-1434.

Ao longo desta dissertação, colaborei ativamente na definição e operacionalização das hipóteses em todos os artigos, bem como na análise e interpretação dos dados que estes reportam. Fui responsável pela redação da versão inicial de todos os manuscritos e participei ativamente na preparação das suas versões finais.

Esta investigação foi realizada no Instituto de Saúde Pública da Universidade do Porto e no Departamento de Ciências da Saúde Pública e Forenses e Educação Médica da Faculdade de Medicina da Universidade do Porto, sob orientação da Professora Doutora Raquel Lucas (Instituto de Saúde Pública e Faculdade de Medicina da Universidade do Porto) e co-orientações do Professor Doutor Henrique Barros (Instituto de Saúde Pública e Faculdade de Medicina da Universidade do Porto) e do Professor Nuno Alegrete (Centro Hospitalar São João e Faculdade de Medicina da Universidade do Porto).

Esta investigação foi financiada pelo Programa Operacional de Saúde – Saúde XXI, Quadro Comunitário de Apoio III, pela Administração Regional de Saúde Norte e pela Fundação Calouste Gulbenkian. Foi também financiada pela Fundação para a Ciência e a Tecnologia, através das bolsas POCI-01-0145-FEDER-016838 e POCI-01-0145-FEDER-016837, sob os projectos PTDC/DTP-EPI/1687/2014 e PTDC/DTP-EPI/3306/2014; e da atribuição de uma bolsa de doutoramento individual [SFRH/BD/85398/2012], co-financiada pelo Programa Operacional Potencial Humano (POPH).

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- Doutora Shirin Shahriari, Investigadora Pós-Doc do Instituto de Saúde Pública da Universidade do Porto;

Dedico esta tese às minhas sobrinhas, Tânia e Flora, pois são a extensão do meu

Presente.

Agradecimentos

À Professora Raquel Lucas, por ter acreditado em mim e nas minhas capacidades desde o primeiro dia de trabalho e, acima de tudo, nunca ter desistido de o fazer apesar de todos os desafios pessoais e profissionais. Pela forma dedicada como sempre exerceu a sua orientação e pelas condições de trabalho que me proporcionou. Principalmente, agradeço o suporte científico imensurável disponibilizado no decorrer deste trabalho conjunto.

Ao Professor Henrique Barros, por ter sempre uma palavra pilar de incentivo e ter permitido através de todo o seu percurso pessoal e institucional elevar a qualidade deste trabalho a um nível superior.

Ao Dr. Nuno Alegrete pela sua disponibilidade constante e vontade com que partilhou o seu conhecimento clínico e científico.

To Professor Laura Howe, Professor Andrew Simpkin, Professor Kate Tilling and Professor Jon Heron I thank the interest for sharing their knowledge on statistical methods, and also for welcoming me to Bristol.

A todos os co-autores dos artigos que constituem esta tese, pelo seu importante contributo.

A todas as pessoas envolvidas no projeto Geração XXI e a todos os colegas do ISPUP-EPIUnit e do Departamento de Ciências da Saúde Pública e Forenses e Educação Médica, pela competência e bom ambiente de trabalho. Um obrigado ao secretariado e serviços académicos e de comunicação do ISPUP por toda a eficiência. Um obrigado pessoal à Cláudia Gouvinhas, à Filipa Fontes, à Ana Henriques e à Sandra Brochado. Agradeço ainda ao Professor Nuno Lunet e à Professora Ana Azevedo por serem também exemplos de profissionalismo de excelência.

Aos colegas da sala de trabalho (sala 406) e aos colegas e ex-colegas do grupo de epidemiologia das doenças musculoesqueléticas do ISPUP. Um especial agradecimento à Poliana Silva por toda a sua coragem e dedicação durante a recolha de dados. Finalmente, um agradecimento à Sara Lourenço por ter sido uma companheira ao longo do meu doutoramento.

À Dra. Paula Valente e à D. Graziela sem as quais seria impossível terminar este trabalho.

A todos os meus amigos, pelo apoio e encorajamento constantes. Ao Pedro Xavier, à Cristiana Silva, ao Renato e ao Rafael, um muito obrigado por serem uma presença constante. Obrigado também às minha amigas Teresa Gaio, Andreia Valente, Raquel Garcês e Jó.

Aos meus Pais, Irmãos, e cunhado pela crença incondicional nas minhas capacidades e pelo apoio sempre disponível independente de qualquer resultado final. Ainda que tenha subestimado o vosso poder durante este trabalho, passámos dificuldades que não se quantificam por palavras. Agradeço principalmente por serem os guerreiros da Vida.

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Abstract

Background

Adult sagittal posture is established during childhood and adolescence. Sagittal postural patterns are associated with back pain in adolescents and adults. However, it is unknown if postural patterns are already observable during childhood. This would confirm childhood as an important period for posture differentiation and thus for chronic pain etiology.

Although anthropometry from birth onwards is expected to be a key influence on sagittal posture design, this has never been assessed during childhood. Additionally, in each specific habitual standing posture, gravitational forces determine the mechanical setting provided to skeletal structures. Bone quality and resistance to physical stress is highly determined by habitual mechanical stimulation. However, the relationship between bone properties and sagittal posture has never been studied in children.

Objectives

In the present work our objectives were:

1. To assess the correlations of anthropometrics and body composition parameters with angles of sagittal standing posture measured at 7 years of age (Paper I)

2. To identify and describe postural patterns among 7-year-old girls and boys, and to explore their associations with anthropometric characteristics (Paper II)

3. To estimate the associations of body size from birth onwards with sagittal postural patterns at 7 years of age (Paper III)

4. To investigate the association between bone physical properties and sagittal postural patterns among 7-year-old children, accounting for the roles of fat and fat-free mass in this association (Paper IV)

Methods

This work was conducted within Generation XXI, a population-based birth cohort of 8647 live born infants and their mothers initially assembled from all five public maternity units covering the six municipalities of the metropolitan area of Porto, Portugal, in 2005–2006. At birth, 91.4% of invited mothers agreed to participate. Four and seven years after birth, 69% and 68%, respectively, of all children recruited at birth were reevaluated by face-to-face interviews and physical examinations. During the 7 year-old follow-up, a subsample of 2998 children consecutively assessed between December 2012 and August 2013, and without a diagnosis of severe neurological impairment, was invited to an additional wave of assessment in which bone physical properties and sagittal standing posture were evaluated. Of those, 80.5% agreed to participate and attended the scheduled assessment.

Birth weight and recumbent length at birth were retrieved from medical records and measurements of weight and height were obtained at 4-, 7-years follow-up and in the additional wave of assessment.

In the additional wave of assessment at age 7, total body less head fat/fat-free mass and bone properties were estimated from whole body dual energy X-ray absorptiometry scans and posture was assessed through right-side photographs during habitual standing with retro-reflective markers placed on body landmarks.

Results

Paper I

In 1021 girls and 1096 boys, girls showed increased values of lumbar angle, head and neck flexion, and craniocervical angle with the largest mean (standard deviation) difference in lumbar angle [281.7º (7.4) vs. 276.8º (7.1), $p<0.001$]. In both genders, weight and body mass index were weakly associated with lumbar angle: $0.24\leq r\leq 0.31$ in girls and $0.16\leq r\leq 0.26$ in boys, all $p<0.001$. Fat and fat-free mass and bone mineral density were weakly associated with lumbar angle in both genders. Body mass index at 7 years old was directly associated with lumbar angle (girls: $\beta=0.80$; 95% CI: 0.53 to 1.07; boys: $\beta=0.64$; 95% CI: 0.37 to 0.91) and inversely associated with sway angle (girls: $\beta=-0.29$; 95% CI: -0.46 to -0.11; boys: $\beta=-0.38$; 95% CI: -0.56 to -0.19), independently of ponderal index at birth and body mass index at 4 years-old and also age.

Paper II

Posture was evaluated in 1147 girls and 1266 boys. Three postural patterns were identified: “Sway” (26.9%), “Flat” (20.9%) and “Neutral to Hyperlordotic” (52.1%) in girls; “Sway to Neutral” (58.8%), “Flat” (36.3%) and “Hyperlordotic” (4.9%) in boys. In girls, higher body mass index was associated with a Sway pattern (vs. Flat, OR=1.21; 95% CI: 1.12-1.29), while in boys, body mass index was higher in the Hyperlordotic pattern (vs. Flat, OR=1.30; 95% CI: 1.17-1.44).

Paper III

In a subsample of 1029 girls and 1101 boys, postural patterns identified were “Sway”, “Flat” and “Neutral to Hyperlordotic” in girls, and “Sway to Neutral”, “Flat” and “Hyperlordotic” in boys; with flat and hyperlordotic postures representing a straightened and a rounded spine, respectively. In both girls and boys, higher weight was associated with lower odds of a Flat pattern compared to a Sway/”Sway to Neutral” pattern, with stronger associations at older ages: e.g. odds ratios (ORs) were 0.68 (95% CI: 0.53-0.88) per standard deviation (SD) increase in birth weight and 0.36 (95% CI: 0.19-0.68) per SD increase in weight at age 7 in girls, with similar findings in boys. Boys with higher ponderal index at birth were more frequently assigned to the Hyperlordotic pattern compared to the “Sway to Neutral” pattern (OR=1.44 per SD; p=0.043).

Paper IV

A subsample of 1138 girls and 1260 were included. The identified patterns were labelled as “Sway”, “Flat” and “Neutral to Hyperlordotic” (in girls) and “Sway to Neutral”, “Flat” and “Hyperlordotic” (in boys). In both genders, children in the Flat pattern showed the lowest body mass index and children with a rounded posture presented the highest: mean differences varying from -0.86kg/m^2 to 0.60kg/m^2 in girls and -0.70kg/m^2 to 0.62kg/m^2 in boys (vs. Sway/”Sway to Neutral”). Fat and fat-free mass were inversely associated with a Flat pattern and positively associated with a rounded posture: OR of 0.23 per SD fat and 0.70 per SD fat-free mass for the Flat and 1.85 (fat) and 1.43 (fat-free) for the Hyperlordotic in boys; with similar findings in girls. The same direction of relationships was observed between bone physical properties and postural patterns. A positive association between bone (especially bone mineral density) and a rounded posture was robust to adjustment for age, height, and body composition (girls: OR=1.79, p=0.006 fat-adjusted, OR=2.00, p=0.014 fat-free mass adjusted; boys: OR=2.02, p=0.002 fat-adjusted, OR=2.42, p<0.001 fat-free mass adjusted).

Conclusions

We identified a meaningful summary model for the distribution of sagittal standing posture for school-aged girls and boys. Patterns were consistent with childhood as a sensitive period for posture differentiation. However, postural dichotomy “neutral vs. non-neutral” clearly does not apply to children and substantial gender heterogeneity in the features and frequency of different patterns existed among school-aged children. This highlights the potential for gender-specific biomechanical frameworks of the spino-pelvis during habitual upright position even in prepubertal ages. Additionally, the mechanical load imposed by body size seems to have a cumulative sculpting role throughout the first decade of life, especially after walking abilities are acquired and our results support that both bone and posture mature in a shared and interrelated mechanical environment modulated by pattern-specific anthropometrics and body composition. This work provides the basis for future research in evaluating if adult health regarding sagittal standing posture can be potentiated through interventions on anthropometrics, and consequently body composition parameters, since early ages.

Resumo

Introdução

A postura sagital dos adultos é estabelecida durante a infância e adolescência. Existe evidência que determinados padrões posturais sagitais estão associados com dor na coluna em adolescentes e adultos, porém permanece ainda por esclarecer se esses padrões posturais são observáveis desde a infância. Perante esta possibilidade a infância poderá ser um período importante para diferenciação da postura, e portanto, para a etiologia da dor crónica.

Apesar de ser expectável que a antropometria desde o nascimento tenha influência no desenho da postura sagital, esta relação nunca foi avaliada durante a infância. Adicionalmente, em cada postura sagital habitual específica, as forças gravitacionais determinam o ambiente mecânico fornecido às estruturas esqueléticas. Ou seja, a qualidade óssea e a resistência ao *stress* físico são altamente determinadas pelo estímulo mecânico habitual. No entanto, esta relação entre a postura sagital e propriedades ósseas também nunca foi avaliada em crianças.

Objetivos

Os objectivos deste trabalho foram:

1. Avaliar as correlações da antropometria e parâmetros de composição corporal com ângulos da postura sagital medidos em pé aos 7 anos de idade (Artigo I)

2. Identificar e descrever padrões posturais em raparigas e rapazes com 7 anos de idade, e explorar as suas associações com características antropométricas (Artigo II)

3. Estimar a associação da corpulência corporal desde o nascimento com os padrões posturais aos 7 anos de idade (Artigo III)

4. Investigar a associação entre os padrões posturais sagitais e as propriedade físicas do osso em crianças com 7 anos de idade, distinguindo a contribuição específica da massa gorda e da massa livre de gordura para esta associação (Artigo IV)

Métodos

Este trabalho foi realizado numa coorte de nascimento de base populacional, a Geração XXI, com 8647 recém-nascidos e as suas mães provenientes de todas as cinco maternidades públicas que cobriam os seis municípios da área metropolitana do Porto, Portugal, em 2005-2006. Ao nascimento, 91,4% das mães convidadas aceitaram participar. Quatro e sete anos após o nascimento, 69% e 68% das crianças recrutadas ao nascimento, respetivamente, foram reavaliadas através de entrevistas presenciais e exames físicos. Durante a avaliação que decorreu aos 7 anos de idade, a subamostra de 2998 crianças consecutivamente avaliadas entre Dezembro de 2012 e Agosto de 2013, e sem um diagnóstico de comprometimento neurológico severo, foi convidada para uma avaliação adicional da saúde musculoesquelética que inclui a avaliação das propriedades físicas do osso e da postura sagital em pé. Deste participantes, 80,5% aceitaram participar e compareceram à avaliação agendada.

O peso e o comprimento ao nascimento foram obtidos através de registos médicos e o peso e a altura foram obtidos nas avaliações aos 4 e 7 anos de idade, bem como na avaliação adicional acima referida.

Na avaliação adicional aos 7 anos de idade, a massa gorda/massa livre de gordura e as propriedades físicas ósseas foram obtidas através de absorciometria de raios-X de dupla energia de corpo inteiro. A postura foi avaliada através de fotografias do perfil direito durante a posição de pé habitual das crianças com marcadores refletores colocados em pontos anatómicos específicos.

Resultados

Artigo I

Os resultados deste trabalho demonstraram que, em 1021 raparigas e 1096 rapazes, as raparigas mostram valores maiores de ângulo lombar, de flexão da cabeça e pescoço, e ângulo crânio-cervical com a maior diferença média (DP) no ângulo lombar [281,7º (7,4) em raparigas *vs.* 276,8º (7,1) em rapazes, $p<0,001$]. Em ambos os sexos, tanto o peso como o índice de massa corporal mostraram estar associados, de forma ténue, com o ângulo lombar ($0,24 \leq r \leq 0,31$ nas raparigas e $0,16 \leq r \leq 0,26$ nos rapazes, todos $p<0,001$). Adicionalmente, observou-se que a massa gorda, a massa livre de gordura e a densidade mineral óssea estiveram ligeiramente associadas com o ângulo lombar em ambos os sexos. O índice de massa corporal aos 7 anos de idade esteve directamente associado com o ângulo lombar (raparigas: β=0,80; IC 95%: 0,53 a 1,07; rapazes: β=0,64; IC 95%: 0,37 a 0,91) e inversamente associado com o ângulo de oscilação (raparigas: β=-0,29; IC 95%: -0,46 a -0,11; rapazes: β=-0,38; IC 95%: -0,56 a -0,19), independentemente do índice ponderal ao nascimento, do índice de massa corporal aos 4 anos de idade e da idade.

Artigo II

A postura sagital foi avaliada em 1147 raparigas e 1266 rapazes. Em cada um dos sexos, foram identificados três padrões posturais que foram nomeados: “Sway” (26,9%), “Flat” (20,9%) e “Neutral to Hyperlordotic” (52,1%) nas raparigas; e “Sway to Neutral” (58,8%), “Flat” (36,3%) e “Hyperlordotic” (4,9%) nos rapazes. Nas raparigas, maior índice de massa corporal esteve associado com o padrão *Sway* (comparativamente ao *Flat*, *OR*=1,21; IC 95%: 1,12-1,29), enquanto nos rapazes o índice de massa corporal foi maior no padrão *Hyperlordotic* (comparativamente ao *Flat*, *OR*=1,30; IC 95%: 1,17-1,44).

Artigo III

Numa subamostra de 1029 raparigas e 1101 rapazes, foram identificados os seguintes padrões posturais: “Sway”, “Flat” e “Neutral to Hyperlordotic” nas raparigas, e “Sway to Neutral”, “Flat” and “Hyperlordotic” nos rapazes; com as posturas *flat* e *hyperlordotic* representando uma coluna retificada e arredondada, respetivamente. Tanto em raparigas como em rapazes, um peso mais elevado associou-se a uma menor *odds* de um padrão *Flat* comparado com o padrão *Sway/*”Sway to Neutral”, com associações mais fortes nas idades mais avançadas: por exemplo, *ORs* foram de 0,68 (IC 95%: 0,53-0,88) por aumento no desvio padrão (DP) do peso ao nascimento e 0,36 (IC 95%: 0,19-0,68) por aumento no DP do peso aos 7 anos de idade nas raparigas; com resultados semelhantes em rapazes. Rapazes com maior índice ponderal ao nascimento foram mais frequentemente alocados ao padrão *Hyperlordotic* comparando com o padrão “Sway to Neutral” (*OR*=1,44 por DP; p=0,043).

Artigo IV

Foi utilizada uma subamostra de 1138 raparigas e 1260 rapazes. Os padrões identificados foram catalogados de “Sway”, “Flat” e “Neutral to Hyperlordotic” (nas raparigas) e “Sway to Neutral”, “Flat” e “Hyperlordotic” (nos rapazes). Em ambos os sexos, as crianças no padrão *Flat* tinham menor índice de massa corporal, enquanto que crianças com uma postura arredondada apresentaram o maior: com diferenças médias que variavam entre -0,86kg/m^2 e 0,60kg/m^2 nas raparigas e entre -0,70kg/m^2 e 0,62kg/m^2 nos rapazes (comparativamente ao *Sway*/”Sway to Neutral”). Uma maior quantidade de massa gorda e massa livre de gordura revelaram-se inversamente associadas com o padrão *Flat* e positivamente associadas com a postura arredondada: *OR* de 0,23 por DP de gordura e 0,70 por DP de massa livre de gordura para o padrão *Flat* e 1,85 (DP gordura) e 1,43 (DP massa livre de gordura) para o padrão *Hyperlordotic* nos rapazes; com resultados similares em raparigas. Observaram-se resultados semelhantes entre as propriedades físicas do osso e padrões posturais. Foi encontrada uma associação positiva entre osso (especialmente densidade mineral óssea) a postura arredondada, que se manteve independentemente da idade, altura e composição corporal (raparigas: *OR*=1,79, p=0,006 ajustado para gordura, *OR*=2,00, p=0,014 ajustado para massa livre de gordura; rapazes: *OR*=2,02, p=0,002 ajustado para gordura, *OR*=2,42, p<0,001 ajustado para massa livre de gordura).

Conclusões

Neste trabalho identificámos um modelo sumário importante da distribuição da postura sagital em pé em raparigas e rapazes em idade escolar. Os padrões foram consistentes com a ideia de que a infância é um período sensível para a diferenciação da postura. No entanto, a dicotomia postural "neutro/não-neutro" claramente não se aplica a crianças e existe uma heterogeneidade substancial ao nível do género tanto nas características como na frequência dos diferentes padrões em crianças em idade escolar. Tal facto destaca o potencial para enquadramentos biomecânicos da espino-pelvis específicos por género durante a posição de pé habitual, mesmo em idades pré-pubertárias. Adicionalmente, a carga mecânica imposta pela corpulência parece ter um papel cumulativo escultural ao longo da primeira década de vida, especialmente após a aquisição das capacidades de marcha e estes resultados suportam que tanto o osso como a postura maturam num ambiente mecânico partilhado e inter-relacionado modulado pela antropometria e pela composição corporal específica para cada padrão postural. Este trabalho pode ser considerado como uma base para que futuras investigações avaliem se a saúde do indivíduo adulto com respeito à postura sagital em pé pode ser potenciada através de intervenções na antropometria, e consequentemente em parâmetros da composição corporal, desde idades precoces.

1. Introduction

The evolutionary adoption by humans of an upright position resulted in broadening and verticalisation of the pelvis together with the appearance of characteristic spinal curves and profoundly modified the structure of the muscles supporting the spine (1). The acquisition of a vertical posture, i.e., the ability Man acquired to extend the trunk, hips, thigh and legs simultaneously – and the resulting bipedal locomotion represented the main transformation in the history of the *Hominidae* (2). Human beings are the only vertebrates to maintain an upright, totally vertical, bipedal position. The organization of the spine in successive curvatures in the sagittal plane is crucial for maintaining this erect, totally vertical, bipedal position (3). Primates have a horizontal pelvis with no lordosis and they use their upper limbs as a counterbalance (4). All primates are able to displace themselves in a bipedal manner. The great apes can achieve an upright position, but only with a semi-erect trunk. Their whole spine looks like a big “C”, a long kyphosis that is incompatible with a constant stable erect posture and walking. *Homo sapiens* is the only one capable of performing it for long distances and long time in a stable manner (4). This is because human is the only vertebrate to have a lordotic lumbar curvature. In addition to diverse other morphological transformations, the spino-pelvic complex played a relevant role in the acquisition of bipedalism. Spinal sagittal curves appear progressively with growth and are well established when the standing position and walking are possible. It is only at the end of skeletal growth that the morphology of the spino-pelvic setting is fixed (4).

The human pelvis has an equally tremendous importance in the development of verticality (4). Its intrinsic anatomical relationship with the spine created mechanisms to modulate posture. The pelvis attempts to couple lumbar lordosis with hip extension in the erect position with minimal expenditure of energy. However, some pelvises can accomplish this task better than others. Transition to an upright posture has resulted in the pelvis becoming a key structure within the human motor apparatus (4). Pelvis forms the bond between the trunk and the posterior limbs. Since the femoral heads are highly mobile, they play an important role in the spatial orientation of the pelvis. They constitute the point at which the thoraco-lumbar load on the pelvis is transferred to the lower limbs. The sacral plateau, which forms the base to support the spine, is the point of transfer of load from the trunk to the pelvis (4).

Pelvic tilt denotes the spatial orientation of the pelvis, which varies according to position, with a greater or lesser degree of tilt forwards or backwards in relation to a transverse axis passing through the two femoral heads (4). In a subject standing normally, the pelvis is slightly inclined forward. The greater the angle of pelvic tilt, the further the center of gravity is projected behind the femoral heads. As pelvic tilt increases, the sacral plateau becomes increasingly horizontal, while the body of the sacrum becomes vertical. In this position, the acetabulum almost completely covers the femoral head towards the back, thus limiting extension.

The degree of the sacral slope determines the position of the lumbar spine, since the sacral plateau forms the base of the spine (5). The pelvis and lumbar spine adapt in accordance with the degree of pelvic tilt and lumbar lordosis (6). Global spinal balance involves harmonization with overlying lumbar lordosis and thoracic kyphosis (7). Ideally, this dynamic chain results in perfect sagittal balance in which body weight is positioned along a line slightly behind the axis of rotation of the two femoral heads (8, 9).

Today, with the anatomy of vertebrae divided into sacral, lumbar, thoracic and cervical, the main curvatures logically follow this division. The curvatures with an anterior concavity in the sagittal plane are called kyphosis whilst curves with a posterior concavity are named lordosis. According to the anatomical segmentation, spine curves are sacral kyphosis, lumbar lordosis, thoracic kyphosis and cervical lordosis (3).

Sagittal standing posture are quantified by distances and angles mainly of thoracic kyphosis, lumbar lordosis and overall sagittal balance (10). In an attempt to optimize postoperative sagittal alignment, several authors have proposed mathematical formulae to aid surgical planning. Some formulae simply provide a target postoperative lumbar-lordosis/thoracic-kyphosis relationship, whereas others estimate the degree of osteotomy resection needed to restore sagittal alignment. Nowadays is known that both pelvic and spinal sagittal alignment needs to be considered for surgical correction of spinal coronal misalignment, as scoliosis (10).

It is important to consider that the ideal spinal alignment allows an individual to assume a standing posture with minimal muscular energy expenditure. Physiologic curvatures of the spine in the sagittal plane, the straight spine in the coronal plane, balanced tension of the spinal ligaments, and activation of intrinsic anterior and posterior musculature should permit extended pain-free erect position (11). This concept is reflected in the “Cone of Economy” (10, 11). Within the center of the cone, the individual may remain in an ergonomically favorable erect position. However, larger deviations in the anterior, posterior or lateral planes will require greater energy use to maintain a standing position. Finally, progression outside of the “stable cone” results in a loss of postural control and the need for external supports. Spinal malalignment to the extremes of the “Cone of Economy” leads to extreme muscular demand, fatigue, and significant pain as well as disability. Once a spinal deformity has reached the level of marked loss in function and quality of life, surgical intervention is often recommended and requested.

1.1. Clinical relevance of sagittal standing posture

Despite the lack of research on the clinical relevance of sagittal standing posture during growth stages of life (i.e., childhood and adolescence), the sagittal standing posture of adults is definitely established during growth (4, 12). Therefore, the clinical importance of sagittal standing posture in children is mainly sustained on the evidence of relationships between posture and health-related measures of quality of life in adulthood.

A well-balanced spine in the sagittal plane is essential for a good musculoskeletal health status, with an anterior displacement of sagittal balance being associated with poorer health-related quality of life scores (13-18). The need for a neutral pelvic (13, 14) and regional spinal (13-15, 19, 20) sagittal alignment in order to preserve health-related quality of life has also been demonstrated.

The relationships between over 100 spino-pelvic postural parameters with measures of health-related quality of life have been investigated in adult patients suffering from spinal deformity (13). Two parameters representing sagittal balance were the most significantly correlated with scores of health-related quality of life: a positive sagittal imbalance was directly associated with higher levels of disabling pain, decreased social function, worse overall quality of life, worse activity and physical function, and also with “standing disability” (13). An anteriorly displaced sagittal balance is described as the most reliable predictor of clinical symptoms even after controlling for the age effect (16).

Regarding standing alignment, pelvic tilt (i.e., pelvic retroversion) was identified as the most important individual parameter of sagittal alignment with a negative effect on health-related quality of life measures as pelvic retroversion increase, regarding activity, physical function and “walking disability” (13). Effective ambulation seems to be compromised due to the activation of spino-pelvic sagittal compensatory mechanisms represented by a higher pelvic tilt, which should negatively affect lower limb alignment through limited hip extension and consequently worsened walking performance (13).

In relation to spinal alignment parameters, lumbar lordosis has been frequently shown to be associated with health-related quality of life measures (13-15, 19, 20), where decreased lordosis in the lumbar region is related with increased pain (13, 20), decreased physical function (13-15), "standing and walking disability" (13), worse general health (19) and poorer overall scores of health-related quality of life (13, 15). The relation between loss of lumbar lordosis and health-related quality of life seems to be partially independent of positive sagittal imbalance (15).

Patients with disc herniation mostly showed a sway or flat posture in clinical practice, and patients with spinal stenosis frequently exhibited a hypercurved spine (21). Additionally, subjects with flattened spines are expected to develop disc pathology and those with a hypercurved spine to develop posterior facets arthritis, Baastrup disease or vertebral listhesis (2).

Adult low back pain patients have smaller pelvic incidence, sacral slope and flattened sagittal spinal curves (22), in accordance with other studies identifying a more vertical sacrum and smaller lumbar lordosis as sagittal characteristics of low back pain patients (23, 24). Low back pain patients were also more likely than asymptomatic controls to depict a flattened posture, and less likely to show a neutral posture (22).

In adolescents of mean age 14.0 years and standard deviation 0.2 years (range: 13.0-15.1 years), where sagittal postures probably reflect a constitutional "true" sagittal morphotype instead of resulting from secondary alignment adaptations, all non-neutral postural types (sway, flat and hyperlordotic) were positively associated with different measures of back pain presence, independently of gender, weight and height (25). Furthermore, in young adolescent boys (mean age 12.6 years and standard deviation 0.54 years), those showing a sway back posture more frequently report low back pain and neck pain than those with neutral postures (26).

1.2. Sagittal standing posture organization in children

A balanced posture is obtained when the spine and sacro-pelvis are aligned in order to minimize energy expenditure and preserve a horizontal gaze (7, 12, 27-29). Adjacent anatomical regions of the spine and sacro-pelvis are interdependent, and their relationships result in a stable and balanced posture (7, 12, 27-29). The net result of the relationships between anatomical regions is best represented by parameters of sagittal global balance (29). Therefore, global balance is maintained in a narrower range than regional alignment parameters in the pediatric population (30).

The schemes of correlations between spino-pelvic alignment parameters in children before walking ages (12) and in children and adolescents from 3 to 18 years old (27) were similar to those previously observed in adults (7). However, weaker correlations were observed in children and that could be partially explained by the presence of "immature" control mechanisms of the sagittal balance in growing individuals. As depicted in Figure 1, pelvic incidence is of prime importance in children to define the orientation of the pelvis (pelvic tilt and sacral slope), as indicated by the strong correlation coefficients. Sacrum orientation (sacral slope) is correlated with the shape (lordosis) and orientation (tilt) of the lumbar spine (27). The most clinically relevant pediatric correlations involve pelvic incidence and lumbar lordosis, as opposed to the moderate correlations between the lumbar and thoracic regions (27).

