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BIOMECHANICS OF CHILDHOOD OBESITY: IMPLICATIONS FOR THE MUSCULOSKELETAL SYSTEM AND ROLE OF PHYSICAL EXERCISE

Biomecánica de la obesidad infantil:
implicaciones para el sistema músculo-esquelético
y rol del ejercicio físico

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KU LEUVEN

DOCTORAL SCHOOL
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BIOMECHANICS OF CHILDHOOD OBESITY

IMPLICATIONS FOR THE MUSCULOSKELETAL SYSTEM AND ROLE OF PHYSICAL EXERCISE

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ABSTRACT

Background: Childhood obesity is one of the major public health problems nowadays. It seems that children and adolescents with overweight/obesity (OW/OB) develop a different body posture and way of moving (biomechanics), with important implications in the development of musculoskeletal disorders (e.g., pain, injuries or osteoarthritis) and daily physical limitations. However, it is still unknown what these biomechanical alterations are, and the impact they have on the musculoskeletal health of these youths. Physical exercise could be a promising approach to fight against these biomechanical alterations and their harmful implications, but, to date, there are still scarce intervention studies proving it.

Purposes: 1) to systematically review and synthetize the literature on the impact of OW/OB on body posture and gait biomechanics in children and adolescents (**SECTION 1**); 2) to study the associations between physical fitness and some biomechanical dimensions such as body posture and movement competence in children with OW/OB (**SECTION 2**); and 3) to investigate the effects of a 13-weeks exercise program on three biomechanical dimensions (body posture, gait biomechanics and movement competence) of children with OW/OB (**SECTION 3**).

Main findings: results from the two systematic reviews included in this Doctoral Thesis (**Study 1 and 2**) reveal that childhood obesity is associated with the presence of postural malalignments and biomechanical alterations during walking and that this could be playing a major role in the onset and progression of musculoskeletal disorders. **Study 1** shows that the OW/OB is associated with the presence of five postural malalignments: rounded shoulders, thoracic hyperkyphosis, lumbar hyperlordosis, genu valgum and flatfoot. In addition, this study demonstrates that children and adolescents with OW/OB have 6.6 times higher risk of presenting genu valgum, 1.5 times higher risk of presenting flatfoot and 1.7 times higher risk of presenting any kind of postural malalignments compared with their normal-weight peers. In the **Study 2** we evidenced that children and adolescents with OW/OB walk with greater step width, longer stance phase, a lower limb valgus position, greater force moments at hip, knee and ankle, higher tibiofemoral contact forces and greater calf muscle activation, all in comparison with children with a normal-weight. Furthermore, in **Study 3 and 4** we found that, although excess of body mass has demonstrated to be a determining factor for the biomechanical detriments, physical fitness seems to be playing a positive role in the body posture and movement competence of children with overweight/obesity. Finally, results from **Study 5, 6 and 7** demonstrate that a 13-week exercise program can lead to positive effects on body posture, movement competence, muscular strength and gait biomechanics (i.e., plantar pressure and kinematics) in children with overweight/obesity.

Overall conclusion: the present Doctoral Thesis represents an important step forward in the knowledge of childhood obesity from a biomechanical perspective, its harmful implications for the musculoskeletal health and the role of physical exercise as a promising treatment against the biomechanical alterations normally experienced in these children and adolescents.

RESUMEN

Antecedentes: La obesidad infantil es uno de los problemas de salud más relevantes en la sociedad actual. Se cree que los niños y adolescentes con sobrepeso/obesidad desarrollan una postura y forma de moverse diferente (biomecánica), lo cual tiene importantes implicaciones en el desarrollo de patologías musculoesqueléticas (ej., dolor, lesiones u osteoartritis) y limitaciones físicas del día a día. Sin embargo, aún se desconoce cuales son esas alteraciones biomecánicas y el impacto que tienen en la salud musculoesquelética de estos jóvenes. El ejercicio físico podría ser un tratamiento prometedor contra esas alteraciones biomecánicas y sus consecuencias, pero hasta la fecha aún hay escasos estudios de intervención que lo demuestren.

Objetivos: 1) realizar una revisión sistemática y síntesis de la literatura sobre el impacto del sobrepeso/obesidad en la postura corporal y la biomecánica al caminar en niños y adolescentes (**SECCIÓN 1**); 2) estudiar la asociación entre la condición física y algunas dimensiones biomecánicas como la postura o la competencia motora en niños con sobrepeso/obesidad (**SECCIÓN 2**); y 3) investigar el efecto de un programa de entrenamiento de 13 semanas sobre tres dimensiones biomecánicas (postura, biomecánica al caminar y competencia motora) en niños con sobrepeso/obesidad (**SECCIÓN 3**).

Resultados principales: los resultados de las dos revisiones sistemáticas incluidas en esta Tesis Doctoral (**Estudio 1 y 2**) revelan que la obesidad infantil se asocia con la presencia de desalineaciones posturales y alteraciones biomecánicas al caminar, y que esto podría estar jugando un papel importante en la aparición y progresión de patologías musculoesqueléticas. El **Estudio 1** muestra que el sobrepeso/obesidad se asocia con la presencia de hasta cinco desalineaciones posturales: hombros caídos, hipercifosis torácica, hiperlordosis lumbar, valgo de rodilla y pie plano. Además, este estudio demuestra que los niños y adolescentes con sobrepeso/obesidad tienen 6.6 veces mayor riesgo de presentar valgo de rodilla, 1.5 veces más riesgo de presentar pies planos y 1.7 veces mayor riesgo de presentar algún tipo de desalineación postural en comparación con sus compañeros con un peso normal. En el **Estudio 2**, pusimos de manifiesto que los niños con sobrepeso/obesidad caminan con una mayor anchura de paso, una fase de apoyo más prolongada, una posición de valgo en los miembros inferiores, mayores momentos de fuerza en la cadera, rodilla y tobillo, mayores fuerzas de contacto en la articulación femorotibial y mayor activación de los músculos sóleo y gastrocnemio en comparación con niños con un peso normal. Por otro lado, en los **Estudios 3 y 4** encontramos que, aunque el exceso de masa corporal ha demostrado ser un factor determinante en el deterioro biomecánico, la condición física parece estar jugando un papel positivo en la postura corporal y competencia motora de los niños con sobrepeso/obesidad. Por último, los resultados de los **Estudios 5, 6 y 7** demuestran que un programa de entrenamiento de 13 semanas puede acarrear efectos positivos en la postura corporal, competencia motora, fuerza muscular y biomecánica al caminar (presión plantar y cinemática) en niños con sobrepeso/obesidad.

Conclusión general: la presente Tesis Doctoral supone un importante avance en el conocimiento de la obesidad infantil desde una perspectiva biomecánica, sus implicaciones perjudiciales en la salud musculoesquelética y el papel del ejercicio físico como un tratamiento prometedor contra las alteraciones biomecánicas

que normalmente presentan estos niños y adolescentes.

GENERAL INTRODUCTION

THE CHILDHOOD OBESITY PANDEMIC

Childhood obesity is considered one of the most serious public health challenges of the 21st century [1]. Recent numbers from the World Obesity Federation reveal that more than 340 million children and adolescents worldwide present overweight or obesity [2]. To have an idea of the dramatic increase in the last decades, in 1975 only 4% of the worldwide paediatric population presented overweight/obesity (OW/OB), whereas in 2016 this figure has increased to 18% and more (**Figure 1**) [2]. Europe has not been exempted of this growth, and amongst European countries, Spain is situated in the top 5 with between 30 and 35% of its children having OW/OB [3]. Although last trends in Europe demonstrate an stabilization in childhood excess weight, the prevalence is still alarming [4].

The World Health Organization (WHO) refers to four main long-term health consequences of childhood obesity [5]: 1) cardiovascular diseases (e.g., heart disease and stroke), 2) diabetes (mainly type II diabetes), 3) musculoskeletal disorders (mainly osteoarthritis), and 4) certain types of cancer (i.e., endometrial, breast and colon). These consequences are so harmful that at least 2.6 million people each year die as a result of having OW/OB [5]. The present Doctoral Thesis focuses on the musculoskeletal consequences of obesity, for which, the biomechanical perspective is of utmost importance.

CHILDHOOD OBESITY FROM A BIOMECHANICAL PERSPECTIVE

Biomechanics encompasses the study of mechanical laws in relation to the structure and movement of the human body. This doctoral thesis includes the study of three biomechanical dimensions in children with OW/OB: 1) body posture, 2) gait biomechanics, and 3) movement competence.

Body Posture

Body posture refers to the positioning of body segments in relation to each other. A healthy body posture is achieved when the body segments are aligned in such a way that the least amount of stress within and between structures occurs, and that it does not require excessive muscle activation to perform daily tasks [6]. Our body posture has an important genetic component that we have inherited from our parents, but there are also many external factors capable of influencing it throughout the lifespan [7].

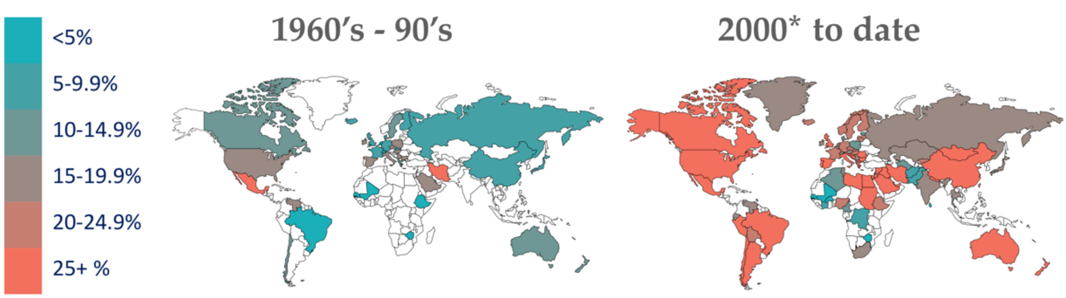

Figure 1. Worldwide change of childhood overweight/obesity prevalence

Concretely, childhood represents a crucial period in the musculoskeletal development coinciding with the acquisition of an upright posture and the basic locomotor skills [8, 9]. Thus, children are especially sensitive to external factors influencing their body posture [10]. It is widely accepted that OW/OB is one of these influential external factors, and leading to aberrant alterations of the body posture of children. However, the reality is that there is no solid evidence describing the effect of childhood obesity on body posture.

Wearing et al. [11], in 2006, were the first to describe in a narrative review the potential consequences of OW/OB in the development and function of the musculoskeletal system of children. They reported that obesity might be leading to structural alterations in the femoral necks, knees and feet of children [11]. Three years later, Chan et al. [12] also addressed this topic in a narrative review concluding that children with OW/OB might be more predisposed to the development of lower limb deformities, such as slipped capital femoral epiphysis, Blount's disease and genu valgum [12]. The authors of both narrative reviews highlighted the lack of knowledge on this topic and suggested that future research investigating the true impact of childhood obesity on the musculoskeletal system is needed. A decade later, the evidence is still very limited. The only available systematic review is solely focused on the foot structure and did not synthetize results in a standardized process (i.e., qualitative synthesis or quantitative meta-analysis) [13].

In the present doctoral thesis, we address the real impact of OW/OB on the musculoskeletal structure of children and adolescents by presenting results from a systematic review and meta-analysis that synthesizes observations from close to 2 million children and adolescents worldwide.

Gait Biomechanics

Gait biomechanics is the systematic study of human walking from a biomechanical perspective. The analysis of gait biomechanics ranges from basic spatiotemporal parameters (e.g., gait speed, stride length and cadence) to more complex parameters such as kinematics (e.g., joint angles and range of motion), kinetics (e.g., joint moment of force and power generation), muscle activity (e.g., muscle activation and force) and plantar pressure (e.g., plantar surface and force peaks). Technological advances in the biomechanics field allow accurate assessment of these complex biomechanical parameters, giving researchers the opportunity to study gait biomechanics characteristics in many populations.

The link between walking and childhood obesity has been traditionally studied from a quantitative perspective (i.e., time and intensity) rather than a qualitative one (i.e., biomechanics) since this population presents worryingly low levels of physical activity [1]. Focusing on the qualitative perspective, it is assumed that OW/OB hampers daily walking ability by affecting the normal gait biomechanics. Runhaar et al. [14] systematically reviewed the gait biomechanics of adults with obesity, finding that, in comparison with normal-weight, they walked slower, with shorter and wider steps, with longer stance duration and presenting lower limb misalignments. However, little is known on the biomechanical alterations resulting from OW/OB in childhood and adolescence.

This doctoral thesis provides a systematic review on the biomechanical characteristics of the gait pattern in children and adolescents with

OW/OB by comparing them with their normal-weight peers. It summarizes evidence from 25 articles including a broad variety of biomechanical dimensions (i.e., spatiotemporal, kinematics, kinetics, centre of mass and muscle activation), which allows us to identify the gait biomechanical alterations normally present in this population.

Movement Competence

The study of movement characteristics in childhood has been inconsistently referred to as "movement competence", "motor competence", "motor proficiency" or "motor ability". All these terms have in common the study of competence when performing those movement patterns necessary for an optimal motor development in childhood [15]. Movement competence, as we will refer to from now on, is the basis on which more complex physical-sport activities are built (**Figure 2**) [15]. In the first step of movement competence we have the Fundamental Movements, basic movement patterns that we naturally acquired in infancy (e.g., squat and lunge patterns). On the step above are the Fundamental Movement Skills, which are more global movement patterns (e.g., run, hop and throw objects) present in most of the physical-sport activities.

Children with OW/OB have demonstrated a worsened performance in movement competence, both in fundamental movements and fundamental movement skills [16, 17]. This is a crucial factor to understand why these children do not have the same predisposition to engaging in physical-sport activities as their peers with normal-weight [16, 18]. Movement competence has also suggested to play a key role in the optimal development of the structure and function of the musculoskeletal system in childhood

Figure 2. Graphical representation of the movement competence components (in blue) in relation to physical-sport activities.

[15, 19]. Nevertheless, there is still needed more evidence relating movement competence to the musculoskeletal system biomechanics in children, and particularly in a vulnerable population such as OW/OB children who have shown a significant detriment in both factors.

With this doctoral thesis we study the relationship between movement competence, concretely fundamental movements, and other biomechanical dimensions such as body posture in children with OW/OB. Furthermore, we include a key piece to this puzzle, which is the physical fitness components (i.e., cardiorespiratory fitness, muscular strength, and speed-agility), a powerful marker of health in childhood [20].

IMPLICATIONS OF THE BIOMECHANICS OF CHILDHOOD OBESITY

Development of Musculoskeletal Disorders

Among the four most accepted comorbidities of childhood OW/OB (i.e., cardiovascular disease, diabetes, musculoskeletal disorders and cancer), the development of musculoskeletal disorders has been received less attention in the literature. It can be easily identified in a quick search in PubMed by introducing the keywords "Pediatric Obesity" AND "Cardiovascular Diseases", "Diabetes Mellitus", "Neoplasms" and "Musculoskeletal Diseases" (**Figure 3**). It is surprising that not much attention is paid to this topic, even known that musculoskeletal disorders are the most diagnosed disease worldwide and the one with the largest health-care expenditures, only in Europe costing more than three hundred billion euros every years [21, 22].

Children with overweight and obesity have a 26% higher prevalence of overall musculoskeletal pain compared to normal-weight children, and for some body parts such as the lower back this prevalence increases up to 42% [23–25]. Furthermore, these children have higher risk of lower extremity injuries during practising physical activities [26]. Some authors suggest that sedentary lifestyles, a worse psychological health and inflammatory processes that are inherent to OW/OB could be leading to the higher prevalence of musculoskeletal disorders in this population [24]. However, a biomechanical perspective has also suggested that structural alteration in the musculoskeletal system, joint misalignments in locomotor tasks, and an altered movement competence could be behind the problem [11, 16, 27, 28].

Limiting Factors for Physical Activity

The biomechanical perspective of childhood obesity is an important piece to understand why these children are less physically active than their normal-weight peers. For instance, the presence of pain and injuries associated to OW/OB has major implications for the normal physical function of children, decreasing their motivation to be physically active [29–31]. Likewise, children with OW/OB need to put in a greater physical effort to walk the same distance as would normal-weight children, which is partially explained because of mechanical inefficiency of their gait pattern [32, 33]. This fact might be determinant for these children to discard physically active behaviours such as the active commuting to school [27]. Lastly, the fact that children with OW/OB have a worse movement competence supposes an important behavioural barrier to engage in physical activities since they feel disadvantaged with respect to their peers with normal-weight [16, 18].

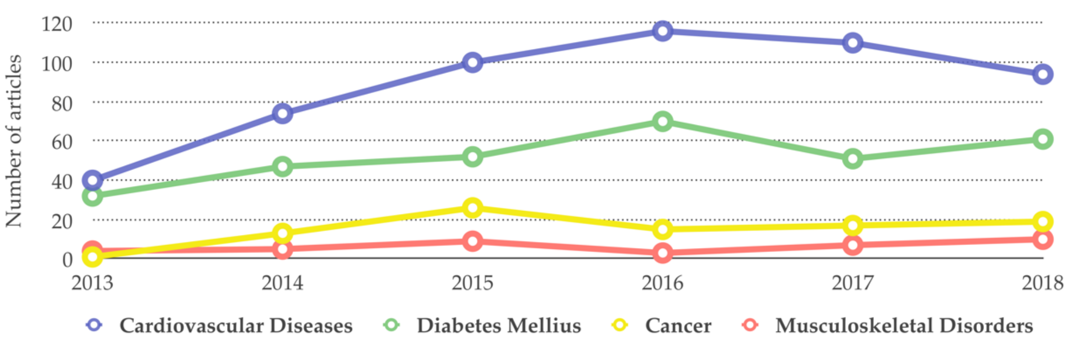

Figure 3. Number of articles divided by year that yield a PubMed search (November 4th, 2019) on the main four diseases associated with childhood obesity

PHYSICAL EXERCISE: A POSSIBLE SOLUTION?

That physical exercise is an indispensable tool to combat OW/OB and its associated diseases is nothing new. Coinciding with the last 2019 Physical Activity Guidelines, the American Colleague of Sport Medicine brought together experts in sport and exercise sciences to publish 15 systematic reviews about the benefits of physical exercise in the main health diseases of today's society [34]. With a moderate and strong level of evidence, physical exercise demonstrated to be beneficial in the prevention of six diseases associated with OW/OB (**Figure 4**), namely: brain health, cardiovascular diseases, osteoarthritis, cancer, cardiometabolic diseases and physical function [35–41].

Despite the overwhelming evidence about the benefits of physical exercise, to date there is little evidence demonstrating whether it induces positive changes in the biomechanics of childhood obesity. To our knowledge, in a childhood population there is only one previous study investigating the effect of exercise on the body posture [42], two on gait kinematics [43, 44], and two on gait plantar pressure [45, 46]. Regarding movement competence, a recently published systematic review demonstrated that exercise interventions are effective in improving fundamental movement skills in children with OW/OB, concretely locomotor and object-control skills [47]. However, this effectiveness has not been demonstrated yet in fundamental movements, the first step in the movement competence acquisition. We identified only three previous trials studying the effects of exercise on fundamental movements in children with normal-weight [48–50], whereas no trial was found in children with OW/OB.

Figure 4. Visual representation of the six diseases in which physical exercise has demonstrated a preventive effect. Single check mark: moderate level of evidence; double check mark: strong level of evidence.

In the present doctoral thesis we have investigated for the first time the simultaneous effects of an exercise program on several biomechanical dimensions of childhood obesity, concretely on body posture, gait kinematics, plantar pressure and fundamental movements. All this was done in combination with the expected improvements in physical fitness, in which exercise effectiveness has been already demonstrated [51, 52]. The exercise program conducted in the present doctoral thesis did not stop at meeting the Physical Activity Guidelines for children; it also was conscientiously designed to target the biomechanical alterations normally experienced in this population. This research implies a step forward in the knowledge on exercise programs in children with OW/OB, moving away from the current dogma mainly focused on the quantitative (i.e., training volume and intensity) rather than qualitative aspects (i.e., biomechanics) of movement [53].

SUMMARY OF KNOWLEDGE GAPS AND CONTRIBUTIONS OF THIS DOCTORAL THESIS

In short, these are the main gaps detected in the literature on biomechanics and childhood obesity:

- There is limited evidence on the real impact of OW/OB on the **musculoskeletal structure** of children and adolescents.
- There is limited evidence whether children with OW/OB present **biomechanical alterations during walking**, the most basic locomotor task.
- The role of **movement competence**, concretely concerning fundamental movements, in the face of other biomechanical dimensions as well as the physical fitness level of children with OW/OB, remains largely unknown.
- Little is known about the **pathogenesis of musculoskeletal disorders** in childhood obesity and whether a biomechanical perspective is contributing to it.
- There is very little evidence studying whether **physical exercise** induces positive changes in the biomechanics of childhood obesity.

Based on these literature gaps, the present doctoral thesis provides the following contributions to the current knowledge:

- A systematic review and meta-analysis on the impact of childhood obesity on structural integrity of the musculoskeletal system in children and adolescents (**Study 1**).
- A systematic review on the biomechanical characteristics of walking in children and adolescents (**Study 2)**.
- A theoretical foundation supporting the implications of the biomechanical alterations of childhood obesity in the onset and progression of musculoskeletal disorders as well as in the mechanical inefficiency during walking (**Studies 1 and 2**).
- Observational evidence on the associations between body posture, movement competence, and physical fitness in children with OW/OB (**Studies 3 and 4**)
- Exercise-based intervention studies on body posture, gait biomechanics, movement competence and physical fitness in children with OW/OB (**Studies 5, 6 and 7**).

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AIMS

AIMS

Overall aim

The overall aim of the present doctoral thesis is to systematically review the impact of overweight/obesity on the body posture and gait biomechanics of children and adolescents, as well as to study the effects of a 13-week exercise program on body posture, movement competence and gait biomechanics in children with overweight/obesity.

Specific aims

SECTION 1. Systematic reviews and meta-analysis: impact of childhood obesity in the musculoskeletal structure and the biomechanics of walking

- **Specific aim 1:** 1) to examine the association between OW/OB indicators (e.g., body mass index [BMI]) and postural malalignments in children and adolescents; and 2) to synthesize evidence on whether children and adolescents with OW/OB are at a higher risk of experiencing postural malalignments in comparison with children with normal-weight.
- **Specific aim 2:** to examine the biomechanical characteristics of the gait pattern in children and adolescents with OW/OB in comparison with normal-weight.

SECTION 2. Cross-sectional studies: role of physical fitness in the biomechanics of childhood obesity

- **Specific aim 3:** 1) to examine the associations of fatness (i.e., BMI), physical fitness components and functional movement quality with body posture in children with OW/OB; and 2) to determine which of these are the best predictors of body posture.
- **Specific aim 4:** 1) to examine the individual association of several indicators of fatness and the components of fitness with functional movement quality in over-weight/obese children; and 2) to explore the independent and combined association of the degree of fatness (i.e. over-weight vs. obesity) and the level of fitness (i.e. fit vs. unfit) with children's functional movement quality.

SECTION 2. Effects of a 13-week exercise program on the biomechanics of childhood obesity

- **Specific aim 5:** to analyse whether a 13-week exercise program based on 'movement quality' and 'multi-games' work is able to induce simultaneous positive effects on body posture, functional movement and physical fitness in children with OW/OB.
- **Specific aim 6:** to analyse the effect of a 13-week exercise program based on "movement quality" and "multi-games" work, on plantar pressure during walking in children with OW/OB.
- **Specific aim 7:** 1) to analyse the effect of a 13-week exercise program, based on movement quality and multi-games, on spatio-temporal and kinematic parameters of gait in children with OW/OB; and 2) to study the effect of the exercise program on the presence of lower limb musculoskeletal pain in children with OW/OB.

METHODS

THE MUBI PROJECT

Design and participants

The MUBI project is an individual non-randomized controlled trial (1:1) that aims to investigate the effect of a 13-week exercise program on movement biomechanics, body posture and motor competence in with overweight/obesity. This project has been accepted by the Ethics Committee in Human Research of the University of Granada (n° 279 / CEIH / 2017). The MUBI project is part of the ActiveBrains project, which was funded by the Spanish Ministry of Economy and Competitiveness and the "Fondo Europeo de Desarrollo Regional (FEDER)" with the following reference number: DEP-2013-47540. The ActiveBrains project has been registered registered in the ClinicalTrials.gov (Identifier: NCT02295072). In both project the principal investigator (PI) is Francisco B Ortega, full-time professor in the Faculty of Sport Sci-ences of the University of Granada, Spain. For further information about the MUBI project, you can access our official website in the following link: http://profith.ugr.es/mubi.

The sample size of MUBI project was 70 children between 8 and 12 years old with overweight/obesity, who meet the following inclusion/exclusion criteria: 1) to be 8 – 12.9 years old; 2) to be classified as children with OW/OB as defined by sex and age-specific World Obesity Federation cutoffs (2); 3) to suffer no physical disabilities or neurological disorders that might impede them doing exercise; 4) in the case of girls, to have not reached menarche at the moment of baseline assessment; 5) to take no medications that might influence central nervous system function; 6) to be right-handed (as measured by the Edinburgh inventory) (8) (the brain hemisphere structure of right-handed children differs substantially from that of left-handed children); and 7) to have not been diagnosed with attention-deficit hyperactivity disorder. Recruitment was done at the Unit of Paediatrics of the University Hospitals *San Cecilio* and *Virgen de las Nieves* as well as health care centres of Granada (Spain). Additionally, we contacted the head teacher of both public and private schools of Granada and we published advertisements in the local media. Parental informed consent was required for all children to participate in the study.

The seventy participants were divided into an exercise group (EG), which carried out the exercise program, and a control group (CG), which continued with their normal life. The objective of this distribution is to study the effects of the exercise program by comparing both groups. The EG of the MUBI project was made up of children who had participated during the previous year as control group participants in the ActiveBrains project (**Figure 1**). For ethical reasons, these children were offered the chance to take part in the MUBI project as members of the intervention group; they did not have the opportunity to exercise in ActiveBrains study due its randomization process. The present MUBI project CG was posteriorly recruited following the same procedure as mentioned above.

Exercise program

The exercise programme had a total duration of 13-weeks, starting the 1st of March 2017 and ending the 26th of May 2017, and was run at the Institute for Mixed Sport and Health Sciences (iMUDS) belonging to the University of Granada. Sessions were conducted by a minimum of two sport science students, who received extensive training for supervising this exercise programme. Following previous trial strategy (1),

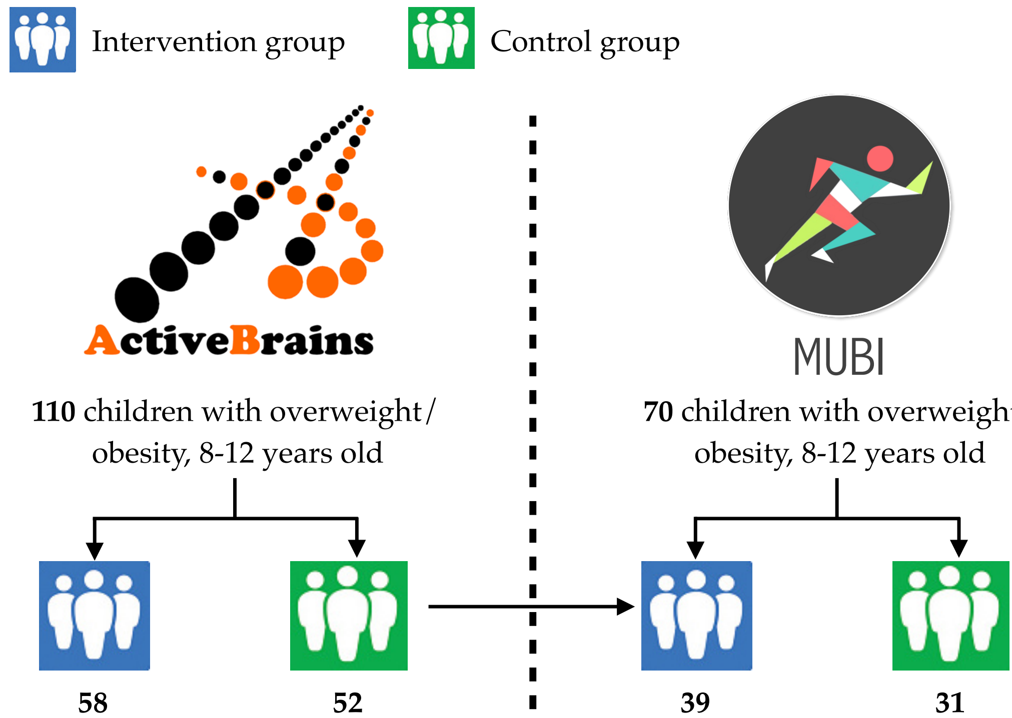


Figure 1. Graphical representation of groups creation for the ActiveBrains and MUBI projects.

group sessions were run every weekday where participants were asked to attend a minimum of 3 sessions per week. This helped to logistically facilitate attendance, allowing participants to select the 3 days that best fit for them and also giving them the possibility to attend the 5 sessions.

Each session had a total duration of 90 minutes, and was divided in two different parts: 30 minutes of 'movement quality', and 60 minutes of the 'multi-games'. The 'movement quality' part of the session was conducted in the gymnasium. The main objectives of this part were that participants acquired awareness of analytic movement mechanics (e.g., anterior and posterior pelvic tilt) and body posture (e.g., optimal spine position), gained body segment mobility (e.g., hip flexion mobility), stability (e.g., core stability) and muscular strength in functional range of motion (e.g., bilateral lower-limb push strength), and learned basic human movements (e.g., squat pattern). The 'multi-games' part of the session was conducted in an outside sport court. Its main objectives were that participants reached a moderate-to-vigorous aerobic intensity, learned and assimilated a wide range of fundamental movement skills (e.g., sprinting, hopping or throwing), and to enjoy while practising physical exercise. In coordination with the children's parents, "exercise homework" was provided for Easter holidays. No specific dietary intervention was conducted in the participants neither in the exercise nor in the control group.

Training methodologies included

The exercise program design was inspired on different training methodologies, specifically selected to address the above mentioned impairments in children with overweight/obesity. Below, is provided a brief definition of these methodologies, the rationale of its inclusion, and the description of how we incorporated them in the exercise program.

1. *Physical activity guidelines for children*

The starting point for the exercise program design was the internationally accepted physical activity guidelines (http://www.health.gov/paguidelines/) for children. These guidelines recommend children to exercise daily, and, therefore, we offered the possibility to attend to the exercise programme daily from Monday to Friday. However, considering that Spanish children usually have 2 sessions of physical education at school, our participants were asked to attend a minimum of 3 sessions per week. Physical activity guidelines also recommend that, within the daily recommended activity, 3 days should include vigorous-intensity physical activity and resistance training. For that reason, one of the objectives of our 'multigame' part of the session was to reach a moderate to vigorous intensity, besides our aims of improving 'movement quality' and gaining of muscle strength.

2. *Positioning statement of youth resistance training*

Far from previous beliefs that children should not practise resistance training, nowadays it is strongly recommended that children and adolescents include this training modality within their physical exercise routines. We have based the present training program on the 'Position Statement on Youth Resistance Training' to design and incorporate resistance training into our 'movement quality' part of the session (6).

2.1. Exercise selection

The main premise in the exercise selection was 'quality in the execution over quantity or load'. Exercise technique was always the main goal, and coaches in charge of sessions were instructed to provide comprehensive technical explanations of each exercise, and give personalized feedback when necessary. We attempted to progressively introduce global bodyweight exercises (e.g. squatting or lunging) and elastic resistance band exercises (e.g., pressing or pulling movements), but it is important to note that our participants were children with overweight/obesity, that overall demonstrated low levels of movement competency and physical functioning. Thus, progression strategies were included through the Dynamic Neuromuscular Stabilization and Integrative Neuromuscular Training approaches that we will explain later in detail.

2.2. Exercise selection

Percentage of an individuals' one Repetition Maximum (1RM) is the most common way to prescribe and control resistance training intensity, but in an untrained population, as is the case of this exercise intervention, the use of 1RM is unnecessary (6). Instead, we first focused on the development of technical competency in each exercise by using low volume and intensity (e.g., 1 set of 2-5 repetitions or 1-2 min of execution time for exercises in pairs), and, above all, emphasizing to children that they should perform each repetition 'slowly and controlled' and 'putting attention on the movement'. Once children learned and mastered exercises, we progressed in volume and intensity, as well as exercise complexity (e.g., 2 set of 5-10 repetitions or 2-3 min of execution time for exercises in pairs).

2.3. Repetition velocity

Execution velocity of our exercises in the 'movement quality' part progressed both, within session and within the training program. Within session, children started with slower and controlled exercise repetition, with less challenging positions such as prone or quadruped, and they finished with rapid exercise that prepare their neuromuscular system to the explosive movement that they performed in the 'multigames' part. Within the training program, coaches encouraged to increase repetition velocity once they noted that technical execution was correct.

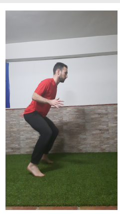
3. *Dynamic Neuromuscular Stabilization approach*

The Dynamic Neuromuscular Stabilization (DNS) approach was developed by Professor Pavel Kolar, a Czech physiotherapist from the Prague School of Manual Medicine (3). DNS proposes to restore an optimal body posture and movement patterns through exercise-position progressions based on the normal development of a healthy baby (3). The 'movement quality' part of the session always followed this type of exercise-position progression (**Table 1**): prone, supine, lateral, quadruped with 4, 3 and 2 points of support, tall-kneeling, half-kneeling, split, squat, base position and one-leg. The session always started with the initial development positions (i.e., supine and prone positions) that are less challenging for children in terms of stabilization demands, and ended with more challenging positions (i.e., split, squat and base position). When initial exercise positions were mastered, we progressed in difficulty by starting the session with more demanding exercise positions. The two trainers in charge of the session emphasised acquiring and maintaining a correct body posture in each exercise-position through visual demonstrations and comprehensible instructions specifically designed for children (e.g., "we are rigid like a stone statue" for stability exercises). Lastly, trainers encouraged the children to do the exercises slow and controlled, always putting awareness in their posture, movement and breathing.

4. *Barefoot training*

Previous observational studies have identified that being habitually barefoot has positive effects on the overall health of children and adolescents' feet, expressed with less prevalence of flatfeet, among others indicators (4,5). Likewise, one previous study has demonstrated that specific barefoot exercises (i.e., short foot exercise) can improve the foot posture, as well as to improve the functional movement patterns in long distance runners (10). Based on this evidence, the whole 'movement quality' part of the session was fully performed barefoot, as well as including specific exercises to train the gait pattern (i.e., gait foot pattern exercises) and to activate intrinsic muscles of the feet (i.e., foot tripod and short foot exercises) (**Table 2**). The inclusion of this barefoot training was expected to help in the activation and strengthening of some key muscles, such as tibialis posterior or flexor hallucis longus, flexor digitorum brevis and abductor hallucis, with also positive adaptations of the bones and ligaments of our participants' feet (5). Furthermore, exercising barefoot could be enhancing a richer environment for the plantar proprioceptors of our participants, being therefore beneficial in maintaining balance, stimulating small nerves of the foot, and getting proximal and distal joint stability (9).

Table 1. Example of the exercise-position progression followed in the 'movement quality' part of

LOWER-LIMBS DEAD BUG	ROLLING PATTERN	FRONT PLANK
		
Supine 	**Supine to prone** 	**Prone** 
LATERAL PLANK	**CRAWLING**	**BIRD-DOG**
		
Lateral 	**Quadruped: 4 points** 	**Quadruped: 2 points** 
HORIZONTAL PULL IN PAIRS	**HORIZONTAL PULL**	**SPLIT IN PAIRS**
		
Tall kneeling 	**Half kneeling** 	**Split** 
SQUAT IN PAIRS	**RAPID RESPONSE BILATERAL**	**SINGLE LEG DEADLIFT**
		
Squat 	**Base position** 	**One leg** 

5. *Integrative Neuromuscular Training*

The most recent position statement on strength training in youth proposes the inclusion of integrative programs enhancing muscular strength together with movement competence and motor proficiency (6). Our exercise program was designed following this philosophy by including the principles of Integrative Neuromuscular Training in each session. Based on the review of Myer GD et al., (7) the Integrative Neuromuscular Training can be defined as a supplemental training program that incorporates general movement pattern (e.g., basics human movement and fundamental movement skills) and specific strength and conditioning exercises (e.g., analytic motor control, mobility and stability) targeted to reconditioned movement mechanics deficits. In this sense, our 'movement quality' part incorporated exercises focusing on analytic motor control (e.g., find and maintain the neutral lumpopelvic or spine positions), mobility (e.g., rolling patterns or hip mobility), stability (e.g., glute bridges or planks) and basic movements (e.g., squat or upper body pulls), whereas the 'multigames' part included activities enhancing fundamental movement skills (e.g., sprinting, hopping or throwing). All these components attempted to: 1) restore normal movement mechanics possibly altered as a consequence of the excess of body weight, 2) learn and master basic human movements inherent to humans (11), 3) gain muscle strength and motor control in functional range of motion, 4) learn and master fundamental movement skills, and 5) gain confidence in their physical functioning.

Duration and periodization of the training program

The training program was divided in 2 phases, graphically shown in Table 4. Phase 1 had a duration of 5 weeks and included sessions 1.1 to 1.4 on a rotary basis. Phase 2 was a progression in exercise complexity and alternated sessions 2.1 and 2.2 from Monday week 6 to Friday week 13, except week 7 in which participants completed an Easter home exercise program.

STUDIES' METHODOLOGICAL OVERVIEW

The present Doctoral Thesis contains a total of 7 studies. **Table 3** shows an overview of the design, participants and variables included in every study contained in this Thesis.

Table 2. Some examples of barefoot exercises included.

FOOT TRIPOD	SHORT FOOT	GAIT FOOT PATTERN
		
Position: split and stand **Description:** distribute the body weight under the 1st metatarsal head, 5th metatarsal head, and heel.	**Position:** split **Description:** find the foot tripod, spread the toes and place them into the ground. In this position, push the big toe down into the ground for 10 seconds.	**Position:** stand **Description:** learn the rollover foot pattern: 1st the heel, 2nd the 5th metatarsal head, 3rd the 1st metatarsal head, and 4th the big toe.

Table 4. Systematic reviews' methodological overview.

Study	Design	Search Strategy	Inclusion criteria	Exclusion criteria	Independent variables	Dependent variables
Study 1	Systematic review and meta-analysis	The search was conducted on PubMed and Web of Science from June 6th 2019	1) prospective longitudinal or cross-sectional studies without any requirement of writing language; 2) children or young (up to 21 years old) assessed by any fatness indicator (e.g., BMI); and 3) outcomes were postural malalignments.	1) not original articles (i.e., meeting abstracts, editorials, or reviews); 2) participants with chronic movement pattern diseases (e.g., cerebral palsy) or 3) adolescents in pregnancy stage.	Overweight/obesity indicators: BMI, fat mass, waist circumference, etc.	Whole body postural malalignments: forward head, thoracic hyperkyphosis, genu valgum, flatfoot, etc.
Study 2	Systematic review	The search was conducted on PubMed and Web of Science from November 12th 2019	1) participants 18 years old or younger; 2) intervention, prospective longitudinal, and cross-sectional articles, without any requirement of writing language; and 3) including gait biomechanical parameters.	1) special populations (e.g., participants with movement pattern disorders or pain); 2) meeting abstracts, editorials or reviews; and 3) gait analysis while carrying extra weight (e.g., backpack).	Overweight/obesity categories using any kind of criteria.	Spatio-temporal (e.g., speed or cadence), kinematics (e.g., joint angular motion), kinetics (e.g., joint moment), centre of mass (e.g., velocity or displacement), and muscle activity (e.g., muscles activation) parameter of gait.

Table 5. Cross-sectional studies' methodological overview.