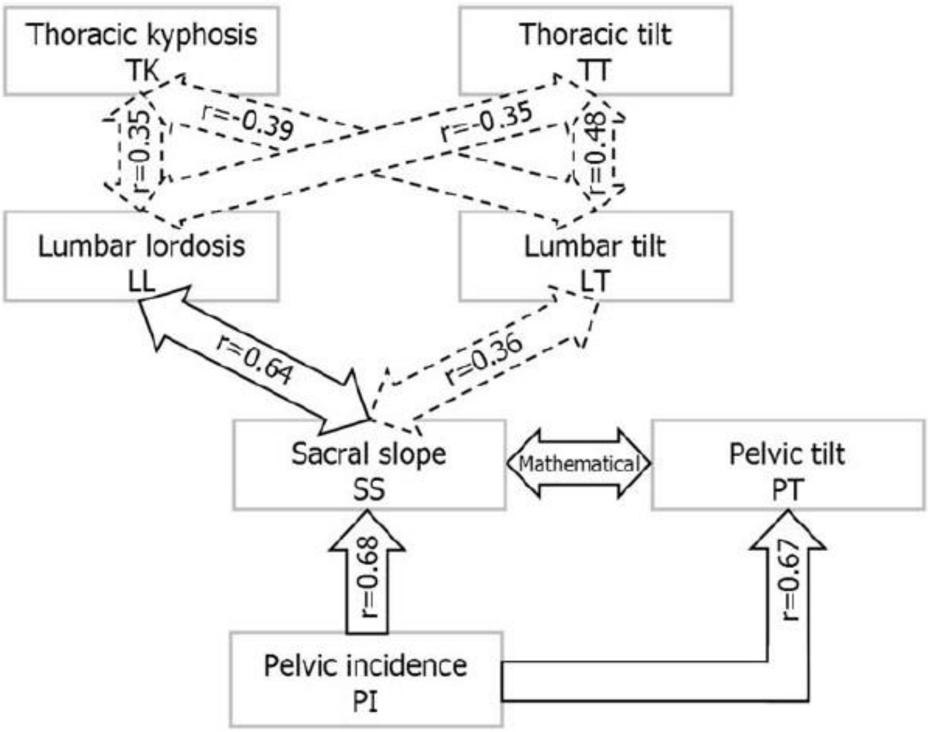

Figure 1. Diagram illustrating the linear chain of linked anatomical areas from the pelvis to the thoracic region. Moderate ($0.3 \leq r < 0.5$) and strong ($r \geq 0.5$) correlations are shown in dotted and full arrows, respectively. The mathematical relationship between pelvic tilt and sacral slope is also shown. The relationships between pelvic incidence and lumbar lordosis and between pelvic incidence and lumbar tilt, as well as weak correlations ($0.1 \leq r < 0.3$) are not included in the figure. Reproduced from Mac-Thiong JM et al (27).

Transition to an upright posture has resulted in the pelvis becoming a key structure within the human motor apparatus (4). The sacral plateau, which forms the base to support the spine, is the point of transfer of load from the trunk to the pelvis. Consequently, pelvic parameters affect the entire underlying sagittal profile of the spine (4, 12).

As previously described in adults (7), the correlation scheme of sagittal postural parameters in children also supports the concept by which parameters of adjacent anatomical regions are interdependent, and their relationships result in a stable and compensated posture, presumably to minimize energy expenditure. This concept does not imply a causal relationship, but suggests that a modification in the shape or orientation parameter in a given anatomical region will affect the adjacent anatomical regions (27).

1.3. A life course approach to sagittal standing posture

The life course approach has had wide application to the study of the distribution and determinants of diseases in human populations (31). Life course epidemiology aims at providing and testing theoretical models of human disease that postulate pathways linking exposures across the life course to later-life health outcomes. According to this approach, health outcomes in adult life may be seen as long-term effects of exposures acting during gestation, childhood, adolescence, young adulthood and later adult life (32). Relevant exposures throughout the life course may be biological, behavioral and psychosocial, as well as countless number of interactions between them. This model tries to surpass some of the reductionist aspects of previous models of disease etiology of conventional adult cohort studies in clarifying early causes of disease. Life course epidemiology has been particularly helpful in the development of the theoretical basis for the complex pathways of the etiology of chronic diseases, such as sagittal standing posture misalignment.

Sagittal standing posture in older ages is seen as the result of multiple influences acting throughout the whole life course. One major aspect is thought to determine the ultimate sagittal standing posture in adults: the development of pelvic and spinal alignment and balance during growth stages of life (4, 12).

Because childhood is a period of constant changes in sagittal standing posture, it is likely to present greater potential for modification or adaptation than other life periods. Such a period may be a critical or sensitive period, i.e., a time frame during which beneficial or harmful exposures have lasting and irreversible effects on postural health that determine later sagittal standing posture (32). Regarding sagittal standing posture it seems more likely that childhood is a sensitive period: a time frame when an exposure has a stronger effect than it would have in other stages of life. This role is probably more consistent with what is known about the effects of modifiable factors such anthropometrics and body composition on sagittal standing posture. Although it is believed they play a particularly important role before definitive sagittal standing acquisition, there is evidence that they may also be associated with sagittal standing posture later in life (33-38).

In this context, using data from a population-based birth cohort is one of the most powerful ways to test life course models (32). Birth cohort studies allow us to state the temporal ordering of exposure variables and their inter-relationships, both directly and through intermediate variables, with the outcome measure. They allow us to operationalize early life course exposures and conceptualize their inter-relationships across the life course, and also to test possible pathways with potential intermediaries or confounding factors. Because different periods across the life course influence phases of biological development, stability or decline, longitudinal studies since birth are essential to test life course models. However, such studies may be restricted with less common diseases. Frequently such studies will have either no data, especially for biological mechanisms, or missing data in subset of participants. However, contrary to historical cohorts and record linkage studies they are not limited to one or two exposures acting in a very specific time window and frequently with limited or no data on other periods of the life course (32).

1.4. Growth-related changes in sagittal standing posture

The growing child needs constant adaptations in the morphology and orientation of the spino-pelvis to maintain an adequate sagittal balance and appropriate configuration in terms of skeletal loads, muscle fatigue, and energy expenditure (12, 27, 29, 39, 40).

Pelvic incidence increases with growth and stabilizes after skeletal maturity is reached (4, 12, 41, 42). Therefore, pelvic incidence is considered a marker of the process of gaining the upright position that persists throughout life. Consequently, the extent of pelvic incidence increase during growth determines the pelvic morphology shown in adulthood (4, 12).

During the initial weeks of life, and with the acquisition of ambulation, pelvic incidence dramatically increases as the result of modifications in the development of the upright position (41) (Figure 2). Firstly, coxofemoral extension occurs by action of the gluteal muscles, allowing a verticalization of the pelvis which tilts backwards and brings the upper sacral endplate into a more horizontal position for constituting the pedestal of the vertebral column. Then, lumbar lordosis arises from the action of the erector spinae muscles as the child begins to acquire the upright position. Because of the insertion of the spinal erector muscle by a thick fascia onto the sacral spinous processes, lordosis leads to horizontalization of the sacrum, i.e. to verticalization of its endplate (41). The pelvic incidence angle reflects this horizontalization, explaining its augmentation after birth and during the first month of life when the lumbosacral junction undergoes modifications, similarly to human evolution during the different ancestral species (12, 41).

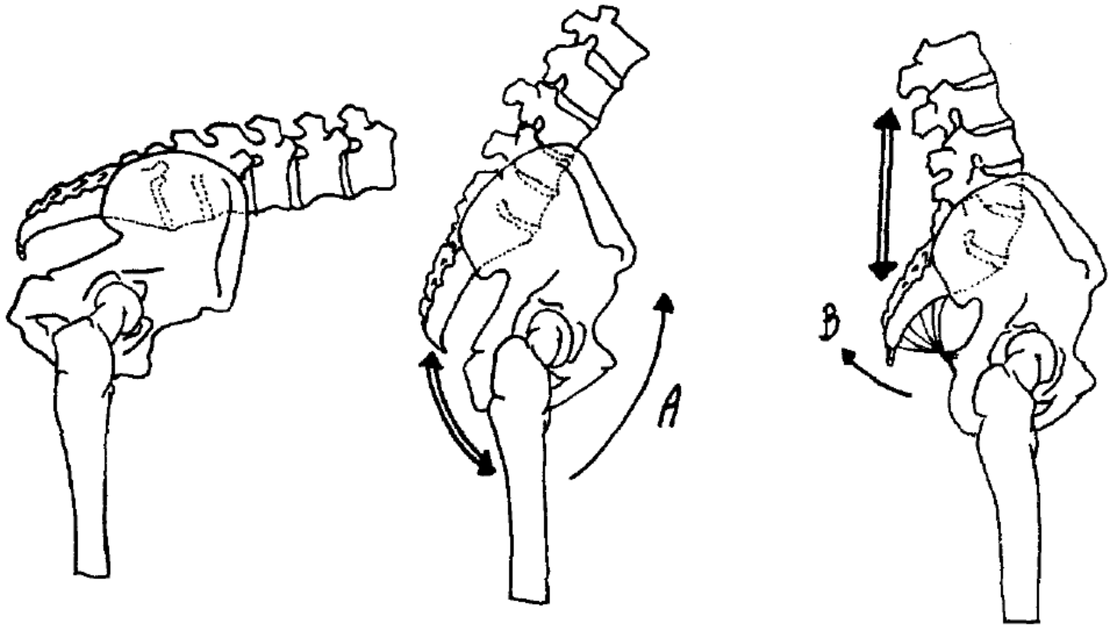

Figure 2. Pelvic modifications during acquisition of the upright position. A – Femoral extension by the gluteal muscles results in verticalization of the pelvis. B – Horizontalization of the sacrum in brought about by the erector spinae muscles. Reproduced from Mangione P et al (41).

Pelvic incidence and the sagittal anatomy of the sacrum are clearly different between young infants (before walking age: mean of eight months and ranging between four and 15 months) and adults, with all the anatomical sacrum parameters studied being significantly smaller among young infants than among adults (12). The sacrum of a young infant is less curved, the first two vertebrae are more ablong and the incidence of a young infant before walking age is significantly smaller. Young infants also showed smaller sacral slope and lumbar lordosis and slightly higher pelvic tilt (12).

Analysis between age and sagittal alignment parameters in children and adolescents showed a tendency for positive associations as growth takes place (12, 29, 40, 42, 43). Pelvic tilt tends to increase with age, indicating that the sacral plate tends to be displaced further posterior with respect to the hip axis. Pelvic tilt serves to optimally position the center of gravity over the hips and lower limbs, by maintaining the sacral plate posterior to the hip axis. Because the upper body weight increases significantly during growth and because the sacral plate (and vertebral column) represents the posterior part of the body, it appears that the pelvic tilt increases to avoid an inadequate anterior displacement of the center of gravity during growth (42).

Lumbar lordosis also increases with age (42). The presence of an adequate lumbar lordosis avoids the forward displacement of the center of gravity that may alter the equilibrium of the standing posture. The action of the erector spinae muscles and the vertebral growth may therefore contribute to the increase of the lumbar lordosis to avoid inadequate forward displacement of the center of gravity, which could be modified by upper body growth. The thoracic kyphosis that also increases with age mainly serves to balance the increasing lumbar lordosis. Conversely, thoracic kyphosis could also be dependent on the development of the respiratory system or on the thoracic vertebral growth pattern (42).

There is a trend for older children to stand with a more negative sagittal balance (backward tilt of the spine over the hips) as they get older (29, 40). This backward tilt of the spine may be required to counterbalance the upper body weight, which is mainly anterior to the spine, in order to maintain a stable posture (27).

1.5. Associations of anthropometry and body composition with sagittal standing posture

Anthropometry is associated with sagittal alignment parameters in adults, namely positive correlations of body mass index with lumbar lordosis (33-35). The biological plausibility for the effect of body mass index on adult sagittal spino-pelvic alignment was suggested to be related with biomechanical constraints induced by higher body mass index during standing posture and gait acquisition in early life, whose influence may deform the sacrum during osseous growth and affect pelvic shape and orientation, and therefore, also lumbar lordosis (33). The same mechanism was supported when analyzing the relation between body mass trajectories (three to 14 years old) and posture types at age of 14 years, where it was suggested that increased biomechanical load as the result of higher body mass index during early stages of life could lead to permanent changes of spinal structures, that then would favor the occurrence of non-neutral postures throughout life (44). Therefore, children's anthropometry is expected to contribute to the mechanical framework of posture modulation, i.e. weight and height theoretically modulate gravitational actions and regulate the net direction of forces imposed on the immature spino-pelvic structures (2). Plastic deformation of bones, discs and other spinal structures can occur (33, 35, 44), as a result of reactive forces by muscles to ensure a stable center of mass (29, 40, 41).

In addition, body size and composition contribute to the mechanical environment of spino-pelvic structures with fat and fat-free mass operating as extra-skeletal modulators of bone morphology. The skeleton has to support and deal with loading moments resulting from weight bearing (2, 45) and adiposity and muscles can also directly affect posture by changing the orientation of vertebral bodies towards increased lumbar lordosis (35, 45-48). Higher forces are applied to bone structures because the skeleton has more weight to support and needs higher muscle moments to regulate amplified oscillations of the upper body over the hips (2, 45). Adiposity also displaces balance forwardly which increases lumbar lordosis as the most efficient compensation to restore a stable basis of support (35, 45, 46). On the other hand, stronger back extensor muscles lead to an increase in lumbar lordosis (47, 48). Fat and lean mass positively affect bone structure through mechanical and endocrine effects (49, 50) with a more important contribution of lean than fat mass during childhood (50, 51). Therefore, both adiposity and muscles can lead to changes in the morphology of vertebral bodies, namely by changing their antero-posterior height ratios (52). These changes modify vertebral tilt and define local alignment (2, 38, 42), and consequently modulate overall posture due to adaptation of adjacent anatomical regions (29). As examples, longitudinal vertebral growth in children may increase lumbar lordosis (42), and both higher thoracic kyphosis (36-38) as well as higher lumbar lordosis (37) seem to have an osteoporotic origin at more advanced ages.

1.6. Posture defines biomechanical spino-pelvic environment

The shape and design of the spine affords efficient distribution and balancing of body mass. Based on biomechanical analysis of sagittal spino-pelvic organization, it has been suggested that compressive forces (resulting from the sum of gravity and muscle action) act differently according to lumbar sagittal orientation (2), as shown in Figure 3.

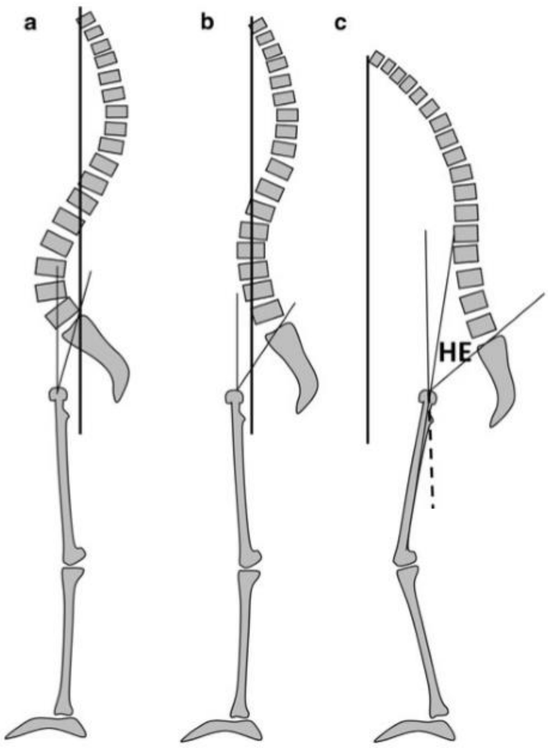

Figure 3. Mechanism of compensation of a progressive kyphosis. a – Normal situation with a slight pelvis retroversion and sagittal vertical axis over the sacral endplate. b – With a progressive loss of lordosis, pelvis retroversion permits maintaining sagittal vertical axis behind the femoral heads. c – In case of severe kyphosis, hip extension (HE) limits the pelvis retroversion. It is compensated by flexion of the knees. Sagittal vertical axis passes forward to the femoral heads. Adapted from Roussouly P and Pinheiro-Franco JL (2).

Contact force on spinal structures is the sum of gravity with forces of posterior spinal muscles to maintain an erect position. The more unbalanced the overall posture is, the more gravity forces increase, and the more muscle forces have to compensate for increasing contact forces (2).

However, one important issue is the direction of forces applied to structures (compressive vs. shear) as the result of muscle moments that will depend on vertebral orientation and positioning (Figure 4).

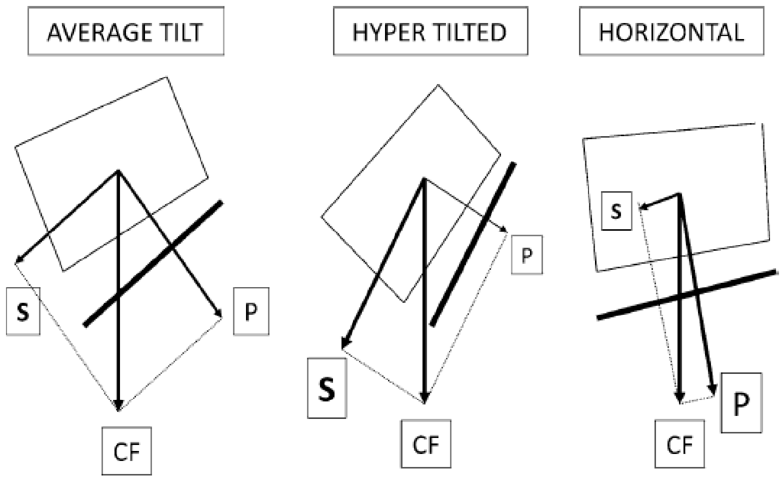

Figure 4. Distribution of contact force with respect to the local intervertebral tilt. CF – Contact force. S – Sliding resultant force; P – Pressure resultant force. Reproduced from Roussouly P and Pinheiro-Franco JL (2).

When the intervertebral tilt increases, the sliding resultant force increases; in case of a horizontal plate orientation, the pressure increases (2). Consequently, a flattened lumbar spine induces compressive forces and they are progressively transferred to shear forces as lumbar lordosis increases (53, 54).

Therefore, in each specific habitual standing posture, gravitational forces determine the mechanical setting provided to skeletal structures. An anteriorly displaced center of mass, as frequently observed due to increased thoracic kyphosis, results in an increased forward bending moment of the upper body leading to higher compressive moments in thoracolumbar and lumbar regions (45). Stronger extensor trunk muscles are then needed to compensate for increased thoracic kyphosis while keeping a stable upright posture, which increases spinal compressive (2, 45, 54, 55) and shear (2, 54, 55) loading. Thus, sagittal standing posture seems to be a key macrostructural factor in defining the amount of physical stimuli imposed on spino-pelvic tissues.

A hyperlordotic posture requires higher muscle moments than all other postures; especially during more demanding tasks (53). A sway posture minimizes muscle work and stresses in the resting standing position (53). As lumbar lordosis increases up to a hyperlordotic posture mechanical loads also increase. Flattened or neutral spines are better suited to minimize muscle work and stress in weight-bearing activities (53) and the extremely pronounced thoracic kyphosis in the sway type can be expected to contribute to higher mechanical stress compared to a flattened posture (45, 54, 55). In the case of a moderate external load, a neutral and well balanced spine is able to reduce the muscle activation in comparison with a hyperlordotic spine, with negligible differences compared to a straighter spine (53). However, such a sagittal configuration (i.e., neutral) is not correlated with a minimization of the loading state in the intervertebral discs, especially regarding antero-posterior shear loads. In the standing posture without any additional load, a less lordotic, more vertical spine was sufficient to ensure minimal spinal loads (53).

Other postural parameters play a significant role in determining body mass distribution and therefore the spine’s biomechanical environment: postural congruency and the use of a compensation technique can act to mitigate any increases in compressive loading associated with an elevated thoracic kyphosis angle (45).

1.7. Measurement of sagittal standing posture

It is important to quantify sagittal standing posture in order to monitor treatment effectiveness on body segments, for physiotherapy, brace or surgical treatment.

Radiograms are considered the gold standard method to measure sagittal standing posture because they allow the clear visualization of bone landmarks, and have been shown to be a reliable method (56). Radiograms are used to assess or monitor change over time in persons presenting with musculoskeletal disorders. However, radiographs involve radiation hazards and thus should not be used for repeated measures of body segment posture, especially in growing children who do not have specific clinical indication.

Electromagnetic motion analysis techniques have been reported to be valid (56) and reliable (57) in adults. However, this method requires expensive equipment and the setting up of apparatus and data management is time-consuming and the data processing is complex. Such equipment may also have a limited number of sensors, making the measurement of multiple angles difficult.

Video rasterstereography involves the multidirectional illumination of the back surface during stereo video imaging to produce a high-resolution three-dimensional computer reconstruction of the back surface, which permits automatic calculation of measures of spinal curvature (58). This method is reliable (59), but has not been shown to be valid compared to radiography (60). Since subjects must have their entire torsos uncovered, it is an unacceptable method of posture assessment for some subjects.

Some manual measurement techniques such as the goniometer (61) and flexicurve (62) have also been shown to be valid, and some of them have good reliability in adults. However, though such manual techniques may be useful for single angular measures, they may be time-consuming if several angles need to be measured.

Overall, radiography, motion analysis, rasterstereography or manual methods are not appropriate for large-scale studies when measuring multiple angles, because of difficulties in application, expenses, safety or practicality (63).

In contrast, static photographic analysis with reflective markers placed on specified anatomical landmarks may be more suited to large-scale studies. This is because it is relatively cheap, requiring only a camera, markers and adhesive tape; is highly portable; and permits the measurement of several posture angles simultaneously (63). It is thus frequently used in field and clinical studies.

Most of angles measured by the photographic method have moderate to good level of correlation with X-rays: in a validation study correlation coefficients were reported to range from 0.60 to 0.97 (64). However, these were in respect to head angle, the cervical angle, the thoracic angle and the arm angle in different sitting positions and more studies are needed evaluating all regions of the body before firm conclusions can be drawn. Furthermore, photographic analysis was previously validated in adolescents (65-67) and adults (68, 69) and is characterized by acceptable reproducibility (63, 64, 70). By extrapolation, photogrammetry is recommended as the safest method for postural evaluation in large-scale studies of children (35, 63, 64) but validation studies are lacking in children.

Marker placement by examiners, parameters (angles/distances) definition, body position, perspective error and biological variability are the factors that can affect intra- or inter-rater reliability of the photographic method (63):

Marker placement may translate in both random and systematic error. For example, an examiner may have an erroneous but repeatable method of locating a body landmark, resulting in systematic error, or may be more generally inattentive to detail, resulting in random error. Examiner training is clearly important to reduce random and systematic marker placement errors.

Parameter definition may include relative difficulty in marker placement, differences in inter-marker distances and vertical reference. For example, difficulties in accurate palpation of the pelvic markers may explain the poorer reliability of lumbar angle and pelvic tilt. This is accentuated when subjects have greater subcutaneous adipose tissue. Longer inter-marker segments will be less sensitive to angular error for a given absolute marker placement error. Vertical referenced angles may have less intra-rater reliability because of errors induced by variations in overall body position (71). All these factors would be present in varying degrees at each postural angle. For example, lumbar and sway angle have lower reliability despite their long inter-marker distances, which might reflect the relative difficulty in greater trochanter palpation (63). Similarly, head and neck flexion are relatively reliable despite their vertical-dependence and short inter-marker distances, which may relate to their more prominent landmarks (63).

Perspective error happens when rotation of the subject away from the sagittal plane relative to the camera position causes over or underestimation of sagittal angles or distances. However, the effect of perspective error only becomes important with larger rotational errors. Body position: subjects are less able to repeat unusual postures, as slump sitting position, comparing to standing or sitting position.

Biological repeatability refers to the ability of subjects to repeat the required positions. There may be greater postural variability in children because of anthropometric and motor control immaturity (70).

Marker and subject positioning are larger sources of error than specific differences in measurement between raters (63). Additionally, intra-rater digitization reliability suggests errors during this process do not contribute significantly to diminished repeatability of the overall posture measurement.

The photographic method is sufficiently reliable to be used in large-scale studies of posture. In addition to standardized protocols, the following recommendations can be made to maximize reliability (63):

1. Use examiners with palpation expertise;
2. Thoroughly train examiners in marker palpation and subject instruction, with regular quality control;
3. Examine the data for rater differences and control for these in analysis;
4. Where possible use parameter with easily palpable landmarks and large inter-marker distances;
5. Measure inter-segmental angles as well as vertical references angles;
6. Minimize perspective error by ensuring camera is perpendicular to subject;
7. Use larger sample sizes for studies involving children and adolescents to allow for potentially greater positional variability.

1.8. Sagittal standing postural patterns

Several authors (21, 25, 26, 72-75) have advocated that analyzing sagittal postural patterns, instead of the conventional analysis focused on isolated sagittal alignment parameters, should provide a more complete understanding of the complex overall sagittal standing alignment. First, interaction among separate segments of sagittal alignment should exist and needs to be considered in the analysis of standing posture (25, 26, 73-75). Second, the same angular change in a similar segment of different subjects may have a different effect on overall sagittal alignment due to the compensatory relationship between separate spino-pelvic segments (73). Third, and finally, the great variability in neutral "normative" ranges of regional spino-pelvic parameters limits the usefulness of isolated parameters when studying sagittal standing posture (21, 72).

Roussouly et al (21), have analyzed the standing radiographs of a sample of 160 asymptomatic adults, having 27 years as mean age (range: 18-48 years). Based on the theoretical framework of correlations between individual regional sagittal alignment parameters and also on the geometrical analysis of thoracic and lumbar spinal curves, they have proposed a classification of four types of overall sagittal standing posture in "healthy" adults (Figure 5):

- Type 1: The sacral slope is smaller than or equal to 35º, which is associated with a low pelvic incidence. The apex of the lumbar lordosis is located in the center of L5 vertebral body. The lower arc of lumbar lordosis is minimal, decreasing toward zero as the sacral slope approaches the horizontal. The inflexion point is low and posterior, creating a short lumbar lordosis dorsally inclined. The thoracic kyphosis is long with an extension to the thoracolumbar area.

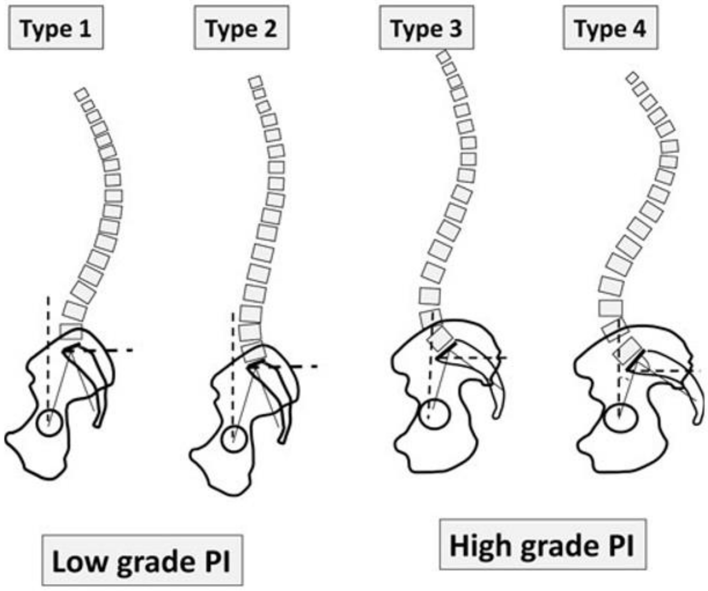

Figure 5. Representation of the sagittal characteristics in each of the four sagittal postural patterns. PI – Pelvic incidence. Reproduced from Roussouly P and Pinheiro-Franco JL (2)

- Type 2: The sacral slope is smaller than or equal to 35º and pelvic incidence is low. The apex of the lumbar lordosis is located at base of the L4 vertebral body. The lower arc of lumbar lordosis is relatively flat. The inflection point is higher and more anterior, decreasing the dorsal inclination of lumbar lordosis but increasing the number of vertebral bodies included in this curve. The entire spine is relatively hypolordotic and hypokyphotic.

- Type 3: The sacral slope is between 36º and 44º, showing a high pelvic incidence. The apex of lumbar lordosis is in the center of the L4 vertebral body. The lower arc of lumbar lordosis becomes more prominent. The inflection point is at the thoracolumbar junction (T12-L1), and lumbar lordosis inclination is near the vertical. An average of four vertebral bodies constitutes the arc of lumbar lordosis. The spine is well balanced.

- Type 4: The sacral slope is greater than or equal to 45º, which is associated with a high pelvic incidence. The apex of the lumbar lordosis is located at the base of the L3 vertebral body or higher. The lower arc of lumbar lordosis is prominent, and its inclination is in line with the vertical or ventrally tilted. The number of vertebrae in lordotic orientation is greater than five, and a state of segmental hyperextension exists.

In 709 asymptomatic adults of mean age 36.8 years, prevalence estimates were: type 1 (4.5%), type 2 (23.3%), type 3 (47.7%), and type 4 (24.5%) (30). In 198 low back pain patients with mean age 39.4 years, 5.1% presented a type 1 postural pattern, 37.4% presented a type 2, 38.9% presented a type 3, and 18.7% presented a type 4 postural pattern (30). Finally, in our previous work in 489 community-dwelling Portuguese adults (39.7% of the participants classified as having 65 or more years of age) the prevalence estimates were 4.9%, 31.3%, 42.3% and 21.5% for the postural types 1, 2, 3 and 4; respectively.

In 766 adolescents (mean age of 14 years and standard deviation 0.2 years; range:13.0 to 15.1 years), sagittal posture was assessed through lateral photographs during habitual standing position and by retro-reflective markers placed on predefined body landmarks (25). Sagittal standing postural patterns were then defined from trunk, lumbar and sway angles by cluster analysis. Four steps were performed to obtain posture clusters. In step 1, a random sample of 100 subjects was used to derive the number of clusters and their cluster centers, using hierarchical (Ward's) followed by nonhierarchical (K-means) cluster analysis of standardized scores for the three postural measures. In step 2, a second random sample of a different 100 subjects was used to confirm the stability of the clusters. In step 3, clusters profiles on gender, height and weight in the two separate samples were examined as criterion validity on variables not used to determine the cluster solution. In step 4, a 4-cluster solution for the entire sample was determined using K-means analysis, using the average of the clusters centers from the K-means cluster analysis from the two subsamples as the cluster center seeds.

Four postural patterns were then identified in adolescents and they corresponded to those previously defined in adults (25):

- Sway posture: Lower sway angle (posterior sway or backward trunk lean), slightly greater trunk angle (more kyphosis) and slightly increased lumbar angle (less lordosis).

- Flat posture: Forward trunk sway, decreased trunk angle (less kyphosis) and increased lumbar angle (less lordosis).

- Neutral posture: Neutral sway angle and slightly decreased trunk and lumbar angle (less kyphosis and more lordosis).