Study	Target population	Project	Participants	Independent variables (instruments)	Dependent variables (instruments)
Study 3	Children with overweight /obesity	MUBI	62 children with overweight / obesity (58% girls, 10.9 ± 1.2 years old and 26.1 ± 3.8 kg/m^2) from Granada, Spain.	Cardiorespiratory fitness (20m shuttle runt test), muscular strength (handgrip, standing long jump and 1RM arm and leg press), speed agility (4x10m shuttle run test) and fundamental movements (Functional Movement Screen™)	Whole body posture (2-dimensional photogrammetry)
Study 4	Children with overweight /obesity	MUBI	56 children with overweight / obesity (59% girls, 10.9 ± 1.2 years old and 25.9 ± 3.7 kg/m^2) from Granada, Spain.	BMI, waist circumference, fat mass percentage and fat mass index (bioelectrical impedance measures), cardiorespiratory fitness (20m shuttle runt test), muscular strength (handgrip, standing long jump and 1RM arm and leg press) and speed agility (4x10m shuttle run test).	Fundamental movements (Functional Movement Screen™)

Table 6. No-randomized control trials' methodological overview.

Study	Target population	Project	Participants	Exercise program	Dependent variables (instruments)
Study 5	Children with overweight /obesity	MUBI	64 children (EG: 33; CG: 31) with overweight / obesity (59% girls, 10.9 ± 1.3 years, 25.91 ± 3.83 kg/m^2) from Granada, Spain	13-week, 5 sessions per week (minimum attendance of 3 sessions) and 90 mins per session: 30 mins of movement quality work (barefoot training, fundamental movements and strength training) and 60 mins of multi-games (moderate-to-vigorous intensity, fundamental movement skills and playful component)	Whole body posture (2-dimensional photogrammetry), fundamental movements (Functional Movement Screen™), cardiorespiratory fitness (20m shuttle runt test), muscular strength (handgrip, standing long jump and 1RM arm and leg press) and speed agility (4x10m shuttle run test)
Study 6	Children with overweight /obesity	MUBI	70 children (EG: 39; CG: 31) with overweight / obesity (59% girls, 10.8 ± 1.2 years, 25.7 ± 3.8 kg/m^2) from Granada, Spain	13-week, 5 sessions per week (minimum attendance of 3 sessions) and 90 mins per session: 30 mins of movement quality work (barefoot training, fundamental movements and strength training) and 60 mins of multi-games (moderate-to-vigorous intensity, fundamental movement skills and playful component)	BMI, plantar pressure during walking (baropodometric analysis) and foot pain (self-reported questionnaire)
Study 7	Children with overweight /obesity	MUBI	50 children (EG: 25; CG: 25) with overweight / obesity (62% girls, 10.8 ± 1.2 years, 25.9 ± 3.6 kg/m^2) from Granada, Spain	13-week, 5 sessions per week (minimum attendance of 3 sessions) and 90 mins per session: 30 mins of movement quality work (barefoot training, fundamental movements and strength training) and 60 mins of multi-games (moderate-to-vigorous intensity, fundamental movement skills and playful component)	Spatiotemporal and kinematics parameters of the gait pattern (i.e., 3-dimensional motion analysis), and musculoskeletal pain (self-reported questionnaire)

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RESULTS AND DISCUSSION

SECTION 1.

Systematic reviews and meta-analysis: impact of childhood obesity in the musculoskeletal structure and function

SECTION 1

Study 1

The impact of obesity on the musculoskeletal structure of children and adolescents: a systematic review and meta-analysis

Draft

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INTRODUCTION

Childhood and adolescence overweight/obesity (OW/OB) is currently considered one of the most serious global public heath challenges affecting 340 million children and adolescents worldwide [1]. Apart from being a major risk factor for other serious diseases such as cardiovascular diseases, cancer and diabetes, OW/OB has been suggested to alter the structure and function of the young musculoskeletal system, although it has received relatively little attention within the literature [2, 3]. Particularly, some authors have reported that OW/OB leads to postural malalignment (PM) in children and adolescents (e.g., lumbar hyperlordosis, genu valgum or flatfoot), which is understood as non-optimal alignments of body segments [2, 4, 5]. These PM involve mechanical stress on bones/joints and muscle over-activation, which over time triggers the onset of pain and more severe musculoskeletal disorders [2, 6]. In fact, recent research revealed that children with OW/OB are at 26% higher risk of experiencing any kind of musculoskeletal disorders (i.e., pain, injuries and fractures) [7], as well as being more predisposed to develop osteoarthritis in adulthood [8].

During childhood and adolescence there are many external factors capable of influencing our posture, since one is then exposed to rapid physical and environmental changes [9, 10]. The presence of OW/OB has been suggested to be an influential external factor, but further evidence is needed. Wearing et al. [2] and Chan et al. [11] were the first to describe in their narrative reviews that childhood obesity may be influencing the optimal lower limb musculoskeletal structure. Stolzman et al. [5] showed, with their systematic review including 13 articles, that children with OW/OB have higher prevalence of presenting with flatfoot than children with normal-weight (NW). However, to date neither has any study systematically reviewed the literature investigating the relationship between OW/OB and PM in the entire musculoskeletal system in children and adolescents, nor have any results been synthesized with a standardized protocol (i.e., meta-analysis and/or qualitative synthesis). This can help us better understand the impact of OW/OB on the musculoskeletal system of children and adolescents and, in turn, its implications on the onset and progression of musculoskeletal disorders.

The aims of the present systematic review and meta-analysis were 1) to examine the association between OW/OB indicators (e.g., body mass index [BMI] or fat mass index) and PM in children and adolescents, and 2) to synthesize evidence on whether children and adolescents with OW/OB are at a higher risk of experiencing PM in comparison with children with normal-weight (NW).

METHODS

This systematic review is guided by the Meta-analysis Of Observational Studies in Epidemiology (MOOSE) [12], and the review protocol was registered in the International Prospective Register of Systematic Reviews (https://www.crd.york.ac.uk/prospero/) with reference number: CRD42019129093.

Data Sources and Searches

PubMed and Web of Science were searched from inception to June 6, 2019. Two researchers with expertise in the topic defined the search strategy (J-V and P-MG), which is available in **Table S1**.

Study Selection

Two researchers (P-MG and D-MA) independently performed the study selection process and any discrepancies were resolved through discussions and consensus. In a first stage, articles identified in both databases were merged, and titles and abstracts were examined to identify those likely to be included. In a second stage, full text of the selected studies were checked to determine final eligibility. Studies were included if the following inclusion criteria were satisfied: (1) designs were prospective longitudinal or cross- sectional without any special requirement of sample size nor writing language; (2) participants were children or young (up to 21 years old) assessed by any fatness indicator (e.g., BMI); and (3) outcomes were PM. Studies were excluded if they: (1) were not original articles (i.e., meeting abstracts, editorials, letters to editor, or reviews); (2) included participants with chronic movement pattern diseases (e.g., cerebral palsy) or (3) included adolescents in pregnancy stage, since this is known to alter their normal body posture.

Data Extraction

The following information was extracted from the included studies: 1) author's name and year of publication, 2) country of the study, 3) total sample size and characteristics of participants, 4) study design, 5) body composition indicators and assessment instruments, 6) body posture measures and assessment instrument, 7) main findings. Results extracted were those relating to body posture measures with body composition indicators, or comparing body posture between obesity categories (i.e., normal-weight, overweight and obesity) in children and young. The selection of the data was done by two independent researchers (P-MG and D-MA) and any disagreements were discussed until consensus was reached.

Main Outcome Measures

After the data extraction was done, we detected ten PM as the most frequently studied: forward head, rounded shoulder, thoracic hyperkyphosis, lumbar hyperlordosis, flat spine, scoliosis, sway-back posture, genu valgum, genu recurvatum and flatfoot. **Table 1** provides a definition of each PM as well as the assessment protocol by which these were diagnosed.

Table 1. Definition and assessment method of the postural malalignments included.

Postural malalignments	Definition	Measures
Forward head	Forward inclination of the head with regards to the thorax, normally accompanied by a cervical spine hyperextension.	2-D photogrammetry [23–25], musculoskeletal examination [22]
Rounded shoulders	Forward inclination of the shoulders with regards to the thorax, associated with a protracted position of the scapula and an internal rotation of the glenohumeral joint.	2-D photogrammetry [16, 17, 23], musculoskeletal examination [22, 26]
Thoracic hyperkyphosis	Increased backward curve in the upper back, characterized by a thoracic flexion.	2-D photogrammetry [10, 16, 21, 24, 25, 28–31], musculoskeletal examination [22, 27]
Lumbar hyperlordosis	Increased lumbar lordosis curve characterized by a hyperextended lumbar spine and an anterior tilt of the pelvis.	2-D photogrammetry [16, 18, 21, 24, 25, 28–33], musculoskeletal examination [22, 34]

Table 1. Definition and assessment method of the postural malalignments included.

Postural malalignments	Definition	Measures
Scoliosis	Lateral curve of the spine toward one side or both sides.	X-ray [37, 40], 2-D photogrammetry [27, 29, 36] musculoskeletal examination [22, 26, 34, 35, 38, 39]
Flat spine	Straight position of the spine characterized by the lack of physiological curvatures in thoracic and lumbar spine, and a posterior tilt position of the pelvis.	2-D photogrammetry [18, 28, 31–33] musculoskeletal examination [22]
Sway-back posture	Backwards inclination of shoulders and chest, whereas forward inclination of the pelvis all with respect to feet position.	2-D photogrammetry [24, 25, 28, 31–33]
Genu valgum	Knees are close each other where feet are apart, characterized by hip adduction with internal rotation and knee abduction.	DEXA images [42, 46], 3-D photogrammetry [47], Goniometry [20, 41, 44, 45, 48, 49, 95], musculoskeletal examination [22, 34, 38],
Genu recurvatum	Hyperextension of the knee accompanied by ankle plantarflexion.	Goniometry [20], musculoskeletal examination [34, 38]
Flatfoot	Drop of medial longitudinal arch of foot which is normally accompanied by a foot pronation pattern (i.e., ankle dorsiflexion and abduction, and talonavicular eversion)	MRI [61], 3-D scan [52, 60, 63] ultrasound [65, 69, 70], footprint [49–51, 58, 67, 68, 71, 74, 76–78], plantar pressure [54, 65, 66, 70, 75, 86] musculoskeletal examination [19, 22, 29, 53, 55–57, 64, 72, 73, 79, 80]

Risk of Bias

The Joanna Briggs Institute Critical Appraisal Tool for Systematic Reviews was used to evaluate the quality of both longitudinal and cross-sectional studies [6, 13]. This tool provides ten quality criteria items for longitudinal studies and eight for cross-sectional studies, each of which have three possible answers: “yes” (criterion met), “no” (criterion not met), and “not applicable.” The percentage of positively scored criteria (i.e., “yes”) with respect to the total number of applicable criteria was calculated for each study as an indicator of quality. A study was considered as “high quality” when the positively scored percentage was at least 75%, whereas studies were considered as “low quality” when the quality score was lower than 75%. Two independent researchers (P-MG and D-MA) accomplished this process, and disagreements were discussed to reach consensus.

Qualitative Evidence Synthesis

All results, both from longitudinal and cross-sectional studies, were synthesized through the method firstly used by Sallis et al. [14], and more recently by Rodriguez-Ayllon et al. [15]. This method rates the results based on the following criteria: 1) If 0–33% of studies reported a statistically significant association of a PM with BMI and/or obesity degree, the result was classified as no association (Ø); 2) if 34–59% of studies reported a significant association of a PM with BMI and/or obesity degree, or if fewer than four studies reported on this PM, the result was classified as being inconsistent/uncertain (?); and 3) if ≥ 60% of studies found a statistically significant association of a PM with BMI and/or obesity degree, the result was classified as positive (+) or negative (−), depending on the direction of the association. In those studies that the association was tested separately in girls and boys or in children and adolescents, we specified it as '♀' or '♂' and 'C' or 'A', respectively. Furthermore, these separate associations were quantified with a 0.5 score instead of 1, as previous authors did [15].

Meta-Analysis

Added to the qualitative evidence synthesis, quantitative meta-analysis was undertaken. Since the majority of included studies compared the prevalence of having PM between children with OW/OB and children with NW, we decided to perform a meta-analysis of dichotomous outcomes. The random-effects models of inverse-variance method was used to calculate pooled risk ratio (RR) and corresponding 95% confidence interval (CI) for different PM in children with OW/OB and children with NW. Additionally, sensitivity analyses were performed excluding studies one by one from the pooled estimates, to evaluate whether any particular study modified the pooled estimates. Meta-regressions were calculated based on children's mean age and BMI. Finally, publication bias was estimated using Egger´s test. Analyses were performed using the Review Manager Version 5.3 (The Nordic Cochrane Center, The Cochrane Collaboration, 2014, Copenhagen, Denmark).

RESULTS

Study Selection

The PRISMA flow diagram (**Figure 1**) outlines the search strategy used to identify articles. Of 1086 non-duplicated articles, 926 were excluded after an abstract review and 92 after a full text review, having thus 68 articles that met our inclusion criteria. Of these studies, 5 used a longitudinal design and the 63 remaining a cross-sectional design.

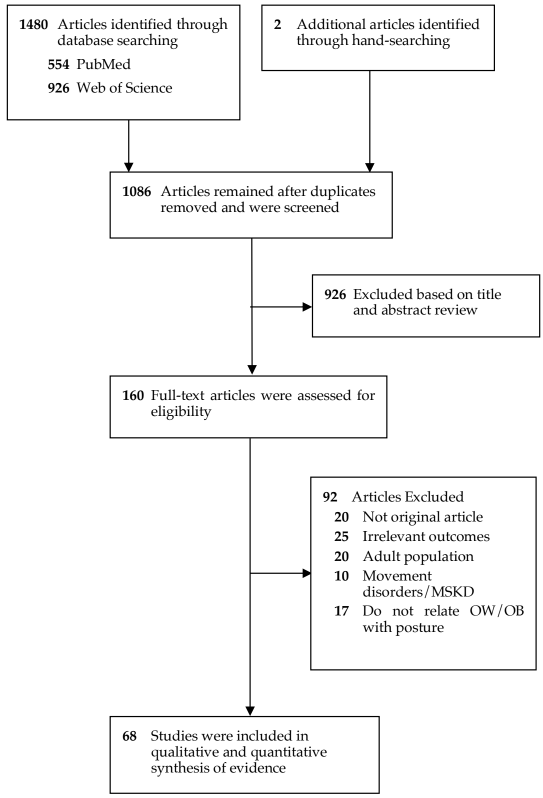

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of study selection, inclusion and exclusion of studies

Study Characteristics

Table S1 summarizes the characteristics of the 68 included studies. The whole sample size of the included studies was 1,761,941 children and adolescents with ages ranging from 0 to 21 years old. All studies used BMI as overweight/obesity indicator, whereas 3 studies additionally reported fat mass composition [16–18], 2 reported muscle mass composition [16, 18], 2 reported waist circumference [19, 20], and 1 reported height-waist circumference [21]. Regarding PM, 4 articles studied forward head [22–25], 5 rounded shoulder [16, 17, 22, 23, 26], 11 thoracic hyperkyphosis [10, 16, 21, 22, 24, 25, 27–31], 12 lumbar hyperlordosis [16, 18, 32–34, 21, 22, 24, 25, 28–31], 11 scoliosis [22, 26, 27, 29, 34–40], 6 flat spine [18, 22, 28, 31–33], 6 forward sway posture [24, 25, 28, 31–33], 13 genu valgum [20, 22, 34, 38, 41–49], 3 genu recurvatum [20, 34, 38], and 37 flatfoot [17, 19, 22, 29, 43, 49–80].

Qualitative Evidence Synthesis

The associations between overweight/obesity and the ten PM were investigated in the sixty-eight included studies (**Table 2**). There was consistent evidence supporting associations of OW/OB with the presence of rounded shoulders (3.5 of 5 studies, 70%), thoracic hyperkyphosis (7 of 11, 63.6%), lumbar hyperlordosis (8.5 of 13, 65.4%), genu valgum (12 of 13 studies, 92.3%), and flatfoot (29.5 of 37 studies, 80.8%). There was consistent evidence supporting the lack of an association of OW/OB with flat spine (4 of 6 studies, 66.7%), with forward head (1 of 4 studies, 25.0%), or with scoliosis (2.5 of 11 studies, 22.7%). There was unclear evidence supporting associations of OW/OB with the presence of forward sway posture (3.5 of 6 studies, 58.3%) and insufficient evidence to determine the association of OW/OB with genu recurvatum (3 of 3 studies, 100%).

Meta-analysis

Figure 2 presents the meta-analysis of the association between overweight/obesity during childhood and adolescence and the presence of PM. Children and adolescents with OW/OB had higher risk of presenting genu valgum (RR: 6.65; 95% CI: 5.13–8.62; P<0.001), flatfoot (RR: 1.54; 95% CI: 1.40–1.70; P<0.001) and overall altered posture (RR: 1.73; 95% CI: 1.37–2.18; P<0.001) compared with their NW peers. Children and adolescents with OW/OB had no higher risk of presenting thoracic hyperkyphosis (RR: 1.45; 95%CI: 0.72–2.91; P=0.300), lumbar hyperlordosis (RR: 1.43; 95% CI: 0.96–2.12; P=0.080) or scoliosis (RR: 0.82; 95% CI: 0.61–1.09; P=0.170) in comparison with NW. A schematic summary of PM found in children and young with OW/OB from both analyses (i.e., qualitative evidence synthesis and meta-analysis) is presented in **Figure 3**.

DISCUSSION

To our knowledge, this is the first review to study the impact of childhood and adolescence OW/OB on the entire musculoskeletal system and also to synthesize the results with a standardized protocol. The main findings of this study were 1) higher OW/OB degree, determined by BMI, was associated with the presence of five PM, namely rounded shoulders, thoracic hyperkyphosis, lumbar hyperlordosis, genu valgum and flatfoot; and 2) children and adolescents with OW/OB had 6.6 times the risk of presenting genu valgum, 1.5 times the risk of presenting flatfoot and 1.7 times the risk of presenting any kind of PM compared to NW.

The musculoskeletal system is in continuous development during childhood and there are some developmental stages when it is especially exposed to external factors, such as OW/OB. For instance, in the newborn to toddler stage (i.e., 0 to 4 years-old), children experience important changes by reaching physiological alignments in the spinopelvic structure and lower limbs, which agrees with the acquisition of upright posture and walking abilities [46, 81]. In this review, those studies that included newborn children until the age of four did not find associations between OW/OB and PM in the spinopelvic structure or lower limbs, whereas they did in older children [22, 33, 46, 49]. This fact evidences

Table 2. Summary table of the associations observed between overweight/obesity indicators and postural malalignments.

Studies	N	Population	Upper body postural malalignments					Lower body postural malalignments				
			Head protraction	Rounded shoulders	Thoracic HK	Lumbar HL	Scoliosis	Flat spine	Forward sway	Genu valgum	Genu recurvatum	Flatfoot
Longitudinal												
Araujo, 2017 [33]	2130	Child				+♂/ Ø♀		-	Ø			
Chen, 2013 [77]	580	Children										+♂/Ø♀
Jankowicz-Szymanska, 2015 [78]	207	Child										+
Martinez-Nova, 2018 [79]	1032	Child										Ø
Smith 2011, [28]	1373	Child & Adol.			+	+		Ø	+			
Cross-sectional												
Alfahed, 2019 [95]	469	C & A								+		
Araujo, 2017 [32]	2398	Child				+		-	+♀/Ø♂			
Araujo, 2017 [18]	2398	Child				+		-				
Araujo, 2019 [25]	2117	Child	Ø		+	+			+			
Arruda, 2009 [29]	100	Child			+	+	+					+
Bafor, 2012 [44]	471	Child								-		
Bonet, 2003 [45]	64	Child								+		
Bout-Tabaku, 2015 [46]	320	Child & Adol								-C/+A		
Briggs, 2017 [47]	40	Child & Adol								+		
Brito-Hernández, 2018 [21]	80	Child			Ø	Ø						
Brzeziński, 2019 [43]	6992	Child								+		+
Carvalho, 2017 [80]	1394	Child										-
Cetin, 2010 [50]	625	Child										+
Chang, 2009 [51]	2083	Child										+
Chen, 2009 [52]	1024	Child										+
Chen, 2011 [53]	1598	Child										+
Ciaccia, 2017 [48]	1050	Child								+		
Cimolin, 2016 [54]	18	Adol										+
de Sa Pinto, 2006 [34]	96	Child & Adol				Ø	Ø			+	+	
Dolphens, 2018 [36]	1196	Child					-♀/♂Ø					
Evans, 2011 [19]	140	Child										-
Evans, 2015 [55]	728	Child & Adol										-
Gijon-Nogueron, 2017 [56]	1798	Child										Ø
Hawke, 2016 [57]	30	Child & Adol										Ø
Hershkovich, 2014 [37]	829791	Adol					-					
Jankowicz-Szymanska, 2016 [49]	1364	Child								+		+
Jankowicz-Szymanska, 2017 [58]	400	Child										+
Jankowicz-Szymanska, 2018 [59]	96	Child										+
Jannini, 2011 [38]	200	Adol					Ø			+	+	
Jiménez-Ormeño, 2013 [60]	1045	Child										+
Kothari, 2016 [61]	84	Child & Adol										Ø
Kratěnová, 2007 [39]	3520	Child & Adol					-					
Kuligowski, 2015 [30]	94	Child			Ø	Ø						
Lonner, 2015 [27]	1523	Child & Adol			+		Ø					

Table 2. Summary table of the associations observed between overweight/obesity indicators and postural malalignments.

Studies	N	Population	Upper body postural malalignments					Lower body postural malalignments				
			Head protraction	**Rounded shoulders**	**Thoracic HK**	**Lumbar HL**	**Scoliosis**	**Flat spine**	**Forward sway**	**Genu valgum**	**Genu recurvatum**	**Flatfoot**
O'Sullivan, 2011 [10]	1596	Child			+							
Ormos, 2016 [23]	428	Child	+	Ø								
Park, 2013 [40]	128	Adol					Ø					
Pfeiffer, 2006 [67]	835	Child										+
Pourghasem, 2016 [86]	1158	Child & Adol										+
Riddiford-Harland, 2000 [68]	431	Children										+
Riddiford-Harland, 2011 [69]	150	Children										+
Riddiford-Harland, 2011 [70]	252	Children										+
Rusek, 2018 [17]	464	Child & Adol		+								
Sadeghi-Demneh, 2016 [71]	667	Children										+
Seah, 2011 [24]	121	Adol	Ø		Ø	+			Ø			
Senadheera, 2016 [72]	722	Child										+
Shohat, 2018 [41]	47588	Adol								+		
Smith, 2008 [31]	766	Child & Adol			+	+		-	+			
Taylor, 2006 [42]	355	Adol								+		
Tenenbaum, 2013 [73]	825964	Adol										+
Villarroya, 2008 [74]	245	Child & Adol										+
Villarroya, 2009 [75]	119	Child & Adol										+
Wozniacka, 2013 [76]	1115	Children										+
Wyszyńska, 2016 [16]	120	Child & Adol		+	+	+						
Zurita, 2014 [35]	295	Child					Ø					
Summary												
+			1.0	3.5	7.0	8.5	1.0	0.0	3.5	12.0	3.0	29.5
-			0.0	0.0	1.0	0.0	2.5	4.0	0.0	1.0	0.0	3.0
Ø			3	1.5	3.0	4.5	7.5	2.0	2.5	0	0	4.5
Consistency (%)			25.00	70.00	63.64	65.38	22.73	66.67	58.33	92.31	100.00	80.82
Final score			**Ø**	**+**	**+**	**+**	**Ø**	**-**	**?**	**+**	**?**	**+**

Consistency was calculated by summing the number of positive or negative associations, the most frequently reported direction, dividing it by the total number of studies in this postural malalignment, and then multiplying the results by 100. If consistency was 0–33%, the result was classified as no association (Ø). If consistency was 34–59%, or if fewer than four studies reported on the outcome, the result was classified as being inconsistent/uncertain (?). If consistency was ≥ 60%, the result was classified as positive (+) or negative (–), depending on the direction of the association.

HK: hyper kyphosis; HL: Hyperlordosis; Child: children; Adol: adolescents; Ø, + or -: indicates no association, positive or negative association, respectively, in boys (♂) or girls (♀); - /+: indicates negative association in children but positive association in adolescents; +/ Ø: indicates positive association in children but no association in adolescents.

Study or Subgroup	Overweight/obesity Events	Overweight/obesity Total	Normal-weight Events	Normal-weight Total	Weight	Risk Ratio IV, Random, 95% CI	Year
Thoracic Hyperkyphosis							
Smith et al. 2008	140	331	165	1040	2.7%	2.67 [2.21, 3.22]	2008
Arruda 2009	20	50	12	40	2.3%	1.33 [0.74, 2.39]	2009
Lonner et al. 2015	46	285	34	886	2.5%	4.21 [2.76, 6.42]	2015
Maciałczyk-Paprocka et al. 2017	10	377	198	2355	2.3%	0.32 [0.17, 0.59]	2017
Brito-Hernández et al. 2018	26	42	20	37	2.6%	1.15 [0.78, 1.67]	2018
Subtotal (95% CI)		**1085**		**4358**	**12.4%**	**1.45 [0.72, 2.91]**	
Total events	242		429				
Heterogeneity: Tau² = 0.58; Chi² = 63.88, df = 4 (P < 0.00001); I² = 94%							
Test for overall effect: Z = 1.04 (P = 0.30)							
Lumbar Hyperkyphosis							
de Sa Pinto et al. 2006	18	49	13	47	2.3%	1.33 [0.74, 2.40]	2006
Smith et al. 2008	140	331	165	1040	2.7%	2.67 [2.21, 3.22]	2008
Arruda 2009	46	50	20	50	2.6%	2.30 [1.62, 3.26]	2009
Maciałczyk-Paprocka et al. 2017	12	377	143	2355	2.3%	0.52 [0.29, 0.94]	2017
Araujo et al. 2017	213	642	414	1647	2.7%	1.32 [1.15, 1.51]	2017
Brito-Hernández et al. 2018	26	42	20	37	2.6%	1.15 [0.78, 1.67]	2018
Subtotal (95% CI)		**1491**		**5176**	**15.3%**	**1.43 [0.96, 2.12]**	
Total events	455		775				
Heterogeneity: Tau² = 0.21; Chi² = 57.49, df = 5 (P < 0.00001); I² = 91%							
Test for overall effect: Z = 1.74 (P = 0.08)							
Scoliosis							
de Sa Pinto et al. 2006	18	49	11	47	2.3%	1.57 [0.83, 2.96]	2006
Arruda 2009	50	50	34	40	2.7%	1.18 [1.03, 1.35]	2009
Nery et al. 2010	3	257	16	1082	1.6%	0.79 [0.23, 2.69]	2010
Jannini et al. 2011	30	100	33	100	2.5%	0.91 [0.60, 1.37]	2011
Zurita et al. 2014	22	158	26	137	2.4%	0.73 [0.44, 1.23]	2014
Hershkovich et al. 2014	9629	134397	83106	647899	2.7%	0.56 [0.55, 0.57]	2014
Lonner et al. 2015	152	285	613	886	2.7%	0.77 [0.69, 0.87]	2015
Maciałczyk-Paprocka et al. 2017	35	377	366	2255	2.6%	0.57 [0.41, 0.79]	2017
Subtotal (95% CI)		**135673**		**652446**	**19.6%**	**0.82 [0.61, 1.09]**	
Total events	9939		84205				
Heterogeneity: Tau² = 0.13; Chi² = 154.52, df = 7 (P < 0.00001); I² = 95%							
Test for overall effect: Z = 1.36 (P = 0.17)							
Genu valgum							
de Sa Pinto et al. 2006	27	49	1	47	0.9%	25.90 [3.66, 183.02]	2006
Jannini et al. 2011	87	100	24	100	2.6%	3.63 [2.54, 5.18]	2011
Ciaccia et al. 2017	72	427	3	603	1.6%	33.89 [10.75, 106.85]	2017
Maciałczyk-Paprocka et al. 2017	144	377	147	2355	2.7%	6.12 [5.00, 7.49]	2017
Shohat et al. 2018	1278	6095	1331	38402	2.7%	6.05 [5.63, 6.50]	2018
Brzeziński et al. 2019	717	1364	295	4730	2.7%	8.43 [7.46, 9.52]	2019
Subtotal (95% CI)		**8412**		**46237**	**13.3%**	**6.65 [5.13, 8.62]**	
Total events	2325		1801				
Heterogeneity: Tau² = 0.06; Chi² = 41.90, df = 5 (P < 0.00001); I² = 88%							
Test for overall effect: Z = 14.30 (P < 0.00001)							
Faltfoot							
Pfeiffer et al. 2006	56	100	295	703	2.7%	1.33 [1.10, 1.62]	2006
Mauch et al. 2008	70	456	182	2257	2.7%	1.90 [1.47, 2.46]	2008
Arruda 2009	46	50	0	40	0.6%	74.76 [4.75, 1176.76]	2009
Chen et al. 2009	77	205	219	819	2.7%	1.40 [1.14, 1.73]	2009
Chang et al. 2010	326	477	578	1018	2.7%	1.20 [1.11, 1.31]	2010
Chen et al. 2011	206	345	492	1060	2.7%	1.29 [1.15, 1.43]	2011
Cetin, 2011	48	100	135	445	2.7%	1.58 [1.23, 2.03]	2011
Tenenbaum et al. 2013	25640	133362	86836	645357	2.7%	1.43 [1.41, 1.45]	2013
Woźniacka et al. 2013	37	306	59	735	2.6%	1.51 [1.02, 2.22]	2013
Lopez-Fuensalida et al. 2016	40	176	31	212	2.5%	1.55 [1.02, 2.38]	2016
Pourghasem et al. 2016	33	122	72	447	2.6%	1.68 [1.17, 2.41]	2016
Sadeghi-Demneh et al. 2016	33	137	80	527	2.6%	1.59 [1.11, 2.27]	2016
Senadheera et al. 2016	4	19	45	367	1.9%	1.72 [0.69, 4.28]	2016
Merder-Coşkun et al. 2017	60	193	16	125	2.4%	2.43 [1.47, 4.02]	2017
Maciałczyk-Paprocka et al. 2017	47	377	190	2355	2.6%	1.55 [1.14, 2.09]	2017
Brzeziński et al. 2019	137	1364	185	4730	2.7%	2.57 [2.08, 3.18]	2019
Subtotal (95% CI)		**137789**		**661197**	**39.4%**	**1.54 [1.40, 1.70]**	
Total events	26860		89415				
Heterogeneity: Tau² = 0.02; Chi² = 69.75, df = 15 (P < 0.00001); I² = 78%							
Test for overall effect: Z = 8.80 (P < 0.00001)							
Total (95% CI)		**284450**		**1369414**	**100.0%**	**1.73 [1.37, 2.18]**	
Total events	39821		176625				
Heterogeneity: Tau² = 0.51; Chi² = 9846.70, df = 40 (P < 0.00001); I² = 100%							
Test for overall effect: Z = 4.61 (P < 0.00001)							
Test for subgroup differences: Chi² = 134.82, df = 4 (P < 0.00001), I² = 97.0%							

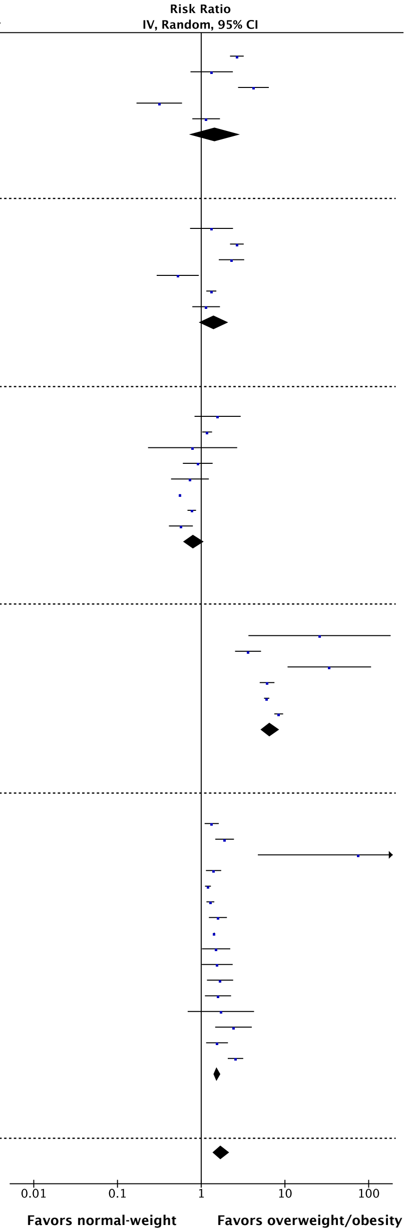

Figure 2. Summary Risk Ratio (RR) of the relationship of having overweight/obesity during childhood and adolescence and to present postural malalignments.

Contributing studies are sorted in chronological order.

that during this first stage of childhood, posture is particularly sensitive to changes due to being OW/OB, suggesting that many PM originate during these stages of growth. Regarding feet, the only two studies analyzing age groups in the first years of life did not find associations between OW/OB and flatfoot at 3-5 years old whereas they started to see differences at 5-7 years old [22, 49].

Puberty is also a critical period for the development of the musculoskeletal system, coinciding with the peak height velocity and sharp gains of body mass [22]. It is also when morphological differences between gender become more evident, especially in the anatomy of the spinopelvic structure and lower limbs [82, 83]. At puberty girls tend to demonstrate more pelvic anteversion (associated with lumbar hyperlordosis) and genu valgum [41, 84], whereas boys demonstrate more thoracic hyperkyphosis [84]. In feet anatomy some authors support a higher prevalence of flatfoot in boys due to a later plantar arch maturation in comparison with girls [52, 56]. The detrimental effect of OW/OB in the musculoskeletal system could be manifesting differently in girls and boys, probably aggra-

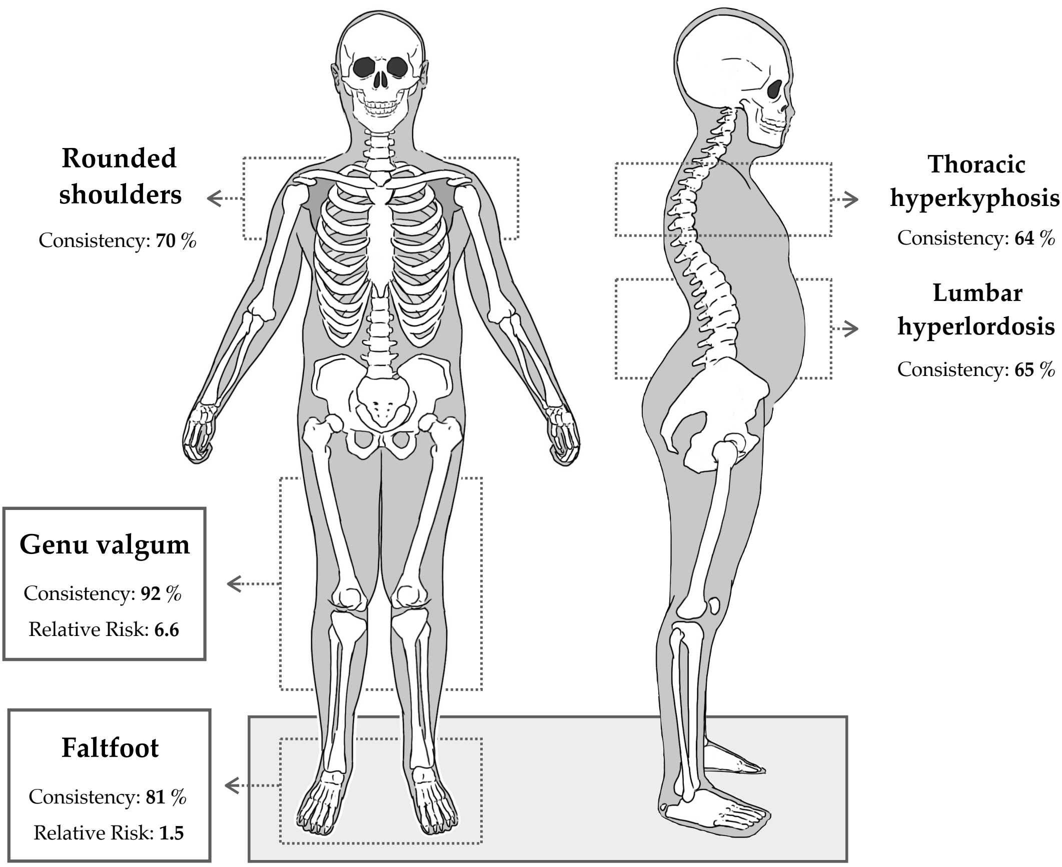

Figure 3. Schematic summary of the postural malalignments associated with the overweight/obesity in children and adolescents.

Postural malalignments presented were those demonstrating a consistent association (i.e., > 60%) with OW/OB in the qualitative evidence synthesis (Table 2), while those within the box also demonstrated a relationship with having overweight/obesity during childhood and adolescence in the meta-analysis (Figure 2). Consistency percentage from the qualitative evidence synthesis and relative risk from the meta-analysis are reported.

vating postural dimorphisms that naturally occur in both genders, but further research is still needed to confirm this general belief.

The majority of studies agree by suggesting that mechanical constraints due to the excess of body mass could be driving the development of PM in childhood and adolescence [10, 18]. In the spinopelvic structure, the excess of body mass could be influencing the mechanical stability of the spinal column, leading to compensations such as hyperkyphosis and hyperlordosis [18, 28]. Araujo et al. [18] found that non-skeletal components of body weight, i.e. fat and muscle mass, were independently associated with a hyperlordotic posture in children. They argued that fat mass accumulation might have a greater implication in the spinal imbalance, which leads to an increase in muscle tone of stabilizer muscles to counteract it [18]. Excessive body mass has also suggested to induce a collapse of the lower limb into a valgus position. In first years of life, children experience a physiological transitioning from varus towards valgus alignments as a mechanical adaptation to carry their increasingly heavy bodies [85]. In children with OW/OB this transition could be exacerbated towards a more pronounced valgus position as an adaptation to support their higher body mass [46]. With regards to feet, some authors suggest that the lower the body mass the foot must support, the better the chance the medial longitudinal arch has to develop in childhood, which is directly linked to the incidence of flatfoot [63]. The continued bearing of excessive body mass has been suggested to lead to structural modifications in the navicular and cuneiform bones, which places muscles and ligaments in an excess of strain to hold a physiological height of the medial longitudinal arch that finally tends to collapse [66, 86]. Others have suggested that flatfoot in children with OW/OB is caused by a thicker plantar fat pad, but this hypothesis was discarded after verifying that no differences exist in the plantar fat pad between OW/OB and NW children [63, 65].

The qualitative evidence synthesis of this review clearly demonstrated no associations of OW/OB with the development of a forward head posture or scoliosis. The prevalence of a forward head posture is believed to have grown among children and adolescents because of the dramatic growth of mobile phone and computer use [87]. Strength of neck stabilizer muscles and cervical mobility are factors associated with an optimal head position but [23], based on our results, OW/OB seems to not separately add to the development of a forward head posture. Some studies reported that not high but low BMI was associated with the presence of scoliosis [27, 36, 37]. It is well known that low body mass during childhood negatively affects bone health (e.g., osteopenia), and poor bone health has been linked with the development of scoliosis and its progression [27]. Some authors, such as Kratěnová et al. [39], even suggest that relatively high body mass in childhood might be positively contributing to the frontal plane alignment of the spine. The association between OW/OB and flat spine is in line with the presence of a hyper curved spine (hyperkyphosis combined with hyperlordosis) in this population. Lastly, a forward sway posture in children and adolescents with OW/OB has not been consistently reported, and there are only three studies on genu recurvatum. Further evidence is still needed investigating these PM in relation to OW/OB.