- Hyperlordotic posture: Neutral trunk sway, increased trunk angle (more kyphosis) and decreased lumbar angle (more lordosis).

In 1373 adolescents of mean age 14.1 years (standard deviation of 0.2 years), pattern prevalence was 26.8% for the sway posture, 22.4% for the flat posture, 28.6% for the neutral posture and 22.2% for the hyperlordotic posture (44).

Despite previous attempts to develop classification systems of sagittal standing posture in young adolescents girls (10.6±0.47 years) (75) and boys (10-13 years (76) and 12.6±0.54 years (26)), different procedures of postural parameters definition preclude comparisons with previous classifications. Particularly, children have been classified in a three-option likert scale of uncorrected posture based on the horizontal deviations of four body landmarks in respect to a vertical line (76) and three global patterns (based on three angles in respect to the vertical) with different magnitude of spinal curves being observable within each pattern (26, 75). Therefore, given the fundamental methodological differences in the individual parameter inputs for the creation of classification rules, these previous studies do not add information for the discussion of our life-course hypothesis on the early determination of sagittal posture typology.

2. Objectives

By using prospective data from children participating in the Generation XXI cohort, the aim of this thesis was to define postural patterns in school-aged children and evaluate their relation with anthropometrics and body composition parameters.

To attain the proposed aim we defined four specific objectives:

1. To assess the correlations of anthropometrics and body composition parameters with angles of sagittal standing posture measured at 7 years of age (Paper I)
2. To identify and describe postural patterns among 7-year-old girls and boys, and to explore their associations with anthropometric characteristics (Paper II)
3. To estimate the associations of body size from birth onwards with sagittal postural patterns at 7 years of age (Paper III)
4. To investigate the association between bone physical properties and sagittal postural patterns among 7-year-old children, accounting for the roles of fat and fat-free mass in this association (Paper IV)

3. Participants and methods

3.1. The Generation XXI birth cohort study

Generation XXI is a birth cohort study assembled during 2005 and 2006 in the Porto Metropolitan Region. It was established as a multi-purpose prospective population-based cohort that aims to chart the growth and development of children born at the dawn of the new millennium, and to address scientific questions as well as policy concerns.

3.1.1. Participants

The cohort comprises 8647 children (8495 mothers), born between April 2005 and August 2006 in the Porto Metropolitan Region (77, 78). Recruitment was conducted at five public maternity units, responsible for 95% of the deliveries in the region at that moment. All resident women, delivering a live birth with more than 23 gestational weeks were eligible to be included. Among those invited, 91.4% agreed to participate. Four and seven years after birth, 69% and 68%, respectively, of all children recruited at birth were reevaluated by face-to-face interviews and physical examinations. During the 7 year-old follow-up, a subsample of 2998 children consecutively assessed between December 2012 and August 2013, and without a diagnosis of severe neurological impairment (n=7), was invited to an additional wave of assessment in which bone physical properties and sagittal standing posture were evaluated. Of those, 80.5% agreed to participate and attended the scheduled assessment.

All the phases of the study complied with the Ethical Principles for Medical Research Involving Human Subjects expressed in the Declaration of Helsinki. The study was approved by the University of Porto Medical School/S. Joao Hospital Centre ethics committee and a signed informed consent according Helsinki Declaration was required for all participants.

3.1.2. Data collection

Birth weight and recumbent length at birth were retrieved from medical records by trained researchers. Ponderal index was then computed (weight in grams/length in centimetres^3

*100).(79) Additionally, weight and height were assessed during the 4 and 7-years follow-ups. Weight was measured in light indoor clothing to the nearest 0.1kg using a digital scale (TANITA®) and height to the nearest 0.1cm using a wall stadiometer (SECA®). Body mass index was defined as weight in kilograms divided by height in squared meters.

Additional wave of assessment

Based on an additional wave of assessment held for 2998 eligible children consecutively attending the 7 year-old follow-up, weight (Xinyu Electronic Company, Limited) and height (SECA®) were measured following similar procedures to those previously described.

Whole body dual energy X-ray absorptiometry (DXA) scans were performed (Hologic Discovery QDR® 4500W, Bedford, MA, USA). Total body less head fat and fat-free mass were used. Fat and fat-free mass indices were then calculated by dividing fat mass and fat-free mass (kg) by height squared (m^2) (80). Total body less head bone mineral content (BMC) was obtained and bone mineral density (BMD) was expressed as BMC (in g) per projected bone area (in cm^2). Area-adjusted BMC (aBMC) was derived as a measure of volumetric BMD by a regression of BMC on bone area and adding the residuals of the linear regression to mean BMC (81). As recommended, total body less head rather than total body measurements were used because the head is less responsive to environmental stimuli (82). Nine trained radiology technicians were involved in DXA evaluations.

Sagittal standing posture evaluation was performed by quantitative assessment of photographs of the sagittal right view of children. This evaluation occurred between March 2013 and February 2014 (median [interquartile range] of 62 [211] and 63 [212] days after the 7-year-old evaluation for girls and boys, respectively).

Using double-faced adhesive tape, spherical retro-reflective markers (12mm and 30mm) were placed over anatomical landmarks on the right-side of the child's body: lateral canthus of the eye, tragus, anterior border of the acromium (30mm), spinous processes of C7 and T12 (30mm), anterior superior iliac spine, greater trochanter, lateral epicondyle of the femur and lateral malleolus. Additionally, a plumb line with two 20mm polystyrene circumferences (50cm distance from each other) was placed behind children and 50cm from the wall (the same distance as the right side of the child's body) in order to allow vertical angle offset and distance calibration during the digitization of photographs. Evaluation was performed by one of two health professionals in a dedicated room. Both examiners received several theoretical and practical sessions of anatomy tuition before data collection.

Children were barefoot, wearing underwear or swimwear and were instructed to rest comfortably in habitual standing position with feet slightly apart, looking straight ahead and moving elbows forward, as previously described in Perry et al (63) to standardize position of participants. Floor markers were further used to regulate the relative position of children in respect to the camera. After the examiner judged that the usual upright position had been attained, full-body flash photographs were obtained using a Canon PowerShot A2300 (4608 x 3456 pixels) attached to a 60cm-high tripod, placed 200cm from the wall and perpendicular to the child. The tripod was fixed on the floor and the zoom feature of the camera was not used.

Anatomical landmarks were then digitized using the valid and reliable postural assessment software PAS/SAPO (83), which allowed computation of nine angles and three distances describing sagittal standing position in accordance with the protocol suggested by Perry et al.(63) This protocol prioritizes biologically relevant measurements (i.e., quantifies the relative position of body segments), avoiding the use of the vertical line reference and therefore optimizing photographic reliability (63, 64, 70). Angles were formed by the lines traced from the labelled anatomic landmarks and the two-dimensional coordinates of each marker were used to determine distances. All the photographs were digitized by one of the researchers who carried out the physical examinations and who is a physiotherapist following specific training in order to measure angles in a systematic manner in terms of order and quality. The zoom feature of the software was used freely.

4. Papers

4.1. Paper I

Araújo FA, Simões D, Silva P, Alegrete N, Lucas R.

Sagittal standing posture and relationships with anthropometrics and body composition during childhood.

[Submitted].

Sagittal standing posture and relationships with anthropometrics and body composition during childhood

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ABSTRACT

Objective To assess the correlations of anthropometrics since birth and body composition parameters with angles of sagittal standing posture in children.

Design Longitudinal follow-up of children enrolled in the Generation XXI study.

Setting Porto, Portugal.

Participants The sample included 1021 girls and 1096 boys. Weight and height were obtained at birth, 4 and 7 years of age. At age 7, total body less head fat/fat-free mass and bone properties were estimated from whole body dual energy X-ray absorptiometry scans and posture was assessed through right-side photographs during habitual standing with retro-reflective markers placed on body landmarks. Relationships between anthropometrics and body composition with sagittal posture angles were estimated through Pearson's correlation coefficients.

Results Girls showed increased values of lumbar angle, head and neck flexion, and craniocervical angle with the largest mean (standard deviation) difference in lumbar angle [281.7º (7.4) vs. 276.8º (7.1), $p<0.001$]. In both genders, weight and body mass index were weakly associated with lumbar angle: $0.24\geq r\leq 0.31$ in girls and $0.16\geq r\leq 0.26$ in boys, all $p<0.001$. Fat and fat-free mass and bone mineral density were weakly associated with lumbar angle in both genders. Age was positively associated with sway angle, especially in boys ($\beta=2.44$; 95% CI: 1.52 to 3.36).

Conclusions Our study showed clear postural heterogeneity between girls and boys in early ages. Lumbar angle was the most important parameter among all angles studied and body mass index the characteristic mostly associated with it, especially in girls. There was a predominant role of the sway angle only among boys.

INTRODUCTION

The development of sagittal posture during childhood and adolescence is crucial for the attainment of adult spino-pelvic alignment.[1, 2] In turn, sagittal spino-pelvic alignment is associated with back pain and physical disability in adults,[3] and sagittal imbalance is the strongest postural predictor of functional loss and dependency in older ages.[4]

Anthropometry and body composition have been suggested to shape pediatric sagittal standing posture.[5-8] Their effects are supposedly related with the natural maturation of the musculoskeletal system in children, with fat leading to plastic changes in muscles, bones and other structures that prevail across the life course.[5-8] We have shown that body size since birth is associated with postural patterns defined at 7 years of age (unpublished work), where weight and height theoretically regulate the net direction of gravitational forces imposed on the spino-pelvic structures.[9] Furthermore, a strong rationale exists for a relation between bone physical properties and posture, as a result of a shared mechanical environment defined by anthropometrics. We also showed that bone mineral content and density were associated with postural patterns in the same direction of anthropometry, i.e., lower bone mineral density was observed in a flat posture while a hyperlordotic posture showed increased density (unpublished work). However, the relationship of anthropometrics since birth and body composition with individual measures of postural parameters in children has never been evaluated, and it is unknown which specific angular parameters contribute to the associations previously observed on postural patterns. Additionally, differences in sagittal standing posture seem to exist between girls and boys in young adolescence,[10, 11] as gender-specific relationships between age and postural measures were also observed.[2] Therefore, our aim in this study was to assess the correlations of anthropometrics and body composition parameters with angles of sagittal standing posture measured at 7 years of age in a population-based birth cohort of children, separately for girls and boys.

METHODS

Subjects

This study was based on the population-based birth cohort Generation XXI, already described elsewhere.[12, 13] A total of 8647 live born infants were enrolled between April 2005 and August 2006 at all five public maternity units that cover the six municipalities of the metropolitan area of Porto (Northern Portugal). At birth, 91.4% of the invited mothers agreed to participate. Invitations to follow-up evaluations were based on children's date of birth. Four and seven years after birth, 86% and 80% of the cohort's children were re-evaluated, respectively. A specific musculoskeletal assessment was held for a subsample of 2998 children attending the 7-year-old follow-up between December 2012 and August 2013 and without a diagnosis of severe neurological impairment. Of those invited, 80.5% agreed to participate and attended the scheduled assessment in which sagittal posture and bone physical properties were evaluated. We excluded 126 girls and 170 boys due to missing information in at least one of the exposure variables considered in the present work. A final sample of 1021 girls and 1096 boys was considered. Ethical approval was obtained from the Ethics Committee of São João Hospital/University of Porto Medical School, and was also approved by the National Committee of Data Protection.

Anthropometric variables

Birth weight and recumbent length at birth were retrieved from medical records. Ponderal index was computed (weight in grams/length in centimetres^3 *100).[14] Anthropometrics were measured by trained examiners in further waves of assessment at mean ages [standard deviation (SD)] of 4.3 (0.3) and 7.4 (0.4) in each gender. Weight was measured in light indoor clothing to the nearest 0.1kg using a digital scale (TANITA® at 4 years and Xinyu Electronic Company, Limited at 7 years in the musculoskeletal assessment) and height to the nearest 0.1cm using a wall stadiometer (SECA®). Body mass index was defined as weight (kg) divided by height squared (m^2).

Body composition parameters

A Hologic device (Discovery QDR® 4500W, Hologic Inc., Bedford, MA, USA) was used to measure total-body-less-head fat and fat-free mass. Fat and fat-free mass indices were calculated by dividing fat mass and fat-free mass (kg) by height squared (m^2).[15] Also, total-body-less-head bone area (cm^2), bone mineral content (BMC, g) and bone mineral density (BMD, g/cm^2) were obtained. As recommended, total-body-less-head rather than total body measurements were used because the head is less responsive to environmental stimuli.[16] Standard quality assurance tests using the calibration block were performed daily, and also each month using the spine phantom. Nine trained radiology technicians were involved in evaluations. Two of the examiners performed 83% of all the whole-body scans.

Sagittal standing posture

Sagittal standing posture was evaluated by quantitative assessment of photographs of the sagittal right view of children,[17] a method validated in other populations with acceptable reproducibility.[18-21]

Spherical retro-reflective markers were placed over anatomical landmarks on the right-side of the child's body by one of two qualified health professionals: lateral canthus of the eye, tragus, anterior border of the acromium, spinous processes of C7 and T12, anterior superior iliac spine, greater trochanter, lateral epicondyle of the femur and lateral malleolus. Children were barefoot, wearing underwear or swimwear and assumed their habitual standing position with feet slightly apart, looking straight ahead and moving elbows forward, as previously described to standardize position of participants.[8, 19] Full-body flash photographs were then acquired. We followed the protocol suggested by Perry et al[19] because it prioritizes the quantification of the relative position of body segments, and therefore, optimizes photographic reliability.[19-21] Angular measures formed by the lines drawn from the anatomical landmarks were obtained using the postural assessment software PAS/SAPO[18] and using a plumb line with two polystyrene circumferences as reference to allow vertical angle offset during the digitization of photographs (as exemplified in Figure 1). Trunk, lumbar and sway angles (panels F, G and I in Figure 1) completely characterize thoraco-lumbo-pelvic sagittal alignment in the standing position and were the measures previously used to identify sagittal postural patterns in children.[17] Additionally, head flexion, neck flexion, craniocervical angle, cervicothoracic angle, thoracic flexion and pelvic tilt were also obtained. We excluded posture distances from the present analysis due to the magnitude of measurement error related to both inter-rater effects and anthropometrics.[19]

Statistical analysis

Each child was evaluated by only one posture examiner. We assumed random allocation by examiner, meaning that differences in distribution of postural measurements could be attributed to observer effects.[22] Therefore, the mean calibration method considering the measurements of the first examiner as the reference was performed, i.e., adding the difference between means obtained by each examiner to the individual values of each child evaluated by the second examiner.[23]

In addition to descriptive statistics, comparisons between genders were performed using independent samples t-test. Relationships of anthropometric variables and body composition parameters with angle measures of sagittal posture were assessed using Pearson’s correlation coefficients and linear regression models were computed to quantify β coefficients and respective 95% confidence intervals (CI), separately for girls and boys. Data were analyzed using STATA® (version 11.1).

RESULTS

Girls were born lighter than boys [mean (SD): 3102.6g (522.6) vs. 3197.6g (516.5), $p<0.001$], but showed similar weight at 4 and 7 years of age. However, girls were shorter in all evaluations and consequently showed higher body mass/ponderal index than boys: average differences varying from $0.03 g/cm^3$ at birth to $0.42 kg/m^2$ at 7 years of age (Table 1).

Girls showed higher fat and lower fat-free mass compared to boys [mean (SD): 8.5kg (3.6) vs. 6.9kg (3.1), $p<0.001$; and 14.7kg (2.3) vs. 15.8kg (2.3), $p<0.001$; respectively]. While bone area was similar between genders, girls showed lower BMC and BMD (average differences of 8.5g and $0.01 g/cm^2$, respectively).

In respect to angle measures of sagittal standing posture (Table 1), girls showed increased values of lumbar angle, head and neck flexion, and craniocervical angle with the largest mean (SD) difference in lumbar angle [281.7º (7.4) vs. 276.8º (7.1), $p<0.001$]. However, girls showed decreased trunk and cervicothoracic angles, thoracic flexion and pelvic tilt, with the largest mean (SD) difference in pelvic tilt [128.6º (7.1) vs. 132.4º (7.0), $p<0.001$]. Similar sway angles were observed between genders.

Girls

Table 2 shows the correlations between exposure variables and angular measures of sagittal posture in girls. Weight and body mass index were weakly associated with lumbar angle: $r=0.24$ and $r=0.27$ at 4 years, and $r=0.28$ and $r=0.31$ at 7 years of age, respectively, all $p<0.001$. Fat and fat-free mass, BMC and BMD were also weakly but positively associated with lumbar angle ($r=0.29$, $r=0.20$, $r=0.15$, $r=0.22$, respectively; all $p<0.001$).

Height and bone area were very weakly associated with cervicothoracic angle: $r=0.16$ at 4 years and $r=0.20$ at musculoskeletal stage (both $p<0.001$) for height, and $r=0.18$ ($p<0.001$) for bone area.

Age was inversely associated with head flexion (β=-5.09; 95% CI: -6.53 to -3.65), and positively associated with cervicothoracic angle (β=2.85; 95% CI: 1.81 to 3.90); independently of all measurements of weight, all measurements of height, fat and fat-free mass, bone area and BMC (Table 4). Additionally, age was positively associated with sway angle (β=1.43; 95% CI: 0.54 to 2.32).

Boys

Table 3 shows the correlations between exposure variables and individual angle measures of sagittal posture in boys. As in girls, weight and body mass index were weakly associated with lumbar angle: r=0.16 and r=0.22 at 4 years follow-up, and r=0.21 and r=0.26 at 7 years of age (respectively), all $p<0.001$. Fat and fat-free mass were also weakly associated with lumbar angle in boys (r=0.24 and r=0.13, respectively, both $p<0.001$).

Height and bone area were slightly associated with cervicothoracic angle: r=0.17 at 4 years and r=0.23 at musculoskeletal stage (both $p<0.001$) for height, and r=0.20 ($p<0.001$) for bone area. Additionally, in boys, height was very weakly and inversely associated with neck flexion, which become stronger with age up to r=-0.16 ($p<0.001$) at age 7.

Age was inversely associated with head flexion (β=-3.31; 95% CI: -4.82 to -1.80), and positively associated with cervicothoracic angle (β=2.77; 95% CI: 1.77 to 3.77); independently of all measurements of weight, all measurements of height, fat and fat-free mass, bone area and BMC (Table 4). Additionally, age seems to be strongly positively associated with sway angle in boys (β=2.44; 95% CI: 1.52 to 3.36)

DISCUSSION

In both genders, weight and body mass index were positively associated with lumbar angle. Concordantly, bone mineral density was also associated with lumbar angle. Height and bone area were associated with cervicothoracic angle in both genders. Both anthropometrics and body composition parameters seem more strongly associated with postural angles in girls, while in boys, age was strongly positively associated with the sway angle (anterior displacement of the spine over the hips).

One of the main findings of this study is the clear postural heterogeneity between genders, with girls especially showing higher lumbar angle since age 7. Structural phylogenetic adaptations of the female spine can justify an increased lumbar angle in girls.[6, 24] Given that balance was similar between genders, those findings taken together seem to highlight different alignment arrangements in order to obtain the same final balanced spino-pelvis. Concordantly, a gender-specific organization of body segments in young adolescents has been previously suggested.[25] However, our study extended these findings to children for the first time, which may imply much earlier differences in biomechanical loads perhaps contributing to the well-known gender differences of pediatric spinal deformities. Furthermore, age was positively associated with sway angle (especially in boys), while associations with lumbar angle were stronger for girls. This is in accordance with our previous postural classifications where pattern aggregations of a neutral labelling were different between genders and suggested a predominance of increased lumbar angle in girls and sway back in boys.[17]

Among all the individual parameters considered, the strongest crude associations in this work were with lumbar angle. This is in accordance with the key role attributed to lumbar lordosis within the open chain of interdependence between anatomical regions of spino-pelvic sagittal alignment in standing position of asymptomatic adults,[5, 26] as well as adolescents and children.[25, 27] The concept of interdependence between spino-pelvic regions implies that a change in shape or orientation at any anatomical level will affect the shape and orientation of adjacent segments, with lumbar lordosis being the key clinical parameter during corrective surgery planning in order to obtain a balanced and harmonious spino-pelvis.[27, 28]

In our work, we confirmed body mass index as the characteristic most strongly associated with lumbar angle. A biological effect of body mass index on adult sagittal spino-pelvic alignment was suggested to be related with biomechanical constraints induced by higher body mass during standing posture and gait acquisition in early life, whose influence may deform the sacrum during osseous growth and affect sagittal standing posture.[5, 6] Adolescents who remained lighter during childhood had an increased likelihood of showing a flattened lumbar lordosis and, on the contrary, those who were heavier showed a hypercurved lower back.[7, 8] Congruent with this mechanical influence of adiposity, our results showed associations stronger for weight than for height, and were also stronger during walking ages (vs. at birth). The same direction of crude associations was observed for fat and fat-free mass and these associations were stronger for fat mass. Furthermore, a correlation with bone mineral density was also observed. Research on the associations between bone parameters and sagittal posture is lacking, but an inverse relation of bone mineral density with a flattened posture and a direct relationship with a hypercurved spine have been shown in the present sample in respect to postural patterns (unpublished work).

Height and bone area were positively associated with cervicothoracic angle and head extension. Despite the lack of research studying the associations of height and bone area with sagittal posture, the observed association can be explained by adaptations to ergonomic mismatch.[29] Taller children need higher thoracic angle combined with head extension to maintain a horizontal gaze. Associations with bone area can be explained by the high collinearity between height and bone area (r=0.76 for girls and r=0.79 for boys; data not shown).

Despite the low age variability in our study, positive associations with age were observed for head extension, cervicothoracic angle and thoracic flexion. This is in accordance with increases in thoracic kyphosis reported to happen during growth.[1, 2] However, age and height were also moderately correlated (r=0.37 for girls and r=0.33 for boys; data not shown).

All the correlations reported in this work were weak (|r|≤0.31), and associations should be viewed in the context of high collinearity between exposure variables which probably even overestimated the individual reported associations. Also, photogrammetry in itself is partially dependent of anthropometrics of children.[19] Furthermore, in the perspective of our previous findings using standing postural patterns (unpublished works), the weak correlations observed in this study argue in favor of using patterns as a functional aggregation of overall posture, following the trend of the most recent research.[6, 8, 26]

Our study showed clear postural heterogeneity between girls and boys in early ages denoting different biomechanical loads. Lumbar angle was the most important parameter among all angles studied and body mass index the characteristic mostly associated with it, especially in girls. There was a predominant role of the sway angle especially among boys, in whom it was positively associated with age. However, all the associations were weak and it seems that the study of patterns of sagittal standing posture is of added value compared to isolated postural measures. Nevertheless, if researchers choose to focus on individual angular measures of sagittal standing posture, lumbar and sway angles are the best proxies for overall posture in children on the basis of their relation with anthropometrics and body composition parameters.

Acknowledgments The authors also gratefully acknowledge the families enrolled in Generation XXI and the contribution of the members of the research team and staff.

Funding The funding for EPIUnit was obtained from the "FCT – Fundação para a Ciência e a Tecnologia" (FCT UID/DTP/04750/2013/002). Generation XXI was funded by the Health Operational Programme – Saúde XXI, Community Support Framework III and the Regional Department of Ministry of Health. It has been further supported by FEDER funds through "Programa Operacional Factores de Competitividade – COMPETE" and by national funds through "FCT – Fundação para a Ciência e a Tecnologia" (projects EXPL/DTP-EPI/0280/2012, PTDC/DTP-EPI/1687/2014 and PTDC/DTP-EPI/3306/2014) and by the Calouste Gulbenkian Foundation. The work of Araújo FA and Lucas R was supported by the "FCT – Fundação para a Ciência e a Tecnologia" (grants SFRH/BD/85398/2012 and SFRH/BPD/88729/2012).

What is already known on this topic?

- Anthropometry and body composition have been suggested to shape pediatric sagittal standing posture.
- Body size since birth is associated with postural patterns defined at 7 years of age.
- Bone mineral content and density were associated with postural patterns in the same direction of anthropometry in 7-years-old children.

What this study adds?

- There was clear postural heterogeneity between girls and boys in early ages denoting different biomechanical loads.
- Lumbar and sway angles are the best proxies for overall posture in children on the basis of their relation with anthropometrics and body composition.
- It seems that the study of patterns of sagittal standing posture is of added value compared to isolated postural measures.

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Table 1 Anthropometric variables, body composition parameters and angles of sagittal standing posture, shown separately for girls and boys

	All (n=2117)		Girls (n=1021)				Boys (n=1096)				
	Mean	SD	Mean	SD	Min	Max	Mean	SD	Min	Max	P
Birth											
Weight, g	3151.8	521.5	3102.6	522.6	940.0	5200.0	3197.6	516.5	925.0	4460.0	<0.001
Length, cm	48.6	2.4	48.3	2.4	35.0	54.0	48.9	2.5	36.5	55.5	<0.001
Ponderal index, 100*(g/cm^3)	2.72	0.27	2.74	0.26	1.52	3.74	2.71	0.27	1.89	5.11	0.017
4 years											
Weight, kg	17.9	2.8	17.9	3.0	11.8	35.4	17.8	2.6	10.4	37.7	0.665
Height, cm	104.9	4.5	104.3	4.5	87.8	120.2	105.4	4.5	91.2	120.7	<0.001
BMI, kg/m^2	16.17	1.75	16.35	1.98	12.40	28.72	16.00	1.49	11.53	27.40	<0.001
7 years											
Weight, kg	27.1	5.5	27.3	5.9	16.7	60.5	27.0	5.1	16.9	51.0	0.278
Height, cm	124.6	5.6	124.1	5.5	105.0	142.7	125.1	5.6	107.4	147.9	<0.001
BMI, kg/m^2	17.38	2.62	17.60	2.84	12.69	32.81	17.18	2.38	12.43	29.86	<0.001
Fat mass, kg	7.7	3.4	8.5	3.6	2.8	29.2	6.9	3.1	2.4	24.8	<0.001
Fat-free mass, kg	15.3	2.4	14.7	2.3	9.2	25.6	15.8	2.3	10.0	25.9	<0.001
FMI, kg/m^2	4.88	1.98	5.43	2.06	1.77	15.82	4.36	1.75	1.66	14.50	<0.001
FFMI, kg/m^2	9.78	0.95	9.47	0.93	7.31	13.90	10.07	0.88	7.80	13.28	<0.001
Bone area, cm^2	961.0	64.1	962.8	62.5	778.9	1211.1	959.4	65.6	705.6	1218.1	0.216
BMC, g	595.8	85.8	591.4	85.4	369.3	935.9	599.9	86.0	360.4	966.4	0.022
BMD, g/cm^2	0.62	0.06	0.61	0.06	0.47	0.79	0.62	0.05	0.46	0.81	<0.001
Age, years	7.4	0.4	7.4	0.4	6.9	8.6	7.4	0.4	6.9	8.7	0.487
Trunk angle, º	204.2	6.6	203.7	6.8	176.8	226.7	204.7	6.4	182.1	226.9	0.001
Lumbar angle, º	279.2	7.6	281.7	7.4	257.5	311.1	276.8	7.1	253.5	299.9	<0.001
Sway angle, º	164.9	4.7	164.9	4.6	151.9	180.6	164.8	4.9	148.7	182.4	0.546
Head flexion, º	74.0	7.7	74.4	7.5	45.4	98.0	73.7	7.8	47.6	101.6	0.033
Neck flexion, º	42.3	4.9	43.3	4.8	29.2	61.8	41.3	4.8	25.5	59.1	<0.001
Craniocervical angle, º	148.2	8.4	148.8	8.3	121.8	178.3	147.5	8.5	125.2	178.3	<0.001
Cervicothoracic angle, º	138.6	5.8	137.0	5.7	116.1	167.2	140.1	5.4	115.6	157.2	<0.001
Thoracic flexion, º	1.1	4.7	0.5	4.6	-17.0	17.7	1.6	4.7	-14.3	16.2	<0.001
Pelvic tilt, º	130.6	7.3	128.6	7.1	105.0	159.4	132.4	7.0	107.7	153.5	<0.001

SD, standard deviation; Min, minimum; Max, maximum; BMI, body mass index; FMI, fat mass index; FFMI, fat-free mass index; BMC, bone mineral content; BMD, bone mineral density.