Childhood obesity has already demonstrated to be linked with a higher prevalence of musculoskeletal disorders (i.e., pain, injuries and fractures), especially in the lumbar spine, hips and knees [7, 88]. Findings from this review will help to gaining a better understood of the pathogenesis of these disorders by pointing PM as a potential development factor. Among the included studies, five analyzed the relationship between PM and musculoskeletal pain, with four of them finding significant associations [10, 27, 31, 38, 39]. For instance, a non-neutral position of the spine (i.e., hyperkyphosis and hyperlordosis) and an overall poor posture were associated with a higher incidence of pain in the cervical spine and low back [10, 27, 31, 39]. The hyper curved spine observed in children and adolescents with OW/OB might have severe consequences across the lifespan, since it has been associated to the presence of low back pain and more severe spine pathologies in adulthood, such as discopathy and spondylolisthesis [33, 89]. In the lower limbs, a non-physiological alignment leads to abnormal load mechanics, which cause damage to the articular cartilages of hip and knee joints over time [46]. Genu valgum posture observed in this population was already reported during walking in a recent systematic review [6], which evidences that these biomechanical alterations occur both in static and dynamic situations. The only previous systematic review investigating flatfoot in pediatric obesity did not find any studies addressing the possible short-term complications in the development of foot pain [5]. However, when flatfoot persists into adulthood it is known to be the cause of foot pain, plantar fasciitis and metatarsophalangeal osteoarthritis [78].

Children and adolescents with OW/OB spend more time in sedentary behaviors and less practicing physical activity, lifestyle factors that might be additionally affecting their body posture above and beyond purely the mechanical factor of carrying additional weight. O'Sullivan et al. [10] found in adolescents that increased television use was associated with a thoracic hyperkyphosis posture during sitting and the presence of low back pain. A higher level of physical activity in childhood and adolescence was related to a more aligned body posture, whereas lower physical activity levels were associated with increased pressure under the midfoot, which is a typical sign of flatfoot [16, 90]. Muscular strength is suggested to play a key role in the foundation of body posture in childhood, and several authors already demonstrated positive associations of intrinsic back and foot muscle strength with a more neutral posture of the spine and foot respectively [10, 91]. Based on this evidence, getting children and adolescents with OW/OB less time in sedentary behaviors and more time undertaking physical activity could help prevent the onset of these PM. In fact, previous exercise-based intervention studies in this population have already demonstrated improvements in thoracic spine or lower limb deformities, or foot structure and function [92–94], but the available evidence is still scarce.

Limitations

Several limitations in this systematic review should be addressed. First, our findings are mainly based on cross-sectional studies (62 of 68 studies) and it does not allow to establish firm causality conclusions between OW/OB and PM in youth. Second, the use of only two databases (PubMed and Web of Science) may have left out some articles related to this topic, although it is expected that those databases cover any influential peer-reviewed articles with low risk of bias. Third, we found a wide variety of assessment protocols to identify PM, which restricts inter-study comparisons. Fourth, only 26 of the 62 included studies accounted for potential confounders such as age, maturational stage or gender in their statistical analysis. Fifth, there is no current literature supporting that the presence of PM due to OW/OB predicts the development of musculoskeletal disorders in later adulthood, and therefore all statements around that are still based on observational studies and assumptions.

Conclusions

Based on the qualitative evidence synthesis, OW/OB is associated with the presence of rounded shoulders, thoracic hyperkyphosis, lumbar hyperlordosis, genu valgum and flatfoot in childhood. Based on the meta-analysis, children and adolescents with OW/OB have 6.6 times the risk of presenting genu valgum, 1.5 times the risk of presenting flatfoot and 1.7 times the risk of presenting any kind of PM compared with their NW peers. These PM might be behind the higher prevalence of musculoskeletal pain in this population and, in if it persists into adulthood, could lead to more severe musculoskeletal disorders. It is safe to say that ongoing and future efforts to prevent and reverse these PM associated to OW/OB in childhood and adolescence are justified.

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SUPPLEMENTARY MATERIAL

Table S1. Search terms used in PubMed and Web of Science databases.

PubMed	Booleans	
Population		
(((("Body Composition"[Mesh]) OR "Body Mass Index"[Mesh]) OR "Obesity"[Mesh]) OR "Overweight"[Mesh]) OR "Pediatric Obesity"[Mesh]	AND	AND
("Child"[Mesh]) OR "Adolescent"[Mesh]		
Outcomes		
"Posture"[Mesh]	OR	
Postur*		
(Alignment*) AND (((((((knee*) OR Lower*) OR Limb*) OR Extremit*) OR spin*) OR pelvi*)		
((((((("genu varus") OR varus) OR varum)) OR ((("genu valgum") OR valgum) OR valgus)) OR (("genu recurvatum") OR recurvatum)) OR "pelvic tilt") OR "forward head"		
((((((((lordosis) OR lordotic) OR hyperlordo*) OR (spine AND curvature*)) OR kyphosis) OR hyperkyphosis) OR "flat back") OR "forward head") OR ((head OR cervical) AND protraction)		
(("pes planus") OR ((flat) AND (feet OR foot))) OR ((pronat*) AND (feet OR foot))		

Web of Science	Booleans	
Population		
TS=(“Body Compositions” OR “Composition, Body” OR “Compositions, Body” OR “Index, Body Mass” OR “Quetelet Index” OR “Index, Quetelet” OR “Quetelet's Index” OR obes* OR “overweight” OR “pediatric obesity” OR “paediatric obesity”)	AND	AND
TS=(child* OR adolescen* OR youth* OR teenager* OR boy* OR girl*)		
Outcomes		
TS=((Alignment*) AND (TS= (knee*) OR TS=(Lower*) OR TS=(Limb*) OR TS=(Extremit*) OR TS=(spin*) OR TS=(pelvi*)	OR	
TS=(Postur*)		
TS=("genu varus" OR varus OR varum OR "genu valgum" OR valgum OR valgus OR “genu recurvatum" OR recurvatum OR "pelvic tilt" OR "forward head")		
TS=(lordosis OR lordotic OR hyperlordo* OR spine AND curvature* OR kyphosis OR hyperkyphosis OR “flat back” OR “forward head”)		
TS= ((head OR cervical) AND (protraction))		
TS=("pes planus" OR ((flat) AND (feet OR foot)) OR ((pronat*) AND (feet OR foot)))		

Table S2. Criteria for the methodological quality assessment of cross-sectional and longitudinal articles, and the percentage of studies meeting these criteria.

Criteria items	Percentage of studies meeting criterion (%)
Cross-sectional studies	
1. Were the sample eligibility criteria adequately describe?	74.6
2. Were the study population recruitment methods, the period of recruitment and the place of recruitment adequately describe?	90.5
3. Were overweight/obesity indicators (e.g. BMI or body fat) measured in a valid and reliable way?	100.0
4. Was the overweight/obesity categorization done in a valid and reliable way?	73.0
5. Were potential confounders (e.g., age and gender) identified?	44.4
6. Were strategies to deal with potential confounders performed?	41.3
7. Was the posture assessment protocol adequately described, and was posture measured in a valid and reliable way?	92.1
8. Was appropriate statistical analysis used?	95.2
Total average	**76.4**
Longitudinal studies	
1. Were the overweight/obesity categories similarly formed from the same population?	100.0
2. Was the overweight/obesity categorization measured similarly in the whole population?	100.0
3. Was the overweight/obesity categorization done in a valid and reliable way?	80.0
4. Were confounding factors identified (e.g., age or gender)?	80.0
5. Were strategies to deal with confounding factors stated?	80.0
6. Were participants free of posture abnormalities at the start of the study?	0.0
7. Were posture measured in a valid and reliable way?	100.0
8. Was the follow up time reported and sufficient to be long enough for posture modification?	100.0
9. Was follow up complete, and if not, were the reasons to loss to follow up described and explored?	40.0
10. Were strategies to address incomplete follow up utilized?	40.0
11. Was appropriate statistical analysis used?	100.0
Total average	**74.5**

Table S3. Quality assessment of cross-sectional and longitudinal articles.

Study	1	2	3	4	5	6	7	8	9	10	11	Quality Score (%)	Risk of Bias
Cross-sectional studyes													
Alfahed, 2019 [95]	✓	✓	✓	×	✓	✓	✓	✓				87.5	Low
Araujo, 2017 [32]	✓	✓	✓	×	✓	✓	✓	✓				87.5	Low
Araujo, 2017 [18]	✓	✓	✓	×	✓	✓	✓	✓				87.5	Low
Araujo, 2019 [25]	✓	✓	✓	×	✓	✓	✓	✓				87.5	Low
Arruda, 2009 [29]	✓	✓	✓	×	✓	✓	✓	×				75.0	Low
Bafor, 2012 [44]	✓	✓	✓	×	✓	✓	✓	×				75.0	Low
Bonet, 2003 [45]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Bout-Tabaku, 2015 [46]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Briggs, 2017 [47]	✓	×	✓	✓	✓	✓	✓	✓				87.5	Low
Brito-Hernández, 2018 [21]	✓	✓	✓	✓	×	×	×	✓				62.5	High
Brzeziński, 2019 [43]	×	✓	✓	✓	✓	×	✓	✓				75.0	Low
Carvalho, 2017 [80]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Cetin, 2010 [50]	×	✓	✓	✓	×	×	✓	✓				62.5	High
Chang, 2009 [51]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Chen, 2009 [52]	✓	×	✓	✓	✓	✓	✓	✓				87.5	Low
Chen, 2011 [53]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Ciaccia, 2017 [48]	×	✓	✓	✓	✓	✓	✓	✓				87.5	Low
Cimolin, 2016 [54]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
de Sa Pinto, 2006 [34]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Dolphens, 2018 [36]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Evans 2011 [19]	×	✓	✓	✓	×	×	✓	✓				62.5	High
Evans, 2015 [55]	×	✓	✓	×	✓	✓	✓	✓				75.0	Low
Gijon-Nogueron, 2017 [56]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Hawke, 2016 [57]	×	✓	✓	×	×	×	✓	✓				50.0	High
Hershkovich, 2014 [37]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Jankowicz-Szymanska, 2016 [49]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Jankowicz-Szymanska, 2017 [58]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Jankowicz-Szymanska, 2018 [59]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Jannini, 2011 [38]	✓	✓	✓	×	×	×	×	✓				50.0	High
Jiménez-Ormeño, 2013 [60]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Kothari, 2016 [61]	✓	×	✓	×	✓	✓	✓	✓				75.0	Low
Kratěnová, 2007 [39]	×	✓	✓	×	✓	✓	✓	✓				75.0	Low
Kuligowski, 2015 [30]	×	✓	✓	✓	×	×	×	✓				50.0	High
Lonner, 2015 [27]	✓	✓	✓	✓	✓	×	✓	✓				87.5	Low
Lopez-Fuenzalida, 2016 [62]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Maciałczyk-Paprocka, 2017 [22]	✓	✓	✓	✓	×	×	✓	✓				75.0	Low
Mauch, 2008 [63]	×	✓	✓	✓	✓	✓	✓	✓				87.5	Low

Table S3. Quality assessment of cross-sectional and longitudinal articles.

Study	1	2	3	4	5	6	7	8	9	10	11	Quality Score (%)	Risk of Bias
Merder-Coskun, 2017 [64]	✓	✓	✓	✕	✕	✕	✓	✓				62.5	High
Mickle, 2006 [65]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Mickle, 2006 [66]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Nery, 2010 [26]	✕	✓	✓	✓	✕	✕	✓	✓				62.5	High
O'Malley, 2012 [20]	✓	✓	✓	✓	✕	✕	✕	✓				62.5	High
O'Sullivan, 2011 [10]	✓	✓	✓	✕	✓	✓	✓	✓				87.5	Low
Ormos, 2016 [23]	✕	✕	✓	✕	✕	✕	✓	✓				37.5	High
Park, 2013 [40]	✓	✕	✓	✕	✕	✕	✓	✓				50.0	High
Pfeiffer, 2006 [67]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Pourghasem, 2016 [86]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Riddiford-Harland, 2000 [68]	✕	✓	✓	✓	✕	✕	✓	✓				62.5	High
Riddiford-Harland, 2011 [69]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Riddiford-Harland, 2011 [70]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Rusek, 2018 [17]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Sadeghi-Demneh, 2016 [71]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Seah, 2011 [24]	✕	✓	✓	✓	✓	✓	✓	✓				87.5	Low
Senadheera, 2016 [72]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Shohat, 2018 [41]	✕	✓	✓	✓	✓	✓	✕	✓				75.0	Low
Smith, 2008 [31]	✓	✓	✓	✕	✓	✓	✓	✓				87.5	Low
Taylor ty al. 2006 [42]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Tenenbaum, 2013 [73]	✓	✓	✓	✓	✕	✕	✓	✓				75.0	Low
Villarroya, 2008 [74]	✕	✓	✓	✓	✕	✕	✓	✓				62.5	High
Villarroya, 2009 [75]	✓	✓	✓	✓	✓	✓	✓	✓				100.0	Low
Wozniacka, 2013 [76]	✓	✓	✓	✕	✕	✕	✓	✕				50.0	High
Wyszyńska, 2016 [16]	✓	✕	✓	✓	✕	✕	✓	✓				62.5	High
Zurita, 2014 [35]	✕	✓	✓	✓	✕	✕	✓	✓				62.5	High
Longitudinal studies													
Araujo, 2017 [33]	✓	✓	✕	✓	✓	✕	✓	✓	✓	✓	✓	81.8	Low
Chen, 2013 [77]	✓	✓	✓	✓	✓	✕	✓	✓	✓	✓	✓	90.9	Low
Jankowicz-Szymanska, 2015 [78]	✓	✓	✓	✓	✓	✕	✓	✓	✕	✕	✓	72.7	High
Martinez-Nova, 2018 [79]	✓	✓	✓	✓	✓	✕	✓	✓	✕	✕	✓	72.7	High
Smith, 2011 [28]	✓	✓	✓	✕	✕	✕	✓	✓	✕	✕	✓	54.5	High

Note that the quality score is calculated by dividing the number of criteria met in one study by the total number of criteria (i.e., 8). Note that the criterion score is calculated by dividing the number of studies meeting one criterion by the total number of studies (i.e., 25). ✓: meet the methodological quality criterion; ✕: not meet the methodological quality criterion.

Table S4. Summary of included studies (n = 68)

Nº	**Risk of bias**	**Authors, year [ref]** **Country**	**N participants (age range; %girls)** **Design; target population**	**Body composition indicators** **Assessment instruments**	**Postural alterations** **Assessment instruments**	**Main finings**
1	Low Risk	Alfahed, 2019 [95] Saudi Arabia	469 (2-16 years, 0% girls) Cross-sectional; children and adolescents	BMI Scale and stadiometer	Genu valgum Tibiofemoral angle, and intercondylar and intermalleolar distances	BMI has a negative correlation with the intermalleolar distance (r = -0.086, P = 0.064). There was no statistically significant correlation between the BMI and the mean tibiofemoral angle or the intercondylar distance
2	Low Risk	Araujo, 2017 [33] Portugal	2130 (4-7 years; 48 % girls) Prospective longitudinal study; children	BMI. Scale and stadiometer	Hyperkyphosis, hyperlordosis, flat spine, and sway-back posture 2-D photogrammetry (PAS/SAPO software)	Higher weight in both, boys and girls, was associated with lower odds of a flat pattern compared with a "sway to neutral" pattern, with stronger associations at older ages (0 vs 4 vs 7). Boys with higher PI at 0 and 4 years old were more frequently assigned to the hyperlordotic pattern (OR=1.44 per SD; p=0.043).
3	Low Risk	Araujo, 2017 [18] Portugal	2398 (7 years; 47 % girls) Cross-sectional study; children	BMI, Fat and fat free mass. Digital scale and stadiometer, and DXA	Hyperkyphosis, hyperlordosis, flat spine, and sway-back posture 2-D photogrammetry (PAS/SAPO software)	In both genders, children with flat pattern showed the lowest BMI, and children with a hyperlordotic posture presented the highest BMI. Fat and fat-free mass were inversely associated with a flat pattern and positively associated with a hyperlordotic posture in both genders.
4	Low Risk	Araujo, 2017 [32] Portugal	2398 (7 years; 47 % girls) Cross-sectional study; children	BMI Scale and stadiometer.	Hyperkyphosis, hyperlordosis, flat spine, and sway-back posture 2-D photogrammetry (PAS/SAPO software)	In girls, a higher BMI was associated with a sway pattern (versus a flat pattern: OR=1.21; 95% CI=1.12, 1.29), whereas in boys, a higher BMI was associated with a hyperlordotic pattern (versus a flat pattern: OR=1.30; 95% CI=1.17, 1.44)
5	Low Risk	Araujo, 2019 [25] Portugal	2117 (4 and 7 years; 48% girls) Cross-sectional study; children	BMI, Fat and fat free mass. Scale and stadiometer.	Hyperkyphosis, hyperlordosis, flat spine, and sway-back posture 2-D photogrammetry (PAS/SAPO software)	In girls, BMI was weakly associated with lumbar angle: r=0.27 at 4 years, and r=0.31 at 7 years of age, both p < 0.001. Fat and fat-free masswere also weakly but positively associated with lumbar angle: r=0.29 and r=0.20, respectively; both p < 0.001. In boys, BMI was weakly associated with lumbar angle: r=0.22 at 4 years old, and r=0.26 at 7 years old, both p < 0.001. Fat and fat-free mass were also weakly associated with lumbar angle (r=0.24 and r=0.13, respectively, both p < 0.001).
6	Low Risk	Arruda, 2009 [29] Brazil	100 (8-10 years; 50%) Cross-sectional; children	BMI Scale and stadiometer.	Hyperkyphosis, hyperlordosis, scoliosis and flatfoot 2-D photogrammetry (*Posturograma da Fisiometer Softwares*) and footprint (podoscope)	BMI was correlated with scoliosis, lumbar hyperlordosis, thoracic hyperkyphosis and flatfoot.
7	Low Risk	Bafor, 2012 [44] Nigeria	471 (3-10 years; 48% girls) Cross-sectional; children	BMI Scale and stadiometer.	Genu valgum Tibiofemoral angle (goniometer)	Tibiofemoral angle was negatively correlated with BMI (r = − 0.210), so that BMI does not cause an increase in tibiofemoral angle.
8	Low Risk	Bonet, 2003 [45]	64 (7-12 years, 70% girls)	BMI and obesity categories (95th percentile)	Genu valgum	Intermalleolar distance was greater in over- weight children than in the non-overweight group (11.0 ± 0.6 vs 2.90 ± 0.43; p < 0.001). A positive correlation

Table S4. Summary of included studies (n = 68)

		Spain	Cross-sectional; children	Scale and stadiometer.	Intermalleolar distance	between genu valgum and the BMI was observed.
9	Low Risk	Bout-Tabaku, 2015 [46] USA	320 (4-20 years, 61% girls) Cross-sectional; children, adolescents & young adults	BMI and obesity categories through CDC. Scale and stadiometer.	Genu valgum Tibiofemoral angle and metaphyseal-diaphyseal angle from 2-D photogrammetry of DEXA images (eFilm Lite DICOM)	Compared with NW controls, OB had less valgus of the MDA prior to the onset of puberty (+ 2.0°, p = 0.001), but had greater valgus at later pubertal stages (–1.9°, p = 0.01).
10	Low Risk	Briggs, 2017 [47] USA	40 (11-18 years, 35% girls) Cross-sectional; children and adolescents	BMI and obesity categories through 95th–98th BMI percentiles. Scale and stadiometer.	Genu valgum Thigh and shank angle (3-D photogrammetry, Visual 3D software)	The youth who were OB demonstrated greater knee valgus in standing (P = 0.02) than their NW peers.
11	High Risk	Brito-Hernández, 2018 [21] Chile	80 (12 years, 0% girls) Cross-sectional; children	BMI and height-waist index Scale, stadiometer and measuring tape.	Hyperlordosis and hyperkyphosis. 2-D photogrammetry.	Height-waist index was associated with the presence of thoracic kyphosis, whereas there was no significant associations between BMI with spine posture and between height-waist index with lumbar hyperlordosis.
12	Low Risk	Brzeziński, [43]	6992 (8-12 years, 50% girls) Cross-sectional; children	BMI and obesity categories through IOFT cut-points Scale and stadiometer.	Genu valgum, genu varum, valgus heel and flatfoot Intercondylar distance, linear vertical compass, footprint (posdoscope).	Limb defects were most commonly diagnosed in OB (90.2%) with significantly fewer diagnosed in normal weight (25.7%). The increase in the BMI percentile by one unit was associated with a significant increase in valgus knee (9.0%), valgus heel (1.0%) and flatfoot (2.0%).
13	Low Risk	Carvalho, 2017 [80] Brazil	1394 (10-14 years, 66% girls) Cross-sectional; children and adolescents	BMI and obesity categories through IOFT cut-points Scale and stadiometer.	Flatfoot FPI-6	The overweight and obese group scored lower than the normal BMI group (p = 0.039; p = 0.001, respectively). A higher BMI in adolescence is not indicative of a pronated foot type.
14	High Risk	Cetin, 2010 [50] Turkey	625 (6-13 years, 48% girls) Cross-sectional; children	BMI and obesity categories (95th percentile) Scale and stadiometer.	Flatfoot Footprint	Flatfoot prevalence was associated with BMI, and overweight children had greater flat foot prevalence compared to normal and underweight children (P=0.05.
15	Low Risk	Chang, 2009 [51] Taiwan	2083 (7-12 years, 46% girls) Cross-sectional; children	BMI and obesity categories (Taiwan Department of Health) Scale and stadiometer.	Flatfoot Footprint (Denis' classification of flatfeet)	Children who were obese or overweight were 2.66 and 1.39 times more likely to have flatfoot than those of average weight. The results of this study indicate that the prevalence of flexible flatfoot is highest among males who are obese and overweight, particularly in the age range of 7 to 8 years.
16	Low Risk	Chen, 2009 [52] Taiwan	1024 (5-13 years, 54% girls) Cross-sectional; children	BMI and obesity categories (IOTF) Scale and stadiometer.	Flatfoot 3D coordinate measurement system (Faro Technologies Inc., Lake Mary, FL) and footprint (arch index)	A significant difference in the prevalence of flatfoot occurred between normal-weight (27%), overweight (31%), and obese (56%) children (chi-square = 18.0; p < 0.001). The obesity effect was significant (p < 0.01) for most foot dimensions.
17	Low Risk	Chen, 2011 [53]	1598 (3-6 years, 48% girls)	BMI, obesity categories (percentile	Flatfoot	Children with bilateral flatfoot had increased BMI in comparison with unilateral flatfoot and normal foot (p <

Table S4. Summary of included studies (n = 68)

				cut-off from the Taiwan Department of Health)		0.05). Overweight and obese children demonstrated twice the risk of bilateral flatfoot compared to normal children (OR= 1.90 and 1.77 respectively; p = 0.005 and 0.001 respectively).
		Taiwan	Cross-sectional; children	Scale and stadiometer.	Clinical diagnosis by an experienced clinician	
18	Low Risk	Chen, 2013 [77]	580 (3-6 years, 49% girls)	BMI and obesity categories (Taiwan Department of Health)	Flatfoot	Children who were relatively younger, male, obese, and experiencing excessive joint laxity were more likely to experience the signs of flatfoot at 1-year follow up.
		Taiwan	Prospective longitudinal; children	Scale and stadiometer.	Footprint (Chipaux-Smirak index)	
19	Low Risk	Ciaccia, 2017 [48]	1050 (5-13 years, 49% girls)	BMI and obesity categories (WHO)	Genu valgum	The chance of occurrence of knee valgus in overweight and obese schoolchildren was, respectively, 6.0 and 75.7 times greater than among normal-weight children.
		Brazil	Cross-sectional; children and adolescents	Scale and stadiometer.	Intermalleolar distance (regular ruler)	
20	Low Risk	Cimolin, 2016 [54]	18 (14-18 years, 50% girls)	BMI, obesity categories (BMI>97th percentile)	Flatfoot	OB had high contacts areas in forefoot and midfoot regions and not in rearfoot region, in comparison with NW. Higher peak force and pressure values were found in OB with respect to NW participants, especially in the forefoot and midfoot. Obese feet displayed low arch than NW (arch index) representing of flatfoot.
		Italy	Cross-sectional; adolescents	Scale and stadiometer.	Upright standing plantar pressure, Pedar-X in-shoe system (Novel GmbH, Munich, Germany)	
21	Low Risk	de Sa Pinto, 2006 [34]	96 (7-14 years, 45% girls)	BMI, obesity categories (sex-, race- and age-specific 95th percentile)	Hyperlordosis, scoliosis, genu valgum, genu varum and genu recurvatum	A higher frequency of at least one osteoarticular manifestation was observed in obese patients (55%) compared with the control group (23%) (P = 0.001). A statistically significant association was also found between obesity and genu valgum, genu recurvatum and tight quadriceps.
		Brazil	Cross-sectional; children and adolescents	Scale and stadiometer.	Musculoskeletal examination by a pediatric rheumatologist.	
22	Low Risk	Dolphens, 2018 [36]	1196 (10-13 years, 47% girls)	BMI and obesity categories through IOFT cut-points	Scoliosis	OW or OB girls face a substantial (58%) decrease in the odds for trunk asymmetries compared to NW subjects (p = 0.04)
		Belgium	Cross-sectional; children pre-peak growth velocity	Scale and stadiometer.	Surface topography and 2-D photogrammetry (ImageJ software)	
23	High Risk	Evans 2011 [19]	140 (6-10 years, 51% girls)	BMI and waist circumference	Flatfoot	A significant relationship between foot posture and BMI (FPI (L) r = -0.243 (p < 0.01), FPI(R) r = -0.263 (p < 0.01), and between body posture and waist circumference (FPI (L) r = -0.213 (p < 0.05), FPI(R) r = -0.228 (p < 0.01). Children with higher BMI and waist circumference have less flat feet.
		Australia	Cross-sectional; children	Scale, stadiometer and measure tape.	FPI-6	
24	Low Risk	Evans, 2015 [55]	728 (3-15 years, NA% girls)	BMI and obesity categories (IOTF)	Flatfoot	Very weak, but significant, correlation was found between BMI and FPI (r = −0.077, p < 0.05), which indicates a cavus trend. This study found no association between increased body mass and flatfeet in children.
		Australia	Cross-sectional; children and adolescents	Scale and stadiometer.	FPI-6	
25	Low Risk	Gijon-Nogueron, 2017 [56]	1798 (6-12 years, 51% girls)	BMI and obesity categories (BMI percentiles)	Flatfoot	There were no significant differences between BMI categories in the FPI at different age groups. In children aged between 6 and 12 years, BMI does not appear to have an important bearing on static foot posture.
		Spain	Cross-sectional; children	Scale and stadiometer.	FPI-6	
26	High Risk	Hawke, 2016 [57]	30 (7-15 years, 67% girls)	BMI	Flatfoot	There was no association between FPI and BMI.

Table S4. Summary of included studies (n = 68)

		New Zealand	Cross-sectional; children and adolescents	Scale and stadiometer.	FPI-6	
27	Low Risk	Hershkovich, 2014 [37] Israel	829791 (NA years, 43% girls) Cross-sectional; adolescents	BMI and obesity categories (U.S. Center for Disease Control) Scale and stadiometer.	Scoliosis Standing X-ray assessment	Below normal BMI is associated with severity of spinal deformities, whereas above-normal BMI apparently has a protective effect.
28	Low Risk	Jankowicz-Szymanska, 2015 [78] Poland	207 (3-5 years, 51% girls) Prospective longitudinal; children	BMI and obesity categories (IOTF) Scale and stadiometer.	Flatfoot Clarke's and gamma angles (podoscope)	Obese children decreased the Clarke's angle after 2-years follow-up (p = 0.031), whereas normal-weight children increased it (p = 0.001). At 2-years follow-up, the Clarke's angles of NW children were higher than OW (p = 0.029) and OB (p = 0.00039) children. Children with OW/OB have lower medial longitudinal in comparison with NW, and after 2-years follow-up, OB have a tendency to keep collapsing medial longitudinal arch.
29	Low Risk	Jankowicz-Szymanska, 2016 [49] Poland	1364 (3-7 years, 48% girls) Cross-sectional; children	BMI and obesity categories (IOTF) Scale and stadiometer.	Genu valgum and flatfoot Intermalleolar distance and footprint (Clarke's and gamma angles)	Genu valgum was more common in children who were overweight. Significant correlations among BMI, intermalleolar distance, and Clarke's angle (P < .05) were also discovered. Children who are overweight or demonstrate obesity are more likely to develop genu valgum and flat feet.
30	Low Risk	Jankowicz-Szymanska, 2017 [58] Poland	400 (10-12 years, 48% girls) Cross-sectional; children	BMI and obesity categories (IOTF) Scale and stadiometer.	Flatfoot Footprint (Clarke's angle)	OW/OB children had significantly lower Clarke's angles, which indicates flat feet, and notably smaller ankle dorsiflexion range of motion than those with NW.
31	Low Risk	Jankowicz-Szymanska, 2018 [59] Poland	96 (10-12 years, 100% girls) Cross-sectional; children	BMI and obesity categories (IOTF) Scale and stadiometer.	Flatfoot Footprint (Arch Index)	A significant correlation between BMI and the Arch Index in the right and left foot was disclosed, indicating that excessive body weight contributes to the development of flat feet.
32	High Risk	Jannini, 2011 [38] Brazil	200 (10-19 years, 54% girls) Cross-sectional; adolescents	BMI and obesity categories (percentiles NCHS) Scale and stadiometer.	Scoliosis, genu valgum, genu varum, genu recurvatum and hallux valgus Musculoskeletal examination by a pediatric rheumatologist	Postural disorders (98 vs. 76%, p < 0.001), tight quadriceps (89 vs. 44%, p < 0.001) and genu valgum (87 vs. 24%, p < 0.001) were significantly more prevalent in obese adolescents than in controls. Obesity can cause osteoarticular system damage at the start of adolescence, particularly to the lower limbs.
33	Low Risk	Jiménez-Ormeño, 2013 [60] Spain	1045 (6-12 years, 57% girls) Cross-sectional; children	BMI and obesity categories (IOTF) Scale and stadiometer.	Flatfoot 3D morphological measures (feet digitalizer)	Excess weight affects the foot structure of children (i.e., higher frequency of flat feet, higher dimensions, and less changes in widths). Significant differences were found between the feet of children with NW and OW (2.6 to 9.0 %) and among children with NW and OB for all variables (3.9 to 17.3 %).
34	Low Risk	Kothari, 2016 [61] England	84 (8-15 years, 45% girls) Cross-sectional; children and adolescents	BMI Scale and stadiometer.	Flatfoot Sagittal T1-weighted MRI scan	BMI was not a significant predictive factor for foot posture (p = 0.566).
35	Low Risk	Kratěnová, 2007 [39]	3520 (7-15 years, 50% girls)	BMI and obesity categories (percentiles of Czech reference cut-points)	Scoliosis	The chance for the occurrence of x-ray–confirmed scoliosis was significantly lower both in OW (OR = 0.20, 95% CI = 0.05-0.85, p = 0.001) and in OB (OR = 0.27, 95% CI = 0.09-0.88, p = 0.030) children compared to NW.

Table S4. Summary of included studies (n = 68)

		Czech Republic	Cross-sectional; children and adolescents	Scale and stadiometer.	Musculoskeletal examination by an experienced physicians	
36	High Risk	Kuligowski, 2015 [30] Poland	94 (7-9 years, 52% girls) Cross-sectional; children	BMI and obesity categories (WHO cut-points) Scale and stadiometer.	Hyperkyphosis. 2-D photogrammetry (Posturometr-S)	OW have lower thoracic spine angle than NW (p < 0.05). Overall, these results show that BMI categories do not affect the sagittal shape of the spine in school children.
37	Low Risk	Lonner, 2015 [27] USA	1523 (10-21 years, 71% girls) Cross-sectional; children and adolescents	BMI and obesity categories (National Institute of Health) Scale and stadiometer.	Hyperkyphosis and scoliosis Medical diagnosis	Kyphotic patients are at increased risk for elevated BMI. T5-T12 kyphosis was weakly correlated with BMI (r=0.17), whereas max kyphosis correlated well with BMI (r=0.39, p<0.001). Idiopathic scoliosis patients are at increased risk for issues related to low BMI (i.e., underweight) but not to OW/OB.
38	Low Risk	López-Fuenzalida, 2016 [62] Chile	388 (6-10 years, 52% girls) Cross-sectional; children	BMI and obesity categories (WHO z-scores) Scale and stadiometer.	Flatfoot Footprint (Clarke's angle)	There was a significant higher prevalence of flatfoot in OB children in relation to OW and NW children. BMI categorization is associated with greater prevalence of flatfoot in children
39	Low Risk	Maciałczyk-Paprocka, [22] Poland	2732 children (3–18 years) (1363b;1369g) Cross-sectional, children and adolescents	BMI Scale and stadiometer.	Forward head, rounded shoulder, hyperkyphosis, hyperlordosis, scoliosis, flat spine, genu valgum and flatfoot Medical diagnosis	In OB girls, the postural error prevalence ratio was 2x higher than normal weight group (p = 0.004). In children aged 3–6, OW/OB have not increased the chances of postural errors. In the group 7–12 years, the prevalence ratio was higher in OW/OB compared to NW in both, boys (p = 0.042) and in girls (p = 0.007). OW/OB boys aged 13–18 had lower prevalence rate of postural errors than NW (p = 0.021). The most frequently observed postural errors in children with excessive BMI aged 3–6 were incorrect shoulder alignment (not significant) and protruding abdomen (p = 0.044), in 7-12 years old were valgus knees, incorrect abdominal alignment and flat feet. In the 13–18 age group of obese and overweight students, valgus knees (p = 0.0001) and flat feet (p = 0.041).
40	Low Risk	Martinez-Nova, [79] Spain	1032 children (505b, 527g); (8.2 ± 1.5 years) Prospective longitudinal study; children	BMI Scale and stadiometer.	Flatfoot FPI-6	At initial assessment only around 2% (r2=0.024, p=0.001) of the whole FPI value could be explained by BMI (b=−0.441). At final follow up, only BMI (b=−0.033) is able to explain the 0.5% of the post FPI value. There is minimal relationship of foot posture with BMI in children.
41	Low Risk	Mauch, 2008 [63] Germany	2887 (6-13 years, 49.77% girls) Cross-sectional, children	BMI and obesity categories (IOTF) Scale and stadiometer	Flatfoot 3D foot scanner (Pedus, Human Solutions Inc., Germany) and ScanWorX 2.8.5 SL1 (Human Solutions Inc.)	Flat feet were less frequent in underweight children and more frequent in overweight children.
42	High Risk	Merder-Coskun, 2017 [64] Turckey	318 (8-12 years, 50% girls) Cross-sectional, children	BMI and obesity categories (NA) Scale and stadiometer.	Flatfoot Musculoskeletal examination: Pediatric Gait, Arms, Leg, Spine (pGALS) screening method	Pes planus was more common in overweight/obese children than their normal weight peers (p=0.000).

Table S4. Summary of included studies (n = 68)

43	Low Risk	Mickle, 2006 [65] Australia	38 (3-5 years , 74% girls) Cross-sectional, children	BMI and obesity categories (IOTF) Scale and stadiometer	Flatfoot Pressure platform and ultrasound system	No significant between subject group differences (p=0.39) in the thickness of the midfoot plantar fat pad. OW/OB children had a significantly lower plantar arch height (0.9±0.3 cm) than their NW counterparts (1.1±0.2 cm; p=0.04).
44	Low Risk	Mickle, 2006 [66] Australia	34 (3-5 years, 50% girls) Cross-sectional, children	BMI and obesity categories (IOTF) Scale and stadiometer	Flatfoot plantar pressure measures	OW/OB children displayed significantly greater contact areas and forces in all foot regions (rearfoot, midfoot and forefoot). OW/OB had larger mean peak pressure, force-time integrals and pressure-time integrals underneath the midfoot.
45	High Risk	Nery, [26] Brazil	1340 children (49.0%g) (12.7 years) Cross-sectional, children	BMI Scale and stadiometer	Rounded shoulder and scoliosis Musculoskeletal examination (Adam's test).	No statistically significant association was found between body overweight and scoliosis. However, there was a statistically significant association between body overweight and scalene muscle asymmetry (p = 0.001).
46	High Risk	O'Malley, [20] Ireland	17 children (7b:10g; 12.21years) Cross-sectional, children	BMI and waist circumference Scale, stadiometer and measuring tape.	Genu valgum and genu recurvatum Intermalleolar distance	Positive correlations were observed between BMI and genu recurvatum (r = 0.55, P < .001) and genu valgum (r = 0.67, P < .001). OB children had less knee flexion (P = 0.015) than NW.
47	Low Risk	O'Sullivan, [10] Australia	1596 adolescents (no info about %boys vs girls) 14.1±0.2 years. Cross-sectional, children	BMI Scale and stadiometer	Hyperkyphosis Sitting degree of slump (2-D photogrammetry, Peak Motus motion analysis system)	Greater degree of slump in sitting posture was associated with higher BMI.
48	High Risk	Ormos, [23] Hungary	428 children (206b; 222g) aged 9, 12 and 16 years old. Cross-sectional and Longitudinal prospective, children	BMI Scale and stadiometer	Forward head Measuring tape and 2-D photogrammetry from sagittal images.	In 12 years old children, the BMI was inversely related to the craniovertebral angle (r=0.362 (p=0.01).
49	High Risk	Park, [40]	128 adolescents (no more information given) Cross-sectional, adolescents	BMI Scale and stadiometer	Scoliosis X-ray, Cobb angle: DK2 525R (Dongkang Medical: Korea)	According to the posthoc test result, there were no differences among the scoliosis groups but their BMI was smaller than that of the normal group.
50	Low Risk	Pfeiffer, [67] Austria	835 children (411g:424b) (3 to 6 years) Cross-sectional, children	BMI Scale and stadiometer	Flatfoot Footprint	Significant differences in prevalence of flatfoot between OW (51%), OB (62%), and NW(42%) were observed (p < 0.05). OW have a 27% higher risk of having flatfoot, and OB have a risk almost 3 times as much as NW. OW boys have the highest risk for flatfoot. Of the overweight and obese boys, 55.6% have a flatfoot.
51	Low Risk	Pourghasem, 2016 [86] Iran	1158 (6-18 years, 44% girls) Cross-sectional, children and adolescents	BMI and obesity categories (WHO) Scale and stadiometer.	Flatfoot Pressure platform measure	There was a significant difference in the prevalence of flatfoot among the underweight (13.9%), normal weight (16.1%), overweight (26.9%), and obese (30.8%) children (p=0.002).