Table 2 Correlations (Pearson's coefficient) of anthropometrics variables and body composition parameters with angles of sagittal standing posture, in girls (n=1021)

	Trunk angle	Lumbar angle	Sway angle	Head flexion	Neck flexion	Craniocervical angle	Cervicothoracic angle	Thoracic flexion	Pelvic tilt
Birth									
Weight	0.10†	0.06	-0.03	0.02	0.05	0.01	-0.01	0.02	0.03
Length	0.09†	0.02	-0.02	0.03	0.03	-0.01	0.00	0.04	0.04
Ponderal index	0.06	0.07*	-0.03	0.01	0.05	0.02	-0.04	0.00	0.01
4 years									
Weight	0.13‡	0.24‡	-0.01	0.06	0.04	-0.03	0.00	0.03	-0.04
Height	0.10†	0.09†	0.02	0.05	-0.11†	-0.11‡	0.16‡	0.07*	-0.02
BMI	0.11‡	0.27‡	-0.03	0.05	0.12‡	0.03	-0.11‡	-0.02	-0.04
7 years									
Weight	0.15‡	0.28‡	-0.04	0.04	0.06*	0.00	-0.04	0.00	-0.02
Height	0.12‡	0.09†	0.03	0.01	-0.13†	-0.09†	0.20‡	0.10†	0.00
BMI	0.13‡	0.31‡	-0.07*	0.05	0.14‡	0.04	-0.16‡	-0.06	-0.02
Fat mass	0.15‡	0.29‡	-0.03	0.03	0.14‡	0.05	-0.11‡	0.00	-0.01
Fat-free mass	0.12‡	0.20‡	-0.03	0.05	-0.06	-0.08†	0.08†	0.02	-0.02
FMI	0.14‡	0.31‡	-0.05	0.03	0.18‡	0.08*	-0.17‡	-0.03	-0.01
FFMI	0.08*	0.22‡	-0.08*	0.08*	0.01	-0.06	-0.05	-0.06	-0.03
Bone area	0.07*	0.03	0.05	-0.01	-0.11‡	-0.06	0.18‡	0.09†	-0.01
BMC	0.09†	0.15‡	0.01	0.02	-0.07*	-0.06*	0.11†	0.05	-0.03
BMD	0.10†	0.22‡	-0.03	0.05	-0.03	-0.06*	0.04	0.00	-0.04
Age	0.05	-0.07*	0.12‡	-0.21‡	-0.12‡	0.12‡	0.22‡	0.16‡	0.03

BMI, body mass index; FMI, fat mass index; FFMI, fat-free mass index; BMC, bone mineral content; BMD, bone mineral density.
* Significant with $P<0.05$; † Significant with $P<0.01$; ‡ Significant with $P<0.001$

Table 3 Correlations (Pearson's coefficient) of anthropometrics variables and body composition parameters with angles of sagittal standing posture, in boys (n=1096)

	Trunk angle	Lumbar angle	Sway angle	Head flexion	Neck flexion	Craniocervical angle	Cervicothoracic angle	Thoracic flexion	Pelvic tilt
Birth									
Weight	0.04	-0.01	-0.07*	0.00	-0.06	-0.03	0.04	-0.01	0.07*
Length	0.08*	-0.02	-0.08*	0.00	-0.08†	-0.05	0.07*	0.00	0.10†
Ponderal index	-0.04	0.04	-0.02	-0.01	0.02	0.02	-0.04	-0.03	-0.03
4 years									
Weight	0.09†	0.16‡	-0.06*	0.02	-0.06*	-0.06	0.06*	0.01	-0.01
Height	0.09†	0.02	-0.01	0.03	-0.12‡	-0.10†	0.17‡	0.07*	0.06*
BMI	0.05	0.22‡	-0.08†	0.01	0.01	0.00	-0.06	-0.05	-0.07*
7 years									
Weight	0.12‡	0.21‡	-0.07*	0.00	-0.03	-0.02	0.03	0.00	0.00
Height	0.08†	0.04	0.04	-0.01	-0.16‡	-0.09†	0.23‡	0.10†	0.02
BMI	0.11‡	0.26‡	-0.13‡	0.01	0.06	0.02	-0.11‡	-0.06*	-0.01
Fat mass	0.14‡	0.24‡	-0.12‡	0.01	0.05	0.01	-0.06*	-0.03	0.02
Fat-free mass	0.07*	0.13‡	0.01	-0.01	-0.11‡	-0.06	0.14‡	0.05	-0.02
FMI	0.14‡	0.25‡	-0.14‡	0.01	0.08†	0.03	-0.12‡	-0.05	0.02
FFMI	0.03	0.17‡	-0.04	0.00	-0.02	-0.01	0.00	-0.02	-0.05
Bone area	0.03	0.00	0.04	0.00	-0.15‡	-0.09†	0.20‡	0.08†	0.01
BMC	0.04	0.09†	0.02	-0.01	-0.12‡	-0.07*	0.16‡	0.06*	-0.03
BMD	0.04	0.16‡	0.00	-0.01	-0.09†	-0.05	0.10†	0.03	-0.05
Age	0.01	-0.03	0.20‡	-0.13‡	-0.08†	0.07*	0.23‡	0.18‡	-0.05

BMI, body mass index; FMI, fat mass index; FFMI, fat-free mass index; BMC, bone mineral content; BMD, bone mineral density.
* Significant with P<0.05; † Significant with P<0.01; ‡ Significant with P<0.001

Table 4 Linear regression analysis between selected parameters of sagittal standing posture and anthropometrics and body composition parameters at 7 years of age.

	Lumbar angle		Sway angle		Head flexion		Cervicothoracic angle	
	β	**95% CI**	**β**	**95% CI**	**β**	**95% CI**	**β**	**95% CI**
Girls (n=1021)								
Weight	**0.40**	**0.26 to 0.54**	**-0.14**	**-0.22 to -0.05**	0.13	-0.01 to 0.27	**-0.26**	**-0.37 to -0.15**
Height	**0.20**	**0.05 to 0.35**	-0.04	-0.13 to 0.05	**0.17**	**0.02 to 0.32**	0.03	-0.08 to 0.14
BMI	**0.80**	**0.53 to 1.07**	**-0.29**	**-0.46 to -0.11**	0.19	-0.09 to 0.47	**-0.52**	**-0.73 to -0.31**
Fat mass	-0.31	-1.19 to 0.58	**0.65**	**0.08 to 1.21**	-0.52	-1.44 to 0.40	-0.10	-0.77 to 0.57
Fat-free mass	-0.71	-1.68 to 0.27	0.38	-0.24 to 1.01	-0.06	-1.08 to 0.96	0.46	-0.28 to 1.20
Bone area	-0.02	-0.03 to 0.004	0.01	-0.01 to 0.02	-0.02	-0.04 to 0.004	0.01	-0.01 to 0.02
BMC	0.01	-0.01 to 0.03	0.00	-0.02 to 0.01	0.01	-0.01 to 0.03	0.00	-0.02 to 0.01
BMD	8.40	-8.47 to 25.26	-4.12	-14.96 to 6.72	12.43	-5.17 to 30.02	-3.82	-16.57 to 8.94
Age	**-1.94**	**-3.32 to -0.56**	**1.43**	**0.54 to 2.32**	**-5.09**	**-6.53 to -3.65**	**2.85**	**1.81 to 3.90**
Boys (n=1096)								
Weight	**0.37**	**0.23 to 0.51**	**-0.18**	**-0.28 to -0.09**	0.05	-0.11 to 0.20	**-0.20**	**-0.31 to -0.10**
Height	**0.18**	**0.03 to 0.33**	-0.03	-0.13 to 0.07	0.07	-0.09 to 0.23	0.07	-0.04 to 0.18
BMI	**0.64**	**0.37 to 0.91**	**-0.38**	**-0.56 to -0.19**	0.05	-0.25 to 0.36	**-0.41**	**-0.62 to -0.20**
Fat mass	0.39	-0.79 to 1.57	0.28	-0.54 to 1.09	0.88	-0.45 to 2.22	-0.07	-0.95 to 0.82
Fat-free mass	0.19	-1.04 to 1.43	0.59	-0.26 to 1.44	0.77	-0.63 to 2.16	0.26	-0.66 to 1.19
Bone area	**-0.03**	**-0.05 to -0.01**	-0.01	-0.02 to 0.01	0.00	-0.02 to 0.03	0.00	-0.01 to 0.01
BMC	**0.02**	**0.002 to 0.04**	0.00	-0.01 to 0.02	0.00	-0.02 to 0.02	0.00	-0.01 to 0.01
BMD	10.16	-4.92 to 25.24	0.10	-10.32 to 10.52	3.37	-13.73 to 20.47	0.08	-11.26 to 11.41
Age	-1.21	-2.54 to 0.12	**2.44**	**1.52 to 3.36**	**-3.31**	**-4.82 to -1.80**	**2.77**	**1.77 to 3.77**

CI, confidence interval; BMI, body mass index; BMC, bone mineral content; BMD, bone mineral density. Bold type indicates statistical significance.
Weight: adjusted for weight at birth and 4 years-old plus age.
Height: adjusted for length at birth and height at 4 years-old plus age.
BMI: adjusted for ponderal index at birth and BMI at 4 years-old plus age.
Fat: adjusted for all measurements of weight, all measurements of length/height, fat-free mass and age.
Fat-free mass: adjusted for all measurements of weight, all measurements of length/height, fat mass and age.
Bone area: adjusted for all measurements of weight, all measurements of length/height, fat and fat-free mass, BMC and age.
BMC: adjusted for all measurements of weight, all measurements of length/height, fat and fat-free mass, bone area and age.
BMD: adjusted for all measurements of weight, all measurements of length/height, fat and fat-free mass and age.
Age: adjusted for all measurements of weight, all measurements of length/height, fat and fat-free mass, bone area and BMC.

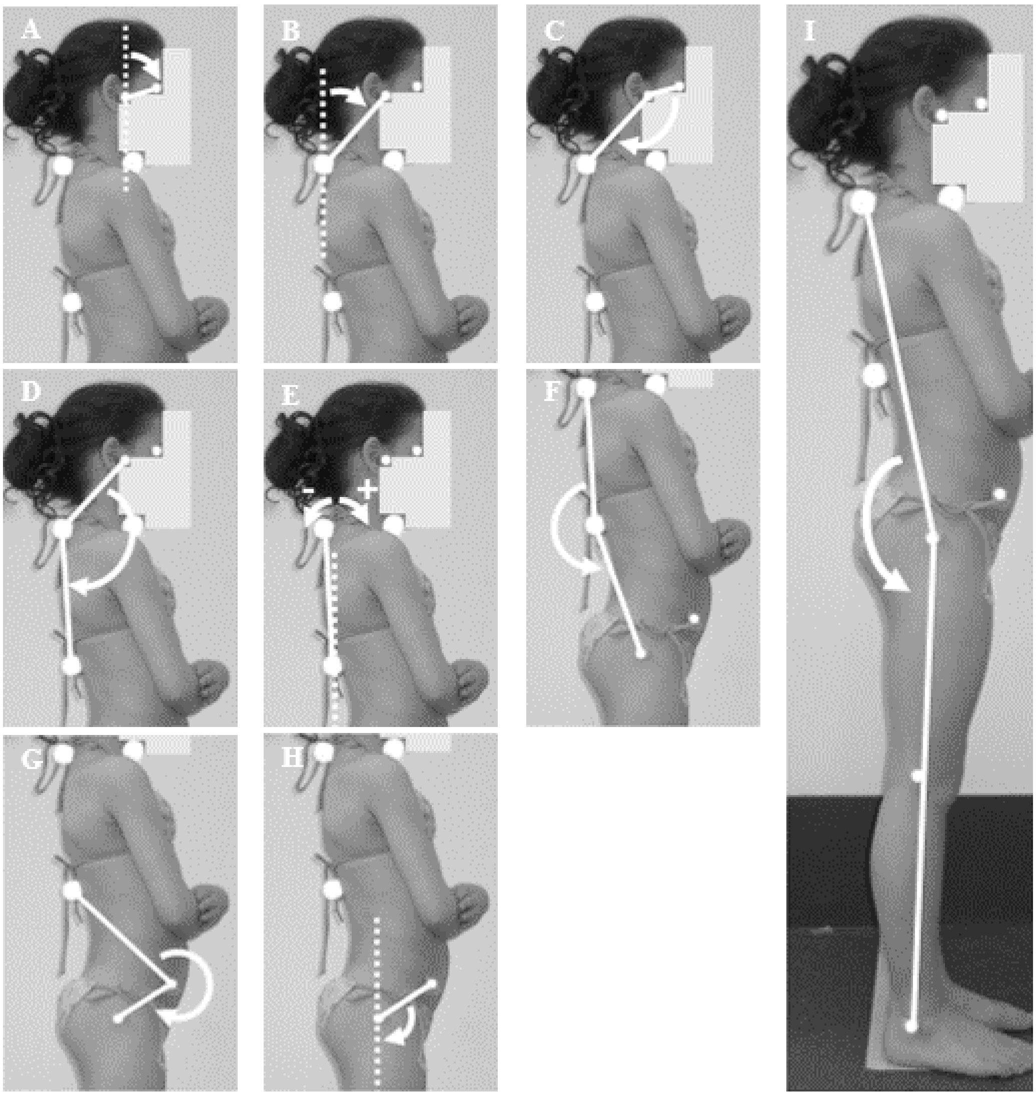

Figure 1 Definition of angles describing sagittal standing posture: (A) Head flexion; (B) Neck flexion; (C) Craniocervical angle; (D) Cervicothoracic angle; (E) Thoracic flexion; (F) Trunk angle; (G) Lumbar angle; (H) Pelvic tilt; (I) Sway angle. Dashes lines indicate the vertical.

4.2. Paper II

Araújo FA, Severo M, Alegrete N, Howe LD, Lucas R.

Defining patterns of sagittal standing posture in girls and boys of school age.

Phys Ther. 2017;97(2):258-67.

Original Research

Defining Patterns of Sagittal Standing Posture in Girls and Boys of School Age

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[Araújo FA, Severo M, Alegrete N, et al. Defining patterns of sagittal standing posture in girls and boys of school age. *Phys Ther.* 2017;97:258–267.]

Published Ahead of Print: October 6, 2016
Accepted: September 26, 2016
Submitted: January 10, 2016

Background. Sagittal postural patterns are associated with back pain in adolescents and adults. However, whether postural patterns are already observable during childhood is unknown. Such a finding would confirm childhood as a key period for posture differentiation and thus for chronic pain etiology.

Objective. The aims of this study were to identify and describe postural patterns in girls and boys of school age.

Design. This was a cross-sectional study.

Methods. Eligible children were evaluated at age 7 in the population-based birth cohort Generation XXI in Portugal. Posture was assessed through right-side photographs during habitual standing with retroreflective markers placed on body landmarks. Postural patterns were defined from trunk, lumbar, and sway angles with model-based clusters, and associations with anthropometric measures were assessed by multinomial logistic regression.

Results. Posture was evaluated in 1,147 girls and 1,266 boys. Three postural patterns were identified: sway (26.9%), flat (20.9%), and neutral to hyperlordotic (52.1%) in girls and sway to neutral (58.8%), flat (36.3%), and hyperlordotic (4.9%) in boys. In girls, a higher body mass index was associated with a sway pattern (versus a flat pattern: odds ratio=1.21; 95% CI=1.12, 1.29), whereas in boys, a higher body mass index was associated with a hyperlordotic pattern (versus a flat pattern: odds ratio=1.30; 95% CI=1.17, 1.44).

Limitations. Photogrammetry as a noninvasive method for posture assessment may have introduced some postural misclassifications.

Conclusions. Postural patterns in 7-year-old children were consistent with those previously found in adults, suggesting that childhood is a sensitive period for posture differentiation. Sagittal morphology differed between girls and boys, emphasizing sex-specific biomechanical loads during a habitual upright position even in prepubertal ages.

Established abnormal sagittal spinopelvic alignment is associated with back pain and physical disability,[1–3] with overall sagittal imbalance showing a high predictive ability for functional loss and dependency in older ages.[4] Sagittal spinopelvic alignment in adulthood is the end result of the complex process of gaining, during childhood and adolescence, the upright position, which stabilizes after skeletal maturity.[5–7] An initial vertical orientation of the pelvis occurs after birth, with the lordotic curve arising at the lower back as the child begins to assume a sustained upright position. Then, pelvis shape and physiologic curves of the spine gradually develop with growth to ensure adequate balance and an appropriate configuration in terms of responses to skeletal loads and energy expenditure.[5–7] For instance, a progressive increase in the lumbar angle complemented with a backward tilt of the spine over the hips is observed.[8]

Different classifications of sagittal phenotypes have been proposed[9–13]; these generally take, as a reference, a neutral postural pattern characterized by intermediate values of alignment and representing a well-balanced spine. Nonneutral sagittal postures are then characterized by deviations from the neutral pattern and feature different combinations of regional alignment and global balance. Because postural patterns account for the potential synergistic effects of different spinopelvic characteristics aggregated into a unique phenotype, they are expected to offer an advantage for the understanding of standing posture. In terms of clinical meaning, nonneutral sagittal standing postural patterns have been associated with back pain in adulthood[3,14] and in late[10] and early[11] adolescence. However, to our knowledge, classification of postural patterns in children has not been attempted, and whether the division of people into neutral and nonneutral variants occurs in the early stages of life, when extensive growth and development of the musculoskeletal system take place, is unknown.[15] Therefore, our hypothesis is that empirically obtained patterns in children of school age are consistent with those observed in midadolescence and adulthood in terms of sagittal morphology, although less differentiated patterns can be expected because of the continuing development of the musculoskeletal system in children.

To study early childhood as a sensitive period for the development of sagittal postural patterns, it important to focus on children who are prepubertal because both sexes at that age are still largely homogeneous with regard to sexual and skeletal development—that is, before pubertal timing begins to modulate individual posture development.[16] Therefore, we aimed to identify and describe postural patterns in 7-year-old girls and boys and to explore their associations with anthropometric characteristics.

Method

Participants

This study was conducted within Generation XXI, a population-based birth cohort of 8,647 live-born infants and their mothers initially assembled from all 5 public maternity units covering the 6 municipalities of the metropolitan area of Porto, Portugal, in 2005 and 2006.[17,18] At the birth of the infants, 91.4% of the invited mothers agreed to participate. Written informed consent was obtained from the participants. Invitation to the follow-up of the 7-year-old children was carried out on the basis of the children's birth dates, and 79.7% of the children initially recruited participated in this wave of assessment. A subsample of 3,005 children consecutively attending the evaluation of 7-year-old between December 2012 and August 2013 were eligible for posture assessment (Fig. 1). Potential bias was assessed by comparing Generation XXI children who were included and those who were not included.

Data Collection

As part of the evaluation of the 7-year-old children, data were collected by trained interviewers in face-to-face assessments. Weight was measured to the nearest tenth of a kilogram with a digital scale (Tanita, Tokyo, Japan), and height was measured to the nearest tenth of a centimeter with a wall stadiometer (Seca, Chino, California). Body mass index (BMI) was computed as weight (in kilograms) over squared height (in meters).

Sagittal Standing Posture

The sagittal standing posture evaluation was performed by quantitative assessment of photographs of the sagittal right view of children, a method previously validated in adolescents[19–21] and adults[22,23] and characterized by acceptable reproducibility.[24–26] By extrapolation, photogrammetry is recommended as the safest method for postural evaluation in large-scale studies of children.[13,24,25] This assessment occurred between March 2013 and February 2014 (medians of 62 [interquartile range=211] and 63 [interquartile range=212] days after the evaluation of 7-year-old girls and boys, respectively). For both sexes, the median age was 7.3 years (25th percentile–75th percentile=7.1–7.7 years).

With double-faced adhesive tape, spherical retroreflective markers (12 and 30 mm) were placed over anatomical landmarks on the right side of the child's body: lateral canthus of the eye, tragus, anterior border of the acromium (30 mm), spinous processes of C7 and T12 (30 mm), anterior superior iliac spine, greater trochanter, lateral epicondyle of the femur, and lateral malleolus. Additionally, a plumb line with two 20-mm polystyrene circumferences (50-cm distance from each other) was placed behind children and 50 cm from the wall (the same distance as the right side of the child's body) to allow vertical-angle offset and distance calibration during the digitization of photographs. The evaluation was performed by 1 of 2 health professionals in a dedicated room. Both examiners received several theoretical and practical sessions of anatomy tuition before data collection.

Children were barefoot, were wearing underwear or swimwear, and were instructed to rest comfortably in a habitual standing position with the feet slightly apart, looking straight ahead, and moving elbows forward, as previously described by Perry et al,[24] to standardize their positions. Floor markers

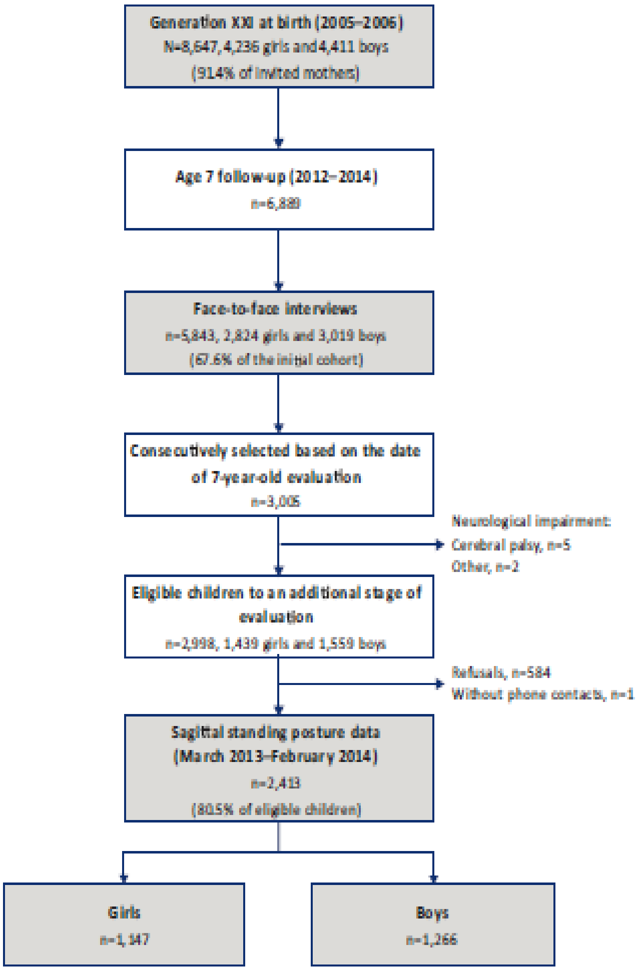

Figure 1.
Flow diagram for inclusion of Generation XXI children. The 584 refusals included 252 children who refused to participate in the posture evaluation and 332 participants who scheduled 3 appointments for evaluation but did not keep the appointments or did not respond to our invitation after at least 5 attempts.

also were used to regulate the relative position of a child with respect to the camera. After the examiner judged that the usual upright position had been attained, full-body flash photographs were obtained with a Canon PowerShot A2300 (4,608 × 3,456 pixels; Canon USA Inc, Arlington, Virginia) attached to a 60-cm-high tripod placed 200 cm from the wall and perpendicular to the child. The tripod was fixed on the floor, and the zoom feature of the camera was not used.

Anatomical landmarks were digitized with the valid and reliable postural assessment software PAS/SAPO,[27] which allowed computation of 9 angles and 3 distances describing the sagittal standing position, in accordance with the protocol suggested by Perry et al.[24] This protocol prioritizes biologically relevant measurements (ie, quantifies the relative positions of body segments), avoiding the use of the vertical line reference and, therefore, optimizing photographic reliability.[24–26] Angles were formed by the lines traced from the labeled anatomical landmarks, and the 2-dimensional coordinates of each marker were used to determine distances, as exemplified in Figure 2. All of the photographs were digitized by one of the researchers who carried out the physical examinations (F.A.A., a physical therapist) in accordance with specific training to measure angles in a systematic manner in terms of order and quality. The zoom feature of the software was used freely.

Data Analysis

Interobserver calibration. Each child was evaluated only by one examiner. Because participants were randomly allocated to each examiner, differences in the distributions of measurements were attributed to observer effects.[28] Therefore, calibration was performed by considering the measurements of the physical therapist examiner as the reference, that is, adding the difference between means obtained by each examiner to the individual values for each child evaluated by the second observer—for this purpose, called calibrated measures.[29]

Sagittal postural patterns. Trunk, lumbar, and sway angles (Figs. 2F–2H) completely characterize thoraco-lumbo-pelvic sagittal alignment in the standing position,[10] corresponding to the most relevant sagittal characteristics evaluated in clinical settings[30] and, therefore, were used to identify postural patterns.

The calibrated measures explained earlier were used to define postural patterns. Because spinal postures differed between girls and boys and seem to contribute to the unequal prevalence of postural deformities in the sexes,[31,32] we chose to identify patterns separately for girls and boys. Model-based clustering[33] was used to identify groups of children who shared similar postures. This clustering procedure was chosen instead of conventional heuristic methods because it has the key advantage of allowing the testing of different variances of angle measures within and across clusters. In this procedure, postural angles

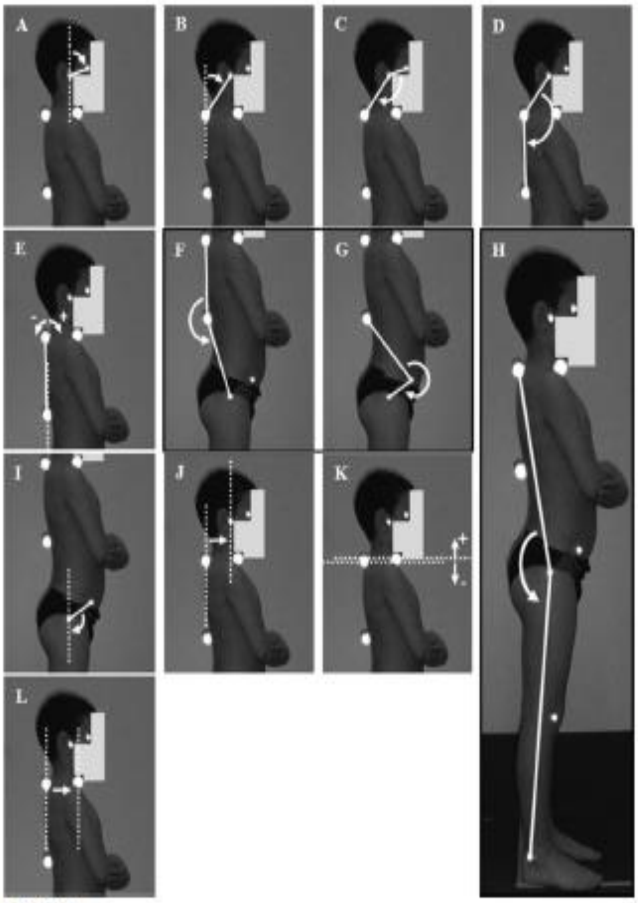

Figure 2.
Definition of angles (A–I) and distances (J–L) describing sagittal standing posture. (A) Head flexion. (B) Neck flexion. (C) Craniocervical angle. (D) Cervicothoracic angle. (E) Thoracic flexion. (F) Trunk angle. (G) Lumbar angle. (H) Sway angle. (I) Pelvic tilt. (J) Head displacement. (K) Scapular elevation. (L) Scapular displacement. Dashed lines indicate vertical or horizontal. Delimited angles (F–H) were used in model-based patterns of sagittal standing posture.

are assumed to have a multivariate normal distribution, parameterized by their means and covariances. The geometric features (orientation, volume, and shape) of the distributions are estimated from the data, and their differences across clusters are tested.[34] Initially, the model assessed as being optimal in terms of geometric features and number of clusters was determined to be that with the smallest Bayesian Information Criterion.[35] Additionally, the choice was also informed by previously identified patterns at older ages[9,10]: increased kyphosis with spinal backward tilt (sway), straight spine with forward trunk lean (flat), neutral alignment and balance (neutral), and increased thoracic and lumbar spinal curves (hyperlordotic). Data analysis was conducted with R software version 2.14.1 (R Foundation; https://www.r-project.org/foundation/).

Associations with covariates. Associations between postural clusters and weight, height, and BMI were assessed through analysis of variance or Kruskal-Wallis tests. Age-adjusted odds ratios (ORs) and respective 95% confidence intervals (CIs) for postural patterns were estimated by multinomial logistic regression models as a function of weight, height, and BMI. For assessment of the effect of weight, estimates were additionally adjusted for height.

Role of the Funding Source

The funding for EPIUnit was obtained from the Fundação para a Ciência e a Tecnologia (FCT) (UID/DTP/04750/2013/002). Generation XXI was funded by the Health Operational Programme–Saúde XXI, Community Support Framework III, and the Regional Department of Ministry of Health. It has been further supported by FEDER funds through the Programa Operacional Factores de Competitividade, by national funds through the FCT (projects PIC/IC/83038/2007, SFRH/BD/72723/2010, and EXPL/DTP-EPI/0280/2012), and by the Calouste Gulbenkian Foundation. The work of Mr Araújo and Professor Lucas was supported by the FCT (grants SFRH/BD/85398/2012 and SFRH/BPD/88729/2012). The funding sources had no role in the design or conduct of the study; collection, management, analysis, or interpretation of the data; preparation, review, or approval of the manuscript; or decision to submit the manuscript for publication.

Results

Posture was evaluated in 1,147 girls and 1,266 boys after exclusions and refusals. Included children were slightly older than those not included ($P<.001$ for both sexes), and the mother's level of formal education was higher for included children (median years for both sexes: 12.0 versus 9.0; $P<.001$). Despite these differences, the anthropometric characteristics at birth of included children and those not included were similar (eTab. 1, available at academic.oup.com/ptj).

Statistical Criterion for Postural Patterns

Crude analysis revealed very weak linear pair-wise associations between individual postural angles ($|r|<.20$; data not shown); therefore, we chose to not consider covariance parametrizations

Table 1.
Selected Postural Measures and Anthropometrics Used in Model-Based Sagittal Postural Patterns[a]

Measure	Girls: All	Girls: 1: Sway Pattern (n=309, 26.9%)	Girls: 2: Flat Pattern (n=240, 20.9%)	Girls: 3: Neutral to Hyperlordotic Pattern (n=598, 52.1%)	Girls: P	Boys: All	Boys: 1: Sway to Neutral Pattern (n=745, 58.8%)	Boys: 2: Flat Pattern (n=459, 36.3%)	Boys: 3: Hyperlordotic Pattern (n=62, 4.9%)	Boys: P	P for Girls vs Boys
Trunk angle, °	203.7 (6.8)	211.1 (4.4)	205.9 (3.4)	199.0 (4.7)	<.001	204.8 (6.4)	207.7 (5.4)	201.4 (4.9)	194.6 (5.6)	<.001	<.001
Lumbar angle, °	281.7 (7.4)	281.9 (7.2)	275.4 (6.0)	284.2 (6.5)	<.001	276.8 (7.2)	276.4 (6.8)	275.8 (6.5)	288.9 (5.2)	<.001	<.001
Sway angle, °	164.9 (4.6)	161.2 (3.7)	167.5 (3.4)	165.8 (4.2)	<.001	164.8 (4.9)	162.3 (3.4)	169.3 (3.5)	162.7 (4.3)	<.001	.683
Weight, kg	24.8 (22.2–28.9)	25.6 (22.6–30.4)	23.9 (21.5–27.0)	24.8 (22.3–28.7)	<.001	25.0 (22.6–28.2)	25.3 (22.9–28.6)	24.3 (22.1–27.2)	26.2 (23.7–30.3)	<.001	.563
Height, cm	122.8 (5.1)	123.2 (5.0)	122.6 (5.4)	122.7 (5.1)	.237	123.9 (5.3)	124.1 (5.3)	123.6 (5.2)	124.4 (4.7)	.343	<.001
Body mass index, kg/m²	16.49 (15.18–18.60)	16.89 (15.35–19.52)	16.03 (14.87–17.45)	16.55 (15.28–18.62)	<.001	16.30 (15.25–17.77)	16.41 (15.35–17.99)	15.90 (14.94–17.01)	17.36 (15.75–19.35)	<.001	.018

[a] Information for anthropometric measures was missing for 2 girls and 1 boy. Angles and height are reported as mean (standard deviation); weight and body mass index are reported as median (25th percentile–75th percentile).

that allowed correlations between individual measures within patterns. However, after comparison of different types of parametrizations in our postural models, the smallest Bayesian Information Criterion was found for a one-group solution for all of these parametrizations. Therefore, on the basis of the statistical criterion alone, the cluster solution suggested postural homogeneity. The single-cluster solution seemed inappropriate for identifying a theoretically plausible cluster structure featuring expected postural variability at the population level.