Table S4. Summary of included studies (n = 68)

52	High Risk	Riddiford-Harland, 2000 [68] Australia	431 (8-9 years, 50% girls) Cross-sectional, children	BMI and obesity categories (WHO) Scale and stadiometer.	Flatfoot Footprint, footprint angle (FA) and Chippaux-Smirak Index (CSI)	OB had lower FA (p<0.001) and higher CSI (p<0.001) when compared with NW. This results evidence a lower longitudinal internal arch, a flatter cavity and a broader midfoot in OB.
53	Low Risk	Riddiford-Harland, 2011 [69] Australia	150 (7-9 years, 66% girls) Cross-sectional, children	BMI and obesity categories (IOTF) Scale and stadiometer	Flatfoot: foot morphology, thickness of plantar fat pad and medial longitudinal arch height. Combination level and ultrasound system	OB had greater values for all foot morphological (p<0.005), greater medial midfoot fat pad thickness (p<0.001), and lower medial longitudinal arch height relative to the leaner children (p=0.006) compared to NW.
54	Low Risk	Riddiford-Harland, 2011 [70] Australia	252 (6-10 years, 55% girls) Cross-sectional, children	BMI and obesity categories (IOTF) Scale and stadiometer	Flatfoot: plantar fat pad thickness and plantar pressure measures Ultrasound system and dynamic plantar pressure	Medial midfoot plantar fat pad thickness and medial midfoot plantar pressure were positively correlated with BMI (r=0.401, p<0.001 and r=0.465, p<0.001, respectively).
55	Low Risk	Rusek, [17] Poland	464 children (234b; 230g) 6 to 16 years (11.52±2.99) Cross-sectional, children and adolescents	BMI and Body mass composition Scale, stadiometer and bioelectrical impedance (Tanita MC 780 MA)	Scapular distance, shoulder asymmetry, pelvic torsion and obliquity. 2-D photogrammetry from frontal and transversal images (Zebris system)	Children with the lower contents of fat tissue presented greater pelvic obliquity (p=0.030). Higher percentage of the fat tissue correlated with greater asymmetry in the scapula (p=0.025) and shoulder asymmetries (p=0.013). A reverse relation was observed between the content of fatty tissue and pelvic asymmetry (p=0.015). Children with higher contents of fatty tissue (p=0.016) presented shoulder asymmetry
56	Low Risk	Sadeghi-Demneh, 2016 [71] Iran	667 (8-12 years, 49% girls) Cross-sectional, children	BMI and obesity categories (IOTF) Scale and stadiometer	Flatfoot Static footprint (podoscope)	OB showed a higher rate of flatfoot (25% rigid and 52.8% flexible) than OW (10% rigid and 19.8% flexible) and NW (4.2% rigid and 14.2% flexible). BMI was associated with higher prevalence of flatfoot (x2 = 38.7, P < 0.001) and with the arch index (r = 0.24, P < 0.001).
57	Low Risk	Seah, [24] Australia	121 adolescents (55b: 66g) Age: boys 15.7± 4.5; girls: 16.0±3.7 Cross-sectional, adolescents	BMI Scale and stadiometer	Forward head, hyperkyphosis, hyperlordosis and sway-back posture 2-D photogrammetry from sagittal images (LabVIEW 8.6.1 software, Austin, TX, USA)	Girls in the hyperlordotic group had a significantly larger BMI than those in the other postural groups combined.
58	Low Risk	Senadheera, 2016 [72]	722 (6-10 years, 50% girls) Cross-sectional; children	BMI and obesity categories (WHO cut-points) Scale and stadiometer.	Flatfoot Normalized navicular height	Prevalence of flatfoot was high in OW than NW children, and there was a significant association between prevalence of flatfoot and BMI (p>0.05, r = 0.019).
59	Low Risk	Shohat, 2018 [41] Israel	47588 (16-19 years, NA% girls) Cross-sectional; adolescents	BMI and obesity categories (Cut-points from CDCP) Scale and stadiometer.	Genu valgum Intercondylar and intermalleolar distances.	Genu varum was significantly (P < 0.001) less prevalent among OW (2.5%) and OB subjects (1.4%) compared to NW subjects (12.5%). Genu valgum was significantly (P < 0.001) more prevalent among both OW (17.7%) and OB subjects (28.8%) compared to NW (3.4%).
60	Low Risk	Smith, 2008 [31]	766 (13-15 years, 48% girls)	BMI	Hyperkyphosis, hyperlordosis, flat spine and	After controlling for height and gender, the mean weight of the neutral

Table S4. Summary of included studies (n = 68)

		Australia	Cross-sectional; adolescents	Scale and stadiometer	sway-back posture 2-D photogrammetry from sagittal images (Peak Motus motion analysis system)	posture group was lower than the hyperlordotic (i.e., more kyphosis and more lordosis) group (mean diff. 10.1±1.0 kg, P<0.001) and the sway group (mean diff. 3.0±0.9 kg, P<0.001), and there was not significantly different to that of the flat group (mean diff. 1.4±1.0 kg, P = 0.134). Adolescents with greater weight were more likely to present hyperlordotic and sway posture than neutral posture, independently of what were their height or age.
61	Low Risk	Smith, 2011 [28] Australia	1373 (3, 5, 10 and 14 years, 50% girls) Prospective longitudinal; children to adolescents	Six BMI trajectories at the ages of 3, 5, 10 and 14 years): Very Low, Low, Average, Ascending, Moderate High and Very High. Scale and stadiometer	Hyperkyphosis, hyperlordosis, flat spine and sway-back posture 2-D photogrammetry from sagittal images (Peak Motus motion analysis system)	BMI trajectory class was strongly associated with postural subgroup, with significantly higher proportions of adolescents in the Very High, High and Ascending BMI trajectory classes displaying a Hyperlordotic (RR: 10.91, 2.30 and 3.47 respectively; all P < 0.001) or Sway posture (RR: 2.84, 1.47 and 2.07 respectively; all P < 0.05) than a Neutral posture at age 14. Childhood obesity, and how it develops, is associated with standing sagittal postural alignment in adolescence.
62	Low Risk	Taylor ty al. 2006 [42] USA	355 (9-15 years, 56% girls) Cross-sectional; adolescents	BMI and obesity categories (Cut-points of USA) Scale and stadiometer.	Genu valgum Tibiofemoral angle and metaphyseal-diaphyseal angle (2-D photogrammetry from DEXA images)	Both metaphyseal-diaphyseal and tibiofemoral angle measurements showed greater malalignment in OW compared with NW, and metaphyseal-diaphyseal angle was negative correlated with BMI z-score (r=-0.10; p=0.017). OW group had a greater prevalence of abnormal lower extremity alignment than NW, and greater BMI was associated with greater knee valgus posture.
63	Low Risk	Tenenbaum, 2013 [73] Israel	825964 (16-19 years, 43% girls) Cross-sectional, adolescents	BMI and obesity categories (CDC) Scale and stadiometer	Flatfoot Physical examination	BMI was associated with flexible flatfoot. The strongest association was found between OB males and severe flatfoot (OR = 2.720; P < 0.0001).
64	High Risk	Villarroya, 2008 [74] Spain	245 (9-16 years, 47% girls) Cross-sectional; children and adolescents	BMI and obesity categories (IOTF) Scale and stadiometer.	Flatfoot Footprint: Chipaux-Smirak index and footprint angle.	The increase of BMI is related to a lower medial longitudinal arch and a greater toe out position.
65	Low Risk	Villarroya, 2009 [75] Spain	119 (9-16 years, 42% girls) Cross-sectional, children and adolescents	BMI and obesity categories (IOTF) Scale and stadiometer	Flatfoot Footprint and plantar pressure: Chippaux-Smirak index (CSI), footprint angle (FA), the talus-first metatarsal angle (TFMA), and the calcaneal inclination angle (CIA).	OB had lower FA and higher CSI than NW, which evidences flatfoot. OB had a CIA mean value lower than 17°, threshold from which flatfoot is reported.
66	High Risk	Wozniacka, 2013 [76] Poland	1115 (3-13 years, 49% girls) Cross-sectional, children	BMI and obesity categories (IOTF) Scale and stadiometer	Flatfoot Footprint: clark angle and medial longitudinal arch index	Obesity levels and medial longitudinal arch in the right foot were correlated in both girls and boys (p<0.001 and p<0.05, respectively). A stronger relationship was noticed among girls(γ=0.429; r=0.179) than boys (γ=0.229; r=0.130).

Table S4. Summary of included studies (n = 68)

67	High Risk	Wyszyńska, 2016 [16] Poland	120 (11-13 years, 51% girls) Cross-sectional; children and adolescents	BMI and obesity categories (Cut-points of Poland), body fat and muscle mass. Scale and stadiometer and bioelectrical impedance.	Rounded shoulders, hyperkyphosis, hyperlordosis 2-D photogrammetry (MORA 4 Generation System)	Children with the lowest content of muscle mass showed the greater scapular height malalignment in the frontal plane. Children with excessive body fat had less slope of the thoracic-lumbar spine (thoracic kyphosis and lumbar lordosis), greater difference in the depth of the inferior angles of the scapula (greater scapular winging), and greater angle of the shoulder line (shoulder malalignment).
68	High Risk	Zurita, 2014 [35] Mexico	295 (9-12 years, 57% girls) Cross-sectional; children	BMI and obesity categories (Cut-points of Mexico) Scale and stadiometer.	Scoliosis Musculoskeletal examination (Adam's test and Kendall posture classification)	There were no differences in the prevalence of scoliosis in children with OW with respect to NW

DEXA: Dual energy X-ray absorptiometry; MRI: Magnetic resonance imaging; IOTF: International Obesity Task Force; CDC: Centers for Disease Control and Prevention; FPI: foot posture index;

SECTION 1

Study 2

A systematic review on biomechanical characteristics of walking in children and adolescents with overweight/obesity: Possible implications for the development of musculoskeletal disorders

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INTRODUCTION

The World Health Organization (WHO) considers obesity in childhood as "one of the most serious public health challenges of the 21st century" [1]. Walking is the most common physical activity in our daily life, and thus, increasing the daily number of steps in children and adolescents has received considerable attention for combating the obesity epidemic [2, 3]. Obesity is known to be associated with biomechanical alterations in the gait pattern, which may predispose children and adolescents with overweight or obesity (OW/OB) to short- and long-term musculoskeletal disorders [4–6]. From early childhood, OW/OB has been associated to the development of various musculoskeletal disorders (i.e., musculoskeletal pain, injuries and fractures) [6] which may be extended to adulthood with notable consequences with regard to physical disability, quality of life and health-care economic costs [7, 8]. Among other suggested explanations, increased joint loads, together with biomechanical alterations during locomotor tasks, may be underlying the higher prevalence of musculoskeletal disorders in this population [4, 9, 10]. Furthermore, previous research has revealed that OW/OB show energetic inefficiency during walking, which could be partially explained by a biomechanically inefficient gait pattern [9, 11, 12]. Altogether, the increased musculoskeletal disorders and an energetic inefficiency during walking could be key to the loss of motivation to be physically active, creating a vicious circle which aggravates health issues associated with this population [10, 13].

Recent technological advances in motion capture systems allow accurate assessment of complex biomechanical parameters, which has the potential to provide a comprehensive observation of human movement patterns. These advances have allowed some studies to report numerous gait biomechanical parameters of OW/OB compared to children and adolescents with normal-weight, such as spatiotemporal data (e.g., gait speed or cadence), kinematics (e.g., joint angles or range of motion), kinetics (e.g., joint moments or joint power generation), centre of mass parameters (e.g., velocity, or displacement) or muscle activation and force parameters. In this regard, a previous systematic review studied the biomechanical alterations during walking in adults with obesity [14], but to the best of our knowledge, the biomechanical alterations in early stages of life have not yet been systematically reviewed. Thus, the aim of this systematic review was to examine the biomechanical characteristics of the gait pattern in OW/OB versus normal-weight.

METHODS

For those readers less familiar with the biomechanical terminology, **Table 1** provides definitions of the main biomechanical terms used in this review. Our reviewing procedures were guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) [15] and the review protocol was registered in the International Prospective Register of Systematic Reviews (https://www.crd.york.ac.uk/prospero/) with reference number: CRD42017067072.

Data sources and search strategy

A systematic literature search was performed in PubMed and Web of Science encompassing publications from inception to November 12th, 2018. The search strategy was defined by two reviewers with experience in biomechanics and gait pattern analysis (J-V and P-MG) and two additional reviewers with experience in database searching (C-CS and J-HM). The complete search strategies used for each database are available in **Table S1**.

Eligibility criteria

Inclusion criteria were defined as follows: 1) participants ≤ 18 years old; 2) intervention, prospective longitudinal, and cross-sectional articles, written in English, and without any special requirement of sample size; and 3) studies which compared spatiotemporal, kinematics, kinetics, centre of mass or muscle activation/forces parameters of gait between OW/OB and normal-weight. After verifying that there were no intervention and prospective longitudinal studies published on this topic, only cross-sectional articles were included in this systematic review.

Exclusion criteria were defined as follows: 1) special populations (e.g., participants with movement pattern disorders, musculoskeletal disorders, or pain); 2) meeting abstracts, editorials, letters to editor and reviews; and 3) studies which evaluated gait while carrying extra weight (e.g., participants carrying a backpack). Plantar pressure assessments during gait were beyond the scope of this review and were also not included.

Study selection

The selection process of relevant articles was performed in two stages by two

Table 1. Definition of the biomechanical parameters of gait used in this review

Variable	Definition
Spatiotemporal	**The study of spatial (distance) and temporal (time) parameters during gait**
Gait Speed	Walking speed. Is reported in $m.s^{-1}$.
Stride length	The interval between the first and second contact of the same foot. Is reported in m or cm.
Step length	The interval between initial contact of each foot. Is reported in m or cm.
Step width	The distance between the lateral margins of the feet. Is reported in m or cm.
Stance phase	The entire period during which the foot is on the ground. Is reported in a percentage of gait cycle or in s
Swing phase	The entire period during which the foot is in the air. Is reported in a percentage of gait cycle or in s
Single support	The period in which only one foot is on the floor. It starts when the opposite foot is lifted and ends with the opposite foot contacting again. Is reported in a percentage of gait cycle or in s
Double support	The period in which both feet are on the floor, starts with the initial contact of one foot and ends with the lifting of the opposite foot. Is reported in a percentage of gait cycle or in s.
Cadence	The number of steps per minute. Is reported in steps per minute
Kinematics	**The study of displacement parameters of body segments during gait in the three anatomical planes of motion (sagittal, frontal and transversal)**
Joint angular motion	The angular displacement of a joint in a specific anatomical plane of motion (sagittal, frontal and transversal). Is reported in degrees
Maximum angular motion	The furthest observed angular displacement of a joint in an anatomical plane of motion (sagittal, frontal and transversal). Is reported in degrees
Kinetics	**The study of force parameters associated with body segment motion during gait in the three anatomical planes of motion (sagittal, frontal and transversal)**
Joint moment	The net joint rotational effort produced by all muscles spanning a joint. Is reported in N.m.
Joint power generation	The rate at which joint work is performed. Has a positive value with the generation of energy, typically associated with concentric muscle activity. Is reported in Watts or Joules per second
Joint power absorption	The rate at which joint work is performed. Has a negative value with the absorption of energy, typically associated with ecccentric muscle activity. Is reported in Watts or Joules per second
Joint compressive force	Vector force acting perpendicular to the joint surface along the bone's longitudinal axis, which compresses the joint structures. Is reported in Newtons
Joint shear force	Vector force acting in parallel with the joint surface, which causing shear stress to the joint structures. Is reported in Newtons
Joint loading rate	The rate at which joint force increases, typically reported for joint compressive forces. Is reported in Newtons per second
Centre of mass	**The study of the point representing the mean position of body mass during gait**
Centre of mass velocity and acceleration	The velocity or acceleration of the centre of mass during gait. Is reported in $m.s^{-1}$ and $m.s^{-2}$, respectively.
Centre of mass displacement	The displacement of the centre of mass during gait. Is reported in m or cm
Muscle activity/force	**The study of muscle activity patterns and muscle forces during gait**
Muscle activation	Defined as having an amplitude greater than the mean amplitude plus two standard deviations of a static trial. Is reported as a percentage of gait phases
Muscle force	Estimated muscle force from model simulations. Reported in Newtons

independent researchers (PM-G and AP-F). In the first stage, studies identified in the Web-based systematic review software package "Covidence" (Veritas Health Innovation), which detected duplicate articles. Once the duplicates were deleted from the database, titles and abstracts were examined to identify those likely to be included. In the second stage, full-text of the remaining articles were checked for the final inclusion or exclusion decision. The researchers applied the eligibility criteria at both stages, and disagreements about study selection were resolved in a consensus meeting. Finally, reference lists of included articles were checked for further studies meeting the inclusion criteria, but none were found.

Data extraction

The selection of the data to be extracted was done by one experienced researcher in the field of human biomechanics (J-V), whereas the subsequent extraction process was done by one researcher (P-MG) and double-checked by two independent researchers (J-HM and C-CS). Defined items to extract were: 1) study reference; 2) biomechanical outcomes measured; 3) sample characteristics; 4) criteria for classification of overweight and obesity; 5) biomechanical instruments used for the assessment; 6) gait assessment protocol characteristics; and 7) main results. When studies included multiple gait analysis conditions (i.e., different treadmill inclinations, walking speeds and illumination), only data from normal conditions were extracted (i.e., no inclination, self-selected walking speed and normal light condition). The joint moments belonging to the kinetic parameters were presented as net internal moments. Disagreement between the reviewers in regards to the extracted data was discussed until consensus was reached.

Quality assessment

The quality assessment of the selected studies was conducted with The Joanna Briggs Institute Critical Appraisal Tool for Systematic Reviews (**Table S2**) [16] as used by previous authors [17, 18]. This tool was specifically designed to assess quality in cross-sectional studies, and consists of 8 items, each of them with three possible answers as follows: 'yes' (criterion met), 'no' (criterion not met) and 'not applicable'. Whilst potentially ambiguous due to unequal weightings between criteria, a total quality score was calculated for each study to provide a general indication of quality. This was done by dividing the number of positively scored (i.e., 'yes') criteria by the total number of applicable criteria. A study was considered as 'high quality' when the quality score was at least 0.75 (i.e., 75%), whereas studies were considered as 'low quality' when the quality score was lower than 0.75 [18]. Furthermore, a summary score of each criterion was calculated, by dividing the number of positively scored by the total number of included studies (i.e., 25), to provide an overview of how well the current literature scores on each criterion. Two independent researchers (P-MG and A-PF) accomplished this process, and disagreements were discussed to reach consensus.

Evidence synthesis

Due to the diversity of outcomes from the main biomechanical parameters of gait, a quantitative meta-analysis was not undertaken. We therefore conducted a qualitative evidence synthesis, structuring the evidence in those studies reporting significant differences between OW/OB and normal-weight against those studies reporting no significant differences. The level of evidence was rated similarly to previous literature [17, 18], which considered the number of included studies, their methodological quality and the consistency of findings. Findings were considered consistent if at least 75% of results pointed in the same direction, showing significant or non-significant differences between OW/OB and normal-weight (significance defined as $P < 0.05$). The rating protocol was used in previous studies [17, 18], and is described as follows:

Strong evidence: consistent findings in multiple (≥ 2) high-quality studies, pooled with findings from low-quality studies if any existed.

Moderate evidence: consistent findings in 1 high-quality study and at least 1 low-quality study, consistent findings in multiple (≥ 2) low-quality studies or consistent findings in multiple (≥ 2) high-quality studies but inconsistent findings when low-quality studies are considered.

Inconsistent evidence: inconsistent findings in multiple (≥ 2) studies.

Insufficient evidence: only one study available.

RESULTS

The database search revealed a total of 2,704 articles, of which 353 were duplicates. The titles and abstracts of the remaining 2,351 articles were independently screened by the two researchers, finally including a total of 47 articles which needed a full-text screening. After the full-text screening, 25 cross-sectional articles were

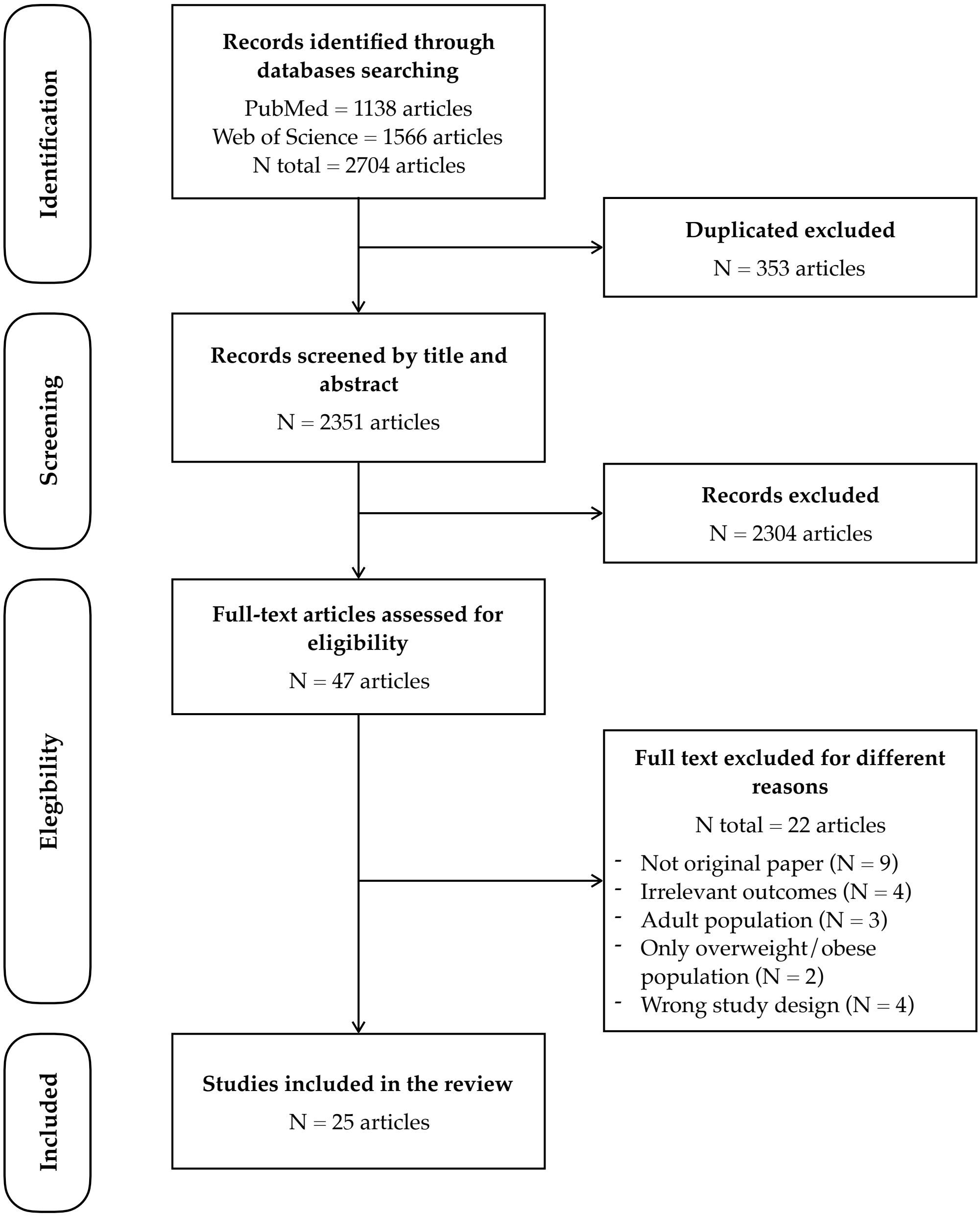

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of study selection, inclusion and exclusion of studies

deemed to meet the inclusion criteria and were subsequently included in this review. The detailed study selection process is shown in **Figure 1.**

Study and sample characteristics

Table S3 describes the characteristics of the 25 included studies. Sample sizes of the included studies ranged from 14 to

111 participants. Participants' ages in the included studies ranged from 8 to 18 years old, and the majority of them (73%) were focused on children (i.e., ≥ 8 and ≤ 11 years old) while the remainder (27%) were focused on adolescents (i.e., ≥ 12 and ≤ 18 years old). All included studies were cross-sectional and included different weight categories: underweight (4%), normal-weight (100%), overweight (32%) and obesity (76%). Regarding the criteria to classify participants as underweight, normal-weight, OW or OB, 48% of the included studies used the WHO BMI z-scores [19], 28% used the extended international World Obesity Federation criteria, formerly named as International Obesity Task Force (IOTF) BMI cut-offs [20], 12% used the Centers for Disease Control and Prevention growth charts for age and sex [21], 4% used body fat percentiles, and 8% did not report any criterion.

Quality assessment

Inter-rater reliability for the initial agreement between both researchers (PM-G and AP-F) was high to very high (κ = 0.79). Among the 25 articles included, 68% were categorized as 'high quality' and 32% as 'low quality'. **Table S2** shows the percentage of studies meeting the quality criteria, whereas **Table S4** provides detailed information on the quality score of each study.

Biomechanical characteristics of OW/OB

A summary of the evidence of gait biomechanics differences between OW/OB and normal-weight is presented in **Table 2.**

Table 2. Evidence synthesis of gait biomechanical differences between overweight/obese and normal-weight children and adolescents, including article references

Gait biomechanical parameters	N studies	Significant difference		No significant difference		Consistency %	Level of Evidence
		High Quality	Low Quality	High Quality	Low Quality		
Spatio-temporals							
Gait Speed	9 [24–28, 30, 32, 33, 43]	2 [26, 27]	3 [30, 33, 43]	3 [24, 25, 28]	1 [32]	56	Inconsistent
Cadence	6 [24, 27, 29–32]	1 [27]	1 [30]	2 [24, 29]	2 [31, 32]	67	Inconsistent
Stride length	8 [24, 25, 27–30, 32, 33]	1 [27]	2 [30, 33]	4 [24, 25, 28, 29]	1 [32]	63	Moderate no diff.
Step width	6 [24–27, 29, 33]	4 [24–27]	-	1 [29]	1 [33]	67	Moderate diff.
Stance phase	8 [24, 27–33]	3 [27–29]	2 [30, 31]	1 [24]	2 [32, 33]	62	Moderate diff.
Double support phase	6 [24, 26, 27, 31, 32, 45]	2 [26, 27]	2 [31, 45]	1 [24]	1 [32]	67	Inconsistent
Swing phase	6 [24, 26, 29–31, 45]	2 [26, 29]	1 [31]	1 [24]	2 [30, 45]	50	Inconsistent
Single support phase	3 [27, 30, 32]	1 [27]	1 [32]	-	1 [30]	67	Inconsistent
Upper extremities							

Table 2. Evidence synthesis of gait biomechanical differences between overweight/obese and normal-weight children and adolescents, including article references

Kinematics	1 [33]	-	1 [33]	-	-	100	Insufficient
Pelvis and hip							
Kinematics							
Sagittal	7 [24, 28, 29, 34, 36, 38, 40]	4 [28, 34, 38, 40]	-	3 [24, 29, 36]	-	57	Incon.
Frontal	8 [28, 29, 34, 36, 38–40, 46]	4 [28, 34, 39, 46]	-	4 [29, 36, 38, 40]	-	50	Incon.
Transversal	2 [28, 34]	2 [28, 34]	-	-	-	100	Strong diff.
Kinetics							
Sagittal	6 [28, 29, 35–37, 68]	5 [28, 29, 35–37]	1 [68]	-	-	100	Strong diff.
Frontal	4 [29, 35–37]	4 [29, 35–37]	-	-	-	100	Strong diff
Transversal	2 [35, 37]	1 [37]	-	1 [35]	-	50	Incon.
Contact force	1 [38]	1 [38]	-	-	-	100	Insufficient
Knee							
Kinematics							
Sagittal	9 [24, 28, 29, 34, 36, 40, 44, 46, 69]	5 [28, 29, 34, 40, 46]	1 [69]	3 [24, 36, 44]	-	66	Incon.
Frontal	4 [29, 36, 39, 40]	3 [29, 39, 40]	-	1 [36]	-	75	Strong diff.
Transversal	1 [34]	1 [34]	-	-	-	100	Insufficient
Kinetics							
Sagittal	7 [29, 32, 35–37, 69, 70]	5 [29, 35–37, 41]	-	-	2 [32, 69]	71	Moderate diff.
Frontal	7 [29, 35–37, 44, 69, 70]	5 [35–37, 41, 44]	1 [69]	1 [29]	-	86	Strong diff.
Transversal	1 [36]	1 [36]	-	-	-	100	Insufficient
Contact force	2 [43, 44]	1 [44]	1 [43]	-	-	100	Moderate diff.
Ankle and foot							
Kinematics							
Sagittal	7 [24, 28, 29, 34, 36, 40, 55]	4 [24, 28, 40, 55]	-	3 [29, 34, 36]	-	57	Incon.
Frontal	6 [29, 34, 36, 39, 40, 55]	3 [34, 39, 55]	-	3 [29, 36, 40]	-	50	Incon.
Transversal	3 [34, 36, 55]	2 [34, 55]	-	1 [36]	-	67	Incon.
Kinetics							
Sagittal	7 [28, 29, 32, 35–37, 69]	4 [28, 35–37]	1 [69]	1 [29]	1 [68]	71	Moderate diff.
Frontal	2 [29, 36]	1 [36]	-	1 [29]	-	50	Incon.
Transversal	1 [36]	1 [36]	-	-	-	100	Insufficient
Centre of mass							
Velocity/acceleration	1 [45]	-	1 [45]	-	-	100	Insufficient
Lateral displacement	1 [45]	-	1 [45]	-	-	100	Insufficient
Muscle Activation							
Psoas and iliacus	1 [38]	-	-	1 [38]	-	100	Insufficient
Gluteus complex	2 [38, 46]	1 [46]	-	1 [38]	-	50	Incon.
Quadriceps	4 [38, 43, 46, 48]	-	1 [43]	3 [38, 46, 48]	-	75	Strong no diff.
Hamstring	3 [38, 43, 48]	-	1 [43]	2 [38, 48]	-	67	Moderate no diff.

Table 2. Evidence synthesis of gait biomechanical differences between overweight/obese and normal-weight children and adolescents, including article references

Gastrocnemius/soleus	2 [43, 46]	1 [46]	1 [43]	-	-	100	Moderate diff.
Tibialis anterior	1 [48]	-	-	1 [48]	-	100	Insufficient

Note that the percentage of consistency is calculated by dividing the number of studies reporting significant or no significant differences (depending on where the evidence points) by the total number of studies reporting this specific gait biomechanical parameter. Consistent findings (≥ 75% of results showed significant or no significant differences). N studies: number of studies reporting a biomechanical parameter; Incon: Inconsistent; diff: difference between children and adolescents with overweight/obese vs their normal-weight peers.

Furthermore, a schematic summary of main results based on strong and moderate evidence reporting gait biomechanical differences between OW/OB and normal-weight is presented in **Figure 2**. These results were classified into the previously mentioned gait biomechanical parameters (i.e., spatiotemporal, joints kinematics and kinetics, centre of mass and muscle activation/force), and also divided into the gait phases and tasks proposed by Perry et al. [22] and Whittle et al. [23] (**Figure S1**). Furthermore, **Table S5** provides quantitative information on how large differences presented in **Figure 2** were expressed in their original absolute units and as standardized effect sizes (i.e., Cohen's D). Lastly, in order to summarize the information provided in this section, only biomechanical characteristics of gait in OW/OB during the main gait phases (i.e., whole gait cycle, stance phase and swing phase) are presented below. To further scrutinize these biomechanical characteristics during all gait phases and tasks, please refer to **Figure 2** and **Table S5**.

Spatiotemporal parameters

We found moderate evidence to support that OW/OB walk with greater step width [24–27] and prolonged stance phase [27–31] in comparison with normal-weight. On the contrary, there was moderate evidence for non-significant differences between OW/OB and normal-weight in the stride length [24, 25, 28, 29, 32]. The remaining spatiotemporal parameters (i.e., gait speed, cadence, double support, swing and single support phases) demonstrated an inconsistent level of evidence.

Upper extremities kinematic and kinetic parameters

Given that only one study investigated differences between OW/OB and normal-weight in upper extremity kinematics of gait, the level of evidence was set as insufficient. Notwithstanding, this study found that OW/OB walk with greater arm

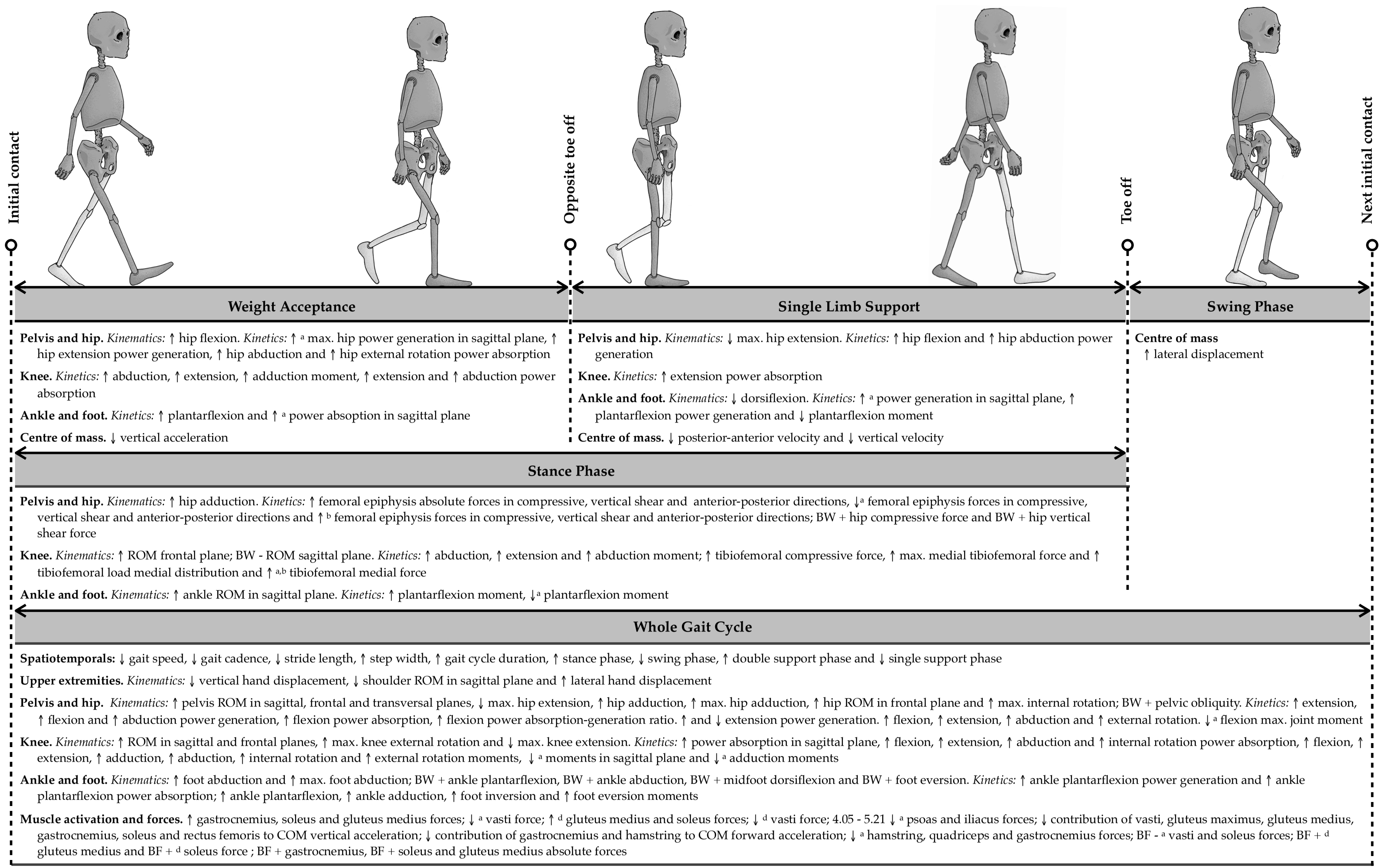

Figure 2. Schematic summary of main gait biomechanical differences between children and adolescents with overweight/obesity and normal-weight divided by key gait phases.

↑: indicates significantly higher values in children and adolescents with overweight/obesity versus their normal-weight peers; ↓ indicates significantly lower values in children and adolescents with overweight/obesity versus their normal-weight peers; a normalized for body mass (kg); b normalized for the physis cross-sectional area (cm2) motion in the frontal plane, while they display less arm and shoulder motion in the sagittal plane [33].

Pelvis and hip kinematic and kinetic parameters

We found strong evidence that OW/OB have greater pelvis transversal plane motion and higher hip internal rotation across the entire gait cycle compared to their normal-weight peers [28, 34]. However, we did not find unanimity in kinematic results in the sagittal and frontal planes, and therefore the level of evidence was set as inconsistent. With regard to kinetic parameters, there was strong evidence supporting higher hip flexion, extension and abduction moments and power generation/absorption in OW/OB compared to normal-weight [28, 29, 35–37]. Kinetics of transversal plane showed inconsistent evidence, while there was insufficient evidence, with only one study available [38], to determine differences between OW/OB and normal-weight in terms of contact forces acting on the femoral head during walking.

Knee kinematic and kinetic parameters

Analysing the whole gait cycle, we found moderate evidence supporting greater knee frontal plane motion and a knee abducted position for OW/OB in comparison with normal-weight [29, 39, 40]. Moreover, kinematic results from the sagittal plane demonstrated inconsistent evidence, and there was insufficient evidence on transverse plane kinematics to determine differences between OW/OB and normal-weight. Regarding kinetic parameters, we found moderate evidence supporting higher knee flexion and extension moments and higher power generation/absorption in OW/OB than in normal-weight [29, 35–37, 41], as well as moderate evidence supporting higher knee abduction and adduction moments and power generation/absorption [29, 35–37, 41, 42]. Furthermore, we found moderate evidence indicating higher tibiofemoral compressive forces and a more medially loaded distribution in OW/OB compared to normal-weight during the stance phase of gait [43, 44]. Lastly, there was insufficient evidence on transverse plane knee kinetics with only one study reporting on this [36].

Ankle and foot kinematic and kinetic parameters

Over the whole gait cycle, there was inconsistent evidence reporting differences of ankle and foot kinematics in all three planes (i.e., sagittal, frontal and transverse). Concerning kinetic parameters, we found moderate evidence for higher ankle plantarflexion moments and power generation in OW/OB with respect to normal-weight [28, 35–37, 42]. Differences between OW/OB and normal-weight in frontal plane kinetics were inconsistent, whereas insufficient evidence was available on transverse plane kinetics [36].

Centre of mass parameters

We identified only one study investigating differences in centre of mass parameters between OW/OB and normal-weight during walking [45], indicating an insufficient level of evidence. In this single study, OW/OB showed a lower centre of gravity vertical acceleration during the stance phase in comparison with normal-weight. Moreover, during the stance phase, they displaced their centre of mass with lower velocities than normal-weight in vertical and anterior-posterior directions, whereas during the swing phase they demonstrated a greater centre of mass lateral displacement.

Muscle activation and forces parameters

Analysing the whole gait cycle, there was moderate evidence indicating that OW/OB have higher activation and generate higher forces with gastrocnemius and soleus muscles compared to normal-weight [46, 47]. On the other hand, there was moderate evidence supporting no differences between OW/OB and normal-weight on quadriceps [38, 46, 48] and hamstring muscle [38, 48] activations and forces, respectively. The remaining muscles studied in the gait pattern of OW/OB and normal-weight were inconsistent (i.e., gluteus complex) or insufficient (i.e., psoas, iliacus and tibialis anterior).

DISCUSSION

In the present systematic review, we provide an overview of the biomechanical characteristics of gait in OW/OB with respect to normal-weight, based on a systematic review of the literature. The main findings of this study were: 1) based on strong evidence, the gait patterns of OW/OB present greater pelvis transversal plane motion, higher hip internal rotation, higher hip flexion, extension and abduction moments and power generation/absorption, greater knee abduction/adduction motion, and higher knee abduction/adduction moments and power generation/absorption; and 2) based on moderate evidence, OW/OB walk with greater step width, longer stance phase, higher tibiofemoral contact forces, higher ankle plantarflexion moments and power generation and greater gastrocnemius and soleus activation/forces.

Spatiotemporal parameters

Among all spatiotemporal parameters of gait studied, we only found consistent results between studies supporting that OW/OB walk with a greater step width and longer stance phase than their normal-weight peers. These characteristics could arise from a necessity to generate added stability by walking with a greater base of support in the frontal plane, expressed through a wider step [49]. Lengthening the stance phase could also indicate a poorer overall stability in this population, likely accompanied by a greater difficulty decelerating and reaccelerating their body mass for the next step [28, 50, 51]. Concerning the remaining spatiotemporal parameters, there were no consistent differences between OW/OB and normal-weight. Further studies should determine whether the presence of overweight/obesity has an effect on these parameters, preferably under non-laboratory conditions (e.g., pedometry or accelerometry) where children tend to present a more natural gait pattern.

Pelvis and hip kinematics and kinetics

Pelvis and hip kinematics of OW/OB only showed differences with respect to normal-weight in the transverse plane, with increased pelvis transverse plane motion and hip internal rotation. This increased pelvis motion has been associated with a lack of stability and motor control in the lumbopelvic region [52]. The increased hip internal rotation in this population could be due to the adipose tissue accumulated between their thighs hampering movement in the sagittal plane and requiring compensations in the transverse plane [27, 53]. With regard to kinetics, OW/OB generated higher hip extension and abduction power, possibly to prevent lower-limb collapse and maintain an upright posture [28, 37]. Some authors demonstrated that these altered power generation patterns remained after accounting for body mass, which could indicate a locomotor adaptation to walking with extra weight [35].