Statistical and Theoretical Criteria for Postural Patterns

We chose the next-best-fitting models: 2- and 3-pattern solutions (with similar Bayesian Information Criterion values) in girls and 3-pattern solutions in boys (eFigs. 1 and 2, available at academic.oup.com/ptj). We opted for the 3-pattern model of equal volume, equal shape, and coordinate axis orientation (which assumed different variances between variables within patterns and equal variances between patterns) for both sexes because this model had a better Bayesian Information Criterion than models that assumed different variances between patterns. The selected models were characterized by average probabilities of pattern assignment of 60% in girls and 73% in boys (detailed information regarding quality assignment is provided in eFig. 3, available at academic.oup.com/ptj). Table 1 and Figure 3 show the features of the final 3-pattern solution, separately for girls and boys. Additional postural characterization is provided in eTable 2 (available at academic.oup.com/ptj).

Girls

In girls, patterns were labeled as sway (26.9%), flat (20.9%), and neutral to hyperlordotic (52.1%). Type 1 was labeled as sway because it showed the largest trunk angle and the smallest sway angle, with means of 211.1 degrees (SD=4.4°) and 161.2 degrees (SD=3.7°), respectively. Type 2 was labeled as flat because it showed the smallest lumbar angle (275.4° [SD=6.0°]) and the largest sway angle (167.5° [SD=3.4°]). Type 3 was the most frequent (present

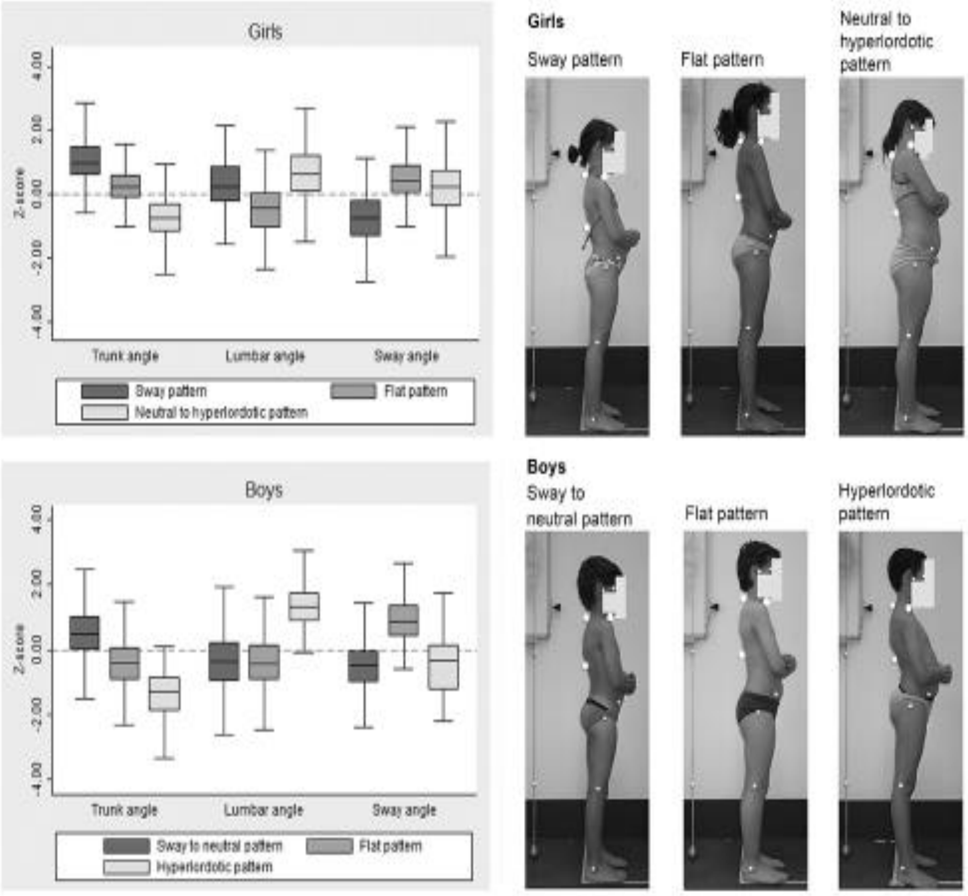

Figure 3.
Box plots showing the distribution (median, interquartile range, and range) for each postural measure, standardized to a mean of 0 and a standard deviation of 1, across model-based sagittal standing postural patterns (left) and examples of patterns (right). Data are shown separately for girls and boys.

in more than half of the sample) and showed the smallest trunk angle (199.0° [SD=4.7°]) and the largest lumbar angle (284.2° [SD=6.5°]); therefore, it was labeled as neutral to hyperlordotic.

Boys

In boys, patterns were labeled as sway to neutral (58.8%), flat (36.3%), and hyperlordotic (4.9%). Type 1 in boys showed the same postural organization as that in girls (trunk angle: 207.7° [SD=5.4°]; sway angle: 162.3° [SD=3.4°]). However, unlike in girls, this was the most prevalent pattern in boys (58.8%) and, therefore, was labeled as sway to neutral. Type 2 was labeled as flat because it showed the smallest lumbar angle (275.8° [SD=6.5°]) and the largest sway angle (169.3° [SD=3.5°]). Type 3 was much less frequent in boys (4.9%) than in girls but had more extreme features—a smaller trunk angle (194.6° [SD=5.6°]) and a larger lumbar angle (288.9° [5.2°]—and, therefore, was labeled as hyperlordotic.

Associations With Covariates

In both sexes, children with the flat pattern were lighter and shorter, with a median weight of 23.9 kg (25th percentile–75th percentile range=21.5–27.0) and a mean height of 122.6 cm (SD=5.4) for girls and corresponding values of 24.3 kg (25th percentile–75th percentile range=22.1–27.2) and 123.6 cm (5.2) for boys. Girls with the sway pattern and boys with the hyperlordotic pattern were the heaviest (25.6 kg [25th percentile–75th percentile range=22.6–30.4] and 26.2 kg [25th percentile–75th percentile range=23.7–30.3], respectively) (Tab. 1).

Tables 2 and 3 show the adjusted associations of anthropometrics (independent variables) with postural patterns (dependent variables), with the flat pattern as a reference for both sexes to improve comparability. For girls, after adjustment for age and height, the proportional increases in ORs per

Table 2.
Adjusted Associations Between Model-Based Postural Patterns (Dependent Variables) and Anthropometrics (Independent Variables) for Girls[a]

Measure	Sway Pattern			Flat Pattern	Neutral to Hyperlordotic Pattern			
	Odds Ratio[b]	95% CI	*P*	Odds Ratio	Odds Ratio[b]	95% CI	*P*	*P*[c]
Weight, kg	1.13	1.08–1.19	<.001	1	1.08	1.03–1.12	.001	<.001
Height, cm	1.03	1.00–1.07	.067	1	1.01	0.98–1.04	.489	.011
Body mass index, kg/m²	1.21	1.12–1.29	<.001	1	1.11	1.04–1.19	.001	<.001

[a]Information for anthropometric measures was missing for 2 girls.
[b]All variables were adjusted for age; weight also was adjusted for height.
[c]For the overall test of differences in odds ratios across the 3 groups. Comparisons of the sway pattern and the neutral to hyperlordotic pattern reached statistical significance ($P < .05$) for weight and body mass index.

Table 3.
Adjusted Associations Between Model-Based Postural Patterns (Dependent Variables) and Anthropometrics (Independent Variables) for Boys[a]

Measure	Sway to Neutral Pattern			Flat Pattern	Hyperlordotic Pattern			
	Odds Ratios[b]	95% CI	*P*	Odds Ratios	Odds Ratios[b]	95% CI	*P*	*P*[c]
Weight, kg	1.08	1.04–1.12	<.001	1	1.17	1.09–1.26	<.001	<.001
Height, cm	1.02	1.0009–1.05	.042	1	1.04	0.98–1.09	.179	<.001
Body mass index, kg/m²	1.14	1.08–1.21	<.001	1	1.30	1.17–1.44	<.001	<.001

[a]Information for anthropometric measures was missing for one boy.
[b]All variables were adjusted for age; weight also was adjusted for height.
[c]For the overall test of differences in odds ratios across the 3 groups. Comparisons of the sway to neutral pattern and the hyperlordotic pattern reached statistical significance ($P < .05$) for weight and body mass index.

1-kg increase in weight were 1.13 (95% CI=1.08, 1.19) for having the sway pattern and 1.08 (95% CI=1.03, 1.12) for having the neutral to hyperlordotic pattern. After adjustment for age, for a BMI of 1 kg/m², the ORs were 1.21 (95% CI=1.12, 1.29) for having the sway pattern and 1.11 (95% CI=1.04, 1.19) for having the neutral to hyperlordotic pattern. For boys, after adjustment for age and height, the proportional increases in ORs per 1-kg increase in weight were 1.08 (95% CI=1.04, 1.12) for having the sway to neutral pattern and 1.17 (95% CI=1.09, 1.26) for having the hyperlordotic pattern. After adjustment for age, for a BMI of 1 kg/m², the ORs were 1.14 (95% CI=1.08, 1.21) for having the sway to neutral pattern and 1.30 (95% CI=1.17, 1.44) for having the hyperlordotic pattern.

Discussion

In the present study, we identified 3 patterns of sagittal standing posture in girls and boys of school age that are consistent with those previously described in adults. The flat pattern was observable in both sexes, but the relative prevalence in boys was higher. In addition, the sway and neutral to hyperlordotic patterns were identified in girls, whereas the sway to neutral and hyperlordotic patterns were found in boys. In both sexes, the patterns differed according to anthropometric measures—a finding supporting them as biologically plausible types of sagittal posture in 7-year-old children.

Our types 1 and 2 in both sexes resembled, in their relative features, those previously described in adults as sway (increased kyphosis with backward tilt of the spine over the hips) and flat (straight spine with forward trunk lean), respectively. Our type 3 corresponded to the neutral pattern (relatively increased lumbar lordosis and intermediate body sway) in girls and to the hyperlordotic pattern (extremely increased lumbar lordosis) in boys. However, 4 postural patterns were previously described in adults (age range=18–48 years)[9] and then were suggested to be present in adolescents (between 13 and 15 years old) as well[10]: sway, flat, neutral, and hyperlordotic patterns. Therefore, our type 3 in girls was labeled as neutral to hyperlordotic. The aggregation of these 2 patterns seemed to result from a larger lumbar angle in girls than in boys (4.9°; $P \leq .001$). In one other type, nearly 60% of boys and 2 different patterns were aggregated; this type (type 1) was labeled as sway to neutral.

These findings support the hypothesis that, when statistical and theoretical criteria are both used, sagittal patterns are observable even in early childhood. It seems likely that, to some extent, they will track over time, leading to the patterns described in adolescence[10] and adulthood.[9] Our finding of a single-pattern solution when only statistical criteria were applied is in accordance with an initial hypothesis of less differentiated patterns in children, in which a progressive maturational process of the constitutional sagittal typology is expected because of a stronger control of sagittal balance as children get older.[7,26]

Longitudinal studies are required to confirm that both covariance structure and number of patterns will change over time, but our hypothesis is further supported by the direction of the relationships between the observed patterns and anthropometrics. In particular, an increasing gradient of BMI from the flat pattern to the hyperlordotic pattern was observed, in agreement with the increasing gradient reported across the flat, neutral, sway, and hyperlordotic types.[10,13,36] Furthermore, differences in BMI across patterns in the present study still hold after comparison of patterns weighted by the probability of pattern membership (data not shown). Body mass index is indeed the most consistent determinant of sagittal posture development[13] because adiposity is thought to cause plastic deformation of spinopelvic structures in the early stages of life, thus allowing tracking of specific sagittal patterns throughout life. Additionally, when we used the same statistical procedures as those used for research with adolescents (ie, hierarchical analysis by the Ward method followed by the K-means algorithm)[10] separately for each sex, the best solution was congruent with the results of the present study (data not shown). The same postural patterns were observed, despite the homogeneous prevalence of patterns (varying from 30% to 37%).

In the present study, the neutral to hyperlordotic pattern was by far the most prevalent in girls (52.1%), and 58.8% of the boys showed a sway to neutral pattern. The most plausible reason for the clear differences in patterns between girls and boys seems to be a true sex-related heterogeneity of postural types in children of school age. Although in girls the hyperlordotic posture was merged with the broad neutral type and this merging seemed to have been driven by the similar high lumbar angles,[9,10] in boys the sway and neutral types were the most similar—probably because of the predominant backward tilt of the spine in children,[7] which was observed only in boys in the present study. Differences in lumbar lordosis between the sexes have been reported incongruently,[13] but the female spine features structural phylogenetic adaptations that may justify an increased lumbar angle in girls.[13,31,32,37,38]

Concordantly, only a small group of boys with hyperlordosis (4.9%) was identified, and model-based procedures were able to differentiate this pattern, with a large lumbar angle, from those for all of the other boys, with a smaller angle in the lumbar region. Therefore, we still chose to retain this solution despite the small group of boys with the hyperlordotic pattern.

The flat pattern was the only one commonly observed in both sexes, but it seems to have been more prevalent in boys than in girls (36.3% versus 20.9%), as reported in adolescents[10,36] and adults[13,39] and in agreement with the general knowledge that the male spine is less curved in the lumbar region.[13,31,32,37,38]

Evidence of the clinical relevance of postural patterns is compelling.[3,9-11,14,40,41] In adults, both flat and lordotic postural types have been associated with back pain.[3,14] Additionally, the sway and flat types are expected to contribute to the mechanical etiology of discopathy, and the hyperlordotic type is expected to contribute to vertebral listhesis.[3,40,41] In midadolescence, all nonneutral types were associated with different measures of back pain,[10] and in boys who were 12.6 years old, sway-backed balance was associated with a higher prevalence of pain in the low back and neck.[11] Follow-up of the children in our sample to assess the onset of back pain will be of great value for improving knowledge regarding the clinical role of posture throughout life. However, one of the main findings of this work—the lack of a neutral variant of sagittal standing posture in both sexes—emphasizes the need for caution regarding the interpretation of neutral alignment or balance as the ideal variant in children of school age—a notion frequently implied in clinical settings.[9,11,42]

To our knowledge, the present study is the largest population-based investigation of sagittal postural patterns so far and the first to focus on children younger than 10 years. According to cluster analysis, the recommended sample size would be $5{\times}2^k$ (where k is the number of input variables)[43]—in this case, a minimum sample size of 40—meaning that our sample size clearly provided enough power to carry out the present analysis. Model-based clustering allowed us to assess the most appropriate configuration among 10 different solutions of covariance structures, whereas previously used[10-12] heuristic clustering methods (Ward method and K-means algorithm) considered only 1 restricted covariance structure.[35]

Conceptually, sagittal patterns are an attempt to categorize a continuum of the postural spectrum. Classifying children into mutually exclusive classes may lead to some misclassification, especially if children show a combined distribution of individual postural angles that is compatible with more than one pattern. For example, children classified as having the flat pattern still had a 31% average probability of being classified as having the neutral to hyperlordotic pattern (girls) and a 25% average probability of being classified as having the sway to neutral type (boys) (eFig. 3). Nevertheless, our statistical approach allowed us to quantify uncertainty for each pattern assignment; this approach is particularly useful for modeling sagittal posture within a probabilistic framework.[44]

Finally, the use of photogrammetry to assess our major outcome may have introduced some misclassification because of systematic or random differences in the placement of markers between and within examiners, which can depend on children's anthropometric characteristics; for example, lower accuracy in pelvic anatomical identification can occur in children with higher subcutaneous adiposity.[24] However, these issues were not expected to compromise our findings for several reasons: systematic differences were accounted for by quantifying the distance between the children's values and the average values within each examiner's distribution; consistent statistically significant associations between weight or BMI and postural types were still observable in both sexes; and we confirmed the validity of proposed patterns against postural measures not used in the cluster solution and expected to vary across clusters (as shown in eTab. 2). Prominent landmarks were used to obtain these postural measures; therefore, they were not expected to be associated with the accuracy of landmark identification. Additionally, we identified 3 main patterns that were clearly distinct from each other (differences varying from 6.3° to 13.1°); the random error of the measurement method was estimated to vary between 3.5 and 6.7 degrees.[24] Furthermore, sagittal posture assessment by photogrammetry is well recognized as the safest available method for the postural evaluation of children.[13,24,25]

We identified a meaningful summary model for the distribution of sagittal standing posture in girls and boys of school age. The patterns were consistent with childhood as a sensitive period for posture differentiation. However, postural dichotomy (neutral versus nonneutral) clearly did not apply to children, and substantial sex-related heterogeneity in the features and frequencies of different patterns existed among children of school age. These findings highlight the potential for sex-specific biomechanical frameworks of spinopelvic structures during a habitual upright position even in prepubertal ages, implying different biomechanical loads and perhaps contributing to the well-known sex differences in pediatric spinal deformities, such as higher frequencies of scoliosis in girls and Scheuermann disease in boys.

Author Contributions and Acknowledgments

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Data analysis: F.A. Araújo, M. Severo, L.D. Howe

Project management: R. Lucas

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The authors gratefully acknowledge the families enrolled in Generation XXI and the contributions of the members of the research team and staff.

Ethics Approval

The Generation XXI cohort study was approved by the Ethics Committee of Centro Hospitalar São João/University of Porto Medical School and complies with the Helsinki Declaration and current national legislation and was also approved by the National Committee of Data Protection.

Funding

The funding for EPIUnit was obtained from the Fundação para a Ciência e a Tecnologia (FCT) (UID/DTP/04750/2013/002). Generation XXI was funded by the Health Operational Programme–Saúde XXI, Community Support Framework III, and the Regional Department of Ministry of Health. It has been further supported by FEDER funds through the Programa Operacional Factores de Competitividade, by national funds through the FCT (projects PIC/IC/83038/2007, SFRH/BD/72723/2010, and EXPL/DTP-EPI/0280/2012), and by the Calouste Gulbenkian Foundation. The work of Mr Araújo and Professor Lucas was supported by the FCT (grants SFRH/BD/85398/2012 and SFRH/BPD/88729/2012). The funding sources had no role in the design or conduct of the study; collection, management, analysis, or interpretation of the data; preparation, review, or approval of the manuscript; or decision to submit the manuscript for publication.

DOI: 10.2522/ptj.20150712

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eTable 1.

Characteristics of Children Included and Not Included in the Study[a]

Characteristic	Girls			Boys		
	Included (n=1,147)	**Not Included (n=3,089)**	***P***	**Included (n=1,266)**	**Not Included (n=3,145)**	***P***
Age, y[b]	8.3 (0.3)	8.6 (0.4)	<.001	8.3 (0.3)	8.6 (0.4)	<.001
Maternal education, y	12.0 (8.0–16.0)	9.0 (6.0–12.0)	<.001	12.0 (9.0–16.0)	9.0 (7.0–12.0)	<.001
Birth weight, g	3,097.3 (528.3)	3,087.2 (531.2)	.584	3,195.3 (523.7)	3,208.9 (546.0)	.448
Length, cm	48.5 (47.0–50.0)	48.5 (47.0–50.0)	.689	49.5 (48.0–50.5)	49.3 (48.0–50.5)	.659
Ponderal Index, 100×(g/cm³)	2.74 (0.26)	2.74 (0.32)	.806	2.71 (0.27)	2.72 (0.26)	.507

[a] Age, birth weight, and Ponderal Index are reported as mean (standard deviation); maternal education and length are reported as median (25th percentile–75th percentile). Missing information for girls: weight (n=1), length and Ponderal Index (n=35), and maternal education (n=22); missing information for boys: length and Ponderal Index (n=38) and maternal education (n=34).

[b] June 30, 2014, was used as a reference.

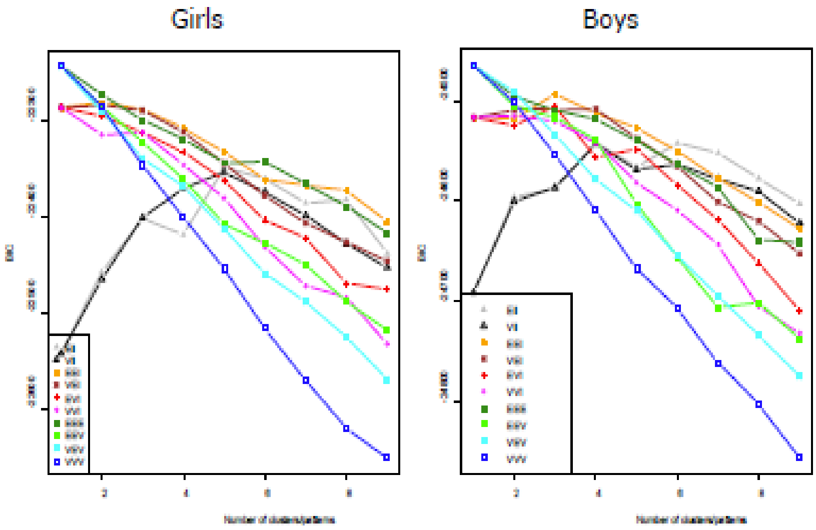
eTable 2.

Postural Measures Not Used in the Cluster Solution Across Model-Based Sagittal Postural Patterns[a]

Measure (°)	**Girls**					**Boys**				
	All	**1: Sway Pattern (n=309, 26.9%)**	**2: Flat Pattern (n=240, 20.9%)**	**3: Neutral to Hyperlordotic Pattern (n=598, 52.1%)**	***P***	**All**	**1: Sway to Neutral Pattern (n=745, 58.8%)**	**2: Flat Pattern (n=459, 36.3%)**	**3: Hyperlordotic Pattern (n=62, 4.9%)**	***P***
Head flexion	74.4 (7.6)	74.7 (7.4)	73.1 (8.0)	74.8 (7.5)	.008	73.7 (7.8)	74.3 (7.6)	72.8 (8.1)	73.7 (7.9)	.010
Neck flexion	43.3 (4.9)	45.1 (4.8)	43.7 (4.7)	42.2 (4.7)	<.001	41.4 (4.8)	42.0 (4.8)	40.8 (4.7)	37.9 (4.2)	<.001
Craniocervical angle	148.8 (8.3)	150.4 (7.9)	150.5 (8.4)	147.4 (8.2)	<.001	147.6 (8.5)	147.7 (8.5)	147.9 (8.5)	144.0 (7.7)	.003
Cervicothoracic angle	136.9 (5.7)	136.7 (5.7)	139.9 (5.4)	135.8 (5.5)	<.001	140.2 (5.5)	139.4 (5.3)	142.0 (5.3)	135.5 (4.8)	<.001
Thoracic flexion	0.5 (4.6)	2.0 (4.4)	3.9 (3.4)	−1.7 (4.0)	<.001	1.7 (4.7)	1.7 (4.3)	2.9 (4.4)	−6.5 (3.7)	<.001

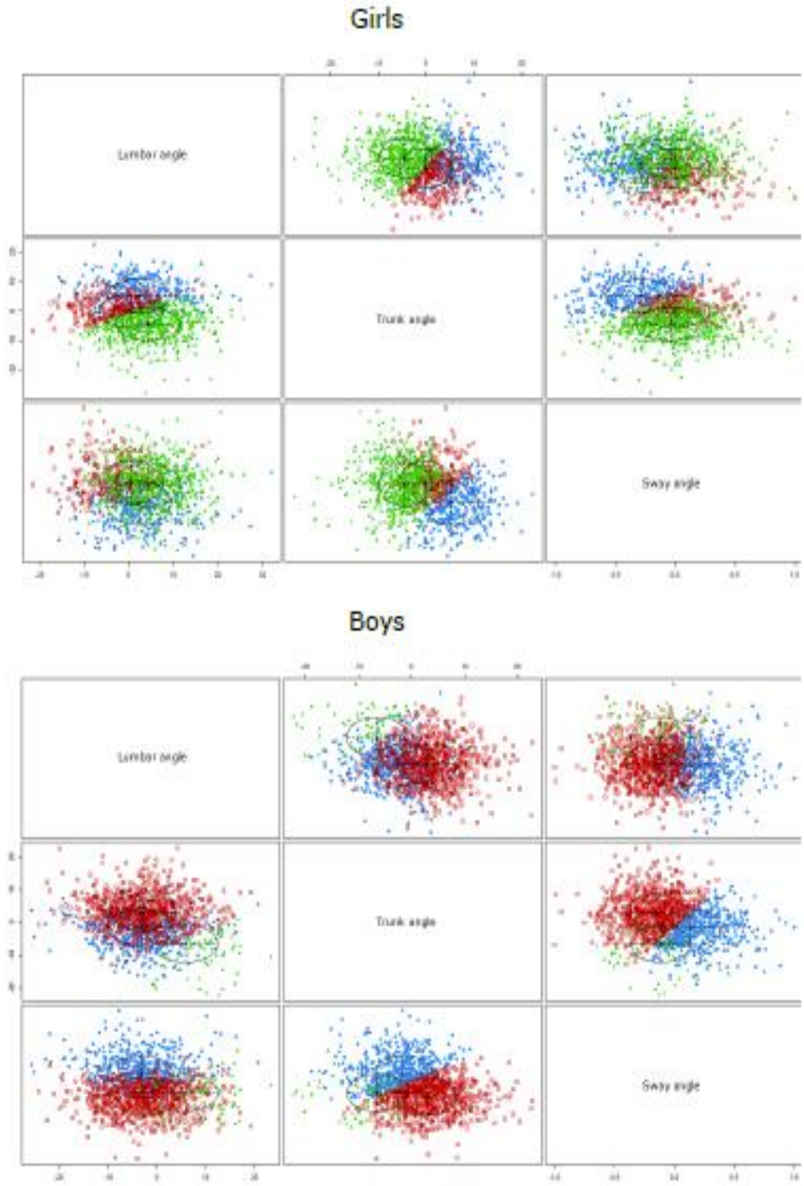
Pelvic tilt	128.7 (7.0)	132.2 (6.8)	132.8 (5.6)	125.2 (5.7)	<.001	132.4 (7.0)	134.7 (6.4)	130.0 (6.0)	121.6 (5.8)	<.001
Head displacement	8.7 (1.0)	8.9 (1.1)	8.5 (1.0)	8.6 (1.9)	<.001	8.3 (1.0)	8.4 (1.0)	8.1 (1.0)	8.1 (1.0)	<.001
Scapular elevation	0.0 (1.4)	−0.1 (1.5)	−0.3 (1.4)	0.3 (1.3)	<.001	−0.1 (1.4)	−0.2 (1.4)	−0.1 (1.3)	1.1 (1.0)	<.001
Scapular displacement	9.9 (1.4)	10.2 (1.4)	9.4 (1.5)	9.8 (1.4)	<.001	9.9 (1.4)	10.1 (1.4)	9.4 (1.3)	10.1 (1.2)	<.001

[a] Data are reported as mean (standard deviation).



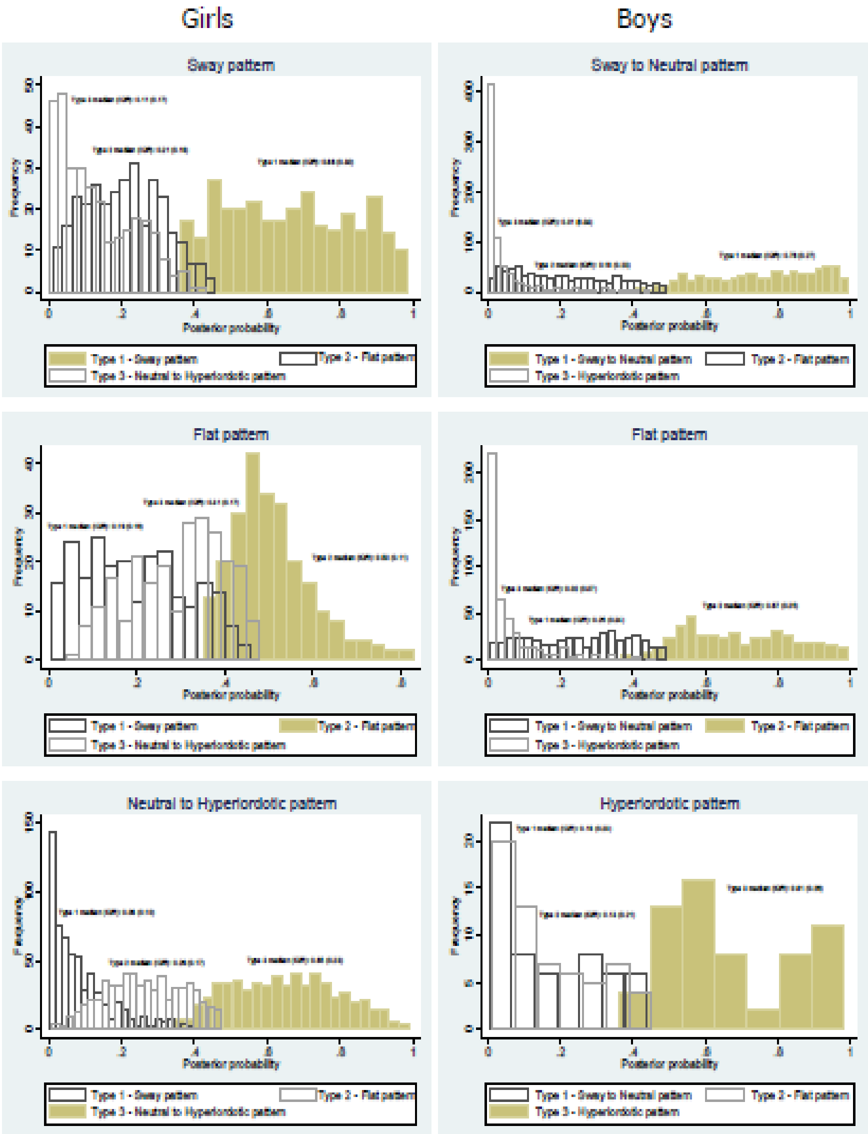
eFigure 1.