On the other hand, results from the pelvis and hip kinematics in the sagittal and frontal plane, as well as kinetics in the transverse plane, were inconsistent. To date, one of the main limitations of gait analysis in OW/OB is the presence of soft tissue artefacts in the data, especially around the pelvis and thigh where this population accumulates greater adiposity [54]. Only studies of Briggs et al. [41], Lerner et al. [38, 44] and Strutzenberger et al. [29] addressed soft tissue artefacts, by using virtual markers relative to anatomical structures less likely to present adiposity (e.g., the sacrum), or by measuring the distance between anatomical landmarks (e.g., left and right anterior superior iliac spines) in order to recreate the adequate position of markers. Possibly this limitation, together with the use of different methodologies to measure kinematic and kinetic parameters, can partially explain the inconsistencies observed at the pelvis and hip. We could only identify one study which investigated the influence of paediatric obesity on hip joint contact forces during walking [38]. Lerner et al. [38] found that OW/OB are exposed to higher femoral head forces in compressive and anterior-posterior directions compared to normal-weight during the gait pattern. Further research is warranted to confirm these higher hip contact forces in OW/OB, and to propose gait analysis procedures to minimize soft tissue artefacts in this specific population.

Knee kinematics and kinetics parameters

An important finding of this review is the presence of knee kinematic and kinetic alterations observed in OW/OB during walking, which consist of greater knee frontal plane motion and higher knee frontal plane moments and power generation/absorption. These results might be linked to the greater step width and hip internal rotation position above mentioned, which together could be indicating a lower limb valgus position commonly adopted by OW/OB during gait [36]. Some authors have suggested that this valgus position helps provide a better dynamic stability in the frontal plane during gait, and that it could be a subconscious strategy to reduce loading on the medial compartment of the knee joint [29, 34]. In agreement with the aforementioned findings in pelvis and hip, OW/OB still presented greater knee abduction power absorption than normal-weight after taking into account their body mass, suggesting again that gait biomechanical alterations of this population are not only explained by the presence of excessive body mass [29, 35]. We did not find consistent evidence of knee kinematic and kinetic differences in the sagittal plane of OW/OB with respect to normal-weight, whereas there was insufficient literature in the transverse plane. The available literature suggests that OW/OB present a knee externally rotated position and higher knee transverse plane moments and power generation/absorption, nonetheless future studies will need to corroborate these findings [34, 36].

Concerning tibiofemoral contact forces, OW/OB have demonstrated higher absolute compressive forces and, furthermore, they seem to walk with a more medial tibiofemoral load distribution [44, 47]. To further explore how obesity affects knee contact forces relative to the skeletal structure, Lerner et al. [44] accounted for physis cross-sectional area in their analysis, and they discovered that the medial tibiofemoral forces were still 1.77 times greater in OW/OB. It could imply that OW/OB not only have higher medial tibiofemoral forces than their normal-weight peers, but also that their skeletal structure is not adapted to supporting the greater mechanical stresses [44].

Ankle and foot kinematics and kinetics parameters

Concerning ankle and foot biomechanics during the whole gait cycle, we only found consistent evidence supporting higher ankle plantarflexion moments and power generation in OW/OB compared to normal-weight. Some authors have acknowledged this compensation as a need to decelerate and propel their heavier body mass into the next step [28, 37]. Ankle and foot kinematics in all three planes, as well as kinetics in the frontal plane, demonstrated inconsistent results. In this sense, it is important to highlight that only Mahaffey et al. [55] took into account the complex motion of the multiple foot segments in their study, whereas the rest of the authors considered the foot as a single rigid segment. Future studies should specifically focus on ankle and foot biomechanics during gait in this population from a multiple segments perspective, with a special emphasis on kinematic parameters.

Muscle activation and forces

This systematic review evidences a higher activation and forces of the gastrocnemius and soleus complex in OW/OB than normal-weight during the whole gait cycle, which is in agreement with the higher ankle plantarflexion moment and power generation previously mentioned [44]. Furthermore, some authors revealed that higher body fat percentage was associated with higher soleus forces independently of participants´ muscle mass, which reveals a real hyper-activation of this muscle during walking since this population has demonstrated not only greater body mass, but also greater muscle mass [46, 56]. Additionally, the fact that, after adjusting for body mass, OW/OB displayed lower forces in gastrocnemius and soleus muscle complexes, denotes the importance of excess of weight in the greater muscle force requirements [46, 47].

On the other hand, quadriceps and hamstring muscles have demonstrated a similar activation and forces profile in both OW/OB and normal-weight, results which seem to not be consistent with the above-mentioned higher hip and knee kinetic values in OW/OB. Among the remaining muscles studied, the gluteus complex showed inconsistent results whereas psoas iliacus and tibialis anterior presented insufficient evidence to draw solid conclusions. On the basis of the above, further investigation is necessary to determine whether muscle activation patterns during walking between OW/OB and normal-weight are meaningfully different.

Clinical implications

Development of musculoskeletal disorders

Findings from this systematic review support the belief that gait biomechanical alterations observed in OW/OB could have harmful implications on their musculoskeletal system. This population has demonstrated a higher prevalence of musculoskeletal disorders, especially in lumbar, hip and knee regions [5, 6, 13]. Interestingly, our systematic review revealed that OW/OB present kinematic and kinetic alterations in these regions while walking, which could be a factor to consider in the onset and development of musculoskeletal disorders in this population. Lower limb kinematic alterations during locomotor tasks, such as those found in this review, are considered a risk factor for the development of osteoarthritis through a progressive degeneration of articular cartilage and soft tissues [4]. Moreover, higher contact forces applied on the hip and knee joints could partially explain the increased prevalence of hip and knee pain in this population, as well as the long-term development of osteoarthritis [38, 57].

It is important to note that these gait biomechanical alterations have been reported during walking, where individuals must typically endure peak loads of 1.2 times their body weight, whereas in other activities such as running or jumping, the loads can increase 2 to 5 times body weight [58, 59]. If the biomechanical alterations observed in walking would also extend to higher intensity physical activities, OW/OB could experience an even greater risk for developing musculoskeletal disorders. The gait patterns of OW/OB suggested in this review present similarities with other populations suffering from musculoskeletal disorders. For instance, some authors have reported that patients undergoing low back pain present increased pelvis transverse plane motion during walking [60], whereas patients present with knee osteoarthritis also walk with higher knee adduction moments than healthy-patients [61].

Among other possible consequences, the development of musculoskeletal disorders will likely decrease motivation of OW/OB to be physically active, leading them into a downwards spiral of accelerated disease progression [10, 13]. This creates a huge direct burden on society [62], but has also major implications for mobility and quality of life during adulthood and old age [8, 63]. It is important to highlight that all associations between biomechanical alterations and musculoskeletal disorders proposed in this review are based on hypotheses. Longitudinal investigation is needed to determine whether gait biomechanical alterations in OW/OB predict the future development of musculoskeletal disorders.

Energetic inefficiency of walking

The energetic cost of walking, described as the metabolic rate required to walking at a given speed, is greater in OW/OB compared to normal-weight [11, 12]. Obviously, the need to carry extra weight while walking is a primary determinant of the elevated energy expenditure in this population, however, a biomechanically inefficient gait pattern has been proposed as an additional factor [11, 64]. For instance, a greater step width, as has been evidenced in OW/OB, is related to an increased energetic cost in human walking [11, 65]. In addition, higher joint moments and powers, as well as an increased demand for muscle activation, suggest higher energy expenditure during walking at normal speed [27, 66].

Overall, gait biomechanical alterations shown in this review provide further insight into the roles of greater energetic cost of walking in OW/OB. Although an elevated walking energy cost may seem beneficial since obesity is an energy imbalance between calories consumed and expended [67], it also comes with a greater burden on the musculoskeletal system, and a relatively greater effort of walking [9]. The latter could be key in the lack of motivation to be physically active, creating a vicious circle which will aggravate health issues associated with this population.

Strengths and limitations

A strength of this work is the combination of a systematic review of the literature with an evidence synthesis based on methodological quality, which allows us to not only draw conclusions from the included articles but also to establish the level of evidence of our findings. Moreover, we provide two different formats to report our findings: a graphical and schematic summarized figure containing the gait biomechanical characteristics of OW/OB found in this review (**Figure 2**), and a detailed table providing quantitative information of these characteristics (**Table S5**).

One limitation of this review is that it only includes cross-sectional studies, due to the lack of intervention and longitudinal studies, preventing any causality conclusions between the presence of excessive body mass and biomechanical alterations during walking. With regard to the search strategy, the use of only two databases (PubMed and Web of Science) may have included out some articles related to this topic. Nevertheless, it is expected that those databases cover any influential peer-reviewed journals in which one expects to find relevant articles for this review. We need to acknowledge that there is no current evidence supporting that the biomechanical alterations experienced by OW/OB predict musculoskeletal disorders in adulthood and, therefore, any conclusions around that are based on assumptions and hypotheses. It is also important to acknowledge that the gait pattern is under a development process during childhood, and future research should therefore focus on determining the age at which these biomechanical alterations become apparent in OW/OB. Lastly, the included articles presented considerably different instruments, assessment protocols and data processing methodologies to analyse the gait pattern, a fact which should be acknowledged in future studies in order to make the results more comparable.

Conclusion

Findings from this review reveal strong and moderate evidence supporting biomechanical differences in the gait pattern of OW/OB with respect to normal-weight. Overall, there was strong evidence that gait patterns of OW/OB present greater pelvis transversal plane motion, higher hip internal rotation, higher hip flexion, extension and abduction moments and power generation/absorption, greater knee abduction/adduction motion, and higher knee abduction/adduction moments and power generation/absorption. Furthermore, based on moderate evidence, OW/OB walk with greater step width, longer stance phase, higher tibiofemoral contact forces, higher ankle plantarflexion moments and power generation and greater gastrocnemius and soleus activation/forces. These alterations observed in OW/OB could be determinant in the short and long-term development of musculoskeletal disorders and could be a key factor to understanding the energetic inefficiency experienced by this population during walking.

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SUPPLEMENTARY MATERIAL

Table S1. Search terms used in PubMed and Web of Science databases.

PubMed
((((((((("Child"[Mesh]) OR "Adolescent"[Mesh])) AND ((("Overweight"[Mesh]) OR "Pediatric Obesity"[Mesh]) OR "Obesity"[Mesh])))))) AND ((((((Kinemat*) OR "Gait"[Mesh]) OR walk*) OR "Kinetics"[Mesh]) OR "Locomotion"[Mesh]) OR biomechanic*))
Web of Science
(("child*" OR "adolescen*" OR "youth*" OR "teenager*" OR "boy*" OR "girl*") AND ("obes*" OR "overweight") AND ("Kinematic*" OR "Gait" OR "walk*" OR "Kinetic*" OR "Locomotion*" OR "biomechanic*"))

Table S2. Criteria for the methodological quality assessment of included articles and percentage of studies meeting these criteria.

Criteria items		Percentage of studies meeting criterion (%)
1.	Were the criteria for inclusion in the sample clearly defined?	88
2.	Were the study population recruitment methods, the period of recruitment and the place of recruitment adequately described?	68
3.	Was the biomechanical assessment protocol adequately described, and did the instruments have acceptable reliability?	84
4.	Was the obesity categorization adequately reported?	92
5.	Were confounding factors identified (e.g. age, sex, BMI or gait speed)?	76
6.	Were strategies to deal with confounding factors stated?	52
7.	Were the anthropometric variables (e.g. weight, height or body fat) measured in a valid and reliable way?	44
8.	Was appropriate statistical analysis used?	92

Table S3. Quality assessment of included articles.

Study	1	2	3	4	5	6	7	8	Quality Score %	Quality Category
Blakemore et al. 2013 [48]	✓	✓	✓	✓	✓	✓	×	✓	87.5	High
Briggs et al. 2017 [68]	✓	✓	✓	✓	✓	✓	✓	✓	100	High
Cimolin et al. 2015 [28]	✓	✓	✓	✓	×	×	✓	✓	75	High
Colné et al. 2008 [45]	×	×	✓	×	×	×	×	×	12.5	Low
D´Hondt et al. 2011 [24]	✓	✓	✓	✓	✓	✓	✓	✓	100	High
Deforche et al. 2009 [25]	✓	✓	✓	✓	✓	✓	✓	✓	100	High
Dufek et al. 2012 [26]	✓	✓	✓	✓	✓	✓	✓	✓	100	High
Gushue et al. 2005 [69]	✓	×	✓	✓	×	×	×	✓	50	Low
Hills et al. 1992 [30]	×	×	×	×	✓	×	×	×	12.5	Low
Huang et al. 2014 [27]	✓	✓	✓	✓	✓	×	×	✓	75	High
Huang et al. 2013 [43]	×	×	✓	✓	✓	×	×	✓	50	Low
Hung et al. 2013 [33]	✓	×	×	✓	✓	×	×	✓	50	Low
Lerner et al. 2016 [38]	✓	✓	✓	✓	✓	✓	✓	✓	100	High
Lerner et al. 2016 [44]	✓	×	✓	✓	✓	×	✓	✓	75	High
Lerner et al. 2014 [46]	✓	×	✓	✓	✓	✓	×	✓	75	High
Mahaffey et al. 2016 [55]	✓	✓	✓	✓	✓	✓	✓	✓	100	High
McGraw et al. 2000 [31]	✓	✓	×	✓	×	×	✓	✓	62.5	Low
McMillan et al. 2010 [40]	✓	✓	✓	✓	✓	✓	×	✓	87.5	High
McMillan et al. 2009 [39]	✓	✓	×	✓	×	×	✓	✓	62.5	Low
Nantel et al. 2006 [32]	✓	✓	✓	✓	×	×	×	✓	62.5	Low
Shultz et al. 2014 [37]	✓	✓	✓	✓	✓	✓	×	✓	87.5	High
Shultz et al. 2014 [34]	✓	✓	✓	✓	✓	✓	✓	✓	100	High
Shultz et al. 2010 [35]	✓	✓	✓	✓	✓	×	×	✓	75	High
Shultz et al. 2009 [36]	✓	✓	✓	✓	✓	✓	×	✓	87.5	High
Strutzenberger et al. 2017 [29]	✓	×	✓	✓	✓	✓	×	✓	75	High
Criterion Score %	88	68	84	92	76	52	44	92		

Note that the quality score is calculated by dividing the number of criteria met in one study by the total number of criteria (i.e., 8). Note that the criterion score is calculated by dividing the number of studies meeting one criterion by the total number of studies (i.e., 25). ✓: meet the methodological quality criterion; ×: not meet the methodological quality criterion.

Table S4. Summary of study characteristics of articles included in review.

References	Outcome Measures	Descriptives N (UW/NW/OW/OB), N girls/N boys, Age, BMI	Criteria for OW/OB	Biomechanical Assessment Instruments	Gait conditions surface; speed; shoes
Blakemore et al. 2013 [48]	**Muscle activation:** tibialis anterior, vastus lateralis and semitendinosus muscle activation duration, expressed as a percentage of gait phases (%)	20 (7/7/6/0), 10/10 UW: 9.0 ± 0.82 yr., 14.28 ± 0.27 kg/m2; NW: 9.14 ± 0.90 yr., 16.83 ± 1.01 kg/m2; OW: 9.33 ± 0.52 yr., 23.05 ± 6.42 kg/m2.	BMI Z-scores	Channel surface electromyography	Overground; self-selected, slow speed (90%) and fast speed (130%); shod
Briggs et al. 2017 [68]	**Kinetics:** knee sagittal and frontal planes moment (Nm/kg) and peak external moments during the stance phase of gait, un-normalized and normalized for body weight	40 (0/20/0/20), 14/26 NW: 14.10 ± 2.02 yr., 20.36 ± 2.59 kg/m2; OB: 14.05 ± 2.09 yr., 29.20 ± 2.16 kg/m2.	BMI Z-scores	10 infrared cameras and 6 force plates	Overground; self-selected; NR
Cimolin et al. 2015 [28]	**Spatio-temporals:** gait speed (m/s), % stance and step length (m) **Kinematics:** pelvis (all 3 planes), hip (sagittal and frontal), knee (sagittal) and ankle (sagittal) peak angles (deg) for all 3 planes **Kinetics:** hip and ankle moments, power generation and absorption (W/kg) in sagittal plane at gait phases	24 (0/10/0/14), 0/24 NW: 14.74 ± 3.54 yr., 20.29 ± 3.71 kg/m2; OB: 15.71 ± 14.64 yr., 32.89 ± 3.67 kg/m2.	BMI Z-scores	6 infrared cameras, 2 force plates and 12 infrared cameras	Overground; self-selected; barefoot
Colné et al. 2008 [45]	**Spatio-temporals:** duration of double support (ms) and swing phase (s) **Centre of mass:** vertical and anterior-posterior velocities (m/s) and acceleration (m/s2) of the participant´s centre of gravity.	26 (0/10/0/16), 20/6 NW: 17.00 ± 1.00 yr., 20.00 ± 1.00 kg/m2; OB: 16.00 ± 1.00 yr., 40.00 ± 5.00 kg/m2.	NR	1 force plate	Overground; NR; NR
D´Hondt et al. 2011 [24]	**Spatio-temporals:** gait speed (m/s), cadence (steps/min), stride length (m) and width (m), and time in stance, swing and double support (s) **Kinematics:** Hip, knee and ankle joint angles (deg) for the sagittal plane.	32 (0/16/0/16), 24/8 NW: 11.2 ± 1.6 yr., 17.46 ± 1.85 kg/m2; OB: 11.2 ± 1.5 yr., 29.92 ± 4.90 kg/m2.	IOTF	8 infrared cameras	Overground; self-selected; barefoot
Deforche et al. 2009 [25]	**Spatio-temporals:** gait speed (cm/s), step width (cm) and step length (cm)	57 (0/32/0/25), NR/NR NW: 9.3±0.8 yr., 16.3±1.2 kg/m2; OB: 9.3±1.0 yr., 23.8±3.1 kg/m2	IOTF	1 force plate	Overground; "As fast as possible"; shod
Dufek et al. 2012 [26]	**Spatio-temporals:** gait speed (m/s), stance width (cm), double support (% gait cycle) and swing phase (% gait cycle)	111 (0/56/55OW and OB), 47/64 NW, OW and OB: 14.20 ± 1.40 yr.,	CDCP	Walkway system	Overground; self-selected and fast (maximum speed); shod
Gushue et al. 2005 [69]	**Kinematics:** knee angles (deg) for the sagittal plane **Kinetics:** moments (Nm) at knee (sagittal and frontal plane) and ankle (sagittal plane)	23 (0/10/13/0), 10/13 NW: 12.2 ± 1.6 yr., 18.0 ± 2.2 kg/m2; OW: 11.9 ± 1.2 yr., 29.9 ± 5.4 kg/m2.	BMI Z-scores	3 infrared-emitting diodes and 2 force plates	Overground; self-selected; shod
Hills et al. 1992 [30]	**Spatio-temporals:** gait speed (m/s), cadence (steps/min), and duration (s) and percentage (%) of gait cycle and gait phases (stance, swing, single support)	22 (0/13/0/9), NR/NR NW: 16.00 ± 0.79 kg/m2; OB: 26.00 ± 1.60 kg/m2	NR	2 photosonics cameras	Overground; Self-selected, Slow (90%) and fast (130%); barefoot
Huang et al. 2014 [27]	**Spatio-temporals:** gait speed (m/s), cadence (steps/min), step width (cm), stride length (m) and time (s), % of stance phase, single and double support	32 (0/16/0/16), NR/NR NW: 10.84 ± 0.57 yr., 18.00 ± 2.75 kg/m2; OB: 10.97 ± 0.78 yr., 29.08 ± 3.22 kg/m2	IOTF	16 camera digital video-based motion	Overground; self-selected; barefoot
Huang et al. 2013 [43]	**Spatio-temporals:** gait speed (m/s) **Kinetics:** compressive Tibiofemoral Force (N)	16 (0/8/0/8), 0/16 NW: 8-12 yr., 18.8 ± 3.8 kg/m2; OB: 8-12 yr., 31.0 ± 3.4 kg/m2.	IOTF	16 camera digital video-based motion	Overground; self-selected; barefoot

Table S4. Summary of study characteristics of articles included in review.

	Muscle activation: muscle forces (N) of hamstring, quadriceps and gastrocnemius. Individual muscles (vasti, gluteus maximus and medius, hamstrings, gastrocnemius, soleus and rectus femoris) contribution to the vertical and forward COM acceleration (m/s^2)				
Hung et al. 2013 [33]	**Spatio-temporals:** gait speed (m/s), stride length (m), step width (m) and % stance phase **Kinematics:** range of motion (deg) of shoulder, elbow, spine	24 (0/12/12/0), 11/13 NW: 8.7 ± 3.0 yr., 17.0 ± 2.1 kg/m^2; OW: 8.9 ± 3.0 yr., 22.0 ± 4.7 kg/m^2.	CDCP	7 infrared cameras and 2 force plates	Overground; self-selected; barefoot
Lerner et al. 2016 [38]	**Kinematics:** hip joint angles in sagittal and frontal plane (deg) **Kinetics:** hip joint load vectors and load rates (sagittal and transverse planes) normalized to body weight (MN/kg) and to each physis cross-sectional area (MN/m^2) **Muscle activation:** Body weight normalized muscle force (N/kg) of iliacus, psoas, gluteus minimis, gluteus maximus, gluteus medius, biceps femoris and rectus femoris	20 (0/10/0/10), 9/11 NW: 9.6 ± 1.4 yr., 16.0 ± 1.7 kg/m^2; OB: 9.5 ± 0.9 yr., 26.0 ± 3.1 kg/m^2.	BMI Z-scores	10 infrared cameras and ground reaction forces collected from treadmill	Treadmill; Controlled (1m/s); barefoot
Lerner et al. 2016 [44]	**Kinematics:** knee flexion angle in sagittal plane (deg) **Kinetics:** tibiofemoral peak medial and lateral contact force (N), normalized by body weight (N/kg) and bone mineral density ($N/kg•cm^2$), during stance phase. Tibiofemoral medial load share (%), loading rate (kN/s) and loading rate normalized by bone mineral density ($kN/s•cm^2$). Knee adduction moment (frontal plane) (N•m) during stance phase	20 (0/10/0/10), 9/11 NW: 9.6 ± 1.4 yr., 16.0 ± 1.7 kg/m^2; OB: 9.5 ± 0.9 yr., 26.0 ± 3.1 kg/m^2.	BMI Z-scores	10 infrared cameras, ground reaction forces collected from treadmill and surface electromyography	Treadmill; Controlled (1m/s); barefoot
Lerner et al. 2014 [46]	**Kinematics:** Pelvis (frontal plane) and knee (sagittal plane) joint angles (deg) **Muscle activation:** vasti, gastrocnemius, gluteus medius and soleus absolute force (N) and normalized for body weight and lean body (N/kg).	14 (0/5/4/5), 8/6 10.1 ± 1.5 yr., 29.6 ± 8.7 %	BF	9 infrared cameras and ground reaction forces collected from treadmill	Treadmill; self-selected; barefoot
Mahaffey et al. 2016 [55]	**Kinematics:** shank, calcaneus, midfoot and metatarsals angular motion in all three planes (deg)	55 (0/29/12/6), 0/55 9,55 ± 1,18 yr., 18,41 ± 4 kg/m^2	BMI Z-scores	8 infrared cameras, 2 force plates	Overground; self-selected; barefoot
McGraw et al. 2000 [31]	**Spatio-temporals:** walk cadence (cycles/min), percentages of gait cycle (%): double support, stance and swing phases, at three different speeds	20 (0/10/0/10), 0/20 NW: 8.60 yr., 17.40 ± 1.14 kg/m^2; OB: 9.10 yr., 30.30 ± 7.86 kg/m^2	BMI Z-scores	1 video camera and 1 force plate	Overground; Self-selected, Slow (90%) and fast (130%); barefoot
McMillan et al. 2010 [40]	**Kinematics:** hip, knee and ankle angles at specific events and peak angles (deg) during stance phases for sagital and frontal plane	36 (0/18/0/18), 30/6 NW: 14.6 ± 1.8 yr., 20.3 ± 2.0 kg/m^2; OB: 15.0 ± 1.5 yr., 44.6 ± 10.2 4 kg/m^2.	BMI Z-scores	8 infrared cameras and 2 force plates	Overground; self-selected; barefoot
McMillan et al. 2009 [39]	**Kinematics:** Hip, knee and ankle peak motion amplitude (deg), peak motion timing (%) at stance phase for frontal plane.	14 (0/7/7/0), 0/14 NW: 10.8 ± 0.8 yr., 17.0 ± 3.3 kg/m^2; OW: 11.9 ± 0.7 yr., 40.5 ± 10.0 kg/m^2.	BMI Z-scores	6 infrared cameras and 1 force plate	Overground; self-selected; barefoot
Nantel et al. 2006 [32]	**Spatio-temporals:** gait speed (m/s), cadence (steps/min), stride length (m), and % stance, single and double support **Kinetics:** energy generation and absortion (W/kg) of ankle, knee and hip in the sagittal plane, normalized to body weight.	20 (0/10/0/10), NR/NR NW: 9.4 ± 1.4 yr., 18.1 ± 2.8 kg/m^2; OB: 9.7 ± 2.0 yr., 26.7 ± 7.1 kg/m^2.	BMI Z-scores	8 infrared cameras and 2 force plates	Overground; self-selected; barefoot
Shultz et al. 2014 [37]	**Kinetics:** peak power at weigh acceptance and propulsion (W) of hip (all 3 planes), knee (sagittal and frontal planes) and ankle (sagittal plane) un-normalized and normalized for body weight.	40 (0/20/0/20), 18/22 NW: 10.4 ± 1.6 yr., 17.2 ± 1.4 kg/m^2; OB: 10.8 ± 1.4 yr., 24.3 ± 2.7 kg/m^2.	IOTF	11 infrared cameras and 2 force plates	Overground; self-selected; barefoot

Table S4. Summary of study characteristics of articles included in review.

Shultz et al. 2014 [34]	**Kinematics:** maximal angular displacement (deg), and area under the angular displacement curve (deg•s) for hip (all 3 planes), knee (sagittal and transversal planes), ankle and foot (all 3 planes) joints	40 (0/20/0/20), 18/22 NW: 10.4 ± 1.6 yr., 17.2 ± 1.4 kg/m_2; OB: 10.8 ± 1.4 yr., 24.3 ± 2.7 kg/m_2.	IOTF	11 infrared cameras and 2 force plates	Overground; self-selected; barefoot
Shultz et al. 2010 [35]	**Kinetics:** power absorption and power generation (W) of hip (all 3 planes), knee (sagittal and frontal planes) and ankle (sagittal and transversal planes), un-normalized and normalized to body weight.	28 (0/14/14/0), NR/NR NW: 10.79±1.37 yr., 17.03±1.26 kg/m_2; OB: 10.43±1.51 yr., 29.74±4.91 kg/m_2.	IOTF	5 infrared cameras and 2 force plates	Overground; self-selected and fast (+30%); barefoot
Shultz et al. 2009 [36][36]	**Kinematics:** Hip (sagittal and frontal planes), knee (sagittal and frontal planes) and ankle (all 3 planes) angular displacement (deg) in all 3 planes **Kinetics:** Peak moments (Nm) at the hip, knee and ankle in all three planes	20 (0/10/10/0), NR/NR NW: 10.40 ± 1.58 yr., 16.85 ± 1.31 kg/m_2; OW: 10.4 ± 1.6 yr., 30.47 ± 5.54 kg/m_2	CDCP	5 infrared cameras and 2 force plates	Overground; self-selected; barefoot
Strutzenberger et al. 2017 [29]	**Spatio-temporals:** cadence (strides/min), relative stance and swing phase (%), step length (m) and step width (m) **Kinematics:** hip, knee and ankle angles (º) for the sagittal and frontal planes, at initial contact and the whole gait cycle **Kinetics:** Maximum and minimum moments and 1_{st} peak moment of hip, knee and ankle moments (Nm/kg) in sagittal and frontal planes, as well as power of hip, knee and ankle (W/kg) in sagittal plane, normalized for body weight	22 (0/11/0/11), 12/10 NW: 14.30 ± 1.86 yr., 19.00 ± 1.70 kg/m_2; OB: 14.50 ± 1.41 yr., 31.10 ± 3.50 kg/m_2	BMI Z-scores	8 infrared cameras and 2 force plates	Overground; Controlled (1.08–1.14 m/s); barefoot

UW: under-weight; NW: normal-weight; OW: overweight; OB: obese; BMI: body mass index; CDCP: Centers for Disease Control and Prevention growth charts for age and sex; IOTF: Extended international BMI cut-offs for thinness, overweigth and obesity; BF: Body fat percentiles; NR: not reported; deg: degrees; N: newton; W: watt; COM: centre of mass; MN: meganewton; kN: kilonewton; mV: micro volt; EMG: electromyography.

SECTION 2.

Cross-sectional studies: role of physical fitness in the biomechanics of childhood obesity

SECTION 2

Study 3

Role of physical fitness and fundamental movements in the body posture of children with overweight/obesity

Submitted in Gait & Posture

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INTRODUCTION

Body posture refers to the positioning of body segments in relation to each other and, far from being unalterable, many external factors are known to have an impact on it throughout a lifetime [1]. Particularly childhood represents a critical period for body Wosture conformation, due to growth but also since children are exposed to physical and environmental changes that may impact body posture [1–3]. Worrying insights from current epidemiological evidence reveal that 68% of the young population could be experiencing at least one postural alteration [3]. These postural alterations may result in muscular overactivation and mechanical stress on the musculoskeletal system, which could lead to the onset of pain and more severe musculoskeletal disorders [4, 5].

Childhood obesity is considered to have a negative impact on body posture through multiple interconnected mechanisms. Proof of this is the higher prevalence of postural alterations (e.g., thoracic hyperkyphosis, lumbar hyperlordosis or lower limb valgus) in children with overweight/obesity (OW/OB) compared to children with normal-weight [6–8]. Behind this higher prevalence of postural alterations, some authors have suggested a re-positioning of musculoskeletal structures so that these are more capable of supporting and carrying their heavier body mass [8], but this may not be the only mechanism. The presence of OW/OB during childhood is associated with lower physical fitness performance [9], which could be an important factor likely to influence children's body posture. Nevertheless, to date there are no studies demonstrating a relationship between health-related physical fitness components (i.e., cardiorespiratory, muscular and speed-agility fitness) and body posture in the childhood population.

Movement competence (e.g., fundamental movements quality) has a suggested impact on body posture, due to repetitive non-optimal movement patterns, for example, dynamic malalignments or inadequate joint range of motion, that can cause imbalances in the musculoskeletal system [10]. However, limited evidence exists on the direct association between fundamental movements quality and body posture during childhood. We are only aware of one study, which did not find a relationship between fundamental movements quality (i.e., total Functional Movement Screen score) and body posture (i.e., two-dimensional photogrammetry) in school children aged 8-11 years [11]. As with body posture, fundamental movements quality has been shown to be worse in children with OW/OB than in normal-weight [12]. Thus, in children with OW/OB a relationship between fundamental movements quality and body posture may well be found, playing a role in the future development of weight management interventions.

The objectives of this study were: 1) to examine the associations of fatness (i.e., BMI), physical fitness components and fundamental movements quality with body posture in children with OW/OB, and 2) to determine which of these are the best predictors of body posture.

MATERIAL AND METHODS

Study Design and Participants

This study used cross sectional baseline data from the MUBI project (http://profith.ugr.es/pages/investigacion/recursos/mubi?lang=en), which has been approved by the Ethics Committee on Human Research at the University of Granada (Reference: 279/CEIH/2017). Inclusion/exclusion criteria to participate in the MUBI project can be found elsewhere [13]. A total of 62 children (58% girls, 10.86 ± 1.25 years old and 26.09 ± 3.77 kg/m^2) with available data were included for this study. Parents or legal guardians provided written informed consent for their children's participation.

Physical Fitness Components

Before carrying out any physical assessment, height (cm) and weight (kg) (SECA Instruments, Germany) were determined by the same trained evaluators, and BMI (kg/m^2) was calculated. Participants performed a lab-based one-repetition maximum (1RM) of the arm press (kg) and leg press (kg) exercises using pneumatic resistance machines (Keiser Sports Health, Fresno, CA, USA), and following a protocol adapted to children [14]. We used the field-based ALPHA (Assessing Levels of Physical fitness and Health in Adolescents) health-related physical fitness test battery, which has demonstrated to be valid, reliable, and feasible for assessing physical fitness components in young individuals [15]. In brief, upper and lower body muscular strength were assessed using the maximum handgrip strength test (kg) and the standing long jump test (cm), respectively. Cardiorespiratory fitness was assessed by estimating the VO_2max (ml/kg/min) during a 20 m shuttle run test [16]. Speed-agility was evaluated by timing (s) the 4×10 m shuttle run test [15]. Absolute measures of muscular strength (i.e., arms and legs press 1RM, and handgrip strength) were expressed taking into account participants' body weight since previous studies have demonstrated a potential effect of body weight in this population [17]. Speed-agility measures were inverted by multiplying test completion time by −1, so that higher values indicate a better fitness level.

Fundamental Movements

Fundamental movements was evaluated using the Functional Movement Screen™ (FMS), which has demonstrated a good inter- and intrarater reliability [18]. The full FMS protocol includes seven tasks, but we included a four-task adaptation (i.e., deep squat, hurdle step, shoulder mobility, and active straight leg raise) following a previous study conducted in children with OW/OB [12]. According to the FMS scoring criteria, each task received a score from 1 to 3 points and in the case of bilateral tasks (i.e., hurdle step, shoulder mobility, and active straight leg raise) performed with both the left and right members, the lowest score was selected. Scores of individual tasks were summed to obtain a total FMS score ranging from 4 to 12 points, where higher values indicated a better fundamental movements quality. Two certified evaluators with extensive experience scored all videos separately, and any discrepancy was reviewed in a consensus meeting until reaching an agreement of the final score.

Body Posture

Body posture was assessed using the two-dimensional photogrammetry approach, which has demonstrated to be reliable evaluating human posture and valid against other gold-standard methods such as X-Ray analysis [19]. A Basler acA2000-50gc (Germany) camera with a fixed focal lens Fujinon HF12.5SA-1 (Japan) was fixed on a tripod with 115 cm of height and at 3.1 m away from the center of the square platform where children were evaluated. Participants were instructed to be in underwear conditions, wearing bathing clothes or sleeveless tight-fitting sports clothes. Six retro-reflective markers were placed by the same trained examiners on several anatomical locations previously used in the literature: [20, 21] 7th cervical vertebrae (C7), 12th thoracic vertebrae (T12), right anterior superior iliac spine (ASIS), right trochanter, right lateral condyle, and right lateral malleolus. Children were asked to stand comfortably looking straight ahead while two photographs were taken, the first from an anterior perspective and the second one from the right side.

Images were calibrated based on an image with a vertical plumb and a posture grid placed on the wall. The image analysis program ImageJ (National Institutes of Health, Bethesda, MD) was used to digitize the *x* and *y* coordinates of each retro-reflective marker, and this process was undertaken by the same experienced researcher [22]. Six angles and one distance previously were calculated, and all them have demonstrated a good-to-excellent inter- and intra-rater reliability [20, 23–25]: craniocervical angle, thoracic flexion angle, trunk angle, tragus-to-plumb distance, lumbar angle, lower limb sagittal angle and lower limb frontal angle. **Table 1** shows how body posture indicators were defined, as well as the interpretation of their values, whereas **Figure 1** provides a graphical representation of their creation.

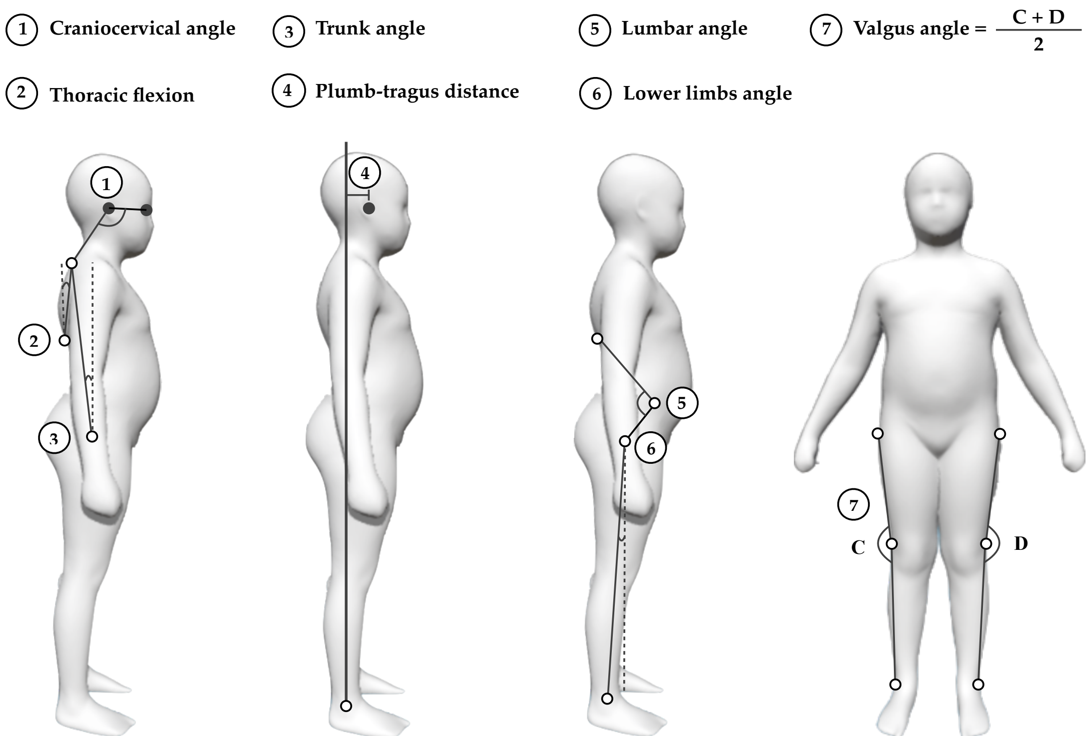

Figure 1. Graphical representation of the body posture indicators

Table 1. Definition and interpretation of the body posture indicators.

Name	Definition	Interpretation
Sagittal plane		
Cervicothoracic angle	The angle between the line of tragus with C7, and the line of C7 with T12.	High values (close to 180º) indicate a cervical retracted position, while low values indicate a cervical protracted position.
Thoracic flexion	The angle between the line connecting C7 and T12 with respect to the vertical line from T12.	Positive values indicate a thoracic flexed position, while negative values indicate a thoracic extended position.
Trunk angle	The angle between the line connecting C7 and trochanter with respect to the vertical line from trochanter.	A decrease in trunk angle indicates a posterior tilt of the trunk with respect to the pelvis.
Lumbar angle	The angle between the line of T12 with ASIS, and the line of ASIS with trochanter.	High values indicate a pelvis posterior tilt position, while low values indicate a pelvis anterior tilt position.
Lower limb sagittal alignment	The angle between the line connecting lateral malleolus and greater trochanter with respect to the vertical line from greater trochanter.	Positive values indicate a pelvis forward position with respect to the feet, while high negative values indicate a backward pelvis position.
Plumb-tragus distance	Distance of the ear tragus with respect to the vertical plumb	Zero indicate an optimal alignment of the head in the sagittal plane, positive values indicate an anterior shift of the head, and negative values indicate a posterior shift of the head.
Frontal plane, anterior view		
Lower limb frontal alignment	The angle between the line of trochanter with lateral condyle, and the line of lateral condyle with ASIS lateral malleolus.	Values close to 180º indicate an optimal alignment, higher values indicate a lower limb varus position and lower values indicate a lower limb valgus position.

Statistical Analysis

Descriptive characteristics of participants are presented as means and standard deviations (SD). Kolmogorov-Smirnov test and visual inspection of histograms were performed, and all variables demonstrated normal distributions.

Stepwise regression analysis was used to check which potential confounders (i.e., age, gender, maturity status, and parental education level) were the best predictors (i.e., explain the largest proportion of the variance) of body posture. To explore the associations of fatness, fitness and fundamental movements with body posture, linear regression analysis was performed adjusted by those confounders previously identified through the stepwise regression analysis. The variable presenting the highest adjusted R-squared value was considered the main predictor of body posture. All analyses were performed using SPSS software (version 24.0, IBM Corporation), and the level of significance was set at $p < 0.050$.

RESULTS

Sample characteristics, also separating boys and girls, are presented in **Table 2**. Linear regression analyses of fatness, physical fitness

Table 2. Descriptive characteristics of the total study sample and divided by gender.