Bayesian Information Criterion (BIC) for models considering different geometric features (orientation, volume, and shape) of data distribution according to number of clusters, separately for girls and boys. The plots depict the BIC value multiplied by −1. EII=equal volume, equal shape, nonapplicable orientation; VII=variable volume, equal shape, nonapplicable orientation; EEI=equal volume, equal shape, coordinate axis orientation; VEI=variable volume, equal shape, coordinate axis orientation; EVI=equal volume, variable shape, coordinate axis orientation; VVI=variable volume, variable shape, coordinate axis orientation; EEE=equal volume, equal shape, equal orientation; EEV=equal volume, equal shape, variable orientation; VEV=variable volume, equal shape, variable orientation; VVV=variable volume, variable shape, variable orientation.



eFigure 2.

Classification for the final 3-cluster solution considering equal volume, equal shape, and coordinate axis orientation (corresponding to different variances between variables within patterns but similar variances between patterns, with a covariance between variables of 0), separately for girls and boys. The ellipses correspond to the covariances of each estimated pattern.



eFigure 3.

Distribution of posterior probabilities of the occurrence of each pattern according to the pattern assigned (most likely occurrence), separately for girls and boys. IQR=interquartile range.

4.3. Paper III

Araújo FA, Lucas R, Simpkin AJ, Heron J, Alegrete N, Tilling K, Howe LD, Barros H.

Associations of anthropometry since birth with sagittal posture at age seven in a population-based birth cohort: the Generation XXI study.

BMJ Open. 2017;7(7): e013412.

BMJ Open

Associations of anthropometry since birth with sagittal posture at age 7 in a prospective birth cohort: the Generation XXI Study

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To cite: Araújo FA, Lucas R, Simpkin AJ, *et al*. Associations of anthropometry since birth with sagittal posture at age 7 in a prospective birth cohort: the Generation XXI Study. *BMJ Open* 2017;7:e013412. doi:10.1136/bmjopen-2016-013412

► Prepublication history and additional material for this paper are available online. To view these files please visit the journal online (http://dx.doi.org/10.1136/bmjopen-2016-013412).

Received 9 July 2016
Revised 27 April 2017
Accepted 2 May 2017

ABSTRACT

Objectives Adult sagittal posture is established during childhood and adolescence. A flattened or hypercurved spine is associated with poorer musculoskeletal health in adulthood. Although anthropometry from birth onwards is expected to be a key influence on sagittal posture design, this has never been assessed during childhood. Our aim was to estimate the association between body size throughout childhood with sagittal postural patterns at age 7.

Design Prospective cohort study.

Setting and participants A subsample of 1029 girls and 1101 boys taking part in the 7-year-old follow-up of the birth cohort Generation XXI (Porto, Portugal) was included. We assessed the associations between anthropometric measurements (weight, height and body mass index) at birth, 4 and 7 years of age and postural patterns at age 7. Postural patterns were defined using latent profile analysis, a probabilistic model-based technique which allows for simultaneously including anthropometrics as predictors of latent profiles by means of logistic regression.

Results Postural patterns identified were sway, flat and "neutral to hyperlordotic" in girls, and "sway to neutral", flat and hyperlordotic in boys; with flat and hyperlordotic postures representing a straightened and a rounded spine, respectively. In both girls and boys, higher weight was associated with lower odds of a flat pattern compared with a sway/"sway to neutral" pattern, with stronger associations at older ages: for example, ORs were 0.68 (95% CI 0.53 to 0.88) per SD increase in birth weight and 0.36 (95% CI 0.19 to 0.68) per SD increase in weight at age 7 in girls, with similar findings in boys. Boys with higher ponderal index at birth were more frequently assigned to the hyperlordotic pattern (OR=1.44 per SD; p=0.043).

Conclusions Our findings support a prospective sculpting role of body size and therefore of load on musculoskeletal spinopelvic structures, with stronger associations as children get older.

Strengths and limitations of this study

- This is the first study evaluating the role of anthropometric characteristics from birth through early childhood in shaping standing posture organisation in children.
- We assessed a large population-based cohort of 1029 girls and 1101 boys who were followed prospectively up to age 7—the Generation XXI study.
- Postural patterns were defined using a probabilistic, model-based method—latent profile analysis—which included anthropometrics in addition to postural parameters.
- Although photogrammetry is the safest available method for postural evaluation of children, radiograms would have been the gold standard method for curvature measurement.
- Some degree of bias cannot be excluded, since children from the original cohort who were not included in this study were heavier and taller in the 4 and 7-year follow-up evaluations, and this could have changed the association between anthropometrics and postural patterns.

INTRODUCTION

Sagittal standing posture evolves with growth and it contributes to the development of paediatric spinal deformities.[1–3] Posture is also crucial in the long term,[4–8] since mature sagittal spinopelvic alignment is involved in a variety of orthopaedic disorders,[7] such as degenerative disease and vertebral listhesis, as well as unspecific back pain and loss of function.[7 9 10]

In the first months after birth, profound morphological changes to the pelvis and spine take place.[4 5 8] There is an initial verticalisation of the pelvis, followed by the rising of the lordotic curve in the lower back as the child begins to assume a sustained upright position, leading the sacrum to a more horizontal position.[4] Then, as walking abilities are acquired, constant dynamic adaptation takes place between pelvis shape, sagittal anatomy of the sacrum and physiological curves of the spine, all of which gradually develop and interact during growth.[5 8]

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Children's anthropometry is expected to contribute to the mechanical framework of posture modulation, that is, weight and height modulate gravitational actions and regulate the net direction of forces imposed on the immature spinopelvic structures.[11] Plastic deformation of bones, discs and other spinal structures can occur,[12–14] as a result of reactive forces by muscles to ensure a stable centre of mass.[4 6 8]

Overall, there is strong biomechanical support for the hypothesis that children's anthropometric trajectories have the potential to shape postural morphotypes. However, this has never been empirically tested in a paediatric population. Longitudinal, population-based evidence is essential to assess the potential effects of body size in promoting a healthy posture, and also, to identify periods in childhood when prevention and management of weight disorders may be more effective for avoiding long-term musculoskeletal consequences of posture misalignment in later life.

By using prospective data from the Generation XXI birth cohort, our aim was to estimate the associations of body size from birth onwards with sagittal postural patterns at age 7.

METHODS

This study is based on the population-based birth cohort Generation XXI, which has been previously described at length.[15 16] Briefly, participants were recruited between 2005 and 2006 at five public maternity units serving the six municipalities of the metropolitan area of Porto, Portugal. At birth, 8647 infants were enrolled in the cohort (91.4% of mothers invited agreed to participate). Four and 7years after birth, 69% and 68%, respectively, of all children recruited at birth were re-evaluated by face-to-face interviews and physical examinations. During the 7-year-old follow-up, a subsample of 2998 children consecutively assessed between December 2012 and August 2013, and without a diagnosis of severe neurological impairment, was invited for sagittal standing posture evaluation. Of those, 80% agreed to participate and attended the scheduled assessment. After excluding 118 girls and 165 boys with missing information on anthropometrics, 1029 girls and 1101 boys were included in the present analysis. The Generation XXI cohort study was approved by the Ethics Committee of São João Hospital/University of Porto Medical School and complies with the Helsinki Declaration for medical research and with current national legislation, and was also approved by the National Committee of Data Protection. Written informed consent was obtained from all parents or legal guardians.

Birth weight and recumbent length at birth were retrieved from medical records by trained researchers. Ponderal index was then computed (weight in grams/length in cm^3×100).[17] Additionally, weight and height were assessed at mean ages (SD) 4.3 (0.3) and 7.1 (0.2) years. Weight was measured in light indoor clothing to the nearest 0.1 kg using a digital scale (TANITA) and height to the nearest 0.1 cm using a wall stadiometer (SECA). Body mass index (BMI) was defined as weight in kilograms divided by height in squared metres.

Sagittal standing posture evaluation in both genders occurred at 7.4 years of age on average (SD: 0.4), 0 to 420 days after the anthropometric evaluation (50% of children evaluated within 61.5 days). Spherical retroreflective markers were placed over anatomical landmarks on the right side of the child's body: spinous processes of C7 and T12, anterior superior iliac spine, greater trochanter and lateral malleolus. Children were instructed to rest comfortably in habitual standing position with feet slightly apart, looking straight ahead and moving elbows forward.[18 19] Floor markers were used to standardise children positioning. Full-body flash photographs of the sagittal right view of children were then acquired, after the examiner judged that the usual upright position had been attained. Angular measures formed by the lines drawn from the anatomical landmarks were obtained using the postural assessment software PAS/SAPO[20]: trunk, lumbar and sway angles (figure 1). These individual parameters were used to define postural morphotypes through the clustering algorithm Mclust,[21] and a three-pattern solution was obtained separately for girls and boys.[22] The geometric features (orientation, volume and shape) of the distributions of postural parameters were estimated from the data and allowed to vary between clusters or constrained to be the same for all the clusters.[23] We then selected the type of model and number of clusters with the smallest Bayesian Information Criterion (BIC).[24] This clustering procedure was chosen instead of the conventional heuristic methods[15 19 25–27] because it has the key advantage of allowing for testing different variances of angle measures within and across clusters.

In this paper, we replicated the three-pattern solution using the software Mplus V.6.12 (Muthén & Muthén, Los Angeles, CA, USA), because the previously used clustering algorithm in the R package Mclust does not allow joint estimation of postural clusters and their associations with anthropometrics in the same model. This one-step approach was used to account for uncertainty in the assignment of patterns and consequently to obtain unbiased estimates of the association between anthropometrics and posture.[28] Specifically, five latent profile models (different parametrisations of variance–covariance matrices) were tested in Mplus, with a fixed three-class solution for each gender. We selected the model with the highest concordance (observed agreement) for pattern assignment compared with the solution previously found in Mclust.[22] Overall, concordance was 70% in girls and 78% in boys (detailed information provided in online supplementary table S1).

To quantify the associations of weight, height/length and body mass/ponderal index at birth, 4 and 7 years of age with postural patterns, we reran the selected models simultaneously using multinomial logistic regression (ie, including anthropometrics as predictors of postural

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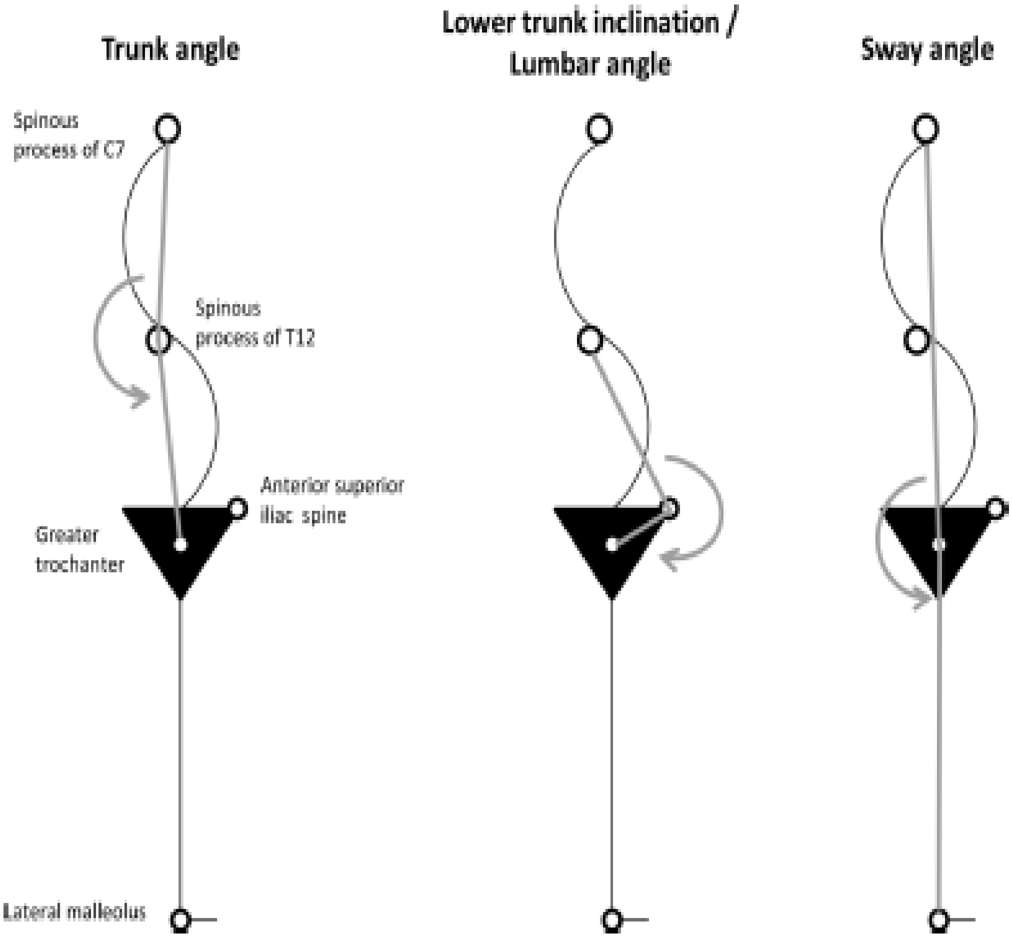

Figure 1 Individual angular measures used to identify sagittal postural patterns (using Mplus latent profile analysis).

latent profiles). Since the distributions of anthropometric variables change considerably during childhood, weight, height and BMI were standardised within each age through z-score transformations, by subtracting the mean value in the sample from each individual's value and dividing the result by the sample SD; units for associations are presented per SD. Estimates at age 4 were adjusted for birth measurements, and estimates at age 7 were adjusted for measurements at birth and 4 years; that is, weight estimates were adjusted for previous measurements of weight and similarly for height and BMI.

RESULTS

There was no association between inclusion in this study and anthropometric characteristics at birth. However, included girls and boys were lighter and shorter than those not at 4 and 7 years old (mean differences (95% CI)): −0.29 kg (−0.53 to −0.05), −0.40 kg (−0.81 to 0.01), −0.64 cm (−1.02 to −0.26) and −0.42 cm (−0.83 to −0.01) in girls, and −0.62 kg (−0.83 to −0.40), −0.81 kg (−1.20 to −0.43), −0.84 cm (−1.21 to −0.46) and −0.53 cm (−0.92 to −0.15) in boys, respectively.

Identification of postural patterns

Individual angular measures were different between genders (multivariate analysis of variance, p<0.001) with the main difference being higher lower trunk inclination/lumbar angle in girls (4.90°, p<0.001).

In girls, the selected model was the one restricting variance of angular measures to be the same within patterns (identity covariance matrix) but allowing them to vary across patterns, while homogeneous variance was constrained only across patterns in boys (diagonal matrix). The average latent class probabilities (for the most likely latent class membership) varied between 0.75–0.81 in girls and 0.72–0.86 in boys. Figure 2 displays the features of the three postural patterns and angular values are provided in online supplementary table S2. The patterns were characterised by: increased trunk angle with backward tilt of the spine over the hips—decreased sway angle (sway in girls and 'sway to neutral' in boys given the high gender-specific prevalence of this pattern); straight

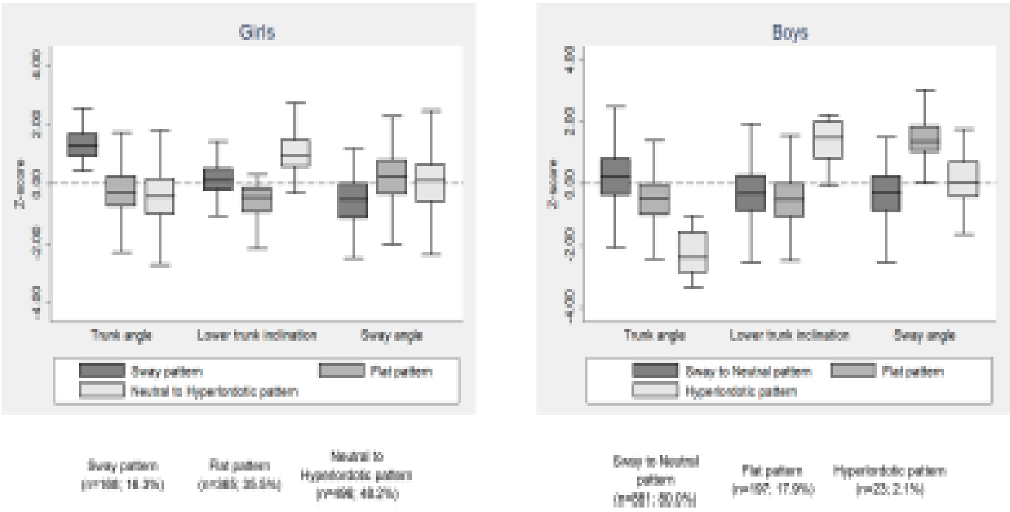

Figure 2 Box plots showing the distribution (median, IQR and range) of each separate postural angle, standardised to have a mean of zero and SD of one, across sagittal standing postural patterns, shown separately for girls and boys.

spine with forward trunk lean—increased sway angle (flat pattern in both genders); relatively increased lower trunk inclination and intermediate body sway ('neutral to hyperlordotic' pattern in girls) or extremely increased lower trunk inclination (hyperlordotic pattern in boys).

Associations between anthropometry and sagittal posture

Table 1 and figure 3 show descriptive analyses of the average anthropometric characteristics at birth and ages 4 and 7 years according to participants' most likely class assignment. ORs and respective 95% CI for the associations between anthropometric traits and posture are shown in table 2, using the sway and 'sway to neutral' patterns as reference given their intermediate overall anthropometric profile.

Girls

Girls with the lowest average weight at all ages belonged more frequently to the flat pattern at age 7. Higher weight at birth was associated with the sway pattern, while higher weight at ages 4 and 7 was related with a 'neutral to hyperlordotic' pattern. Per one SD increase in weight at birth, the odds of a flat pattern compared with sway changed by 0.68 (95% CI 0.53 to 0.88). This association became stronger with age, with an OR of 0.36 (95% CI 0.19 to 0.68) at age 7. The same directions of associations were observed for body mass/ponderal index, with an OR of 0.68 (95% CI 0.51 to 0.89) for flat compared with sway pattern per SD increase in birth weight and 0.39 (95% CI 0.21 to 0.70) per SD increase in weight at 7. Lower height was observed in children with the flat pattern, with mean (SD) height at age 7, 122.45 cm (4.91) for the flat, 123.00 cm (5.25) for the 'neutral to hyperlordotic' and 123.06 cm (5.08) for the sway pattern. Taller girls were 22% to 40% less likely to develop a flat pattern at age 7 ($p \le 0.080$), but these associations were weaker than those for weight/BMI.

Boys

As in girls, higher birth weight in boys was associated with the 'sway to neutral' pattern, while the highest weight thereafter was shown for those assigned to the hyperlordotic pattern. Per SD increase in weight, the OR for a flat pattern compared with sway/neutral was 0.66 at birth and 0.33 at 7 years old. The same decreasing trend for the flat type was observed in body mass/ponderal index with the OR being stronger than for weight. Boys who were born with higher ponderal index were more likely to have the hyperlordotic pattern (OR=1.44 per 0.27 g/cm^3; p=0.049). Regarding length/height, boys showing a 'sway to neutral' pattern were born 0.97 cm longer, but those assigned to a hyperlordotic pattern reach a similar stature at 4 years old and were 1.04 cm taller at 7 years old, while shorter boys at birth were more likely to show a flat pattern (OR=0.65 per SD (2.47 cm); p=0.001).

Sensitivity analysis

Similar associations between anthropometry and sagittal posture were observed after restricting the sample to children assigned to the same postural pattern in both Mplus and Mclust (online supplementary table S3). Additionally, sensitivity analyses excluding twins (girls: n=46; boys: n=49) and children born small or large for gestational age[29] (small: n=153, large: n=45 in girls; small: n=155, large: n=27 in boys) and also including adjustment for gestational age at birth did not change the previous overall patterns of associations. Furthermore, socioeconomic conditions at birth were not clearly associated with postural patterns at 7 years old (maternal education: p=0.163 in girls and p=0.074 in boys; household income: p=0.436 in girls and p=0.098 in boys). Therefore, we opted not to include them as confounders of the relationships between anthropometrics and postural patterns.

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Table 1 Anthropometric characteristics at birth and ages 4 and 7 years according to sagittal standing postural patterns, shown separately for girls and boys

	All	Sway pattern	Flat pattern	Neutral to hyperlordotic pattern
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Girls, n=1029				
Weight				
Birth, g	3102.1 (521.3)	3155.7 (507.5)	3063.1 (539.3)	3112.5 (511.2)
4 years, kg	17.9 (3.0)	18.0 (3.3)	17.3 (2.7)	18.3 (3.1)
7 years, kg	25.9 (5.4)	26.1 (5.7)	24.6 (4.6)	26.9 (5.6)
Length/height, cm				
Birth	48.2 (2.3)	48.4 (2.1)	48.2 (2.5)	48.2 (2.3)
4 years	104.3 (4.5)	104.6 (4.5)	104.1 (4.4)	104.4 (4.6)
7 years	122.8 (5.1)	123.1 (5.1)	122.4 (4.9)	123.0 (5.3)
Ponderal index/BMI				
Birth, 100×(g/cm³)	2.74 (0.26)	2.77 (0.26)	2.71 (0.26)	2.76 (0.27)
4 years, kg/m²	16.36 (1.99)	16.36 (2.21)	15.92 (1.78)	16.67 (2.00)
7 years, kg/m²	17.08 (2.67)	17.11 (2.79)	16.31 (2.30)	17.63 (2.75)
	All	**Sway to neutral pattern**	**Flat pattern**	**Hyperlordotic pattern**
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Boys, n=1101				
Weight				
Birth, g	3198.9 (516.1)	3229.3 (491.0)	3064.1 (600.0)	3189.3 (519.0)
4 years, kg	17.8 (2.6)	17.9 (2.6)	17.3 (2.3)	18.4 (1.6)
7 years, kg	25.8 (4.7)	26.0 (4.8)	24.5 (3.9)	26.9 (4.1)
Length/height, cm				
Birth	48.9 (2.5)	49.1 (2.3)	48.2 (3.1)	48.2 (2.9)
4 years	105.3 (4.5)	105.5 (4.5)	104.8 (4.6)	106.4 (3.3)
7 years	123.9 (5.3)	123.9 (5.4)	123.3 (5.3)	125.0 (5.4)
Ponderal index/BMI				
Birth, 100×(g/cm³)	2.71 (0.27)	2.71 (0.27)	2.70 (0.28)	2.85 (0.36)
4 years, kg/m²	16.00 (1.49)	16.06 (1.52)	15.71 (1.32)	16.55 (1.26)
7 years, kg/m²	16.70 (2.19)	16.85 (2.24)	16.00 (1.79)	17.19 (1.98)

BMI, body mass index.

DISCUSSION

In this population-based birth cohort we analysed the associations of anthropometrics at different ages during childhood with sagittal posture at 7 years old. In both genders, children who remained lighter had an increased likelihood of a flat posture, and this relationship became stronger with increasing age. Concordantly, being heavier at 4 and 7 years old was associated with a posture characterised by increased lower trunk inclination/lumbar angle: 'neutral to hyperlordotic' in girls and hyperlordotic in boys. Shorter girls tended to present a flat posture and taller boys a hyperlordotic pattern.

This is the first study evaluating the role of anthropometric characteristics from birth and throughout childhood in shaping standing posture organisation. Our findings showed that adiposity was inversely related with a flattened spine, and concordantly, directly associated with a hyperlordotic posture. Only one other research group evaluated the relation between anthropometrics and patterns of standing posture before skeletal maturity is reached,[18 19] and cross-sectional analyses have shown that 14-year-old adolescents with a flat pattern had the lowest weight/BMI, while those in the hyperlordotic pattern were the fattest.[18] Similarly, children in the flat pattern less frequently belonged to ascending, high or very high trajectories of body size defined from 5 to 14 years of age, while those in the hyperlordotic pattern were at higher risk of showing overweight trajectories.[18]

Classification systems of sagittal standing posture have been attempted in young adolescent girls[26] and boys.[25 27] However, different procedures for the definition of postural parameters preclude comparisons with our work. Particularly, children have been classified using a three-point Likert scale of uncorrected posture based

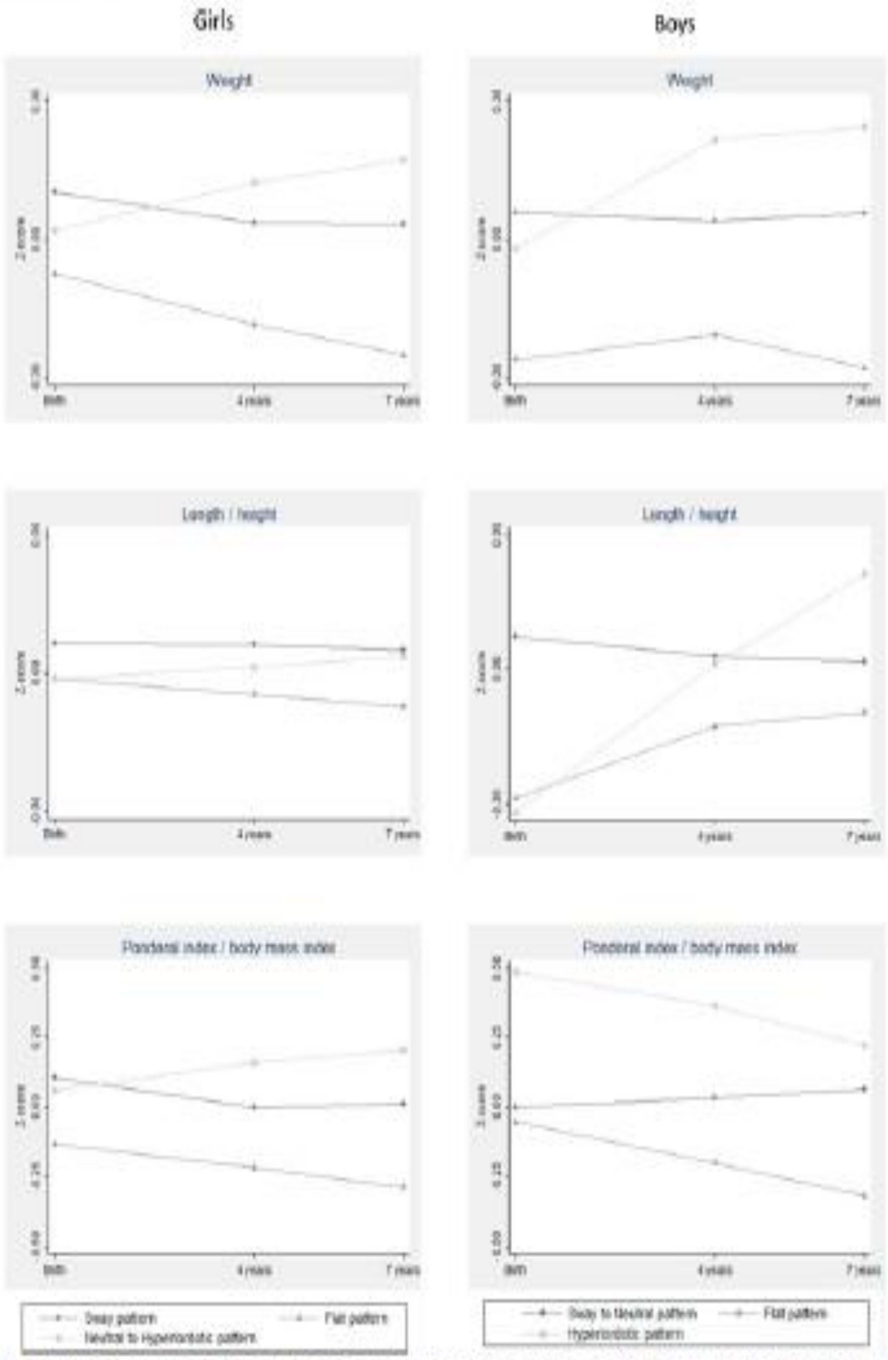

Figure 3 Standardised cross-sectional means of anthropometric characteristics at birth and ages 4 and 7 years across sagittal standing postural patterns, shown separately for girls and boys.

on the horizontal deviations of four body landmarks in respect to a vertical line[27] and three global patterns (based on three angles with respect to the vertical) with different magnitude of spinal curves being observable within each pattern.[25 26] Our approach was to model postural patterns following three criteria: (1) to use postural parameters as continuous variables as a better representation of the natural spectrum of posture, (2) to search for variants comparable with those published in adolescents and adults, in a life course perspective and (3) to use a model-based method that allowed for testing different variances of angle measures within and across clusters. Nevertheless, our patterns are comparable to those published by Dolphens *et al*,[25 26] at least regarding the suggested global

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Table 2 Associations between standardised anthropometric measures at birth, 4 and 7 years of age and sagittal postural patterns, shown separately for girls and boys

	Sway pattern	Flat pattern			Neutral to hyperlordotic pattern		
	OR	OR	95% CI	p Value	OR	95% CI	p Value
Girls, n=1029							
Weight							
Birth	1	0.68	0.53 to 0.88	0.003	0.83	0.64 to 1.07	0.154
4 years	1	0.53	0.35 to 0.79	0.002	1.32	0.84 to 2.07	0.228
7 years	1	0.36	0.19 to 0.68	0.002	1.89	0.87 to 4.10	0.110
Length/height							
Birth	1	0.78	0.61 to 1.01	0.056	0.84	0.67 to 1.05	0.133
4 years	1	0.76	0.57 to 1.02	0.070	0.93	0.70 to 1.24	0.618
7 years	1	0.60	0.34 to 1.06	0.080	1.20	0.38 to 3.76	0.751
Ponderal index/BMI							
Birth	1	0.68	0.51 to 0.89	0.005	0.92	0.72 to 1.18	0.534
4 years	1	0.49	0.30 to 0.78	0.003	1.34	0.81 to 2.21	0.249
7 years	1	0.39	0.21 to 0.70	0.002	1.63	0.89 to 2.97	0.111
	Sway to neutral pattern	**Flat pattern**			**Hyperlordotic pattern**		
	OR	OR	95% CI	p Value	OR	95% CI	p Value
Boys, n=1101							
Weight							
Birth	1	0.66	0.51 to 0.87	0.003	0.92	0.56 to 1.51	0.745
4 years	1	0.62	0.35 to 1.09	0.099	1.93	1.43 to 2.60	<0.001
7 years	1	0.33	0.11 to 0.99	0.048	1.88	0.90 to 3.92	0.092
Length/height							
Birth	1	0.65	0.50 to 0.84	0.001	0.70	0.49 to 0.998	0.049
4 years	1	0.86	0.65 to 1.14	0.300	1.00	0.59 to 1.72	0.993
7 years	1	1.39	0.70 to 2.74	0.349	2.33	1.10 to 4.98	0.028
Ponderal index/BMI							
Birth	1	0.93	0.73 to 1.19	0.568	1.44	1.01 to 2.04	0.043
4 years	1	0.51	0.25 to 1.03	0.061	2.08	1.34 to 3.25	0.001
7 years	1	0.23	0.11 to 0.51	<0.001	1.50	0.88 to 2.56	0.139

BMI, body mass index.

alignment classifications: neutral, sway back and leaning forward. In comparison to our classification and focusing on their features regarding the sway angle, those would, to some extent, correspond to the neutral, sway and flat patterns, respectively.