	All sample (N = 62) Mean ± SD	Boys (N = 26) Mean ± SD	Girls (N = 36) Mean ± SD
Age (years)	10.86 ± 1.25	11.13 ± 1.26	10.68 ± 1.22
Weight (kg)	58.2 ± 13.24	60.98 ± 10.99	56.30 ± 14.42
Height (cm)	148.45 ± 9.08	149.82 ± 8.07	147.51 ± 9.71
Body mass index (kg/m2)	26.09 ± 3.77	27.00 ± 3.20	25.47 ± 4.04
Physical fitness			
1RM arms/weight (kg/kg)	0.42 ± 0.12	0.42 ± 0.12	0.43 ± 0.12
1RM legs/weight (kg/kg)	2.56 ± 0.50	2.54 ± 0.48	2.57 ± 0.52
Handgrip/weight (kg/kg)	0.33 ± 0.07	0.32 ± 0.07	0.34 ± 0.07
Standing long jump (cm)	114.41 ± 20.38	117.58 ± 22.34	112.19 ± 18.88
20m shuttle run (ml/kg/min) [a]	40.55 ± 3.12	40.57 ± 2.82	40.53 ± 3.35
4×10 m shuttle run (s) [b]	-14.80 ± 1.52	-14.49 ± 1.57	-15.02 ± 1.47
*Functional movement quality**			
Total FMS score (4-16)	7.02 ± 1.80	6.23 ± 1.51	7.55 ± 1.80
Body posture			
Craniocervical angle (º)	142.07 ± 6.39	141.78 ± 6.19	142.26 ± 6.6
Thoracic flexion angle (º)	5.15 ± 3.91	6.02 ± 3.09	4.56 ± 4.31
Trunk angle (º)	171.04 ± 3.33	171.67 ± 3.62	170.68 ± 3.09
Plumb-tragus distance (cm)	5.70 ± 2.72	5.88 ± 2.22	5.57 ± 3.03
Lumbar angle (º)	82.21 ± 10.22	82.95 ± 8.41	81.70 ± 11.38
Lower limb sagittal alignment (º)	3.85 ± 2.68	4.48 ± 2.76	3.42 ± 2.57
Lower limb frontal alignment (º)	176.00 ± 1.94	176.34 ± 1.75	175.77 ± 2.06

Notes: SD = standard deviation; FMS = Functional Movement Screen; 1RM = one repetition maximum.
* N was 55 (22 boys and 33 girls) for functional movement quality.
[a] Cardiorespiratory fitness was estimated from the 20 m shuttle run test by the formula described by Leger et al. (Leger, et al., 1988).
[b] Values of the 4x10-m shuttle run test were multiplied by -1 before analyses so that higher values indicate better performance.

components and fundamental movements quality with upper body and lower limb posture are presented in **Table 3** and **Table 4**, respectively. Analyzing upper body posture, BMI was positively associated with craniocervical and thoracic flexion angle (ß = 0.323 and 0.315; both $p < 0.05$). 1RM arms and handgrip strength were negatively associated with thoracic flexion angle (ß = -0.388 and -0.243; all $p < 0.05$) and cardiorespiratory fitness was negatively associated with craniocervical angle (ß = -0.31; p = 0.014). Total FMS score was negatively associated with thoracic flexion angle (ß = -0.373; p = 0.002). Regarding lower limb posture, BMI was negatively associated with lumbar and lower limb frontal alignment (ß = -0.502 and -0.280; both $p < 0.05$). 1RM legs and handgrip strength were positively associated with lower limb frontal alignment (ß = 0.253 and 0.261; both $p < 0.05$), while standing long jump was negatively associated with lower limb sagittal alignment (ß = -0.318; p = 0.017). Cardiorespiratory fitness was positively associated with lumbar angle and lower limb frontal alignment (ß = 0.299 and 0.305 both $p < 0.05$), as well as negatively associated with lower limb sagittal alignment (ß = -0.362; p = 0.017). Speed-agility was negatively associated with lower limb sagittal alignment (ß = -0.325; p = 0.012).

In upper body posture, BMI was the strongest predictor of craniocervical angle (R^2 = 0.090; p = 0.010) and total FMS score of thoracic

Table 3. Linear regression analyses of fatness, physical fitness components and functional movement with upper body posture.

		Craniocervical angle (deg)			Thoracic flexion angle (deg)			Trunk angle (deg)			Tagus to plumb distance (cm)		
	N	ß	R^2	*P*	ß	R^2	*P*	ß	R^2	*P*	ß	R^2	*P*
Fatness	62												
Body mass index (kg/m^2)		0.323	0.090	**0.010**	0.315	0.204	**0.012**	0.018	0.16	0.889	-0.169	0.134	0.188
Physical fitness	62												
1RM arms/weight (kg/kg)		-0.184	0.018	0.152	-0.388	0.252	**0.001**	-0.213	-0.029	0.097	-0.193	0.145	0.119
1RM legs/weight (kg/kg)		0.020	-0.016	0.875	-0.044	0.146	0.718	0.063	0.012	0.622	-0.055	0.112	0.647
Handgrip/weight (kg/kg)		-0.136	0.002	0.288	-0.243	0.176	**0.040**	0.056	0.013	0.665	0.117	0.123	0.332
Standing long jump (cm)		0.070	-0.011	0.587	0.004	0.116	0.977	0.199	0.024	0.119	0.149	0.128	0.247
20m shuttle run (ml/kg/min) [a]		-0.307	0.080	**0.014**	-0.107	0.124	0.464	0.020	0.016	0.877	0.252	0.152	0.083
4×10 m shuttle run (s) [b]		-0.106	-0.005	0.408	-0.041	0.117	0.746	0.093	0.008	0.469	0.073	0.114	0.561
Functional movement	55												
Total FMS score (4-16)		-0.34	-0.018	0.806	-0.373	0.284	**0.002**	-0.120	0.004	0.382	0.043	0.156	0.732

Notes: β = standardized beta coefficients; R^2 = adjusted R-squared. Significant associations (p < 0.05) are highlighted in bold.
Potential confounders (i.e., age, gender, maturational status and parental educational level) were included in all models through a stepwise regression analysis, and only for thoracic and tagus to plumb, age was entered into the model.
[a] Cardiorespiratory fitness was estimated from the 20 m shuttle run test by the formula described by Leger et al. (Leger, et al., 1988).
[b] Values of the 4x10-m shuttle run test were multiplied by -1 before analyses so that higher values indicate better performance.

Table 4. Linear regression analyses of fatness, physical fitness components and functional movement with lower limb posture.

		Lumbar angle (deg)			Lower limb angle (deg)			Lower limb frontal angle (deg)		
	N	ß	R^2	*P*	ß	R^2	*P*	ß	R^2	*P*
Fatness	62									
Body mass index (kg/m^2)		-0.502	0.239	**<0.001**	0.164	0.054	0.228	-0.280	0.063	**0.026**
Physical fitness	62									
1RM arms/weight (kg/kg)		0.246	0.045	0.053	-0.165	0.056	0.204	0.229	0.037	0.073
1RM legs/weight (kg/kg)		0.217	0.031	0.088	-0.015	0.030	0.907	0.253	0.049	**0.045**
Handgrip/weight (kg/kg)		0.247	0.046	0.051	-0.104	0.041	0.414	0.261	0.053	**0.039**
Standing long jump (cm)		0.094	-0.007	0.462	-0.318	0.121	**0.017**	0.164	0.011	0.199
20m shuttle run (ml/kg/min) [a]		0.299	0.075	**0.017**	-0.362	0.120	**0.017**	0.305	0.078	**0.015**
4×10 m shuttle run (s) [b]		0.157	0.009	0.219	-0.325	0.130	**0.012**	0.220	0.033	0.083
Functional movement	55									
Total FMS score (4-16)		0.276	0.059	**0.041**	-0.222	0.046	0.127	0.263	0.052	0.052

Notes: β = standardized beta coefficients; R^2 = adjusted R-squared. Significant associations (p < 0.05) are highlighted in bold.
Potential confounders (i.e., age, gender, maturational status and parental educational level) were included in all models through a stepwise regression analysis, and only for lower limb angle, age and gender were entered into the model.
[a] Cardiorespiratory fitness was estimated from the 20 m shuttle run test by the formula described by Leger et al. (Leger, et al., 1988).
[b] Values of the 4x10-m shuttle run test were multiplied by -1 before analyses so that higher values indicate better performance.
Potential confounders (i.e., age, gender, maturational status and parental educational level) were included through a stepwise regression analysis.

flexion angle ($R^2 = 0.284$; $p = 0.002$). In lower limb posture, BMI was the strongest predictor of lumbar angle ($R^2 = 0.239$; $p < 0.001$), speed-agility of lower limb sagittal alignment ($R^2 = 0.130$; $p = 0.012$) and cardiorespiratory fitness of lower limb frontal alignment ($R^2 = 0.078$; $p = 0.015$). **Figure 2** presents a visual overview of the main findings of this study.

DISCUSSION

This study found in a 8-12y-old sample of children with OW/OB that BMI was associated with head protraction, thoracic hyperkyphosis, lumbar hyperlordosis and lower limb valgus. Physical fitness components and fundamental movements were overall associated with a more aligned posture of the head, lumbar and thoracic spines, and lower limb. BMI was the best predictor of head and lumbar spine posture, cardiorespiratory fitness of lower limb posture in frontal plane, speed-agility of lower limb posture in sagittal plane and fundamental movements of thoracic spine.

Our results in children with OW/OB confirm previous studies by suggesting that the higher the BMI is in youth, the more accentuated the thoracic kyphosis, lumbar hyperlordosis and lower limb valgus position are [3, 8]. Adolescents presenting thoracic hyperkyphosis and lumbar hyperlordosis posture in sitting and

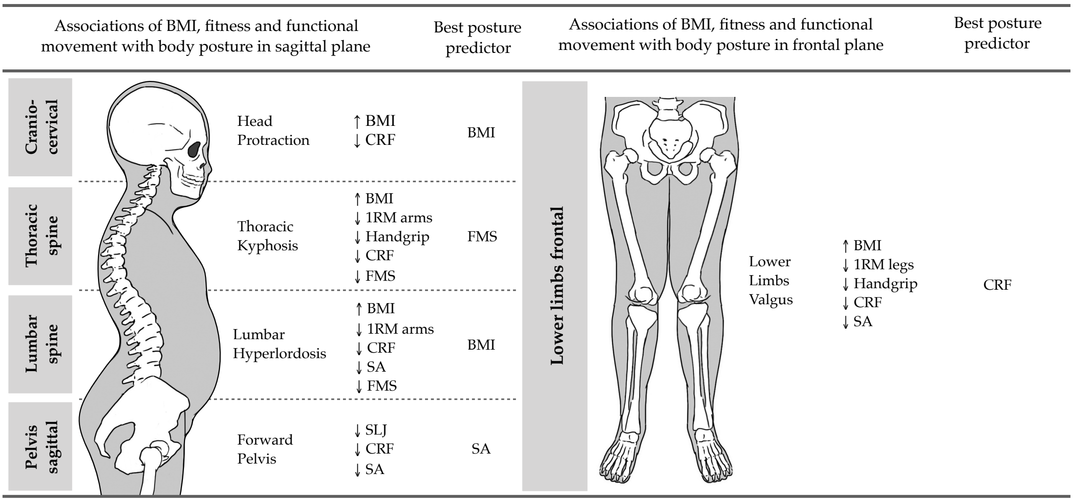

Figure 2. Graphical representation of the main findings of this study.
↑: Positive association; ↓: Negative association; BMI: body mass index; CRF: cardiorespiratory fitness; 1RM: one repetition maximum; FMS: Functional Movement Screen; SA: Speed-agility; SLJ: Standing long jump

standing situations have demonstrated to be at increased risk for having low back pain compared to children with a neutral posture [4, 26]. Similarly, large cohort studies have demonstrated that lower limb malalignments in adults are associated with the progression of knee osteoarthritis [27]. Based on that, the presence of OW/OB could lead children to an especially worrying situation to develop musculoskeletal disorders via postural alterations of their musculoskeletal structures.

Findings from the present study show for the first time that health-related physical fitness components are associated with a better global body posture in children with OW/OB. A better performance in 1RM arms press was associated with a more aligned posture of thoracic and lumbar spines. Upper body press activities require adequate scapular arthrokinematics to facilitate glenohumeral range of motion and force generation [28]. A thoracic hyperkyphosis linked to a lumbar hyperlordosis posture can result in excessive protraction of the scapula together with internal rotation of the glenohumeral joint, leading to the loss of normal arthrokinematics and detriment of functional capacity [29]. Higher performance in 1RM leg press was related to a more aligned lower limb posture in the frontal plane. Analyzing the biomechanics of lower limb press activities, minimal dynamic valgus/varus motion should occur in order to maximize force transference between ankle, knee and hip joints [30]. In addition to reduced performance, dynamic valgus observed in children with high BMI may increase mechanical stress in musculoskeletal structures and predispose them to develop overuse pain and injuries [30]. On the other hand, handgrip strength is not a multi-joint strength activity, as 1RM arms and legs press are, and it is difficult to find a direct biomechanical explanation linked to a better body posture. However, handgrip strength is considered a good indicator of overall muscular strength capacity in childhood [15], and it seems to be directly related to a better posture of children's thoracic spine and lower limb in the frontal plane.

Children who showed better performance in cardiorespiratory fitness and speed-agility also demonstrated a significantly better lumbar spine sagittal alignment, as well as a better lower limb sagittal and frontal alignment. When running and sprinting, pelvic motion is minimized in a relatively neutral sagittal position to conserve energy and maintain efficiency in lower limb motion [31]. Similarly, dynamic lower limb alignment in sagittal and frontal planes is necessary to maintain adequate running mechanics, avoiding force leaks and ensuring force transference[31, 32]. It is plausible that those children more used to running and sprinting have naturally developed a better lower limb posture to be mechanically more efficient, or rather, children presenting a correct body posture are more prepared to perform these tasks. Furthermore, lower limb malalignments have been associated with the onset of musculoskeletal disorders in children with OW/OB, which could directly hamper their physical fitness development [33]. In the case of craniocervical positioning, only cardiorespiratory fitness was associated with a more aligned posture in the sagittal plane. In running activities, minimal craniocervical motion is desirable leading to a high demand on deep cervical stabilizers to allow adequate head positioning [31]. Possibly, this intrinsic musculature responsible of maintaining a correct head posture is more activated in children with better performance in endurance running, rather than in explosive actions.

In the present study, those children having a higher total FMS score also demonstrated a more aligned posture of thoracic and lumbar spines in the sagittal plane. It is important to note that, to get the maximal FMS score, participants need to maintain an upright position of upper torso when performing a deep squat, hurdle step and shoulder mobility tests [34, 35]. Based on these results, it seems that children with a thoracic hyperkyphosis and lumbar hyperlordosis posture also present dynamic malalignments when performing fundamental movements tasks. These dynamic malalignments may occur as a result of poor neuromuscular control and stability of the lumbo-pelvis complex and lower limb, which would be present in both static and dynamic situations [36]. Our results contradict those from Mitchell et al. [11], who did not find associations between static posture and fundamental movements quality. It should be noted that, whereas the present study only includes children with OW/OB, Mitchell et al. [11] had only 9% of participants with OW/OB within their sample. Possibly the relationship between fundamental movements and static posture is only evident in children with a clear detriment of these two conditions, as it is the case of children with OW/OB.

Smith et al. [8] discovered that BMI trajectories in children followed-up from 3 until 14 years old was determining for the development of spinal posture. From our study we can add that BMI is more determining for craniocervical and lumbar spine sagittal plane alignment than other factors affecting body posture, such as physical fitness components and fundamental movements quality. Cardiorespiratory fitness and speed-agility were the strongest predictors for presenting an aligned lower limb posture in children with OW/OB. It suggests that children's capacity to run long distances and accelerate/decelerate in short distances could be even more relevant for the development of an adequate lower limb posture, than their BMI, muscular strength and fundamental movements quality. Fundamental movements quality was the strongest predictor of an adequate thoracic spine alignment in our sample. Based on this, those children able to both maintain an up-right thoracic spine while performing functional tasks and develop an optimal shoulder range of motion are also those with greater chance to present a more aligned thoracic spine posture.

To the best of our knowledge, the study by Schwanke et al. [37] is the only investigation of the effects of exercise on body posture in children with OW/OB. Their four-month exercise program, based on strengthening and stretching exercises, improved thoracic spine alignment of schoolchildren, but no head, lumbar spine and lower limb posture [37]. Our results can guide future research efforts by suggesting that reduction of BMI and improvement of physical fitness components (i.e., cardiorespiratory fitness and muscle strength) together with fundamental movements quality would be worthwhile targets to enhance a better body posture in children with OW/OB. Internationally accepted physical activity guidelines for children (http://www.health.gov/paguidelines/) promote to develop aerobic and resistance training, and the last position statement on strength training in youth proposes integrative programs enhancing muscular strength together with movement competence [38]. Future exercise-based intervention studies including all these components are necessary to corroborate whether it can induce positive effects on global body posture of children with OW/OB.

This study has several limitations that should be acknowledged. We did not include the gold standard method for assessing body posture (i.e., X-Ray analysis) and cardiorespiratory fitness (i.e., gas analyzer), however, two-dimensional photogrammetry and 20m shuttle run test are considered valid and reliable alternatives [15, 19]. Also, the cross-sectional design of this study does not allow us to establish causal interpretations of our findings. Finally, our sample is limited in size and only composed of children with OW/OB from a specific region, and thus results may be different in other geographical regions.

Conclusion

In conclusion, BMI was the strongest predictor of cervical and lumbar spine posture in the sagittal plane, cardiorespiratory fitness and speed-agility of lower limb posture in frontal and sagittal planes respectively, and fundamental movements quality of thoracic spine posture in the sagittal plane. In view of this, although BMI is a determining factor for body posture detriments, physical fitness and fundamental movements quality seem to be positively affecting musculoskeletal positioning in children with OW/OB.

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SECTION 2

Study 4

Fatness and fitness in relation to fundamental movements quality in overweight and obese children

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INTRODUCTION

According to the World Health Organization, one-third of European children present overweight or obesity, which has become a major health problem. In addition to an increased risk for multiple metabolic and cardiovascular diseases [1, 2], the excess of weight in childhood has been associated with several movement pattern alterations as well as poor movement competence levels [3, 4]. These movement alterations generally experienced by overweight/obese children are suggested to hamper their daily physical activity and physical functioning, resulting in a decrease of their health-related quality of life [5]. Furthermore, movement pattern alterations may predispose them to orthopaedic complications and musculoskeletal pain, or vice versa [6, 7].

In the study of movement characteristics in children, different terminology such as 'movement competence', 'motor competence', 'fundamental movement skills', 'motor proficiency' or 'motor ability' has been used inconsistently across literature. All these terms have in common the study of proficiency in 'fundamental motor skills', defined as the global movement patterns (i.e. locomotion, object control skills, or stability tasks) necessary for an optimal motor development [8–10]. In the present study, the term 'movement competence' is used consistently to encompass the study of fundamental motor skills as defined above. On the other hand, the term 'functional movement' has also been used to study movement competence, but rather emphasises the qualitative characteristics of analytical movement patterns (e.g., squatting or stepping in motion) [11]. Therefore, in a continuum of motor development the adequate execution of analytic movement patterns (i.e., functional movement) is necessary to optimally perform more complex and global movement patterns (i.e., fundamental motor skills), which in turn, are needed to perform different physical activities and sports [12].

Evidence suggests an inverse relationship between children's weight status and movement competence [3, 13]. Although to a lesser extent, functional movement has also been studied in relation to weight status in children aged 8-11 years old. Duncan et al. [4, 14] found that overweight/obese children demonstrated significantly poorer functional movement compared to their normal-weight counterparts. However, the study carried out by Ulrike et al. [15] did not find significant differences in functional movement between normal-weight and overweight/obese children. Accordingly, more research is needed to corroborate or contrast these inconsistent results as well as to further scrutinise the associations between additional fatness measures, such as fat mass percentage or fat mass index, with functional movement in this particular population.

Fitness levels have shown to be strongly and positively associated with movement competence in children, suggesting a reciprocal relationship between both variables [10]. Likewise, the level of physical activity seems to be positively related to functional movement in children, strengthening the assumption that functional movement impairment could lead to more sedentary time, or vice versa [4]. Nevertheless, to the best of our knowledge, there are no studies to date investigating how different components of overweight/obese children's fitness (e.g., cardiorespiratory fitness, muscular strength, and speed-agility) are related to their functional movement quality.

Both fatness and fitness are two well-recognized health markers in childhood, and evidence suggests that an optimal level of fitness may attenuate the metabolic consequences associated with excessive fatness [16, 17]. However, there is an important need to gain a better understanding on how both health markers are associated with functional movement quality in overweight/obese children. Therefore, the aims of the present study were: 1) to examine the individual association of several indicators of fatness and the components of fitness with functional movement quality in overweight/obese children; and 2) to explore the independent and combined association of the degree of fatness (i.e. overweight vs. obesity) and the level of fitness (i.e. fit vs. unfit) with children's functional movement quality.

MATERIAL AND METHODS

Study design and participants

The participants of this study were part of the MUévete BIen (MUBI) project. The MUBI project, a sub-study from the ActiveBrains project [18], is a controlled trial designed to examine the effect of an exercise program on body posture and movement biomechanics in overweight and obese children. A total of 56 participants (33 girls, 8-12 years old) from the baseline data of the MUBI project were included in this particular cross-sectional study (**Figure 1**). The project has been approved by the Ethics Committee on Human Research at the University of Granada (Reference: 279/CEIH/2017). Parents or legal guardians were informed about the aims of the study and provided written informed consent for their children's participation.

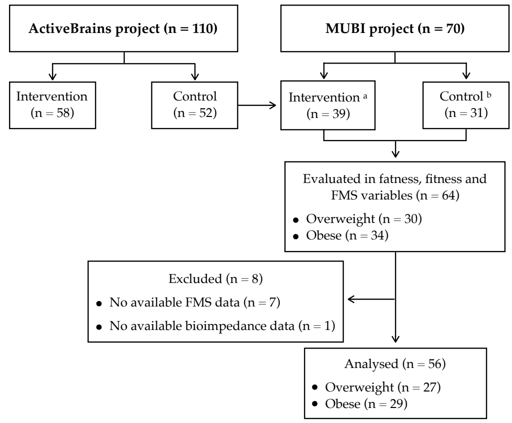

Figure 1. Flow diagram describing the study sample selection.

Notes: FMS = Functional movement screen.
a Intervention group of MUBI project come from the control group of ActiveBrains project.
b Control group of MUBI project was posteriorly recruited and is independently of ActiveBrains project.

Procedures and measurements

Data were collected from 4 to 8 p.m. during January and February 2017 at the Sport and Health Joint University Institute (iMUDS), belonging to the University of Granada. The assessment process was carried out in three different days. The first day, anthropometric and bioelectrical impedance data were collected in a quiet room by the same trained evaluators, and thereafter muscular strength assessment in a laboratory setting was performed. There were no instructions provided to the participants regarding nutrition and exercise before the test. The second day, fitness measures in field conditions were carried out, performed by the same evaluators. The third day, children were evaluated on four tests of the Functional Movement ScreenTM (FMS), performed by the same evaluators.

Fatness

Height (cm), weight (kg), and waist circumference (cm) (SECA Instruments, Germany) were determined. Body mass index (BMI, kg/m²) was calculated to classify the children as being overweight or obese according to the sex- and age-specific international BMI cut-offs for children [19].

Fat mass (kg) was estimated by bioelectrical impedance analysis (BC-418 MA, TANITA International Division, TANITA, UK) to calculate the body fat percentage (BF%) as follows: [fat mass (kg) / body weight (kg)] × 100. Participants' fat mass index (kg/m²) was also calculated by dividing their absolute fat mass (kg) by their squared height (m).

Fitness

In a laboratory setting, the upper and lower-limbs muscular strength were assessed using pneumatic resistance machines (Keiser Sports Health, Fresno, CA, USA). According to previous studies' protocols used in the paediatric population [20, 21], each participant's one-repetition maximum (1RM) strength in the bench press (kg) and leg press (kg) tests was determined in order to report the normalised values by dividing absolute test results by body weight.

In regards to field condition, cardiorespiratory fitness, muscular strength, and speed-agility were assessed according to the ALPHA (Assessing Levels of Fitness and Health in Adolescents) field fitness test battery [22]. Briefly, the participants' maximum oxygen intake or VO2max (ml/kg/min) was estimated based on their performance on the 20 m shuttle run test [23]. Fit and unfit children were categorised based on their VO2max from the 20 m shuttle run test, according to recently defined cut-off points [24]. The muscular strength in the upper and lower limbs was assessed by the handgrip strength test (kg) and the standing long jump test (cm), respectively [22]. To avoid the potential biasing effect of participants´ body size on the estimation of handgrip strength, the absolute measure was divided by body weight as previous literature [25, 26]. Speed-agility was assessed by the 4×10 m shuttle run test (seconds) [22]. As greater times in the latter indicate poorer performances, the recorded time in seconds was inverted by multiplying the test results by −1. It is known that the ALPHA fitness test battery is feasible, reliable, valid, and related to health outcomes later in life [22, 27, 28].

Functional movement

The Functional Movement Screen ™ (FMS) is a screening system aimed to assess the quality of fundamental/analytical movement patterns of an individual in a dynamic and functional way [11]. This protocol, with available normative data, has been widely used in children and adolescents [29]. A recent systematic review and meta-analysis revealed good inter- and intra-rater reliability of the FMS [30]. Although the full FMS protocol includes seven tests, a four tests selected adaptation (i.e., deep squat, hurdle step, shoulder mobility and active straight leg raise) was used for the present study as previous literature [31]. Among the four tests selected, deep squat, shoulder mobility and active straight leg raise have demonstrated an acceptable evidence for intra-rater reliability, whereas only hurdle step has demonstrated conflicting intra-rater reliability [32]. The push-up, rotatory stability, and in-line lunge tests were discarded given the difficulty of execution typically experienced by obese and overweight children [4]. Comprehensive instructions for each test were presented by explanatory videos to provide a visual demonstration and to avoid different instructions to all participants [11]. During the exercises, the children were videotaped from both anterior and lateral directions. Two FMS certified evaluators, with extensive experience in functional movement assessments, reviewed all videos and separately scored each of the FMS exercises according to the scoring criteria [11, 33]. Any discrepancy between both evaluators was reviewed in order to reach a final agreement on the score. Inter-rater reliability for the initial agreement between both evaluators was good for deep squat, shoulder mobility and active straight leg raise (κ = 0.64, 0.76 and 0.79 respectively), and moderate for hurdle step (κ = 0.57). Each of the four selected tests was scored from 1 to 3 points, with the lowest score being selected in bilateral tasks. Subsequently, a total FMS score (ranging from 4 to 12) was calculated by summing the scores of each test, with a higher score indicating a better functional movement quality [11, 33].

Covariates

The participants' age, sex, and their parental educational level were questioned and used as potential confounders in the statistical analyses, since have demonstrated to influence in fatness, fitness, and functional movement quality variables [29, 34]. Maturational stage has also demonstrated an effect on functional movement quality performance [35] but its inclusion resulted in multicollinearity with chronological age in the models. Therefore, we performed sensitivity analyses which showed that chronological age was more determinant than PHV (data not shown), and thus, we included age as confounder.

Parental educational level was assessed by a self-report questionnaire completed by the parents. The responses on education were reported as none, elementary school, secondary school, high school, and university level. We combined the responses of both parents as: (1) none of them had a university degree; (2) one of them had a university degree; (3) both of them had a university degree [36].

Statistical analysis

The characteristics of the study sample are shown as means ± standard deviation or percentages. Prior to all analyses, the main outcomes and residuals were checked for normal distribution through histograms and boxplots. The sex differences were assessed by independent samples T-test and chi-squared tests for continuous and categorical variables, respectively.

To evaluate the relationship of fatness indicators and fitness components with individual functional movement scores and the total FMS score, Spearman´s and Pearson´s correlations were conducted respectively. To further explore the individual associations of fatness indicators and fitness components with the total FMS score, two separate linear regression models were used. Model 1 was adjusted for basic confounders (i.e., age, sex, and parental education), whereas Model 2 was additionally adjusted for BMI when fitness components were the main predictors and for VO2max when fatness indicators were the main predictors. Both additional confounders in Model 2 were selected after performing sensitivity regression analyses aimed to identified the most influenced factor, and also because they are the most commonly used measurements to determine the level of fatness and fitness in children.

A two-way analysis of covariance (ANCOVA) was performed to test differences in the total FMS scores between overweight/obese groups and cardiorespiratory fitness groups, adjusting for the basic confounders. All analyses were performed using the SPSS software (version 24.0, IBM Corporation), and the level of significance was set at p<0.050.

RESULTS

Table 1 shows the characteristics for the total sample and also split by sex. The girls had higher scores than the boys with respect to the active straight leg raise (p=0.001) and the total FMS score (p=0.001)

Table 1. Descriptive characteristics of the total study sample and by weight categories.

	All (N=56)		Overweight (N=27)		Obese (N=29)		p
	N	Mean ± SD	*N*	Mean ± SD	*N*	Mean ± SD	
Age (years)	56	10.9 ± 1.2	27	10.7 ± 1.0	29	10.9 ± 1.5	0.567
Weight (kg)	56	58.2 ± 13.2	27	49.5 ± 8.4	29	65.3 ± 11.9	**<0.001**
Height (cm)	56	148.5 ± 8.9	27	145.9 ± 9.4	29	150.6 ± 8.2	0.053
Gender							0.093
Female	23	41%	8	14%	15	27%	
Male	33	59%	19	34%	14	25%	
Parental education university level							0.133
Neither parent	38	67.9%	18	32%	20	36%	
One parent	12	21.4%	4	7%	8	14%	
Both parents	6	10.7%	5	9%	1	2%	
Fatness							
Body mass index (kg/m^2)	56	25.9 ± 3.7	27	23.1 ± 1.3	29	28.6 ± 3.1	**<0.001**
Waist circumference (cm)	56	88.8 ± 13.2	27	78.9 ± 8.4	29	94.9 ± 7.7	**<0.001**
Body fat percentage (%)	56	36.5 ± 7.2	27	33.4 ± 8.2	29	38.1 ± 5.5	**<0.001**
Fat mass index (kg/m^2) [a]	56	9.4 ± 2.7	27	7.5 ± 1.0	29	11.1 ± 2.6	**0.014**
Fitness							
1RM legs/weight (kg/kg)	56	2.6 ± 0.5	27	2.7 ± 0.5	29	2.5 ± 0.4	**0.044**
1RM arms/weight (kg/kg)	56	0.4 ± 0.1	27	0.5 ± 0.1	29	0.4 ± 0.1	0.078
20m shuttle run (ml/kg/min) [b]	56	40.5 ± 3.1	27	41.7 ± 2.2	29	39.5 ± 3.8	**0.011**
Handgrip/weight (kg/kg)	56	0.3 ± 0.1	27	0.4 ± 0.1	29	0.3 ± 0.1	**0.002**
Standing long jump (cm)	56	114.4 ± 20.4	27	119.1 ± 20.1	29	113.7 ± 19.9	0.315
4×10 m shuttle run (s) [c]	56	-14.6 ± 1.9	27	-14.0 ± 1.9	29	-15.1 ± 1.7	**0.032**
Functional Movement Screen (FMS) Scores							
Deep squat (1-3)							**<0.001**
Score 1	27	48%	6	11%	21	37%	
Score 2	27	48%	19	34%	8	14%	
Score 3	2	4%	2	4%	0	0%	
Hurdle step (1-3)							**0.037**
Score 1	18	32%	5	9%	13	23%	
Score 2	38	68%	22	39%	16	29%	
Score 3	0	0%	0	0%	0	0%	
Shoulder mobility (1-3)							**0.006**
Score 1	19	34%	4	7%	15	27%	
Score 2	19	34%	11	20%	8	14%	
Score 3	18	32%	12	21%	6	11%	
Active straight leg raise (1-3)							0.097
Score 1	10	18%	3	5%	7	13%	
Score 2	32	57%	15	27%	17	30%	
Score 3	14	25%	9	16%	5	9%	
Total FMS score (3-12)	56	7.3±1.8	27	8.2±1.4	29	6.4±1.7	**<0.001**

Notes: Values are presented as mean ± SD or percentages. Significant differences (p < 0.05) are highlighted in bold.
SD = standard deviation.
a Fat mass was obtained from bioelectrical impedance.
b Cardiorespiratory fitness (VO2max) was estimated from the 20 m shuttle run test by the formula described by Leger et al., 1988.
c Values of the 4x10-m shuttle run test were multiplied by -1 before analyses so that higher values indicate better performance.
For continuous variables, p value was obtained by an independent samples T-test (for normally distributed variables) or by a Mann-Whitney test (for non-normally distributed variables) in order to show whether the mean is the same/different for overweight compared to obese children. For categorical variables, p value was obtained by chi-square test. For categorical variables, p value was obtained by chi-square test

The partial correlations are presented in **Table 2**. All fatness indicators were negatively associated with the individual FMS scores (r_s: -0.27 to -0.64; all p<0.05), except for BMI and active straight leg raise (r=-0.23; P=0.093), as well as with the total FMS score (r: -0.45 to -0.58; all p<0.05).

Table 2. Correlations between fatness and fitness with the Functional Movement Screen (FMS) scores.

	DS		HS		SM		ASLR		Total FMS	
	r_s	p	r_s	p	r_s	p	r_s	p	r	p
Fatness										
Body mass index (kg/m^2)	-0.64	**<0.001**	-0.38	**0.004**	-0.36	**0.006**	-0.23	0.093	-0.53	**<0.001**
Waist Circumference (cm)	-0.63	**<0.001**	-0.37	**0.005**	-0.32	**0.018**	-0.33	**0.014**	-0.58	**<0.001**
Body fat percentage (%)	-0.54	**<0.001**	-0.44	**0.001**	-0.39	**0.004**	-0.27	**0.049**	-0.45	**0.001**
Fat mass index (kg/m^2) [a]	-0.63	**<0.001**	-0.47	**<0.001**	-0.42	**0.002**	-0.29	**0.037**	-0.54	**<0.001**
Fitness										
1RM legs/weight (kg/kg)	0.41	**0.002**	0.16	0.251	0.03	0.803	0.33	**0.013**	0.29	**0.031**
1RM arms/weight (kg/kg)	0.41	**0.002**	0.27	**0.048**	0.03	0.837	0.11	0.419	0.22	0.107
20m shuttle run (ml/kg/min) [b]	0.34	**0.011**	0.19	0.174	0.13	0.365	0.11	0.432	0.30	**0.024**
Handgrip/weight (kg/kg)	0.40	**0.003**	0.54	**<0.001**	0.29	**0.029**	0.18	0.197	0.44	**0.001**
Standing long jump (cm)	0.00	0.985	0.48	**<0.001**	0.34	**0.012**	0.10	0.489	0.30	**0.027**
4×10 m shuttle run (s) [c]	0.22	0.115	0.52	**<0.001**	0.37	**0.006**	0.24	0.074	0.44	**0.001**

Notes: DS = deep squat, HS = hurdle step, SM = shoulder mobility, ASLR = active straight leg raise, r_s = Spearman correlation coefficient, r = Pearson correlation coefficient. Significant associations (p < 0.05) are highlighted in bold.
[a] Fat mass was obtained from bioelectrical impedance.
[b] Cardiorespiratory fitness (VO2max) was estimated from the 20 m shuttle run test using the formula described by Leger, et al., 1988.
[c] Values of the 4x10-m shuttle run test were multiplied by -1 before analyses so that higher values indicate better performance.

All fitness components were positively related to at least one individual FMS score. Cardiorespiratory fitness was positively associated with deep squat (r_s=0.34; p=0.011). All muscular strength variables normalised to the participants' body weight (i.e., 1RM legs, 1RM arms, and handgrip strength test) were positively associated with deep squat (r_s: 0.40 to 0.41; all p<0.05). 1RM legs strength were positively associated with active straight leg raise (r_s=0.33; p=0.013), both 1RM arms and handgrip strength test were positively associated with hurdle step (r_s: 0.27 to 0.54: all p<0.05) and handgrip strength was additionally associated with shoulder mobility (r_s=0.29; p=0.029). Standing long jump was positively associated with hurdle step and shoulder mobility (r_s: 0.34 to 0.48: all p<0.05). Speed-agility was positively associated with hurdle step and shoulder mobility (r_s: 0.37 to 0.52: all p<0.05). Finally, better results in cardiorespiratory fitness, 1RM legs and handgrip strength, standing long jump, and speed-agility were associated with better total FMS scores (r: 0.29 to 0.44; all p<0.05).The linear regression analyses between fatness and fitness with the total FMS score are shown in **Table 3**. In Model 1 (a), all fatness outcomes showed a negative association with the total FMS score (β: -0.45 to -0.55;

Table 3. Linear regression analyses between fatness and fitness with total Functional Movement Screen (FMS) score.

	Total FMS score			
	Model 1		Model 2	
	β	p	β	p
(a) *Fatness*				
Body mass index (kg/m^2)	-0.55	**<0.001**	-0.35	**0.013**
Waist circumference (cm)	-0.45	**0.001**	-0.20	0.143
Body fat percentage (%)	-0.47	**<0.001**	-0.31	**0.008**
Fat mass index (kg/m^2) [a]	-0.47	**<0.001**	-0.39	**0.003**
(b) Fitness				
1RM legs/weight (kg/kg)	0.25	**0.049**	0.07	0.507
1RM arms/weight (kg/kg)	0.21	0.105	0.03	0.780
20m shuttle run (ml/kg/min) [b]	0.58	**<0.001**	0.33	**0.045**
Handgrip/weight (N/kg)	0.40	**0.001**	0.18	0.165
Standing long jump (cm)	0.39	**0.003**	0.25	**0.033**
4×10 m shuttle run (s) [c]	0.48	**<0.001**	0.31	**0.010**

Notes: β = standardised beta coefficients. Significant associations (p < 0.05) are highlighted in bold.
[a] Fat mass was obtained from bioelectrical impedance (Tanita).
[b] VO2max was estimated from the 20 m shuttle run test by the formula described by Leger et al., 1988
[c] Values of the 4x10-m shuttle run test were multiplied by -1 before analyses so that higher values indicate better performance.
Model 1 was adjusted for basic confounders (age, sex, and parental education). Model 2 was additionally adjusted for cardiorespiratory fitness (VO2max) and body mass index (BMI) for fatness and fitness variables, respectively.

all p<0.05), with BMI being the strongest predictor. In Model 2 (a), when additionally controlled for cardiorespiratory fitness, all fatness indicators remained significant in their association with the total FMS score (β: -0.31 to -0.39; all p<0.05), with the exception of waist circumference (β=-0.20, P≥0.05). Regarding fitness, in Model 1 (b), all fitness components were positively associated with the total FMS score (β: 0.25 to 0.58; all p<0.05) with the exception of 1RM arms (β=0.21; P≥0.05). In Model 2 (b), when additionally controlling for BMI, the association of cardiorespiratory fitness, standing long jump, and speed-agility with the total FMS score remained significant (β: 0.25 to 0.33; all p<0.05)The two-way ANCOVA analyses conducted to test differences in the total FMS score across BMI (i.e. overweight vs obese) and cardiorespiratory fitness (i.e., fit vs unfit) categories are presented in **Figure 2**. After adjusting for basic confounders, there was no interaction effect between both categories. However, significant differences in the total FMS score were found across BMI categories with overweight children outperforming their obese counterparts (8.2 vs. 6.5, p=0.007), whereas non-significant differences were observed between cardiorespiratory fitness categories. The difference between fit and unfit children appeared to be more pronounced in obese children (7.5 vs. 5.7) than in overweight children (8.3 vs. 7.8).

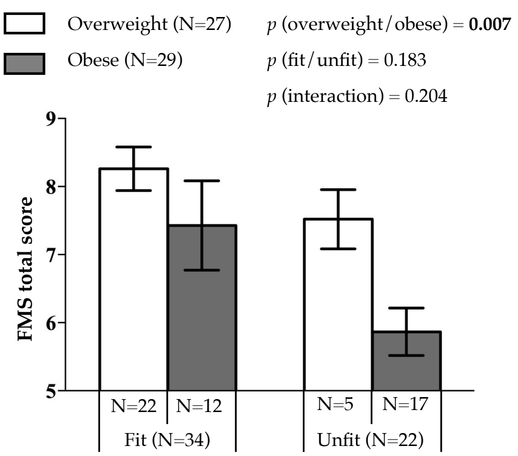

Figure 2. Fatness and fitness categories in relation to total Functional Movement Screen score.