Our results during childhood are also consistent with cross-sectional findings in adult populations,[12 14 50] suggesting that higher adiposity levels during the development of posture is crucial for the shape and orientation of the spinopelvic unit, and implying a role of anthropometrics at early ages in shaping overall postural patterns during adulthood. In adults, both a flattened or hypercurved posture generally represent a poor postural health status on the basis of their relation with back pain[31 32] and also by contributing to the aetiology of pattern-specific spine pathologies, such as discopathy and vertebral listhesis, respectively.[11 33 34] In contrast with later stages of life,[13 14 19 50 53] a neutral labelling was not considered appropriate to characterise postural patterns in children, but non-ideal patterns were already differentiated in childhood (flat and hyperlordotic), and it seems plausible that they will progressively mature and partially track over the life course. In terms of the clinical interpretation of our findings, we may postulate that low birth weight may contribute to a flat back that then may increase the risk of idiopathic scoliosis,[1] while higher weight at 4 and 7 years of age may contribute to a hyperlordotic posture that then may predispose to Scheuermann's kyphosis.[3]

In both genders, anthropometric characteristics at ages 4 and 7 were more strongly associated with posture at 7 than body size at birth, as reflected by the age-related increase in the magnitude of associations between weight and the flat pattern, and also, the association of weight with increased lumbar curve observed only at ages 4 and 7. Previous studies describing the changes in sagittal posture throughout different stages of growth,[1 4–8] highlighted the potential effect of morphological anthropometric-related changes to be stronger during walking ages and potentially having a cumulative mechanical effect over time. Our observations at different ages in childhood support a cumulative result of weight bearing on spinopelvic structures, and that is the reason why our work focused on 7-year-old children. Although most changes in sagittal posture occur during the first months after birth, with the acquisition of upright position and walking abilities,[4 5 8] it is important to allow sagittal curves to develop during growth through the influence of specific anthropometric mechanical environment and allow that different morphotypes could be distinguished within the sample. An additional major concern was to focus on prepubertal children to ensure homogeneity with regard to sexual development.[35]

Although height was associated with postural patterns, associations were generally weaker than for weight. Consequently, the latter seems to be the main driver of the direction and magnitude of the associations seen for BMI, as expected for a mechanical mechanism. However, this was not the case for the hyperlordotic pattern in boys, where height showed a stronger association with posture than weight. This particular relation between height/length and the hyperlordotic pattern may be a consequence of an anterior displacement of the centre of gravity related to an increased weight of the upper body as the child gets older.[7] To re-establish a stable basis of support, the lumbar curve increases by means of higher vertebral growth, reflected in height, and this mechanism seems to be responsible for restoring sagittal balance.[7] In agreement with this hypothesis, the hyperlordotic pattern was characterised by a substantially increased lower trunk inclination/lumbar angle. However, this study was not designed to investigate this pattern-specific association, and the usefulness of length/height to predict the presence of this particular pattern in school-aged boys deserves future specific exploration. Interestingly, the same average ascending trajectory of weight in the hyperlordotic pattern in boys was observed for the 'neutral to hyperlordotic' pattern in girls, even though with less extreme values of weight, which supports a functional aggregation of neutral and hyperlordotic postures in school-aged girls.

Some limitations of this work should be highlighted. Children from the original cohort not included in this study were heavier and taller during the 4 and 7-year follow-up. Bias of our analysis is unlikely, as the association between anthropometry and postural patterns is unlikely to differ between included and excluded children. Although photogrammetry is the safest available method for postural evaluation of children,[14 18 36] radiographies directly allow us to measure spinal curvatures and are the gold standard which would have allowed more robust conclusions. Moreover, despite our efforts to standardise the position of the body and of the arms in particular, enough variability may have remained that could have influenced trunk position and therefore overall sagittal posture. Additionally, the present postural patterns have not yet been reproduced in other samples, and therefore future research is needed to confirm validation of the postural classifications. Furthermore, latent profile analysis in Mplus was performed in this study although Mclust[21] has been previously used for postural pattern identification.[22] Since the two clustering methods use different estimation algorithms,[37] classifications were not completely overlapping (online supplementary table S1). However, the solutions between the two clustering algorithms have been initially compared: while the same three-pattern solution was obtained in boys, for girls, Mplus suggested two and Mclust three patterns (based on the smallest BIC). Based on patterns' interpretability and also because Mplus solution aggregates two of the three groups suggested by Mclust, we opted to use three class models for both genders to replicate the solution provided by Mclust.[22] Despite this, our conclusions should not be meaningfully affected since a good concordance between final models was obtained (≥70%), as well as comparable face validity of patterns (ie, their postural meaning). Our findings were further supported by sensitivity analysis restricted to children assigned to the same postural pattern in both Mplus and Mclust, as shown in online supplementary table S3.

This is the first study evaluating the association of different measures of anthropometry and posture in children, using a large sample of children recruited from a population-based cohort with considerable variability both in exposure and outcome. Additionally, to examine overall postural patterns instead of isolated parameters is a key advantage because patterns allow a better characterisation of overall posture, permitting the analysis to account for the relationships between different anatomical regions.[14 19 34] Our work used, for the first time, a probability-based posture classification (ie, considering posterior probabilities of pattern membership) to avoid bias in the estimates of associations between anthropometry and postural patterns.[28]

We quantified the associations of early anthropometric features with sagittal posture during childhood, and we found that children who were lighter from the time of birth were more likely to develop a flattened posture at age 7, while being heavier was associated with a hyperlordotic posture in both genders. The mechanical load imposed by body size seems to have a cumulative sculpting role throughout the first decade of life, especially after walking abilities are acquired.

Acknowledgements The authors gratefully acknowledge the families enrolled in Generation XXI and the contribution of the members of the research team and staff.

Contributors FAA, RL, NA and HB collaborated in the conceptualisation, design and acquisition of data. FAA, RL, AJS, JH, NA, KT, LDH and HB collaborated in the analysis and interpretation of data. FAA drafted the initial manuscript. RL, AJS, JH, NA, KT, LDH and HB critically reviewed the manuscript. All authors approved the

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final manuscript as submitted and agreed to be accountable for all aspects of the work.

Funding Generation XXI was funded by FEDER through the Operational Programme Competitiveness and Internationalisation and by national funds through the FCT - Fundação para a Ciência e a Tecnologia via grants POCI-01-0145-FEDER-016838 and POCI-01-0145-FEDER-016837, under the projects PTDC/DTP-EPI/1687/2014 and PTDC/DTP-EPI/3306/2014. Support by Administração Regional de Saúde Norte (Ministry of Health), Fundação Calouste Gulbenkian and Unidade de Investigação em Epidemiologia - Instituto de Saúde Pública da Universidade do Porto (EPIUnit) (POCI-01-0145-FEDER-006862; UID/DTP/04750/2013) is also acknowledged. Araújo FA and Lucas R were supported by grants SFRH/BD/85396/2012 and SFRH/BPD/88729/2012, co-funded by FCT and the POPH/FSE.

Competing interests None declared.

Patient consent Obtained.

Ethics approval Ethics Committee of São João Hospital/University of Porto Medical School.

Provenance and peer review Not commissioned; externally peer reviewed.

Data sharing statement No additional data are available.

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Supplementary material

Table S1 Comparison of Mplus and Mclust sagittal postural patterns assignment, shown separately for girls and boys

		Mplus		
		Sway pattern	**Flat pattern**	**Neutral to Hyperlordotic pattern**
		n (%)	**n (%)**	**n (%)**
Girls, n=1029				
Mclust	Sway pattern	156 (92.9)	42 (11.5)	80 (16.1)
	Flat pattern	12 (7.1)	172 (47.1)	26 (5.2)
	Neutral to Hyperlordotic pattern	0 (0.0)	151 (41.4)	390 (78.6)
		Mplus		
		Sway to Neutral pattern	**Flat pattern**	**Hyperlordotic pattern**
		n (%)	**n (%)**	**n (%)**
Boys, n=1101				
Mclust	Sway to Neutral pattern	643 (73.0)	0 (0.0)	0 (0.0)
	Flat pattern	207 (23.5)	195 (99.0)	2 (8.7)
	Hyperlordotic pattern	31 (3.5)	2 (1.0)	21 (91.3)

Table S2 Postural parameters in sagittal postural patterns, shown separately for girls and boys

	Girls				Boys			
	Sway pattern (n=168, 16.3%)	**Flat pattern (n=365, 35.5%)**	**Neutral to Hyperlordotic pattern (n=496, 48.2%)**		**Sway to Neutral pattern (n=881, 80.0%)**	**Flat pattern (n=197, 17.9%)**	**Hyperlordotic pattern (n=23, 2.1%)**	
	Mean (SD)	**Mean (SD)**	**Mean (SD)**	**P**	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**P**
Trunk angle, °	213.2 (3.5)	202.7 (5.0)	201.2 (5.9)	<0.001	205.9 (5.8)	200.9 (5.4)	189.3 (4.7)	<0.001
Lower trunk inclination/ Lumbar angle, °	280.4 (4.0)	274.7 (4.5)	287.4 (5.0)	<0.001	276.9 (6.8)	275.0 (6.9)	289.3 (5.8)	<0.001
Sway angle, °	162.2 (3.7)	166.0 (4.5)	165.0 (4.5)	<0.001	163.2 (3.7)	171.9 (3.0)	165.0 (3.9)	<0.001

SD, standard deviation.

Table S3 Associations between standardized anthropometric measures at birth, 4 and 7 years of age and sagittal postural patterns in children assigned to the same pattern in both Mplus and Mclust, shown separately for girls and boys

	Sway pattern	Flat pattern			Neutral to Hyperlordotic pattern		
	OR	OR	95% CI	P	OR	95% CI	P
Girls, n=718							
Weight							
Birth	1	0.72	0.56-0.92	0.010	0.85	0.69-1.04	0.108
4 years	1	0.67	0.46-0.97	0.032	0.98	0.78-1.24	0.867
7 years	1	0.33	0.18-0.61	<0.001	1.06	0.68-1.64	0.796
Length/Height							
Birth	1	0.81	0.61-1.07	0.141	0.85	0.69-1.05	0.127
4 years	1	0.82	0.61-1.09	0.163	0.91	0.73-1.12	0.360
7 years	1	0.78	0.50-1.21	0.265	1.00	0.71-1.39	0.980
Ponderal index/BMI							
Birth	1	0.71	0.56-0.90	0.005	0.91	0.75-1.11	0.372
4 years	1	0.63	0.41-0.96	0.032	1.02	0.78-1.32	0.894
7 years	1	0.31	0.17-0.56	<0.001	1.05	0.69-1.58	0.830
	Sway to Neutral pattern	**Flat pattern**			**Hyperlordotic pattern**		
	OR	**OR**	**95% CI**	**P**	**OR**	**95% CI**	**P**
Boys, n=859							
Weight							
Birth	1	0.72	0.60-0.86	<0.001	0.87	0.49-1.54	0.628
4 years	1	0.78	0.62-0.97	0.027	1.15	0.86-1.54	0.356
7 years	1	0.51	0.35-0.75	0.001	0.99	0.49-2.02	0.979
Length/Height							
Birth	1	0.70	0.59-0.83	<0.001	0.67	0.48-0.93	0.016
4 years	1	0.91	0.75-1.10	0.321	0.99	0.67-1.46	0.945
7 years	1	1.07	0.76-1.52	0.685	2.51	0.79-8.06	0.120
Ponderal index/BMI							
Birth	1	0.94	0.77-1.14	0.506	1.43	1.01-2.01	0.043
4 years	1	0.72	0.56-0.92	0.009	1.23	0.92-1.64	0.169
7 years	1	0.43	0.29-0.65	<0.001	0.74	0.37-1.49	0.403

OR, odds ratio; CI, confidence interval; BMI, body mass index. Odds ratios are per one standard deviation higher anthropometric measure. Estimates at 4 years of age adjusted for birth measurements; estimates at 7 years adjusted for measurements at birth and 4 years.

4.4. Paper IV

Araújo FA, Martins A, Alegrete N, Howe LD, Lucas R.

A shared biomechanical environment for bone and posture development in children.

Spine J. 2017;17(10): 1426-1434.

ELSEVIER

The Spine Journal 17 (2017) 1426–1434

THE SPINE JOURNAL

Clinical Study

A shared biomechanical environment for bone and posture development in children

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Received 16 August 2016; revised 13 March 2017; accepted 24 April 2017

Abstract

BACKGROUND CONTEXT: In each specific habitual standing posture, gravitational forces determine the mechanical setting provided to skeletal structures. Bone quality and resistance to physical stress is highly determined by habitual mechanical stimulation. However, the relationship between bone properties and sagittal posture has never been studied in children.

PURPOSE: This study aimed to investigate the association between bone physical properties and sagittal standing postural patterns in 7-year-old children. We also analyzed the relationship between fat or fat-free mass and postural patterns.

STUDY DESIGN: Cross-sectional evaluation.

PATIENT SAMPLE: This study was performed in a sample of 1,138 girls and 1,260 boys at 7 years of age participating in the Generation XXI study, a population-based cohort of children followed since birth (2005–2006) and recruited in Porto, Portugal.

OUTCOME MEASURES: Sagittal standing posture was measured through photographs of the sagittal right view of children in the standing position. Three angles were considered to quantify the magnitude of major curves of the spine and an overall balance measure (trunk, lumbar, and sway angles). Postural patterns were identified using latent profile analysis in Mplus.

METHODS: Weight and height were measured. Total body less head fat or fat-free mass and bone properties were estimated from whole-body dual-energy X-ray absorptiometry scans. The associations of fat or fat-free mass and bone physical properties with postural patterns were jointly estimated in latent profile analysis using multinomial logistic regressions.

FDA device/drug status: Not applicable.

Author disclosures: *FAA:* Grant: FCT – Fundação para a Ciência e a Tecnologia (POCI-01-0145-FEDER-016837; PTDC/DTP-EPI/1687/2014; PTDC/DTP-EPI/3306/2014) (Paid directly to institution/employer), FCT – Fundação para a Ciência e a Tecnologia (SFRH/BD/85398/2012), Administração Regional de Saúde Norte (Ministry of Health) (Paid directly to institution/employer), Fundação Calouste Gulbenkian (Paid directly to institution/employer), Unidade de Investigação em Epidemiologia – Instituto de Saúde Pública da Universidade do Porto (EPIUnit) (POCI-01-0145-FEDER-006862; UID/DTP/04750/2013 (Paid directly to institution/employer), pertaining to the submitted manuscript. *AM:* Grant: FCT – Fundação para a Ciência e a Tecnologia (POCI-01-0145-FEDER-016837; PTDC/DTP-EPI/1687/2014; PTDC/DTP-EPI/3306/2014) (Paid directly to institution/employer), Administração Regional de Saúde Norte (Ministry of Health) (Paid directly to institution/employer), Fundação Calouste Gulbenkian (Paid directly to institution/employer), Unidade Investigação em Epidemiologia – Instituto de Saúde Pública da Universidade do Porto EPIUnit) (POCI-01-0145-FEDER-006862; UID/DTP/04750/2013 (Paid directly to institution/employer), pertaining to the submitted manuscript. *NA:* Nothing to disclose. *LDH:* Nothing to disclose. *RL:* FCT – Fundação para a Ciência e a Tecnologia (POCI-01-0145-FEDER-016837; PTDC/DTP-EPI/1687/2014; PTDC/DTP-EPI/3306/2014) (Paid directly to institution/employer), FCT – Fundação para a Ciência e a Tecnologia (SFRH/BPD/88729/2012), Administração Regional de Saúde Norte (Ministry of Health) (Paid directly to institution/employer), Fundação Calouste Gulbenkian (Paid directly to institution/employer), Unidade de Investigação em Epidemiologia – Instituto de Saúde Pública da Universidade do Porto (EPIUnit) (POCI-01-0145-FEDER-006862; UID/DTP/04750/2013 (Paid directly to institution/employer), pertaining to the submitted manuscript.

The disclosure key can be found on the Table of Contents and at www.TheSpineJournalOnline.com.

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http://dx.doi.org/10.1016/j.spinee.2017.04.024

RESULTS: The identified patterns were labeled as Sway, Flat, and "Neutral to Hyperlordotic" (in girls), and "Sway to Neutral," Flat, and Hyperlordotic (in boys). In both genders, children in the Flat pattern showed the lowest body mass index, and children with a rounded posture presented the highest: mean differences varying from −0.86 kg/m² to 0.60 kg/m² in girls and from −0.70 kg/m² to 0.62 kg/m² in boys (vs. Sway or "Sway to Neutral"). Fat and fat-free mass were inversely associated with a Flat pattern and positively associated with a rounded posture: odds ratio (OR) of 0.23 per standard deviation (SD) fat and 0.70 per SD fat-free mass for the Flat pattern, and 1.85 (fat) and 1.43 (fat-free) for the Hyperlordotic pattern in boys, with similar findings in girls. The same direction of relationships was observed between bone physical properties and postural patterns. A positive association between bone (especially bone mineral density) and a rounded posture was robust to adjustment for age, height, and body composition (girls: OR=1.79, p=.006 fat-adjusted, OR=2.00, p=.014 fat-free mass adjusted; boys: OR=2.02, p=.002 fat-adjusted, OR=2.42, p<.001 fat-free mass adjusted).

CONCLUSIONS: In this population-based pediatric setting, there was an inverse association between bone physical properties and a Flat posture. Bone and posture were more strongly positively linked in a rounded posture. Our results support that both bone properties and posture mature in a shared and interrelated mechanical environment, probably modulated by pattern-specific anthropometrics and body composition.

Keywords: Body composition; Body size; Bone density; Child; Sagittal standing posture; Spine

Introduction

Sagittal standing posture refers to the way that people stand upright. Sagittal posture is commonly described by thoracic kyphosis and lumbar lordosis (outward and inward curves of the spine in the sagittal plane, respectively), complemented with sagittal balance, that is, the positioning of the center of mass in the upright position [1]. In each specific habitual standing posture, gravitational forces determine the mechanical setting provided to skeletal structures. An anteriorly displaced center of mass, as frequently observed in patients with osteoporosis due to thoracic hyperkyphosis, results in an increased forward bending moment of the upper body, leading to higher compressive moments in thoracolumbar and lumbar regions [2]. This probably explains hyperkyphosis as a risk factor for new vertebral fractures independently of bone mineral density (BMD) or previous fracture [3,4]. Stronger extensor trunk muscles are then needed to compensate for hyperkyphosis while keeping a stable upright posture, which increases spinal compressive [2,5–7] and shear [5–7] loading that may promote spinal disorders and additional vertebral fractures in the long run. Thus, sagittal standing posture seems to be a key macrostructural factor in defining the amount of physical stimuli imposed on spinopelvic bone tissue.

At the microstructural level, bone quality and resistance to physical stress is highly determined by habitual mechanical stimulation: the network of bone trabeculae is modeled to resist the specific stress to which it is usually exposed [8,9]. Prepubertal years are a particularly sensitive stage for the attainment of optimal bone strength because the skeleton is especially responsive to mechanical loading and shows greater plasticity [10–13]. But despite the direct relationship between bone structure (size and architecture) and vertebrae shape and local alignment [7,14,15], the relationship between bone properties and sagittal posture has never been studied in children.

In addition, body size and composition contribute to the mechanical environment of spinopelvic structures, with fat and fat-free mass operating as extraskeletal modulators of bone morphology. The skeleton has to support and deal with loading moments resulting from weight bearing [2,7], and adiposity and muscles can also directly affect posture by changing the orientation of vertebral bodies toward increased lumbar lordosis [2,16–19]. Thus, mechanical loading of the pediatric skeleton by extraskeletal tissues seems to be a crucial factor to increase bone mineral accrual [10] and promote postural health [16,20,21]. Because both bone and posture are continuously matured in a shared and mutually interrelated mechanical environment, the influences of body size and composition need to be taken into account in evaluating the biological link between bone and posture.

Our primary goal was to investigate the association between bone physical properties and sagittal postural patterns among a large sample of 7-year-old children selected from the Generation XXI birth cohort. We also explored the roles of fat and fat-free mass in this association.

Materials and methods

Subjects

This study was conducted within Generation XXI, a population-based birth cohort of 8,647 live born infants and their mothers [22,23]. Participants were recruited between 2005 and 2006 at five public maternity units serving the six municipalities of the metropolitan area of Porto, North of Portugal. Initially, 91.4% of invited mothers agreed to participate. Seven years after birth, all Generation XXI children were invited to a follow-up evaluation based on their date of birth, and 80% of the cohort's children were reevaluated. The present study was based on an additional wave of assessment held for 2,908 eligible children consecutively attending the 7-year-old follow-up (December 2012 to August 2013), and without a diagnosis of severe neurologic impairment (n=7). This additional evaluation occurred between March 2013 and February 2014. Ethical approval was obtained from the Ethics Committee of São João Hospital/University of Porto Medical School.

Anthropometric variables

Weight was measured in light indoor clothing to the nearest 0.1 kg using a digital scale (Xinyu Electronic Company, Limited [Zhongshan, Guangdong, China]) and height was measured to the nearest 0.1 cm using a wall stadiometer (SECA). Body mass index was defined as weight in kg divided by height squared in m².

Dual-energy X-ray absorptiometry

Whole-body dual-energy X-ray absorptiometry (DXA) scans were performed (Hologic Discovery QDR 4500W, Bedford, MA, USA). Total body less head fat and fat-free mass was used. Fat and fat-free mass indices were then calculated by dividing fat mass and fat-free mass (kg) by height squared (m²) [24]. Total body less head bone mineral content (BMC) was obtained, and BMD was expressed as BMC (in g) per projected bone area (in cm²). Area-adjusted BMC (aBMC) was derived as a measure of volumetric BMD by a regression of BMC on bone area and adding the residuals of the linear regression to mean BMC [25]. As recommended, total body less head rather than total body measurements was used because the head is less responsive to environmental stimuli [26]. The standard quality assurance tests using the calibration block were performed daily, and also each month using the spine phantom. Dual-energy X-ray absorptiometry scans were removed from analysis because of anomalies caused by movement, artifacts, or other logistic issues. Nine trained radiology technicians were involved in DXA evaluations. Two of the examiners performed 84% of all the scans.

Pediatric sagittal postural patterns

Sagittal standing posture evaluation was performed by quantitative assessment of photographs of the sagittal right view of children, which is documented as the safest method for epidemiological studies among children [27,28]. Posture was assessed before DXA scans to facilitate the attainment of the usual upright position.

Spherical retro-reflective markers were placed over anatomical landmarks on the right side of the child's body by one of two qualified health professionals. Children assumed their habitual standing position with feet slightly apart and looking straight ahead [27,29]. Full-body flash photographs of the sagittal right view of children were then acquired. Angular measures formed by the lines drawn from the anatomical landmarks were obtained using the postural assessment software PAS/SAPO (Ferreira, EAG) [30]. Three angles were considered to quantify the magnitude of major curves of the spine (thoracic kyphosis and lumbar lordosis), and also an overall balance measure assessing body sway (as exemplified in the left panel of Fig. 1).

Children were ranked regarding their distance to the average postural values within each examiner's distribution to eliminate potential systematic differences between examiners (ie, individual residuals of mixed effects models) [31], and residuals were used to define postural patterns through the R package Mclust [32]. Based on the interpretability of the patterns among the models with the smallest Bayesian information

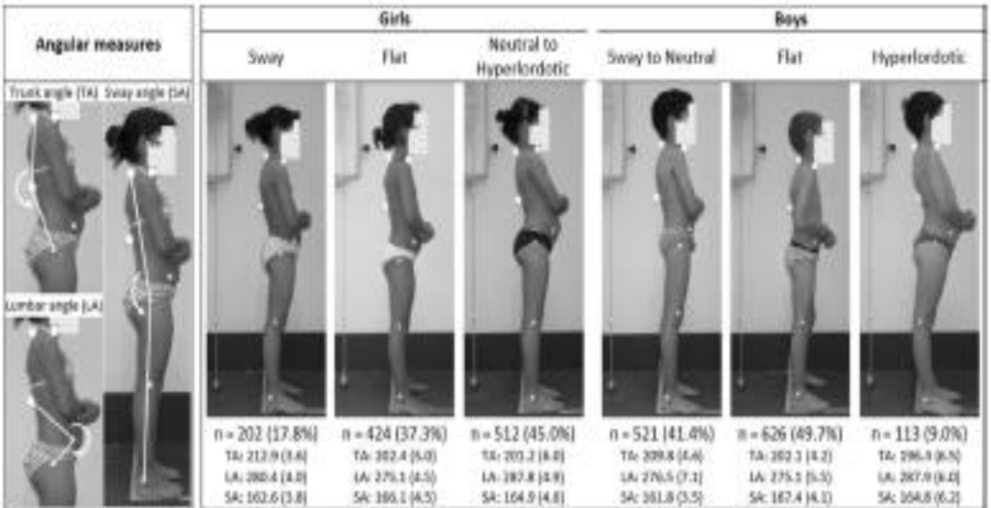

Fig. 1. Individual angular measures used to identify pediatric sagittal postural patterns using Mplus latent profile analysis (left panel), and a typical member of each pattern shown separately for girls and boys (right panel).

criterion [33], a final three-pattern solution was obtained separately for girls and boys. The methods and results of pattern identification are thoroughly described elsewhere [34].

Statistical analysis

Because we wished to estimate the postural patterns and their associations with the exposures in a single step to minimize bias [35], we used the pediatric patterns described above as the basis for reestimation of postural patterns within Mplus (version 6.12, Muthén & Muthén, Los Angeles, CA, USA). Latent profile analysis was performed with multinomial logistic regressions simultaneously computed in the same models (ie, including predictors of estimated postural latent profiles). Initially, five different parameterizations of variance-covariance matrices were tested, with a fixed three-class solution for each gender based on our previous work on pediatric patterns [34]. Then, we selected the type of parameterization that optimized observed agreement of pattern assignment (based on the most likely class). Finally, latent postural classes were reestimated using information provided by each different set of predictors included in the models, and their associations were jointly quantified. This last step was used to account for uncertainty in the assignment of patterns and consequently to obtain unbiased estimates of associations [35]. Sensitivity analysis was carried out by considering regional measures of body composition (trunk, upper, and lower limbs) derived from total body DXA scans.

Results

Pediatric postural patterns

A total of 1,138 girls and 1,260 boys accepted to participate and were included in the analysis (79% and 81% of eligible children, respectively). Compared with previous work on pattern assignment of Generation XXI children [34], final postural models obtained 68.5% concordance in girls and 79.7% in boys (detailed information provided in Supplementary Table S1). The average latent class assignment probabilities (for the most likely latent class membership) varied between 0.72 and 0.86 in girls and between 0.68 and 0.69 in boys.

Fig. 1 (right panel) displays the average features of the three postural patterns and a typical child in each posture:

(1) Sway (girls) and "Sway to Neutral" (boys): increased trunk angle with backward tilt of the spine over the hips;
(2) Flat pattern in both genders: straight spine with forward trunk lean; and
(3) "Neutral to Hyperlordotic" (girls) and Hyperlordotic (boys): relatively increased lumbar angle and intermediate body sway.

Gender-specific aggregation of the neutral labeling was based on a different pattern prevalence between genders (see Fig. 1).

Associations between DXA-derived parameters and postural patterns

Table 1 shows descriptive analyses of anthropometric variables and DXA-derived parameters according to participants' most likely class assignment. Associations between DXA parameters and postural patterns are presented in Table 2 and Fig. 2, using the Sway or "Sway to Neutral" pattern as reference given their intermediate overall profile of anthropometrics and parameters of body composition.

Flat posture

In both genders, children in the Flat pattern showed the lowest body mass index with mean differences of 0.86 kg/m^2 in girls and 0.70 kg/m^2 in boys, compared with the Sway or "Sway to Neutral" pattern. Fat and fat-free mass were inversely associated with a Flat pattern: odds ratio (OR) of 0.36 per fat standard deviation (SD) and 0.60 per fat-free SD in girls (both $p<.01$), and in boys, ORs were 0.23 per fat SD ($p=.001$) and 0.70 per fat-free SD ($p=.023$). However, when adjusted for age and height (model 1), these associations remained statistically significant only for fat mass, and were independent of fat-free mass (model 2b: girls OR=0.34, 95% confidence interval [CI]: 0.21–0.55; boys OR=0.22, 95% CI: .06–0.81). Even though children in the Flat pattern had lower bone properties in crude analysis (especially in girls: ORs ranging from 0.66, 95% CI: 0.46–0.94 per BMD SD to 0.72, 95% CI: 0.53–0.99 per aBMC SD), those associations did not remain in adjusted models. Moreover, when adjusting for fat mass (model 2a), the Flat pattern was associated with increased bone properties, especially in girls (ORs varying from 1.17, 95% CI: 0.86–1.61 per aBMC SD to 1.60, 95% CI: 1.03–2.49 per BMC SD).

"Neutral to Hyperlordotic" or Hyperlordotic posture

Children with a rounded posture presented the highest body mass index: mean differences of 0.60 kg/m^2 in girls and 0.62 kg/m^2 in boys (vs. Sway or "Sway to Neutral"). The likelihood of having a "Neutral to Hyperlordotic" or a Hyperlordotic pattern increased per SD of fat mass and fat-free mass, and the relationships of posture with each component of body size were independent of each other (model 2b and 2a), although not significantly in girls. When adjusted for fat-free mass, ORs for fat mass were increased by 29% in girls ($p=.370$) and 77% in boys ($p=.012$), and when adjusted for fat mass, ORs for fat-free mass were increased by 50% in girls ($p=.113$) and 118% in boys ($p=.016$). Additionally, a rounded posture was associated with higher BMD and content (stronger for BMD than BMC) independently of fat or fat-free mass. In girls, across models 2a and 2b, ORs varied from 1.35 (95% CI: 0.85–2.17) per BMC SD to 2.00 (95% CI: 1.15–3.46) per BMD SD, and in boys, from 1.23 (95% CI: 0.73–2.08) per BMC SD to 2.42 (95% CI: 1.48–3.95) per BMD SD.

Table 1
Descriptive data for anthropometric variables and DXA parameters according to pediatric sagittal postural patterns, shown separately for girls and boys

	All		Sway		Flat		Neutral to Hyperlordotic	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Girls, n=1,138								
Age, y	7.4	0.4	7.4	0.4	7.4	0.4	7.4	0.4
Weight, kg	27.3	5.8	27.7	6.4	25.9	5.0	28.4	6.1
Height, cm	124.1	5.5	124.6	5.7	123.8	5.4	124.2	5.6
BMI, kg/m²	17.61	2.82	17.66	2.98	16.80	2.43	18.26	2.88
Fat mass, kg	8.5	3.6	8.8	3.8	7.5	3.0	9.2	3.8
Fat-free mass, kg	14.7	2.3	14.7	2.5	14.3	2.1	14.9	2.4
Fat mass index, kg/m²	5.45	2.04	5.56	2.1	4.84	1.7	5.90	2.1
Fat-free mass index, kg/m²	9.48	0.92	9.42	1.02	9.32	0.85	9.63	0.92
Area, cm²	962.9	62.7	965.1	63.4	962.0	63.8	962.7	61.6
BMC, g	591.6	85.5	592.9	88.4	582.0	83.5	599.1	85.4
BMD, g/cm²	0.61	.06	0.61	.06	0.60	.05	0.62	.06
aBMC, g	591.6	42.3	590.2	43.5	583.0	39.0	599.3	43.2
	All		Sway to Neutral		Flat		Hyperlordotic	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Boys, n=1,260								
Age, y	7.4	0.4	7.4	0.4	7.5	0.4	7.4	0.4
Weight, kg	27.2	5.2	27.8	5.5	26.4	4.7	28.7	5.8
Height, cm	125.2	5.5	125.4	5.7	124.9	5.5	125.4	5.0
BMI, kg/m2	17.25	2.42	17.55	2.53	16.85	2.12	18.17	3.01
Fat mass, kg	7.0	3.1	7.4	3.3	6.5	2.7	8.0	3.9
Fat-free mass, kg	15.9	2.3	16.0	2.4	15.7	2.2	16.3	2.1
Fat mass index, kg/m²	4.42	1.79	4.66	1.86	4.12	1.56	5.03	2.28
Fat-free mass index, kg/m²	10.08	0.89	10.13	0.93	10.00	0.83	10.32	0.92
Area, cm²	959.7	65.3	961.4	65.7	958.8	66.5	956.8	57.1
BMC, g	601.0	85.4	603.4	88.4	597.5	85.1	609.6	71.9
BMD, g/cm²	0.62	.05	0.62	.06	0.62	.05	0.64	.05
aBMC, g	601.0	36.4	601.4	38.5	598.5	33.4	613.0	39.8

aBMC, area-adjusted BMC; BMC, bone mineral content; BMD, bone mineral density; BMI, body mass index; DXA, dual-energy X-ray absorptiometry; SD, standard deviation.

Sensitivity analysis

Similar results to the main analysis were obtained in the analysis of regional parameters from trunk, upper limb, and lower limb regions. No clear differences were observed between regions in respect to associations of fat or fat-free mass and bone parameters with postural patterns.

Discussion

In both genders, lower adiposity was associated with a flattened spine, and concordantly, higher fat and fat-free mass with a rounded posture type. There was an inverse association between bone physical properties and a Flat posture, but this relationship did not remain after accounting for differences in body composition across postural morphotypes. However, in a rounded posture, bone and posture were more strongly linked, possibly as the result of a shared accumulation of increased mechanical forces: children in the postural pattern characterized by higher lumbar angle ("Neutral to Hyperlordotic" in girls and Hyperlordotic in boys) presented higher BMD, independently of anthropometrics and body composition.

Sagittal postural patterns in this work showed a plausible association with body size and composition among the pediatric population. For instance, both girls and boys with a hypercurved spine were heavier, taller, exhibited higher fat and fat-free mass, and had increased bone mass and density. Because compressive forces on spinopelvic structures are the sum of superincumbent fat and muscle loads acting on vertebral bodies in the axial plane, this implies specific weight-loading profiles for each postural morphotype even if not attributable to its sagittal configuration. In a rounded spine, higher forces are applied to bone structures because the skeleton has more weight to support and needs higher muscle moments to regulate amplified oscillations of the upper body over the hips [2,7]. Our characterization of postural patterns reinforces that children with a flattened spine can keep an anteriorly displaced balance (increased sway angle) because they are lighter, whereas children with a rounded spine need to activate stronger extensor back muscles to avoid falling anteriorly and to reestablish balance in an intermediate range.

Numerous studies showed that low body mass index or weight is associated with a flattened posture and that increased body size is associated with a hypercurved spine [16,21]. However, we showed, for the first time, that both fat mass and fat-free mass contribute to the associations of body size with sagittal posture. After adjustment for height, only

Table 2
Associations between standardized DXA parameters and pediatric sagittal postural patterns, shown separately for girls and boys

		Flat				Neutral to Hyperlordotic			
		OR	95% LCI	95% UCI	p	OR	95% LCI	95% UCI	p
Girls, n=1,138 (reference pattern=Sway)									
Fat mass	Model 0	0.36	0.24	0.55	<.001	1.32	0.81	2.17	.268
	Model 1	0.34	0.21	0.55	<.001	1.51	0.89	2.55	.126
	Model 2b	0.34	0.21	0.55	<.001	1.29	0.74	2.25	.370
Fat-free mass	Model 0	0.60	0.43	0.84	.003	1.33	0.71	2.51	.375
	Model 1	0.59	0.31	1.10	.094	2.21	0.96	5.11	.064
	Model 2a	1.02	0.57	1.84	.150	1.50	0.91	2.49	.113
BMC	Model 0	0.69	0.53	0.90	.007	1.14	0.75	1.74	.530
	Model 1	0.84	0.54	1.32	.460	1.79	1.17	2.74	.008
	Model 2a	1.60	1.03	2.49	.038	1.48	0.97	2.24	.067
	Model 2b	1.26	0.77	2.07	.360	1.35	0.85	2.17	.208
BMD	Model 0	0.66	0.46	0.94	.023	1.49	0.68	3.25	.317
	Model 1	0.75	0.49	1.15	.182	2.39	1.23	4.64	.010
	Model 2a	1.55	1.01	2.38	.046	1.79	1.18	2.72	.006
	Model 2b	0.96	0.57	1.60	.861	2.00	1.15	3.46	.014
aBMC	Model 0	0.72	0.53	0.99	.040	2.27	1.43	3.60	.001
	Model 1	0.75	0.56	1.02	.068	2.28	1.45	3.60	<.001
	Model 2a	1.17	0.86	1.61	.322	1.49	1.07	2.07	.019
	Model 2b	0.78	0.56	1.08	.139	1.91	1.18	3.10	.009

		Flat				Hyperlordotic			
		OR	95% LCI	95% UCI	p	OR	95% LCI	95% UCI	p
Boys, n=1,260 (reference pattern=Sway to Neutral)									
Fat mass	Model 0	0.23	.07	0.71	.001	1.85	1.31	2.60	<.001
	Model 1	0.22	.05	0.95	.043	2.08	1.41	3.08	<.001
	Model 2b	0.22	.06	0.81	.023	1.77	1.14	2.77	.012
Fat-free mass	Model 0	0.70	0.52	0.95	.023	1.43	0.99	2.08	.057
	Model 1	0.72	0.45	1.13	.150	3.45	1.76	6.76	<.001
	Model 2a	1.00	0.58	1.74	.991	2.18	1.16	4.11	.016
BMC	Model 0	0.83	0.59	1.16	.270	1.30	0.89	1.89	.180
	Model 1	0.94	0.62	1.43	.778	2.11	1.30	3.44	.003
	Model 2a	1.22	0.73	2.02	.446	1.40	0.89	2.18	.143
	Model 2b	1.10	0.70	1.74	.672	1.23	0.73	2.08	.430
BMD	Model 0	0.80	0.58	1.10	.168	1.78	1.28	2.46	.001
	Model 1	0.88	0.61	1.26	.484	3.15	1.98	4.99	<.001
	Model 2a	1.25	0.79	1.98	.349	2.02	1.31	3.13	.002
	Model 2b	1.02	0.63	1.63	.949	2.42	1.48	3.95	<.001
aBMC	Model 0	0.82	0.60	1.13	.225	2.21	1.49	3.27	<.001
	Model 1	0.90	0.67	1.20	.463	2.69	1.72	4.21	<.001
	Model 2a	1.23	0.85	1.79	.269	1.90	1.31	2.77	.001
	Model 2b	0.94	0.67	1.33	.728	2.32	1.50	3.59	<.001

aBMC, area-adjusted BMC; BMC, bone mineral content; BMD, bone mineral density; DXA, dual-energy X-ray absorptiometry; LCI, lower confidence interval; OR, odds ratio; UCI, upper confidence interval.

Model 0=crude associations; Model 1=adjusted for age and height; Model 2a=additionally adjusted for fat mass; Model 2b=as model 1 plus adjustment for fat-free mass.

Odds ratios are per one standard deviation higher DXA-derived parameter.

fat mass was inversely associated with a Flat posture, whereas both components of nonskeletal body mass were positively and independently related to a rounded posture type. The effect of adiposity on spinopelvic alignment is mainly derived from biomechanical constraints during posture development, potentially causing plastic deformation of bones and intervertebral discs [16,20,21]. Adiposity also displaces balance forwardly, which increases lumbar lordosis as the most efficient compensation to restore a stable basis of support [2,16,17]. On the other hand, stronger back extensor muscles lead to an increase in lumbar lordosis [18,19], and a hyperlordotic posture, through its sagittal organization alone, also requires higher muscle moments than all other postures, especially during more demanding tasks [36]. These mechanical pathways are congruent with our findings, but the robust and exclusive association (after adiposity adjustment) between fat-free mass and a hyperlordotic posture probably implies a biological threshold for adiposity, above which muscles predominantly control upright balance. This threshold is likely related to balance instability caused by adiposity, which would explain why fat-free mass was not associated with a Flat pattern.

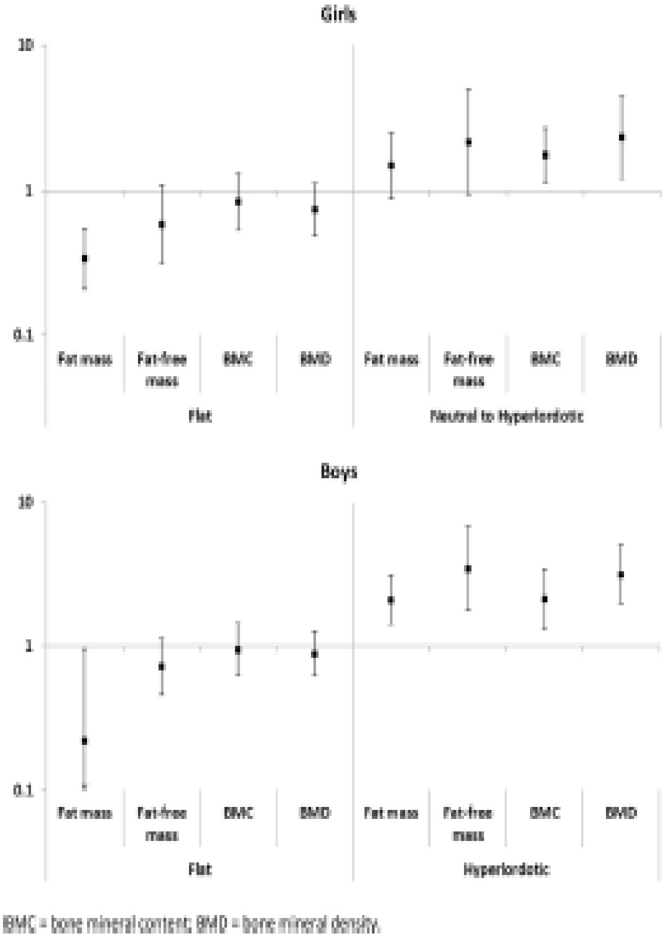

Fig. 2. Graphs showing associations (odds ratio and 95% confidence interval) between standardized DXA parameters and pediatric sagittal postural pattern, shown separately for girls (reference = Sway) and boys (reference= Sway to Neutral). Odds ratios are per standard deviation higher DXA parameter, adjusted for age and height. DXA, dual-energy X-ray absorptiometry.

The inverse relation between bone physical properties and a Flat pattern observed in our work may be explained by the profile of anthropometric and body composition characteristics featured by this typology. However, in the case of a rounded posture, an association between bone quality and posture remains after those adjustments. A specific shape and design of the spine establishes the morphologic configuration for the action of gravity and muscles. A Sway posture minimizes muscle work and stresses in the resting standing position [36]. As lumbar lordosis increases up to a hyperlordotic posture, mechanical loads also increase. Flattened or neutral spines are better suited to minimize muscle work and stress in weight-bearing activities [36], and the extremely pronounced thoracic kyphosis in the Sway type can be expected to contribute to higher mechanical stress compared with the Flat pattern [2,5,6]. Conversely, fat and lean mass positively affect bone structure through mechanical and endocrine effects [37,38], with a more important contribution of lean than fat mass during childhood [38,39]. Therefore, both adiposity and muscles can lead to changes in the morphology of vertebral bodies, namely by changing their anteroposterior height ratios [40]. These changes modify vertebral tilt and define local alignment [7,14,15], and consequently overall postural patterns due to adaptation of adjacent anatomical regions [1]. As examples, longitudinal vertebral growth in children may increase lumbar lordosis [15], and both higher thoracic kyphosis [14,41,42] and higher lumbar lordosis [42] seem to have an osteoporotic origin (decreased BMD) at more advanced ages.

Our population-based finding of bone-posture potentiation in a hypercurved spine suggests that a bidirectional mechanism exists—that is, hyperlordosis promotes mechanical stress but bone growth changes vertebrae tilting—in a pattern-specific dynamic environment also defined by anthropometrics and body composition. This was also supported by regional analysis of body composition, with no clear differences of bone-posture associations between load-bearing regions and the upper limbs. Increased loads and endocrine adaptations in the hyperlordotic posture probably culminate in stronger biological relations of fat, muscle, and bone with sagittal alignment. Probably because of weaker mechanical forces, maturational processes of bone and posture do not seem more closely linked in a Flat than in a Sway posture. Furthermore, associations between bone and posture were stronger for boys than for girls. This may result from different aggregations of postural morphologies in the present classifications ("Neutral to Hyperlordotic" in girls and "Sway to Neutral" in boys), or represent a true gender-specific bone response to mechanical stimuli [43,44].

One of the limitations of this work is the lack of direct measurement of mechanical stimuli imposed by anthropometrics, adiposity, and muscle contractions. Our analyses assumed that mechanical influences are captured by lean mass and reflected in bone physical properties, both quantifiable by DXA measurements. The population-based nature of our work constrained these assessments, but it ensured a wide representation of naturally occurring anthropometrics, body composition, bone physical properties, and postural angles in the pediatric population. Furthermore, it has been previously shown that children participating in this wave of assessment (posture and DXA measurements) were similar to the general Generation XXI cohort at birth regarding anthropometrics, although maternal education was higher for included children [34]. The external validity of our findings is a key advantage because previous evidence had relied mainly on biomechanical model simulations without any empirical measurements of bone quality [2,5,6,36]. Furthermore, it is essential to study posture morphotypes instead of isolated parameters because patterns add the effect of different combinations of regional alignment on health, and consequently, allow a more comprehensive mechanical characterization of the upright posture [2,16,29,36]. Our associations between DXA-derived parameters and postural patterns may be biased because of the use of posture classification not completely overlapping with the initial Mclust grouping, especially in the Flat pattern (Supplementary Table S1). However, given the direction of differences between classifications, this would bias results toward the null hypothesis and not create spurious associations. Further, latent profile analysis in Mplus enables using information provided from model predictors (ie, DXA-derived parameters) to reestimate patterns and jointly quantify unbiased associations [35], which probably surpasses limitations resulting from the use of two different software. Because variables considered in this study have high physiological correlation, differentiating effects of posture from body size or composition on bone may be unrealistic. Moreover, given the observational nature of our study, the causal nature of relationships between body composition, bone, and posture should be seen in the context of homeostatic feedback mechanisms rather than as a set of unidirectional effects.

This study evaluated for the first time the relations between bone physical properties and sagittal posture in 7-year-old children recruited from a population-based birth cohort. There was an inverse association between bone physical properties and a Flat posture, and bone and posture were more strongly positively linked in a rounded posture. As initially hypothesized, our results support that both bone and posture mature in a shared and interrelated mechanical environment modulated by pattern-specific anthropometrics and body composition.

Acknowledgment

Generation XXI was funded by FEDER through the Operational Programme Competitiveness and Internationalization and by national funds through the FCT – Fundação para a Ciência e a Tecnologia via grants POCI-01-0145-FEDER-016838 and POCI-01-0145-FEDER-016837, under the projects PTDC/DTP-EPI/1687/2014 and PTDC/DTP-EPI/3306/2014. Support by Administração Regional de Saúde Norte (Ministry of Health), Fundação Calouste Gulbenkian and Unidade de Investigação em Epidemiologia - Instituto de Saúde Pública da Universidade do Porto (EPIUnit) (POCI-01-0145-FEDER-006862; UID/DTP/04750/2013) is also acknowledged. Araújo FA and Lucas R were supported by grants SFRH/BD/85398/2012 and SFRH/BPD/88729/2012, co-funded by FCT and the POPH/FSE.

The authors also gratefully acknowledge the families enrolled in Generation XXI, and the contribution of the members of the research team and staff.

Supplementary material

Supplementary material related to this article can be at http://dx.doi.org/10.1016/j.spinee.2017.04.024.

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Supplementary Table 1

Comparison of Mplus and Mclust pediatric sagittal postural patterns assignments, shown separately for girls and boys

		Mplus					
		Sway		Flat		Neutral to Hyperlordotic	
		n	%	n	%	n	%
Girls, n=1138							
	Sway	179	88.6	45	10.6	81	15.8
Mclust	Flat	23	11.4	193	45.5	24	4.7
	Neutral to Hyperlordotic	0	0.0	186	43.9	407	79.5
		Mplus					
		Sway to Neutral		**Flat**		**Hyperlordotic**	
		n	**%**	**n**	**%**	**n**	**%**
Boys, n=1260							
	Sway to Neutral	520	99.8	204	32.6	17	15.0
Mclust	Flat	1	0.2	422	67.4	34	30.1
	Hyperlordotic	0	0.0	0	0.0	62	54.9

5. Overall discussion

In this thesis we assessed for the first time the correlations of anthropometrics since birth and body composition parameters with angles of sagittal standing posture measured at 7 years of age (Paper I). Firstly, our study showed clear postural heterogeneity between girls and boys in early ages denoting different biomechanical loads for each gender. Secondly, lumbar angle was the most discriminative parameter among all angles studied and body mass index the characteristic most strongly associated with it, especially in girls. Thirdly, and finally, all the previous associations were weak and it seems that the study of patterns of sagittal standing posture is of added value compared to isolated postural measures. Nevertheless, if researchers choose to focus on individual angular measures of sagittal standing posture, lumbar and sway angles seem to be the best proxies for overall posture in children on the basis of their relation with anthropometrics and body composition parameters.

In this thesis we were also able to define postural patterns in children for the first time (Paper II). This is the largest population-based investigation of sagittal postural patterns so far, and the first to focus on school-aged children under 10 years of age.

Our postural types 1 and 2 in both genders resemble, in their relative features, those previously described in older ages as Sway (increased kyphosis with backward tilt of the spine over the hips) and Flat (straight spine with forward trunk lean), respectively. Our type 3 in girls corresponds to the Neutral pattern (relatively increased lumbar lordosis and intermediate body sway) and to a Hyperlordotic pattern in boys (extremely increased lumbar lordosis). However, four postural patterns have been previously described in adults (age range: 18-48 years) (21) and they were then suggested to be also present in adolescents between 13 and 15 years of age (25): Sway, Flat, Neutral and Hyperlordotic patterns. Therefore, our type 3 in girls was named "Neutral to Hyperlordotic" and the type 1 in boys was named "Sway to Neutral". In this work the

“Neutral to Hyperlordotic” pattern was by far the most prevalent in girls (52.1%), and 58.8% of the boys showed a “Sway to Neutral” pattern. The most plausible reason for the clear different structure of patterns between girls and boys, seems to be a true gender heterogeneity of postural types among school-aged children. While in girls the Hyperlordotic posture was merged within the wide Neutral profile and this seems to be driven by their similarly increased lumbar angle (21, 25), in boys, the Sway and Neutral types were the most similar, probably determined by a predominant backward tilt of the spine in children (27) and only observed in boys.

To examine overall postural patterns instead of isolated parameters is a key advantage because patterns allow a better characterization of overall posture, permitting the analysis to account for the relationships between different anatomical regions (25, 35, 53). The use of model-based clustering in this work allowed us to assess the most appropriate configuration among ten different solutions of covariance structures, whereas previously used (25, 26, 75) heuristic clustering methods – Ward’s and K-means – consider only one restricted covariance structure (84). Therefore, we used a different clustering algorithm (model-based clustering Mclust in the R software) than the one used among adolescents (i.e., hierarchical analysis by Ward’s method followed by the K-means algorithm)[25], and thus, different solutions in patterns of sagittal standing posture may be due to a different stage of life or to the use of different clustering algorithms. We performed sensitivity analysis using the same statistical procedures previously used among adolescents separately for each gender, and the best solution was congruent with the present results of this thesis. The same postural meaning of 3-patterns was observed but aggregation of the neutral labelling was uncertain due to the homogeneous cluster prevalence obtained by K-means clustering (varying from 30% to 37%). Therefore, these findings support the hypothesis that, using statistical and theoretical criteria together, sagittal morphotypes are observable even from early childhood and it seems likely that, to some extent, they will track over time, leading to the patterns described in adolescence (25) and adulthood (21).

Conceptually, sagittal patterns are an attempt to categorize a continuum of the postural spectrum. Classifying children into mutually exclusive classes may have led to some misclassification, especially if children show a combined distribution of individual parameters that is compatible with more than one pattern. Nevertheless, our statistical approach allowed us to quantify uncertainty for each pattern assignment which is particularly useful to model sagittal posture within a probabilistic framework (85).

The identified and proposed patterns were used as outcome in the following two papers of this thesis, namely to assess the associations of body size from birth onwards with sagittal postural patterns at 7 years of age (Paper III) and also to investigate the association between bone physical properties and sagittal postural patterns and to explore the role of fat and fat-free mass in this association (Paper IV).

In order to answer the specific objectives of these studies we used latent profile analysis in Mplus to re-estimate postural patterns because the previously used clustering algorithm in the R package Mclust does not allow joint estimation of postural clusters and their associations with predictors in the same model. This one-step approach was used to account for uncertainty in the assignment of patterns and consequently to obtain unbiased estimates of the association between anthropometrics and body composition with posture (85).

Latent profile analysis in Mplus was performed in these two studies, although we had previously used Mclust (84) for postural pattern identification. Since the two clustering methods use different estimation algorithms (86), classifications were not completely overlapping. However, the solutions between the two clustering algorithms have been compared: while the same 3-pattern solution was obtained in boys, for girls, Mplus suggested two and Mclust three patterns (based on the smallest Bayesian Information Criterion). Based on pattern interpretability and also because the Mplus solution aggregates two of the three groups suggested by Mclust, we opted to use three class models for both genders in order to replicate the solution provided by Mclust. Our conclusions should not be meaningfully affected since a good concordance between final models was obtained (≥68.5%), as well as comparable face validity of patterns, i.e. their postural meaning. Our findings were further supported by sensitivity analysis restricted to children assigned to the same postural pattern in both Mplus and Mclust in Paper III. Furthermore, given the direction of differences between classifications, the use of the two different software would bias results towards the null hypothesis and not create spurious associations.

Consequently, our Papers III and IV used, for the first time, a probability based posture classification (i.e., considering posterior probabilities of pattern membership), in order to avoid bias in the estimates of associations between predictors and postural patterns (85).

In both genders, children who remained lighter had an increased likelihood of a Flat posture, and this relationship became stronger with increasing age. Concordantly, being heavier at 4 and 7 years old was associated with a posture characterized by increased lumbar angle: “Neutral to Hyperlordotic” in girls and Hyperlordotic in boys (Paper III). This was the first study evaluating the association of different measures of anthropometry and posture in children, using a large sample of children recruited from a population-based cohort with considerable variability both in exposure and outcome.

In Paper IV, we evaluated for the first time the relations between bone physical properties and sagittal posture in children. There was an inverse association between bone physical properties and a Flat posture, and bone mass and posture were more strongly positively linked in a rounded posture. As initially hypothesized, our results supported that both bone and posture mature in a shared and interrelated mechanical environment modulated by pattern-specific anthropometrics and body composition.

Only one other research group has evaluated the relation between anthropometrics and patterns of standing posture before skeletal maturity is reached (25, 44) and cross-sectional analyses have shown that 14-year-old adolescents with a Flat pattern had the lowest weight/body mass index, while those in the Hyperlordotic pattern were those showing higher fat (25). Similarly, children in the Flat pattern less frequently belonged to ascending, high or very high trajectories of body size defined from 3 to 14 years of age, while those in the Hyperlordotic pattern were at higher risk of showing overweight trajectories (44). Our results during childhood were also consistent with cross-sectional findings in adult populations (33, 35, 74) suggesting that higher adiposity levels during the development of posture is crucial for the shape and orientation of the spino-pelvic unit, and implying a role of anthropometrics at early ages in shaping overall postural patterns during adulthood.

Numerous studies showed that low body mass index/weight is associated with a flattened posture and that increased body size is associated with a hypercurved spine (35, 44). However, we showed, for the first time, that both fat mass and fat-free mass contribute to the associations of body size with sagittal posture. After adjustment for height, only fat mass was inversely associated with a Flat posture while both components of non-skeletal body mass were positively and independently related with a hyperlordotic posture type. The inverse relation between bone physical properties and a

Flat pattern observed in our work may be explained by the profile of anthropometric and body composition characteristics featured by this typology. However, in the case of a rounded posture, an association between bone quality and posture remains after those adjustments.

Finally, some limitations of this thesis need to be addressed. The use of photogrammetry to assess our major outcome may have introduced some misclassification because of systematic or random differences in placement of markers between and within examiners, which can depend on children's anthropometric characteristics, namely lower accuracy in pelvic anatomical identification in children with higher subcutaneous adiposity (63). However, these issues are not expected to compromise our findings for several reasons: (1) systematic differences were accounted for by quantifying children's distance to the average values within each examiner's distribution; (2) consistent statistically significant associations between weight/BMI and postural types were still observable in both genders; (3) we confirmed the validity of proposed patterns against postural parameters not used in the cluster solution (using prominent landmarks) that are not expected to be associated with the accuracy of landmark identification. This is further supported by the fact that we identified three main patterns that are clearly distinct from each other (differences varying between 6.3º to 13.1º), while random error of the measurement method is estimated to vary between 3.5º and 6.7º (63).

The present postural patterns have not yet been reproduced in other samples and therefore future research is needed to confirm validation of the postural classifications. Measurements of anthropometric characteristics were considered at birth, 4 and 7 years of age and additional measurements across childhood would have provided more detailed information of the growth-related changes in the associations between anthropometrics and posture. One of the limitations of this work is the lack of direct measurement of mechanical stimuli imposed by anthropometrics, adiposity and muscle contractions. Our analyses assumed that mechanical influences are captured by lean mass and reflected on bone physical properties, both quantifiable by whole body dual energy X-ray absorptiometry measurements. The population-based nature of our work constrained these assessments, but it ensured a wide representation of naturally occurring anthropometrics, body composition, bone physical properties and postural angles in the pediatric population. The external validity of our findings is a key advantage because previous evidence had relied mainly on biomechanical model simulations without any empirical measurements of bone quality (45, 53-55). Furthermore, differentiating effects of posture from body size/composition on bone may be unrealistic. Moreover, given the observational nature of our studies, the causal nature of relationships between body size and composition and posture should be seen in the context of homeostatic feedback mechanisms rather than as a set of unidirectional effects.

In the present thesis, we used data from a cohort of children evaluated at three different ages (at birth, 4 and 7 years old). Selection bias at recruitment is unlikely since 70% of the eligible mothers were consecutively invited. Not all eligible mothers were invited due to logistic constraints, namely availability of human resources; in these circumstances women were invited on a basis of first come, first served and 8% of those refused to participate (77). Another important issue is differential losses to follow-up. In the present thesis we consecutively selected a subsample of children among those evaluated at 7 years of age through face-to-face interviews. Among those invited, a high proportion of 80.5% of children were successfully evaluated. Additionally, in each of the present studies, when we compared children who were and were not included regarding characteristics in previous follow-ups, children were similar regarding anthropometrics at birth and they were heavier and taller during the 4- and 7-year follow-up, although the magnitude of differences was small. We opted for complete case analysis in all works of this thesis because censoring is not expected to be related with future sagittal standing posture after adjustment for all the important covariates (87).

6. Conclusions

We identified a meaningful summary model for the distribution of sagittal standing posture for school-aged girls and boys. Patterns were consistent with childhood as a sensitive period for posture differentiation. However, postural dichotomy “neutral vs. non-neutral” clearly does not apply to children and substantial gender heterogeneity in the features and frequency of different patterns existed among school-aged children. This highlights the potential for gender-specific biomechanical frameworks of the spino-pelvis during habitual upright position even in prepubertal ages, implying different biomechanical loads and perhaps contributing to the well-known gender differences of pediatric spinal deformities, such as higher frequency of scoliosis in girls and Scheuermann’s disease in boys.

Additionally, the mechanical load imposed by body size seems to have a cumulative sculpting role throughout the first decade of life, especially after walking abilities are acquired and our results support that both bone and posture mature in a shared and interrelated mechanical environment modulated by pattern-specific anthropometrics and body composition.

This work does not intend to measure the effectiveness of weight reduction to modulate sagittal standing posture, but rather to provide a basis for future research directed to evaluating whether adult postural health can be potentiated through interventions on anthropometrics, and consequently body composition parameters, since early ages.

7. References

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