A two-way analysis of covariance (ANCOVA) was used to test the differences in functional movement quality between overweigh/obesity and/or fitness categories, adjusting for basic confounders (age, sex, and parental education). Adjusted means and standard error of the mean are represented. Significant associations (p<0.05) are highlighted in bold.

DISCUSSION

The main findings of this study were the following: 1) all fatness indicators (except for waist circumference) were negatively associated with the total FMS score, regardless of the overweight/obese participants' cardiorespiratory fitness; 2) fitness components (i.e., cardiorespiratory fitness, lower limbs muscle strength, and speed-agility) were positively associated with the total FMS score, regardless of their BMI; 3) functional movement quality was worse in obese than in overweight children, yet a non-significant difference between fitness categories was observed. The difference in total FMS score according to the weight status (i.e., overweight vs. obesity) was more pronounced in unfit children compared to fit children, but this interaction was not statistically significant.

To our knowledge, this is the first study that examines the associations of different fatness indicators and fitness components with functional movement quality in a population of overweight/obese children. Our results showed that almost every fatness indicator was negatively correlated with the FMS outcomes. When participants´ cardiorespiratory fitness was added as confounder, waist circumference was the only fatness indicator which lost its significant association with FMS total score. It could highlight that cardiorespiratory fitness has an important role in this association, possibly because children with higher waist circumference present greater limitations in dynamic tasks, such as running, than in static tasks, such as those performed in the FMS protocol. Moreover, our findings are in line with previous studies, which reported that BMI was inversely related to the FMS total score in a group of 7 to 11-year-old children with a heterogeneous weight status distribution [4, 14]. Conversely, another study did not find associations between BMI and the total FMS score in children aged 8–11 [15]. However, the homogeneity in the participants´ BMI in the latter study (i.e., 91% of the sample were normal-weight children) could explain these contradictory findings.

This study did not only investigate associations between fatness indicators and functional movement quality, but also differences in functional movement between overweight and obese categories. In line with our results, a previous study demonstrated that the total FMS score was significantly higher, and thus better, in overweight than in obese children [4]. Furthermore, our analysis included several confounders, such as age, sex, and parental educational level, which have previously demonstrated to influence fatness, fitness, and functional movement quality [29, 34]. Taken together, it seems that the detriment of the functional movement quality not only occurs between normal-weight and overweight/obese children, but also between overweight and obese [3, 4, 13]. Thus, children with a higher BMI, and subsequently higher obesity status, could be more predisposed to experiencing movement impairments, which should also be tackled in health-stimulation interventions aimed at this specific population.

The fact that fatness indicators are negatively associated with the total FMS score may have several possible explanations. The optimal performance of the tasks included in the FMS requires optimal joint alignment, muscle strength, functional range of motion, whole body postural control, and balance [11, 33]. In this sense, childhood obesity has been associated with static and dynamic joint misalignment during several tasks, such as standing posture, walking, or jumping [37–39]. The logical assumption is that joint misalignments also occur in functional movement patterns. Moreover, there seems to be a general consensus on the fact that obese adolescents have lower relative strength (i.e. normalised to body mass) than their normal-weight peers, which could lead to a mobility reduction and functional limitation when executing analytical movement patterns [40]. Regarding postural control and balance, obese pre-pubertal children have shown poorer performance on both static and dynamic postural control tasks as compared to non-obese children, which is possibly directly related to the greater inertia of their body as an inverted pendulum [41, 42].

Concerning fitness, evidence also suggests positive associations of muscular fitness, joint range of motion, and cardiorespiratory fitness with movement competence in children [10]. In addition, physical performance has been associated with functional movement quality in a young physically active population, concluding that athletic performance can explain a portion of movement quality, or vice versa [43]. Nevertheless, to date, there are no studies investigating the relationship between fitness components and functional movement quality in a population of overweight/obese children. Our results demonstrate how cardiorespiratory fitness, lower limbs muscular strength (evaluated with the standing long jump test), and speed-agility are all positively associated with functional movement quality, regardless of BMI. A possible explanation is that functional movement quality is associated with activities that require body segmental control whilst simultaneously producing high levels of power (i.e. standing long jump and speed-agility) [43]. Concerning cardiorespiratory fitness, children with better functional movement quality could be developing more efficient motor patterns, and thus decrease the metabolic and mechanical costs of running, similarly to what has been found for gait patterns [44]. On the other hand, 1RM legs and handgrip seem to lost their significant association with functional movement quality after taking into account participants´ BMI, which highlights the determinant influence of body size in absolute muscle strength tasks.

The fat-but-fit paradox suggests that a moderate to high cardiorespiratory fitness (categorised as fit in this study based on VO2max cut-off points) might counteract the negative consequences of overweight/obesity on many health outcomes in children [45]. Our findings in Figure 2 do not demonstrate a combined effect between fatness and fitness categories in relation to functional movement quality. When considering them independently, weight status (i.e. overweight vs. obese) was a significant and stronger determinant of functional movement quality than fitness (i.e. fit vs. unfit). Nevertheless, the difference in functional movement quality between fatness categories (i.e. overweight vs. obese) seems to be lower for fit compared to unfit children. This fact could tentatively highlight that cardiorespiratory fitness level tends to attenuate the disparity in functional movement, caused by an excess BMI or weight status. Altogether, our findings support the need to evaluate functional movement in children, especially in those with a high degree of obesity. Furthermore, prevention exercise programmes should focus on both the development of movement quality as well as the fitness level in this particular population.

Some limitations need to be acknowledged in the present study. Firstly, its cross-sectional design does not allow a causal interpretation of the findings. Secondly, bioelectrical impedance was used for the assessment of adiposity (i.e. estimation of body fat percentage) instead of a gold standard, although previous studies tested that bioelectrical impedance provides a good estimate compared with a gold-standard, i.e., dual-energy x-ray absorptiometry (DXA) [46]. Finally, our sample is limited in size and only composed of overweight/obese children from a specific region, and thus results should be considered with caution and may not be generalizable to a general population.

The strengths of this study, however, include, first of all, the use of reliable field-based fitness tests, also being valid and related to health in children [22, 27, 28]. In addition, all FMS tasks were videotaped and later analysed by FMS certified evaluators with standardised scoring templates, ensuring reliability of the functional movement scores [47, 48]. Finally, our research represents the first study investigating the interrelationship between fatness, fitness, and functional movement quality in a homogenous sample of overweight/obese children.

Conclusion

All fatness indicators, with the exception of the waist circumference, were negatively associated with functional movement quality, regardless of cardiorespiratory fitness. Some fitness components (i.e. lower limbs muscle strength, speed-agility, and cardiorespiratory fitness) were positively associated with functional movement quality, regardless of BMI. When looking at the differences in total FMS according to the distinguished fitness and fatness categories, children's weight status (i.e. overweight vs. obese) was a stronger determinant of functional movement quality than fitness level (i.e. fit vs. unfit), showing higher total FMS score in overweight than in obese children. Furthermore, it seems that fitness might have a protective effect against adverse consequences of fatness in functional movement quality. However, more research is needed to further expand on these findings, and randomised controlled trials should focus on exercise intervention programmes aimed to reduce fatness and/or develop fitness and to test their effect on functional movement quality in overweight/obese children, or vice versa.

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SECTION 3.

Effects of a 13-week exercise program on the biomechanics of childhood obesity

SECTION 3

Study 5

Effects of exercise on body posture, fundamental movements and physical fitness in children and adolescents with overweight/obesity

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INTRODUCTION

Body posture, functional movement, and physical fitness are all factors of great relevance to health in childhood. Body posture refers to the positioning of body segments and is a good predictor of present and future musculoskeletal health [1, 2]. The term 'functional movement' has been used to reflect movement competence and arrives from the study of fundamental movements (e.g., stepping or squatting patterns), typically from a qualitative perspective [3]. The mastery of fundamental movements during childhood seems to be directly related to physical performance, which is essential to consolidate an active lifestyle and its health-related profits [4, 5]. Finally, physical fitness refers to the capacity to perform physical activities and comprises several components (e.g., cardiorespiratory, muscular and speed-agility fitness), all intimately related to the physical and mental health status of children [6]. The presence of overweight/obesity (OW/OB) during childhood has been negatively related to all these factors, which could, therefore, lead to harmful health consequences for this population [1, 5, 7].

Children with OW/OB are 1.5 times more likely to present an incorrect body posture than their healthy-weight peers [8], considering it as a non-optimal alignment of body segments leading to mechanical stress and muscle overactivation [9]. Head and shoulder protracted position, thoracic kyphosis, lumbar hyperlordosis, lower limb valgus position, and flat feet are the most frequently observed postural alterations in these children [8, 10]. All these alterations could predispose them to develop musculoskeletal disorders (e.g., musculoskeletal pain) and reduce their respiratory efficiency (e.g., decreased lungs capacity) [1, 8]. Similarly to body posture, a study showed that weight status during childhood is inversely related to functional movement [3]. In this sense, having a low functional movement might hamper daily physical functioning of children with OW/OB, resulting in a decrease of health-related quality of life together with the development of musculoskeletal disorders [11]. Likewise, children with OW/OB have demonstrated lower levels of physical fitness than normal-weight children, being an additional factor that predisposes them to develop cardiovascular and metabolic risk factors [7].

Exercise interventions are considered a key action in the prevention and mitigation of childhood obesity [7]. Concerning body posture, although exercise has demonstrated to be an effective treatment improving postural alterations in different populations [12], only one study has investigated the effects of exercise on body posture in children with OW/OB to date [13]. Schwanke et al. [13] found that children with OW/OB who participated in a 4-month exercise program based on strengthening and stretching exercises improved their thoracic spine posture, whereas no improvements were found for their head, lumbar spine and lower limb posture. In regard to movement competence, there is a body of evidence suggesting the effectiveness of exercise interventions on improving global movement patterns (i.e., fundamental movement skills or motor coordination) in children with OW/OB, while less attention has been paid to fundamental movements (i.e., functional movement) which, in fact, are the basis for learning and developing these more global movement patterns [3, 14]. We are aware of only three previous trials studying the effects of exercise on functional movement in children with normal weight [15–17], but no trials in children with

OW/OB. These studies show contradictory results since two of them reported improvements in functional movement after an exercise program [15, 17], while the third one found no changes [16]. With respect to physical fitness, results from previous systematic reviews and meta-analyses suggest that exercise interventions are effective for improving cardiorespiratory fitness and muscular strength in children with OW/OB, whereas there are still contradictory findings in speed-agility [18, 19]. Therefore, further research is needed to determine the effects of exercise on body posture and functional movement in children with OW/OB as additional benefits to the expected improvements in physical fitness.

Overall, the effects of exercise interventions on body posture, functional movement and physical fitness have typically been studied separately, with intervention characteristics varying considerably (e.g. aerobic capacity, muscle strengthening, muscle stretching, etc). Therefore, it would be of interest to know whether an intervention that combines exercise modalities to target all three variables at once can induce simultaneous positive effects. To see the exercise program rationale refer here: http://profith.ugr.es/pages/investigacion/proyectos/rationaleexerciseprogram . Thus, the aim of this study was to analyze whether a 13-week exercise program based on 'movement quality' and 'multi-games' work is able to induce simultaneous positive effects on body posture, functional movement and physical fitness in children with OW/OB.

METHODS

Experimental Approach to the Problem

The present study belongs to the MUBI project ("*MUévete BIen*" in Spanish and "Move well" in English"), a non-randomized controlled trial aimed at examining the effects of a 13-week exercise program on biomechanical parameters of children with OW/OB (http://profith.ugr.es/mubi?lang=en). Children who participated in the exercise program (N=33) came from another randomized controlled trial (the ActiveBrains project: http://profith.ugr.es/activebrains?lang=en) in which they had participated as control group the year before. For ethical reasons, we offered an exercise program to those children who did not have the opportunity to exercise because of the randomization. Control group (N=31) was recruited following the same inclusion/exclusion criteria through public and private schools of Granada, Spain. Participants' anthropometric, body posture, functional movement and physical fitness outcomes were measured before (pre-intervention) and after (post-intervention) the exercise program, from February to July 2017.

Subjects

A total of 64 children between 8 and 12 years old (25.91 ± 3.83 kg/m^2, 59% girls) participated in this study after meeting these inclusion/exclusion criteria: 1) to be 8 to 12.9 years-old; 2) to be classified as overweight or obese based on sex and age specific World Obesity Federation cut-off points (15); 3) to not suffer from physical disabilities or neurological disorders that impeded them to exercise; 4) in the case of girls, not to have started the menstruation at the moment of baseline assessments; 5) to report no use of medications that influenced central nervous system function; 6) to be right-handed since these children substantially differ in their brain hemisphere structure from left-handed ones [20]; and 7) to not report an attention-deficit hyperactivity disorder (ADHD). For the per-protocol analysis (see statistical section) a sub-sample of 46 children were selected based on the following criteria: 1) to have viable pre- and post-intervention data; and 2) to have an attendance rate of at least 70% of the recommended 3 sessions/week (for the intervention group). **Figure 2** shows the study flowchart. The exercise group was integrated by the children who participated the previous year as control group in the Active-Brains project [21]. For ethical reasons, we offered an exercise program to those children who

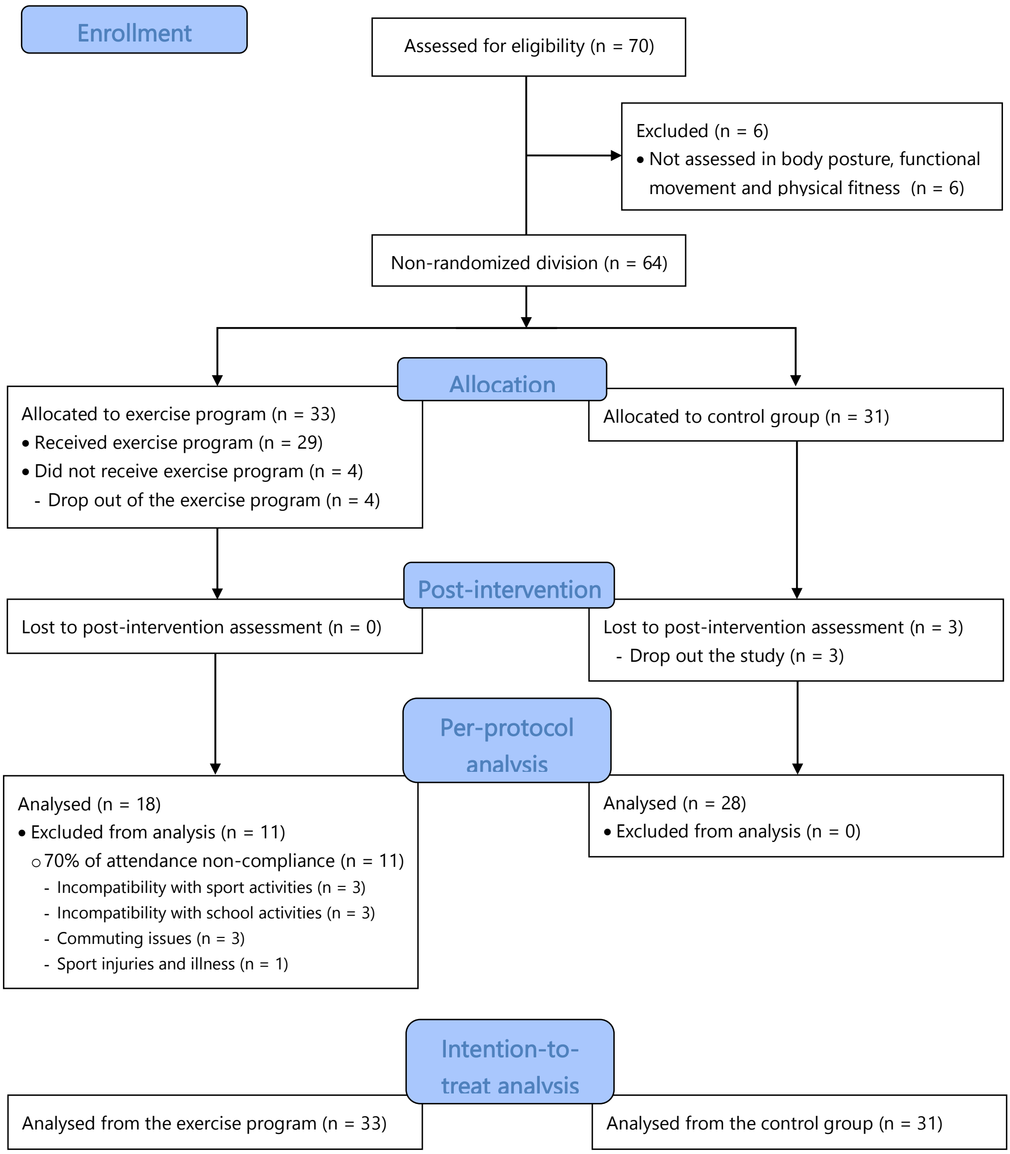

Figure 1. Flow diagram describing the configuration of participants process in per-protocol and intention-to-treat analyses.

did not have the opportunity to exercise because of the randomization. The control group was recruited from primary schools in Granada (Spain) following the above-mentioned inclusion/exclusion criteria, and we also offered them to participate in the exercise program the following year. A signed parental informed consent was asked to participate in the study, and the MUBI project was approved by the Ethics Committee on Human Research (CEIH) at the University of Granada (nº 279/CEIH/2017).

Procedures

Exercise program.

The rationale and detailed description of the exercise program is provided on the official website of our research group (http://profith.ugr.es/mubi?lang=en). Briefly, the exercise program lasted for 13 weeks, from 1st of March 2017 to 29th of May 2017, and was carried out at the Sport and Health University Research Institute (iMUDS) of the University of Granada. The exercise program was offered from Monday to Friday, requiring a minimum attendance of 3 sessions per week. The total duration of each session was 90 minutes, divided into two parts: 30 mins of 'movement quality' work and 60 mins of aerobic 'multi-games'. The main objectives of the "movement quality" part were that participants acquired motor control of joint mechanics (e.g., anterior and posterior pelvic tilt) and body posture (e.g., optimal spine position), gained body segments mobility (e.g., hip flexion mobility), stability (e.g., core stability) and muscular strength in functional range of motion (e.g., bilateral lower limb push strength) and learned and assimilated basics human movements (e.g., squat pattern). Moreover, the main objectives of the "multi-game" part were that participants learned and assimilated a wide range of fundamental movement skills (e.g., sprinting, hopping or throwing), reached a moderate-to-vigorous aerobic intensity and enjoyed while practicing physical exercise. Sessions were supervised by two coaches who were trained on delivering this exercise program. No specific dietary intervention was carried out.

Body Posture.

A two-dimensional photogrammetry approach was used to assess body posture, which has demonstrated to be valid for evaluating human posture against other gold-standard methods, such as X-Ray analysis [22]. The assessment protocol was undertaken following standardized conditions [23, 24]. A basler acA2000-50gc (Germany) camera with a fixed focal lens Fujinon HF12.5SA-1 (Japan) was positioned on a tripod at a height of 115 cm and 3.1 m away from the center of the square platform where children were evaluated. The lens of the camera was pointing to the center of the square platform and was horizontally aligned using a spirit level. Participants were instructed to be in underwear conditions, wearing bathing clothes or sleeveless tight-fit sports clothes. Six retro-reflective markers were placed by the same trained examiners on several anatomical regions previously used in the literature [24]: 7th cervical vertebrae (C7), 12th thoracic vertebrae (T12), right anterior superior iliac spine (ASIS), right trochanter, right lateral condyle, and right lateral malleolus. Children stood comfortably looking straight ahead, and their feet were aligned with a line painted on the square platform to ensure that they were always placed in the same position. Two photographs were taken, the first from the anterior view (frontal plane) and the second from the right side (sagittal plane). Images were calibrated based on a previous image with a vertical plumb and a posture grid placed on the wall. The image analysis program ImageJ (National Institutes of Health, Bethesda, MD) was used to digitize the *x* and *y* coordinates of each retro-reflective marker, and this process was undertaken by the same experienced researcher [25]. The *x* and *y* coordinates were exported from ImageJ software and imported into MS Excel spreadsheets for calculation of eight angles and eight distances previously used in the literature [22–24, 26, 27]. **Table 1** shows how body posture outcomes were defined, as well as the interpretation of their values, whereas **Figure 2** provides a graphical representation of these body posture outcomes. All these measures have demonstrated a good-to-excellent inter- and intra-rater reliability [23, 27].

Table 1. Definition and interpretation of the body posture indicators.

Name	Definition	Interpretation
Sagittal plane		
Cervicothoracic angle [26]	The angle between the line of tragus with C7, and the line of C7 with T12.	High values (close to 180°) indicate a cervical retracted position, while low values indicate a cervical protracted position.
Thoracic flexion [26]	The angle between the line connecting C7 and T12 with respect to the vertical line from T12.	Positive values indicate a thoracic flexed position, while negative values indicate a thoracic extended position.
Trunk angle [23]	The angle between the line connecting C7 and trochanter with respect to the vertical line from trochanter.	An increase indicates a posterior tilt, whereas a decrease indicates an anterior tilt, of the trunk with respect to the pelvis. 169° is the average value observed in normal-weight children/adolescents.
Lumbar angle [23]	The angle between the line of T12 with ASIS, and the line of ASIS with trochanter.	High values indicate a pelvis posterior tilt position, while low values indicate a pelvis anterior tilt position.
Lower limb angle [24]	The angle between the line connecting lateral malleolus and greater trochanter with respect to the vertical line from greater trochanter.	Positive values indicate a pelvis forward position with respect to the feet, while high negative values indicate a backward pelvis position.
Plumb-tragus distance [22]	Distance of the ear tragus with respect to the vertical plumb	Zero indicate an optimal alignment of the head in the sagittal plane, positive values indicate an anterior shift of the head, and negative values indicate a posterior shift of the head.
Frontal plane, anterior view		
Lower limb valgus angle [27]	The angle between the line of trochanter with lateral condyle, and the line of lateral condyle with ASIS lateral malleolus.	Values close to 180° indicate an optimal alignment, higher values indicate a lower limb varus position and lower values indicate a lower limb valgus position.

Functional movement

Four tests from Functional Movement Screen™ (FMS) were used to evaluate functional movement, which have demonstrated good-to-acceptable inter- and intra-rater reliability with the exception of one (hurdle step) demonstrating moderate-to-questionable reliability [3, 28]. The full FMS protocol includes seven tasks, but we included a four-task adaptation (i.e., deep squat, hurdle step, shoulder mobility, and active straight leg raise) given the difficulty of execution of the remaining three tasks (i.e., in-line

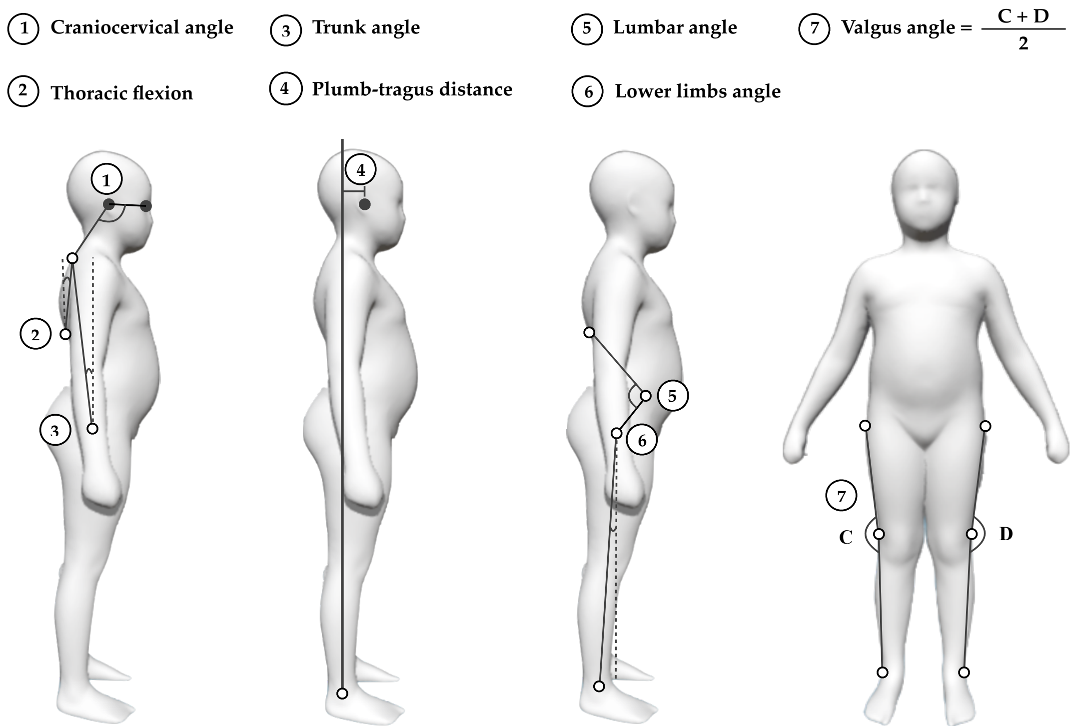

Figure 2. Graphical representation of the body posture indicators

lunge, trunk stability push up and rotary stability) previously observed in children with overweight/obesity [3]. The complete assessment protocol has been previously described [3]. Ac cording to the FMS scoring criteria, each task received a score from 1 to 3 points, and in the case of bilateral tasks (i.e., hurdle step, shoulder mobility, and active straight leg raise) performed with both the left and right members, the lowest score was selected. Thereafter, scores of individual tasks were summed to obtain a total FMS score ranging from 4 to 12 points, where higher values indicated a better functional movement quality. Two certified evaluators with extensive experience scored all videos separately, and any discrepancy was reviewed in a consensus meeting until reaching an agreement on the final score.

Physical fitness

Among physical fitness components, cardiorespiratory fitness and speed-agility were evaluated in field conditions, whereas muscular strength was evaluated in both, field and laboratory conditions. In field conditions, we used the ALPHA (Assessing Levels of Physical fitness and Health in Adolescents) health-related physical fitness test battery, which has demonstrated validity, reliability, and feasibility assessing physical fitness in children [29]. In brief, cardiorespiratory fitness (ml/kg/min) level was estimated from the 20 m shuttle run test [30], muscular strength was assessed using the maximum handgrip strength test (kg) and the standing long jump test (cm), and speed-agility was evaluated by the 4×10 m shuttle run test (sec). Under laboratory conditions, we assessed one-repetition maximum (1RM) in the arm press (kg) and-leg press (kg) exercises using pneumatic resistance machines (Keiser Sports Health, Fresno, CA, USA) and following a previous protocol adapted to children [31]. Absolute measures of muscular strength (i.e., arm and leg press 1RM, and handgrip strength) were divided by body weight, and therefore expressed relative to participants' body weight since previous literature has demonstrated a potential effect of body weight on this population [3]. The speed-agility score was inverted by multiplying the test completion time by −1, so that higher values indicate a better fitness level.

Potential confounders

Body height and weight were measured to the nearest 0.1 kg and cm respectively (SECA Instruments, Germany), and body mass index (BMI, kg/m²) was calculated. The maturational stage of the children was determined by calculating the peak height velocity with the Moore's equations, which use participants' age and standing and sitting height [32]. Parental educational level was determined with a questionnaire, in which parents were classified as: 1) none of them having a university degree, 2) one of them having a university degree, and 3) both of them having a university degree [33].

Statistical Analyses

The characteristics of the sample are presented as means and standard deviations (SD) or percentages. Pre-intervention differences between the IG and the CG were tested through t-tests for continuous outcomes and through chi-squared tests for categorical outcomes.

The exercise program effects were tested according to the per-protocol analysis. Firstly, pre- and post-intervention outcomes were checked for normal distributions through histograms. Secondly, z-scores for each outcome were calculated, and particularly for post-intervention, z-scores were calculated based on the pre-intervention data through the following formula: (participant raw score at post-intervention – sample's mean raw score at pre-intervention) / sample's standard deviation at pre-intervention. Thirdly, a one-way Analysis of Covariance (ANCOVA) was used to examine differences in body posture, functional movement and physical fitness between the IG and the CG at post-intervention using post-intervention raw scores or z-scores as dependents, group as a fixed factor, and pre-intervention scores as covariates. Differences between the pre- and post-intervention assessments of all these outcomes were presented in raw scores and z-transformed values, being this last one interpreted as the change from pre-intervention in standard deviations (SDs) and used as effect size indicator: 0.2 – 0.5 SDs = small effect size; 0.5 – 0.8 SDs = medium effect size; and 0.8 < = large effect size [34]. Additional confounders such as gender, age, maturational status, anthropometric measures, and parental education were discarded after verifying that they did not influence the ANCOVA models (all $p > 0.05$).

Intention-to-treat analyses are presented in the supplementary material. We used multiple imputation for missing values, which were assumed to be lost at random. From here, the intention-to-treat analyses followed the same process as the one explained above for the per-protocol analysis. Also, as supplementary analyses, Wilcoxon Signed-Ranks and Mann–Whitney U tests were used to examine the within-group and between-group changes respectively in each FMS test (i.e., deep squat, hurdle step, shoulder mobility, and active straight leg raise). All analyses were performed using the SPSS software (version 24.0, IBM Corporation), and the level of significance was set at p<0.05.

RESULTS

The pre-intervention characteristics for the whole sample and separately for the IG and the CG are presented in **Table 2**. In regard to body posture, the IG displayed a higher thoracic flexion angle (p < 0.001) than the CG, whereas there were no differences between groups in the remaining body posture outcomes (p < 0.05). The IG showed a worse functional movement performance, achieving lower total FMS score (p = 0.001) than the CG. Lastly, the IG achieved higher values in 1RM arm and handgrip strength than the CG (all p < 0.05).

Table 2. Baseline characteristics of the per-protocol sample and divided by intervention and control group.

	All sample (n=46)	Intervention (n=18)	Control (n=28)	*P*
Age (years)	10.87 ± 1.30	11.3 ± 1.15	10.62 ± 1.33	0.076
Weight (kg)	57.51 ± 13.47	64.32 ± 7.62	53.55 ± 14.61	**0.006**
Height (cm)	147.99 ± 9.19	152.01 ± 6.16	145.66 ± 9.92	**0.018**
Body mass index (kg/m[2])	25.91 ± 3.83	27.82 ± 2.72	24.8 ± 3.97	**0.006**
Gender				**0.002**
Girls	28 (61%)	6 (33%)	22 (79%)	
Boys	18 (39%)	12 (67%)	6 (21%)	
Body posture				
Craniocervical angle (°)	142.27 ± 5.96	140.94 ± 6.48	143.04 ± 5.60	0.237
Thoracic flexion (°)	5.15 ± 4.00	7.68 ± 3.59	3.68 ± 3.50	**<0.001**
Trunk angle (°)	171.11 ± 3.29	172.08 ± 3.62	170.54 ± 2.99	0.113
Lumbar angle (°)	83.79 ± 8.81	84.11 ± 8.44	83.61 ± 9.15	0.851
Lower limb angle (°)	3.36 ± 2.61	3.95 ± 2.92	3.02 ± 2.40	0.230
Lower limb valgus (°)	175.99 ± 1.80	175.92 ± 1.47	176.03 ± 1.98	0.841
Plumb-tragus distance (cm)	5.69 ± 2.51	5.90 ± 2.27	5.57 ± 2.67	0.664
Functional movement				
Total Functional Movement Screen (FMS) score (3-12)	7.05 ± 1.92	5.62 ± 1.50	7.69 ± 1.75	**0.001**
Physical fitness				
1RM arm (kg)[a]	0.44 ± 0.12	0.39 ± 0.08	0.47 ± 0.13	**0.014**
1RM leg (kg)[a]	2.62 ± 0.52	2.51 ± 0.52	2.67 ± 0.52	0.298
20m shuttle run (ml/kg/min)	40.88 ± 3.23	39.83 ± 1.70	41.46 ± 3.71	0.095
Handgrip (kg)[a]	0.34 ± 0.07	0.30 ± 0.04	0.36 ± 0.08	**0.010**
Standing long jump (cm)	115.92 ± 19.81	116.12 ± 20.48	115.81 ± 19.77	0.959
4×10 m shuttle run (s)[b]	-14.46 ± 1.87	-14.74 ± 1.44	-14.31 ± 2.08	0.454

SD = standard deviation; n=sample size; RM: repetition maximum.
[a] Relative to body weight (outcome' value / body weight)
[b] Values of the 4x10-m shuttle run test were multiplied by −1 so that higher values indicate better performance.
Values are presented as mean ± SD or percentages. For continuous variables, p value was obtained by an independent samples T-test, whereas for categorical variables, p value was obtained by chi-square test.
Significant differences (p < 0.05) are highlighted in bold.

Table 3 presents the post-intervention differences between groups adjusted for pre-intervention values for those participants included in the per-protocol analysis. In **Figure 3** the effect sizes of the exercise program are graphically showed. The IG reduced the lower limb angle in the sagittal plane (high effect size: -0.82 SDs; p = 0.001), whereas the CG experienced an increase. The IG had a significantly lower increase of the distance between the ear tragus and the vertical plumb (low effect size: -0.43 SDs; p = 0.038) compared with the CG. In the frontal plane, the IG

Table 3. Per-protocol intervention effects on body posture, functional movement and physical fitness.

Outcomes	Values presentation	Intervention Group (N=18) Mean (95% CI)	Control Group (N=28) Mean (95% CI)	Difference between groups	*p*
Body posture					
Craniocervical angle (º)	Raw score	142.72 (139.60 to 145.84)	143.21 (140.77 to 145.65)	-0.49	0.805
	z Score	0.08 (-0.45 to 0.60)	0.16 (-0.25 to 0.57)	-0.08	
Thoracic flexion (º)	Raw score	4.64 (2.80 to 6.49)	4.30 (2.90 to 5.70)	0.35	0.778
	z Score	-0.13 (-0.59 to 0.34)	-0.21 (-0.56 to 0.14)	0.09	
Trunk angle (º)	Raw score	171.05 (170.09 to 173.00)	170.20 (168.69 to 171.72)	-1.69	0.086
	z Score	0.27 (-0.19 to 0.74)	-0.24 (-0.60 to 0.12)	-0.51	
Lumbar angle (º)	Raw score	83.81 (78.57 to 89.05)	79.02 (74.93 to 83.12)	4.79	0.157
	z Score	0.00 (-0.59 to 0.60)	-0.54 (-1.01 to -0.08)	0.54	
Lower limb angle (º)	Raw score	2.43 (1.45 to 3.41)	4.57 (3.80 to 5.33)	-2.13	**0.001**
	z Score	-0.36 (-0.73 to 0.02)	0.46 (0.17 to 0.75)	-0.82	
Lower limb valgus (º)	Raw score	176.94 (176.19 to 177.69)	175.47 (174.88 to 176.05)	1.48	**0.003**
	z Score	0.53 (0.11 to 0.95)	-0.29 (-0.62 to 0.04)	0.82	
Plumb-tragus distance (cm)	Raw score	5.92 (5.13 to 6.71)	6.98 (6.36 to 7.60)	-1.07	**0.038**
	z Score	0.09 (-0.22 to 0.41)	0.52 (0.27 to 0.76)	-0.43	
Functional movement					
Total FMS score (3-12)	Raw score	8.46 (7.66 to 9.26)	7.32 (6.80 to 7.84)	1.14	**0.029**
	z Score	0.73 (0.32 to 1150.)	0.14 (-0.13 to 0.41)	0.59	
Physical Fitness					
1RM arm/weight (kg/kg)	Raw score	0.43 (0.41 to 0.46)	0.38 (0.36 to 0.40)	0.06	**0.002**
	z Score	-0.05 (-0.26 to 0.17)	-0.51 (-0.67 to -0.34)	0.46	
1RM leg/weight (kg/kg)	Raw score	2.60 (2.36 to 2.83)	2.38 (2.20 to 2.56)	0.21	0.157
	z Score	-0.04 (-0.50 to 0.42)	-0.45 (-0.80 to -0.10)	0.41	
20m shuttle run (ml/kg/min)	Raw score	42.00 (40.86 to 43.13)	41.26 (40.43 to 42.08)	0.74	0.298
	z Score	0.35 (-0.01 to 0.70)	0.12 (-0.14 to 0.37)	0.23	
Handgrip/weight (kg/kg)	Raw score	0.37 (0.35 to 0.38)	0.33 (0.32 to 0.34)	0.04	**<0.001**
	z Score	0.41 (0.20 to 0.61)	-0.13 (-0.27 to 0.02)	0.53	
Standing long jump (cm)	Raw score	123.83 (117.88 to 129.79)	112.23 (107.90 to 116.56)	11.60	**0.003**
	z Score	0.40 (0.10 to 0.7)	-0.19 (-0.41 to 0.03)	0.59	
4×10 m shuttle run (s)	Raw score	-13.89 (-14.51 to -13.27)	-14.50 (-14.96 to -14.05)	0.62	0.113
	z Score	0.31 (-0.03 to 0.64)	-0.02 (-0.27 to 0.22)	0.33	

CI = confidence interval. Raw scores are reported as adjusted values. A one-way analysis of covariance (ANCOVA) was used to test raw and z-score differences between the intervention and control group at the post-intervention, adjusting for basic pre-intervention values. Adjusted means confidence intervals of the mean are represented. Differences between groups are presented as: post-intervention mean minus pre-intervention mean so that positive values indicate that the value was higher at the post-intervention than in the pre-intervention. Significant differences ($p<0.05$) are highlighted in bold.

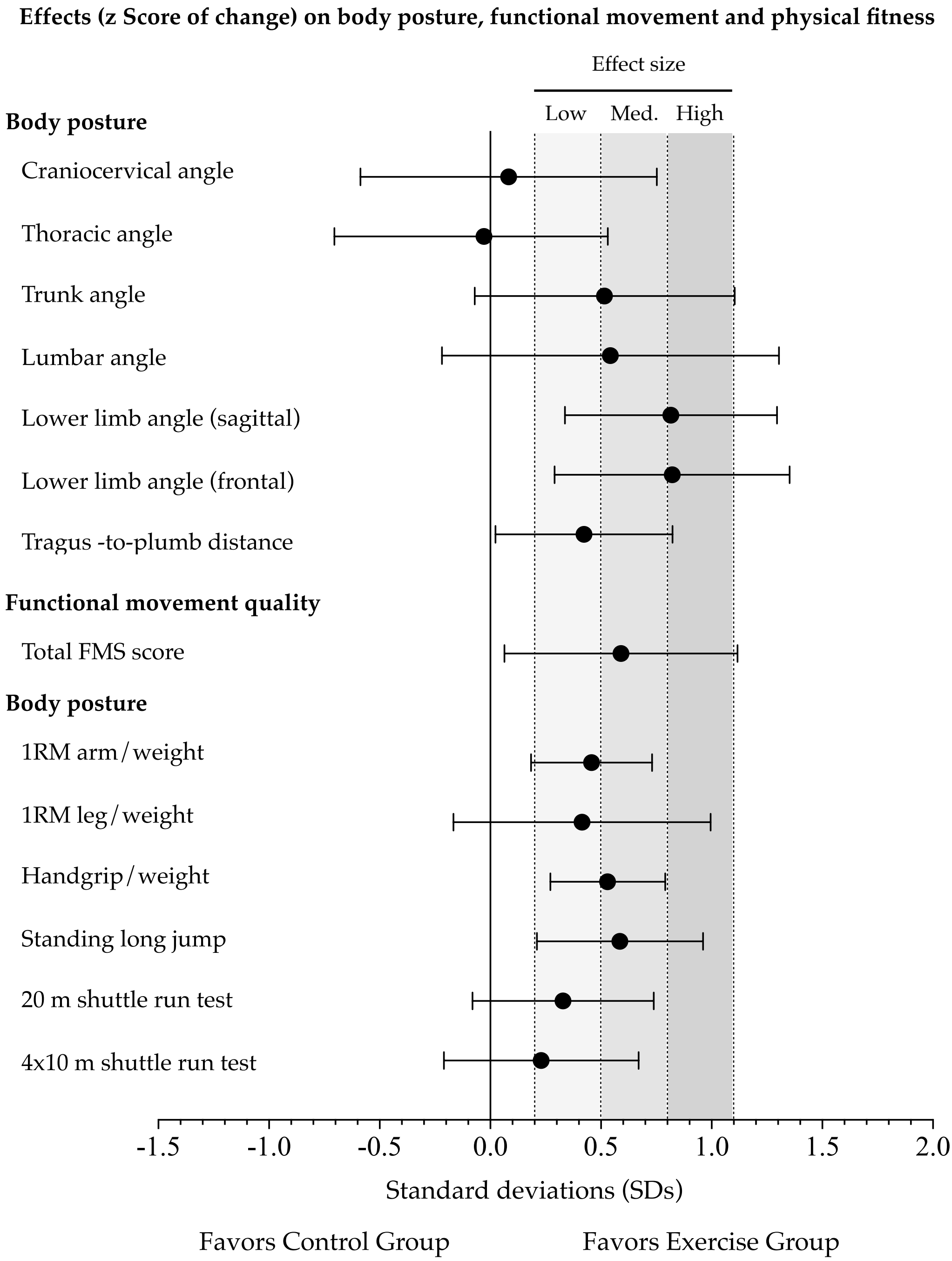

Figure 2. Per-protocol effect sizes of the MUBI exercise program on body posture, functional movement and physical fitness.

A one-way analysis of covariance (ANCOVA) was used to test z-score differences between the exercise and control group at the post-intervention, adjusting for pre-intervention values. Bars represent 95% confidence intervals. Results were inverted (i.e., multiplied by -1) in order to allow all the positive effect sizes to mean also positive results (e.g., a reduction [-0.82 SDs] in lower limb frontal angle implies a positive postural change, so it was multiplied by -1).
FMS: Functional Movement Screen; Med.: Medium.

tion of the lower limb by increasing the lower limb valgus (high effect size: 0.82 SDs; p = 0.003), while the CG decreased this valgus angle. Differences between the IG and the CG were similar after the exercise program in the thoracic flexion and the lumbar angle (all p > 0.05). With regard to functional movement, the IG significantly improved their performance in the total FMS score with respect to the CG, that performed worse at post-intervention (medium effect size: 0.59 SDs; p = 0.029). Lastly, the IG significantly improved their muscle strength with respect to the CG, evaluated through 1RM arm (low effect size: 0.46 SDs; p = 0.002), handgrip strength (medium effect size: 0.53 SDs; p < 0.001) and standing long jump (medium effect size: 0.59 SDs; p = 0.003). Changes in 1RM leg, cardiorespiratory fitness and speed-agility were not significantly different between both the groups after the exercise program (all p > 0.05).

Results from the intention-to-treat analyses are shown in **Table S1**. Briefly, all results remained similar to the pre-protocol results, with the exception of speed-agility which was significantly improved by the IG with respect to the CG at post-intervention (low effect size: 0.38 SDs; p = 0.018). Changes in each FMS test are presented in **Table 4**.

Table 4. Within-group and between-group changes in the individual Functional Movement Screen (FMS) tests.

	Pre-intervention assessment				Post-intervention assessment							
		Scores (%)				Scores (%)			Within-group change		Between-group change	
FMS tests	Mean (SD)	1	2	3	Mean (SD)	1	2	3	Z	p	Z	p
Deep squat											-3.032	**0.004**
IG	1.15 (0.38)	85	15	0	1.81 (0.40)	19	81	0	-2.828	**0.005**		
CG	1.72 (0.53)	31	66	3	1.62 (0.56)	41	55	4	-0.832	0.405		
Hurdle step											-1.237	0.457
IG	1.50 (0.52)	50	50	0	1.81 (0.54)	25	69	6	-1.414	0.157		
CG	1.86 (0.52)	21	72	7	1.86 (0.52)	21	72	7	0.000	1.000		
Shoulder mobility											-0.330	0.770
IG	1.64 (0.67)	45	46	9	2.06 (0.85)	31	31	38	-1.134	0.257		
CG	1.79 (0.73)	38	45	17	2.10 (0.72)	21	48	31	-2.138	**0.033**		
ASLR											-3.529	**<0.001**
IG	1.69 (0.48)	31	68	0	2.31 (0.60)	6	56	38	-2.530	**0.011**		
CG	2.31 (0.60)	7	55	38	2.14 (0.74)	21	45	34	-1.667	0.096		

SD = standard deviation; IG = intervention group; CG = control group; ASLR = active straight leg raise.
Wilcoxon Signed-Ranks and Mann–Whitney U were used to test within-group and between-group changes respectively. Significant differences (p<0.05) are highlighted in bold.

The within-group analyses indicate that the IG had significant improvements in the deep squat and active straight leg raise, whereas the CG significantly improved in shoulder mobility (all p > 0.05). The between-group analyses show that the IG had greater improvements from baseline than the CG in deep squat and active straight leg raise (both p > 0.05).

DISCUSSION

The present study suggests that a 13-week exercise program based on 'movement quality' and 'multi-games' (i.e., aerobic exercise) work leads to positive effects on body posture, functional movement and muscular strength in children with OW/OB. After the exercise program, the IG developed a more vertical alignment of head and pelvis complex in the sagittal plane and improved their lower limb alignment in frontal plane with respect to the CG. Furthermore, the IG improved their performance in the total FMS score and individual tests (i.e., deep squat and active straight leg raise); in addition, they obtained better results in several muscular strength indicators (i.e., 1RM arm, handgrip strength, and standing long jump), all in comparison with the CG.

In contrast with previously observed effects of exercise on body posture in children with OW/OB, [13] we could not determine a direct improvement in the thoracic spine alignment for the IG, but rather we found improvements in the head and lower limb alignment in both sagittal and frontal planes. The differences between studies may reside in the differences between the exercise programs. The exercise sessions from the study of Schwanke et al. [13] consisted of 30-min of strengthening and stretching activities, whereas we complemented a 30-min of 'movement quality' work out with 60-min of 'multi-games'. Given these findings, it seems that an exercise program that only includes strengthening and stretching routines can induce localized postural improvements, whilst a multidimensional exercise program is necessary to achieve whole-body postural improvements in OW/OB.

We have not found previous studies investigating the effects of exercise intervention on functional movement in children with OW/OB, which hamper direct comparisons with our findings. However, three previous studies conducted in normal-weight children exist [15–17]. In agreement with our findings, St. Laurent et al. [17] and Linek et al. [15] demonstrated that 6- and 8-week intervention programs, respectively, both based on suspension training (i.e., exercises with ropes and webbing that allow participants to manage their own body weight), induced improvements in the total FMS score. Conversely, Wright et al. [16] did not find improvements in functional movement when comparing two different intervention programs (i.e., a movement-based program vs a generic multisport program) of 4-week duration. They acknowledged the short duration of the intervention, as well as the lack of a control group which had not exercised, as the main reasons for no changes in functional movement. In this context, neuroscience research suggests that exercise repetition, training intensity and program duration are key factors to induce neural plasticity, which in turn underlie the motor skills learning [35]. Based on these evidences, it seems that at least a 6-week long exercise program is necessary to reach improvements in functional movement in normal-weight children, whereas to date, our 13-week exercise program is the only reference duration proving effectiveness in a sample of children with OW/OB. Future studies should elucidate whether shorter exercise programs can induce the same benefits to functional movement in this population.

There are several potential explanations for the body posture and functional movement improvements found in our study. Our 'movement quality' part of the exercise program included the Dynamic Neuromuscular Stabilization approach, which tries to restore an optimal body posture and movement patterns through exercise-position progressions based on the normal development of a healthy baby [36]. Moreover, our intervention program also included the principles of Integrative Neuromuscular Training [37], incorporating dynamic mobility (e.g., rolling patterns), stability (e.g., planks), basic human movements (e.g., squat), and fundamental movement skills (e.g., sprinting), that together could have helped to improve fundamental movement in our participants. In fact, previous intervention trials applying Integrative Neuromuscular Training have shown to be effective in improving other indicators of movement competence in children such as fundamental movement skills (e.g., run, jump or catch objects) [38]. Lastly, 'movement quality' work was performed barefoot, which has demonstrated to increase the activation of intrinsic foot muscles with positive adaptations on foot posture and movement competence in childhood population [39].

Our findings confirm previous literature demonstrating muscular strength gains through exercise in children with OW/OB [19]. What makes this study different from previous interventions is that our exercise program was not specifically designed to obtain a strength gain, but rather to learn and perform a wide range of movement patterns with special emphasis on execution quality rather than quantity and intensity. To gain insight into our strength-related improvements, it is important to understand that muscular strength development during childhood is driven by neural and biomechanical stimulus, whereas in adolescence hormonal concentrations play a more prominent role in muscular structural changes [40]. In this sense, during the 'movement quality' and 'multi-game' work of our exercise program, children were continually mastering and performing basic human movement patterns, sprints, decelerations and jumps. All this could have helped to develop muscle recruitment, contractile and elastic musculoskeletal properties and intermuscular coordination, necessary for power generation and strength gains [41]. The latest position statement on strength training in youth proposes the inclusion of integrative programs enhancing muscular strength together with movement competence [42]. The present study supports that an exercise program can induce simultaneous positive effects on movement competence and muscular strength in children with OW/OB, with added benefits to body posture.

The present study did not find improvements in cardiorespiratory fitness levels of children from the IG. Analyzing previous systematic reviews, it seems that studies that successfully improved cardiorespiratory fitness were those including the aerobic training as the main objective [18]. It may be that higher aerobic volume and intensity in the 'multi-game' part of our program could have led to improvements in cardiorespiratory fitness levels of our participants. With regard to speed-agility, our IG demonstrated a non-significant improvement in the performance of 4×10 m shuttle run test in comparison with the CG. Accordingly, a previous systematic review has shown inconsistency with respect to the improvement of speed-agility in children with OW/OB [18], and future research should elucidate what is the most effective exercise intervention to improve this fitness component.

We have discussed above the importance of having a correct body posture, as well as presenting optimal levels of functional movement and muscular strength during childhood. Hence, it is logical to assume that exercise-induced improvements found in this study could be beneficial for IG, expressed for instance in the onset-prevention of musculoskeletal disorders. Smith et al. [1] demonstrated that children with a more neutral aligned spine are between 1.5 and 1.8 times less likely to suffer from low back pain. In this sense, we found a non-significant improvement in the spine alignment, evaluated with the trunk and lumbar angles, and future research should identify more effective interventions leading to improvements in this posture indicator. Moreover, large cohort studies have demonstrated that an incorrect lower limb posture (i.e., varus and valgus positions) is associated with the progression of knee osteoarthritis [2]. With regard to functional movement, the systematic review and meta-analysis of Bonazza et al. [28] demonstrated that participants with optimal total FMS scores had a lower likelihood of injuries than those participants with non-optimal scores. Looking at the last position statement on strength training in youth, reaching an optimal muscular strength level is considered a basic strategy to reduce the likelihood of injuries while practicing sport activities [42]. Nonetheless, it is important to bear in mind that these are only assumptions, and future follow-up studies should determine whether positive changes in these variables are therefore related to the actual prevention of musculoskeletal disorders, as well as other health-related benefits.

There are some limitations in the present study that should be acknowledged. Firstly, we did not include the gold-standard methods to assess body posture (i.e., X-Ray analysis) and cardiorespiratory fitness (i.e., gas analyzer); nonetheless, the two-dimensional photogrammetry and the 20m shuttle run test have demonstrated to be valid alternatives [22, 29]. Secondly, we could not randomize the IG and the CG, what could be the reason for the pre-intervention differences observed between groups. However, to control for these differences we statistically adjusted for pre-intervention values to avoid its potential effect on our results. Thirdly, our limited sample size did not allow to detect small changes between groups (i.e., 80% power to detect changes of $F = 0.42$). Fourthly, the exercise intensity during sessions was not recorded, and thus we cannot know the time that children spent in moderate-to-vigorous aerobic intensity. Lastly, all the discussed health-related benefits derived from our findings are based on assumptions and hypotheses, and further research should elucidate the real impact of these results on the overall health of this population.

Conclusions

Findings from this study evidence that a well-designed and supervised exercise program can induce simultaneous positive effects on body posture, functional movement quality and muscular strength in children with OW/OB. One of the main strengths of this study is that our exercise program was designed not only to improve physical fitness level but also to address postural and biomechanical alterations normally experienced in children with OW/OB. The exercise program is explained in detail to be replicated in future studies or to be put into practice. Among other potential implications, the improvements found in the present study could contribute to the prevention of current and future musculoskeletal disorders, which have been shown to be important comorbidities associated with this population. Furthermore, as a result of the increase in muscular strength and movement competence, these children are now better prepared to keep practicing exercise than before our intervention, which could contribute to increasing adherence. We encourage those professionals who work daily with this population (e.g., physical trainers, physical education teachers or physical therapists) to carry out a similar exercise intervention in order to treat together multiple comorbidities derived from childhood obesity.

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SUPPLEMENTARY MATERIAL

Table S1. Intention-to-treat intervention effects on body posture, functional movement and physical fitness.

Outcomes	Values presentation	Intervention Group (N=31) Mean (95% CI)	Control Group (N=34) Mean (95% CI)	Difference between groups	*p*
Body posture					
Craniocervical angle (°)	Raw score	142.44 (140.51 to 144.38)	142.96 (140.96 to 144.96)	-0.52	0.713
	z Score	0.06 (-0.24 to 0.36)	0.14 (-0.17 to 0.45)	-0.08	
Thoracic flexion (°)	Raw score	5.15 (4.03 to 6.28)	4.26 (3.10 to 5.42)	0.89	0.291
	z Score	0.00 (-0.29 to 0.29)	-0.23 (-0.53 to 0.07)	0.23	
Trunk angle (°)	Raw score	171.69 (170.66 to 172.72)	171.79 (170.72 to 172.85)	-0.10	0.896
	z Score	-0.19 (-0.50 to 0.12)	-0.22 (-0.54 to 0.10)	-0.03	
Lumbar angle (°)	Raw score	79.92 (76.34 to 83.5)	79.04 (75.34 to 82.73)	0.89	0.733
	z Score	-0.22 (-0.57 to 0.13)	-0.31 (-0.67 to 0.05)	0.09	
Lower limb angle (°)	Raw score	2.57 (1.92 to 3.22)	4.62 (3.95 to 5.29)	-2.05	**<0.001**
	z Score	-0.48 (-0.72 to -0.24)	0.29 (0.04 to 0.54)	-0.77	
Lower limb valgus (°)	Raw score	176.46 (175.89 to 177.04)	175.58 (174.99 to 176.17)	0.89	**0.034**
	z Score	0.24 (-0.06 to 0.53)	-0.22 (-0.52 to 0.09)	0.46	
Plumb-tragus distance (cm)	Raw score	6.03 (5.47 to 6.58)	6.95 (6.38 to 7.52)	-0.92	**0.024**
	z Score	0.12 (-0.08 to 0.33)	0.46 (0.25 to 0.67)	-0.34	
Functional movement					
Total FMS score (3-12)	Raw score	8.6 (8.13 to 9.07)	7.38 (6.90 to 7.87)	1.22	**0.001**
	z Score	0.94 (0.66 to 1.22)	0.21 (-0.08 to 0.50)	0.73	
Physical Fitness					
1RM arm/weight (kg/kg)	Raw score	0.41 (0.39 to 0.43)	0.37 (0.35 to 0.4)	0.04	**0.030**
	z Score	-0.1 (-0.29 to 0.09)	-0.42 (-0.61 to -0.22)	0.31	
1RM leg/weight (kg/kg)	Raw score	2.49 (2.32 to 2.66)	2.35 (2.18 to 2.53)	0.14	0.269
	z Score	-0.13 (-0.47 to 0.21)	-0.41 (-0.76 to -0.06)	0.28	
20m shuttle run (ml/kg/min)	Raw score	41.32 (40.50 to 42.14)	41.15 (40.3 to 41.99)	0.17	0.777
	z Score	0.25 (-0.01 to 0.52)	0.20 (-0.08 to 0.47)	0.06	
Handgrip/weight (kg/kg)	Raw score	0.36 (0.35 to 0.38)	0.34 (0.32 to 0.35)	0.03	**0.020**
	z Score	0.47 (0.24 to 0.7)	0.06 (-0.18 to 0.30)	0.41	
Standing long jump (cm)	Raw score	124.39 (119.72 to 129.07)	109.54 (104.71 to 114.36)	14.86	**<0.001**
	z Score	0.49 (0.26 to 0.72)	-0.25 (-0.49 to -0.01)	0.73	
4×10 m shuttle run (s)	Raw score	-13.93 (-14.32 to -13.54)	-14.61 (-15.01 to -14.21)	0.68	**0.018**
	z Score	0.39 (0.18 to 0.60)	0.02 (-0.20 to 0.24)	0.38	

CI = confidence interval. A one-way analysis of covariance (ANCOVA) was used to test raw and z-score differences between the intervention and control group at the post-intervention, adjusting for basic pre-intervention values. Adjusted means confidence intervals of the mean are represented. Differences between groups are presented as: post-intervention mean minus pre-intervention mean so that positive values indicate that the value was higher at the post-intervention than in the pre-intervention. Significant differences ($p<0.05$) are highlighted in bold.

SECTION 3

Study 6

Effects of exercise on plantar pressure during walking in children with overweight/obesity

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INTRODUCTION

Nearly a third of 11 year-old children in the European Union are overweight/obese (OW/OB) [1]. Increasing levels of physical activity is widely accepted as one of the most feasible strategies for preventing childhood OW/OB. This can be achieved by increasing the time spent walking - the most common physical activity of daily life [2]. However, children with OW/OB are prone to experience alterations in their plantar pressure while walking [3–5]. Indeed, there is now good evidence that, compared to their normal weight counterparts, children with OW/OB experience increases in a range of plantar pressure variables, especially over the midfoot and over the second to fifth metatarsal heads [4–8]. These high pressures are associated with a pronated foot pattern [5, 9], leaving children with OW/OB at risk of developing movement-derived musculoskeletal disorders [10]. This might induce a vicious circle in which children with OW/OB undertake less physical activity, increasing their risk of gaining weight [11].

Physical activity guidelines for children recommend weight-bearing activities to strengthen their musculoskeletal system [12]. However, the biomechanical alterations described above suggest that programs for children with OW/OB need to be carefully designed in order to avoid exercise-derived foot pain and discomfort. Two recent studies tested the effectiveness of specific exercise programs for children with OW/OB on modifying plantar pressures towards the profile of normal weight children [13, 14]. One, which involved a 10 week face-to-face physical activity program, followed by a further 12 weeks of unaccompanied physical activity [13], reported no significant improvement. The other, however, which involved a 6-month intensive multi-component (exercise, diet, and locomotion-emphasis) program, reported more successful results [14]. Given such contradictory findings, and the scarcity of studies in this area, further studies to examine the effects of exercise interventions on plantar pressure in children with OW/OB are warranted. The aim of the present work was to analyze the effect of a 13-week exercise program based on "movement quality" and "multigames" work, on plantar pressure during walking in children with OW/OB.

METHOD

Study design and participants

This non-randomized controlled trial named *'MUévete Bien'* project (MUBI) ("Move well" in English) was approved by the Review Committee for Research Involving Human Subjects at the University of Granada (Spain) (nº 279/CEIH/2017). The study sample were 70 children (10.8 ± 1.2 years, 32 girls) who met the following criteria: 1) to be 8-12.9 years-old; 2) to be classified as children with OW/OB as defined by sex and age-specific World Obesity Federation cut-offs [15]; 3) to suffer no physical disabilities or neurological disorders that might impede them doing exercise; 4) in the case of girls, to have *not* reached menarche at the moment of baseline assessment; 5) to take no medications that might influence central nervous system function; 6) to be right-handed (as measured by the Edinburgh inventory) [16] (the brain hemisphere structure of right-handed children differs substantially from that of left-handed children); and 7) to have *not* been diagnosed with attention-deficit hyperactivity disorder (ADHD). Further information on the study design can be found at (http://profith.ugr.es/mubi?lang=en).

Of these 70 children, 51 were included in a per-protocol analysis (see Statistical Analysis) after 1) completing the pre- and post-exercise assessments; and 2) completing at least 70% of the recommended 3 exercise sessions/week (for the exercise intervention group; see below) (**Figure 1**).

The exercise intervention group of the MUBI project was made up of children who had participated during the previous year as control group participants in the ActiveBrains study [17]. For ethical reasons, these children were offered the chance to take part in the present study as members of the intervention group; they did not have the opportunity to exercise in ActiveBrains study due its randomization process. The present MUBI project control group was re-

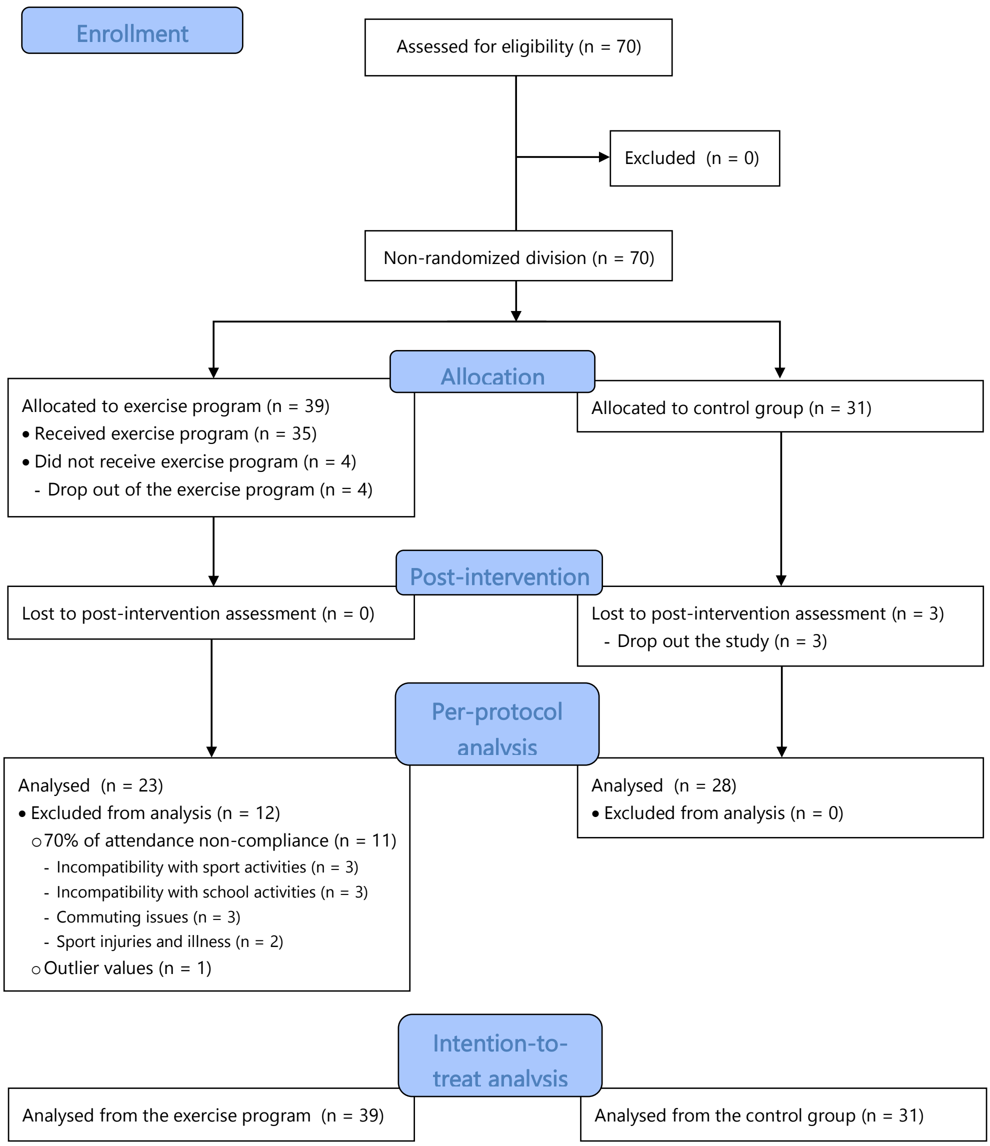

Figure 1. Flow diagram describing the configuration of the per-protocol and intention-to-treat analyses.

cruited from public and private schools in Granada (Spain) adhering to the above-mentioned inclusion/exclusion criteria. Parental informed consent was required for all children to participate in the study. The participants' anthropometric and plantar pressure variables were measured before and after the intervention period.

Anthropometric measurements

Body height (cm) and weight (kg) were determined in a quiet room by trained evaluators using a stadiometer (SECA Instruments, Hamburg, Germany); body mass index (BMI [kg/m²]) was then calculated. The maturational stage of the participants was determined via their peak height velocities, calculated as per Moore's equations [18].

Plantar pressure during walking

Participants were asked to walk barefoot 10 times along a 10 m-long corridor with a 0.4 x 1.84 m long FreeMed® Pro pressure platform (Sensormedica, Rome, Italy) in the middle. This platform had 450,000 pressure sensors (resolution 2 sensors/cm²; monitoring frequency 200 Hz). Familiarization trials were performed to ensure participants walked at a comfortable pace, and that they did so naturally. Participants struck the platform no sooner than their fourth step to ensure that a constant velocity had been reached prior to first contact [19]. FreeStep® software v.1.5 (Sensormedica, Rome, Italy) was used to automatically generate individual foot masks, dividing the foot into 11 regions. Plantar pressure variables were measured in the three areas most commonly analyzed in the literature: the forefoot (from 1st to 5th metatarsal heads, toes and hallux), midfoot (medial and lateral midfoot), and rearfoot (medial and lateral rearfoot) (See **Figure 2**, the eleven-region foot division provided by FreeStep® software). Measurements of foot length (mm), plantar surface area (cm²), maximum force (N), and force-time integrals (N/s) were calculated by averaging all trials for each foot. Between 8 and 20 (maximum available) valid footprints were included for each subject. Footprints were deemed valid when: 1) the subject did not lose balance during gait; 2) was not distracted (e.g., looking around or speaking) while walking; and 3) the whole plantar surface was recorded. The first two criteria were controlled during the assessment; the third was later checked visually by the same evaluator. The use of a minimum eight footprint per child adheres to the recommendations of McPoil et al. [20] who reported a reliability plateau being reached when 5-7 trials were averaged. To avoid problems derived from paired data, plantar pressure outcomes of left and right feet were averaged into a single observation [21].

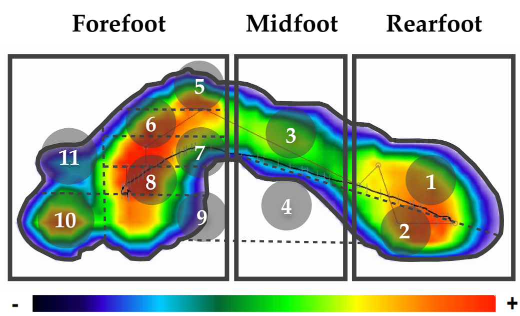

Figure 2. The eleven-region foot division provided by FreeStep® software.
1: lateral rearfoot; 2: medial rearfoot; 3: lateral midfoot; 4: medial midfoot; 5: 5th metatarsal; 6: 4th metatarsal; 7: 3rd metatarsal; 8: 2nd metatarsal; 9: 1st metatarsal; 10: hallux; 11: 2nd to 5th toes..

Foot pain

The Pediatric Pain Questionnaire™ was used to record self-reported musculoskeletal pain [22]. Children were categorized as reporting the "presence of foot pain" when they indicated any pain intensity (i.e., mild, moderate or severe) on a body map, or "no-presence of foot pain" when no pain was indicated. Before completing the questionnaire, a trained evaluator explained to the children the type of pain they should report. All reported pain was reviewed to discard non-musculoskeletal pain.

Exercise program

Thirty-nine children were assigned as described above to a 13-week exercise intervention group (EG). The exercise program was undertaken at the Sport and Health University Research Institute (iMUDS) (iMUDS – University of Granada) between 1st March and 29th May 2017. Group sessions were run from Monday to Friday, and participants were asked to attend a minimum of three per week. Sessions lasted 90 min and were divided into two different parts: 30 min of "movement quality" work and 60 min of "multi-games". The "movement quality" component had the aims of allowing children to acquire an awareness of analytical movement patterns (e.g., anterior and posterior pelvic tilt) and body posture (e.g., optimal spine position), to gain body segment mobility (e.g., hip flexion mobility) and stability (e.g., core stability), to gain muscular strength over a functional range of motion (e.g., bilateral lower limb push strength), and to learn basic exercise patterns (e.g., squat pattern). The "multi-games" component had the aims of allowing children to reach a moderate-to-vigorous intensity of aerobic exercise, to help them learn a wide range of fundamental movement skills (e.g., sprinting, hopping or throwing), and to make physical exercise more enjoyable. **Figure 3** describes a typical session. Further details of the exercise program are available at (http://profith.ugr.es/pages/investigacion/recursos/mubi?lang=en#__doku_exercise_program). No specific dietary intervention was conducted. The control group, formed as described above, was comprised of 31 children.

Statistical analysis

Prior to performing the analyses, the data were winsorized to limit the influence of outlier values [23]. One of the participants was excluded due to extreme values being returned for all plantar pressure variables. All variables were then checked for normal distribution via the visual inspection of histograms. The plantar surface area, maximum force and force-time integrals for the midfoot, as well as the modified arch index, showed non-normal distributions; the data were therefore square root- or Napierian logarithm-transformed as required. Raw continuous variables were recorded as means and standard deviations (SDs), normalized continuous variables were recorded as medians and interquartile ranges, and categorical variables as percentages.

The pre-intervention differences between the EG and CG participants were examined via independent t tests and Chi-squared tests (continuous and categorical variables respectively). The effects of the exercise program were tested according to per-protocol analysis, which required EG participants to complete a minimum 70% of their exercise sessions [23]. Pre-intervention z-scores were calculated for each variable for all participants. Post-intervention z-scores were calculated contemplating the pre-intervention z-scores, via the following formula: (subject post-intervention score – sample mean pre-intervention score) / sample pre- intervention SDs. One-way analysis of covariance (ANCOVA) was

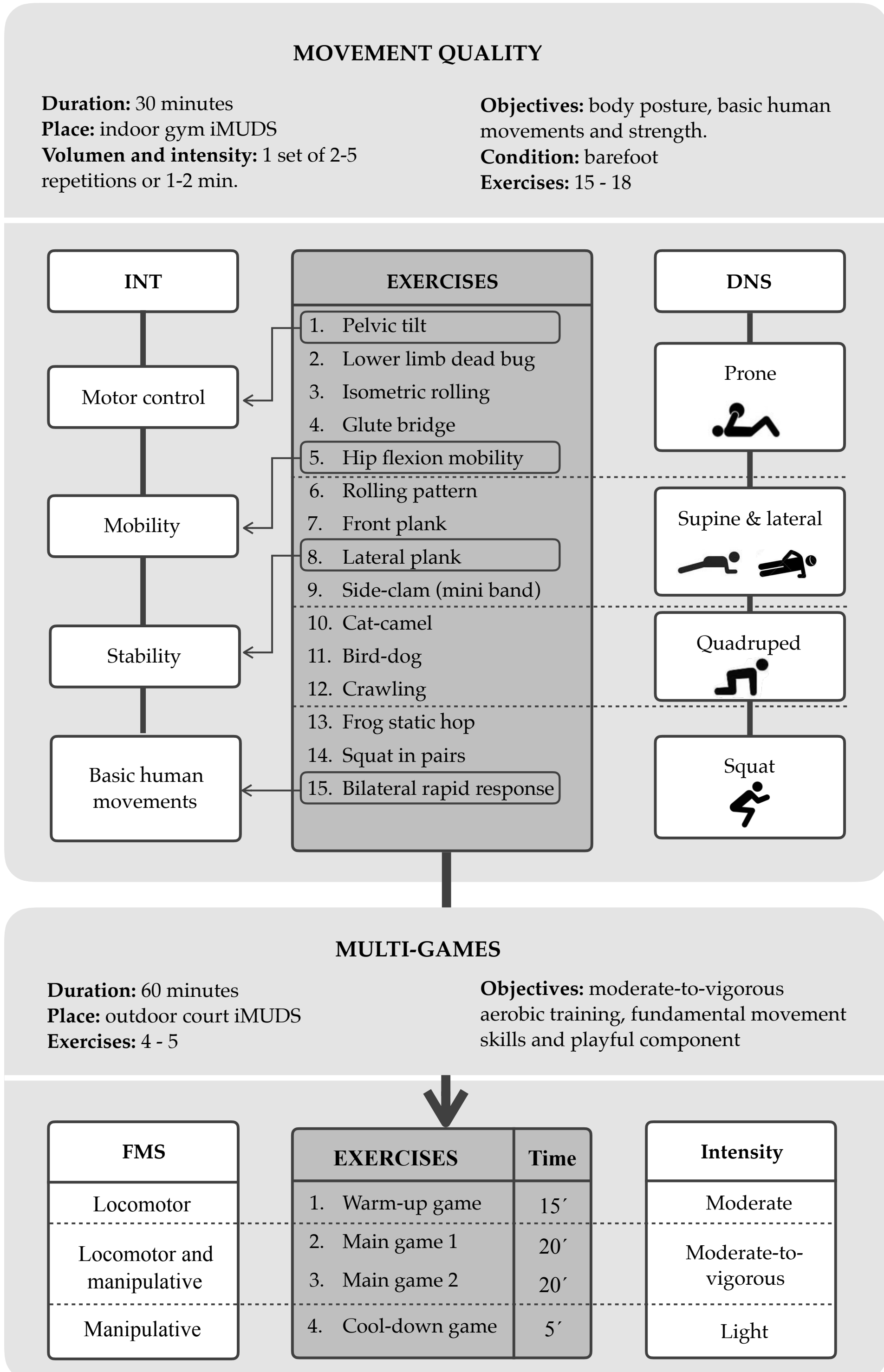

Figure 2. Example of the two parts of the training program.
INT: Integrative neuromuscular training; DNS: dynamic neuromuscular stabilization; FMS: functional movement skills.

and plantar pressure outcomes during walking between the EG and CG groups in the post-intervention assessment, adjusting for pre-intervention values. Differences (pre-intervention – post-intervention) in all outcomes were presented as raw scores and z-transformed values; these latter values were interpreted as the change in SD since the pre- intervention period and were used as an indicator of effect size (value around 0.2=small effect size; 0.5=medium effect size; and 0.8=large effect size) [24]. Additional confounders such as age, gender, maturational stage, body mass index, foot length and gait speed were included in the ANOVA models but discarded after verifying that they had no influence. Supplementary analyses were conducted using the intention-to-treat principle, which included the whole initial sample of 70 children. Multiple imputation was performed for missing values [23]. From this point the intention-to-treat analysis followed the same process as the per-protocol analysis. McNemar's test was used to examine differences in pre- and post-intervention foot pain between the EG and CG groups. All analyses were performed using SPSS software v.24.0. Significance was set at p<0.050.

RESULTS

Table 1 shows the pre-intervention characteristics of the entire sample and of the EG and CG groups. The EG participants were older, their weight, height and BMI were higher, and the proportion of girls was higher than in the CG group (all p<0.05).

Table 1. Pre-intervention characteristics of the total sample and divided by intervention and control group for the per-protocol analysis

	All (n=51)	Intervention (n=23)	Control (n=28)	*P*
	Mean ± SD	Mean ± SD	Mean ± SD	
Age (years)	10.8 ± 1.2	11.3 ± 1.0	10.4 ± 1.1	**0.002**
Weight (kg)	57.1 ± 13.2	62.8 ± 9.2	52.4 ± 14.2	**0.004**
Height (cm)	148.0 ± 9.3	151.5 ± 6.7	145.2 ± 10.2	**0.015**
Body mass index (kg/m^2)	25.7 ± 3.8	27.3 ± 3.3	24.4 ± 3.7	**0.005**
Gender				**0.002**
Girls	63%	39%	82%	
Boys	37%	61%	18%	
Dynamic plantar pressure				
Foot length (mm)	222.4 ± 17.3	230.5 ± 13.6	215.7 ± 17.4	**0.002**
Footprint Surface (cm^2)				
Total foot	46.4 ± 10.	51.7 ± 7.1	42.1 ± 10.1	**<0.001**
Forefoot	25.4 ± 5.1	28.2 ± 4.0	23.2 ± 4.8	**<0.001**
Midfoot [a]	2.22 ± 1.26	2.53 ± 1.24	2.07 ± 0.92	**0.019**
Rearfoot	15.8 ± 3.1	17.1 ± 2.5	14.7 ± 3.1	**0.005**
Modified arch index [b]	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.114
Maximal force (N)				
Forefoot	326.9 ± 75.3	347.2 ± 73.0	310.3 ± 74.3	0.082
Midfoot [a]	6.43 ± 4.17	7.87 ± 4.42	5.65 ± 3.78	0.077
Rearfoot	244.6 ± 55.4	256. ± 42.8	235.2 ± 63.3	0.187
Time-force integral (N/s)				
Forefoot	185.8 ± 68.9	217.8 ± 55.1	159.6 ± 68.7	**0.002**
Midfoot [a]	4.46 ± 3.93	5.66 ± 3.93	4.07 ± 2.84	0.066
Rearfoot	144.2 ± 48.7	155.6 ± 46.3	134.9 ± 49.4	0.131
Musculoskeletal pain				
Presence of foot pain *	26%	37%	19%	0.171
Additional confounders				
Peak high velocity (yr)	-1.03 ± 1.14	-1.15 ± 1.14	-0.96 ± 1.16	0.560
Gait speed (km/h)	3.78 ± 0.50	4.06 ± 0.43	3.62 ± 0.55	**0.007**

SD = standard deviation; n=sample size; N = Newton.

[a] Outcome normalized through square root, and expressed in Median ± interquartile range.

[b] Outcome normalized through Neperian logarithm, and expressed in Median ± interquartile range.

* N was 47 (19 exercise group and 28 control group) for presence of foot pain at pre- and post-exercise.
Values are presented as mean ± SD or percentages. For continuous variables, p value was obtained by an independent samples T-test, whereas for categorical variables, p value was obtained by chi-square test.
Significant differences ($p < 0.05$) are highlighted in bold.

The EG participants also had a greater plantar surface area for the total foot, forefoot, midfoot and rearfoot, and returned higher force-time integrals for beneath the forefoot (all $p<0.05$). **Table 2** shows the results of the one-way ANCOVA analyses to explore the post-intervention differences between the EG and CG groups, adjusting for pre-intervention values.

Table 2. Per-protocol intervention effects on plantar pressure.

	Adjusted post-intervention mean (95% CI)			
Total sample = 51	Intervention group (n = 23)	Control group (n = 28)	Groups difference (IG – CG)	*P*
Anthropometry				
Body weight (kg)				
Raw score	59.12 (58.13 to 60.11)	58.23 (57.36 to 59.1)	0.88	0.203
z Score	0.15 (0.08 to 0.23)	0.09 (0.02 to 0.15)	0.07	
Height (cm)				
Raw score	150.91 (150.22 to 151.61)	150.43 (149.82 to 151.04)	0.48	0.315
z Score	0.31 (0.23 to 0.38)	0.26 (0.19 to 0.32)	0.05	
BMI (kg/m^2)				
Raw score	25.59 (25.2 to 25.99)	25.44 (25.1 to 25.79)	0.15	0.593
z Score	-0.04 (-0.14 to 0.07)	-0.08 (-0.17 to 0.02)	0.04	
Foot length (mm)				
Raw score	230.87 (228.84 to 232.91)	231.92 (230.1 to 233.75)	-1.05	0.465
z Score	0.49 (0.37 to 0.61)	0.55 (0.45 to 0.66)	-0.06	
Dynamic plantar pressure				
Surface (cm^2)				
Total foot				
Raw score	53.89 (52.51 to 55.27)	56.36 (55.13 to 57.6)	-2.47	**0.015**
z Score	0.75 (0.61 to 0.89)	0.99 (0.87 to 1117.)	-0.25	
Forefoot				
Raw score	30.07 (28.94 to 31.2)	30.28 (29.28 to 31.29)	-0.21	0.793
z Score	0.91 (0.69 to 1134.)	0.95 (0.76 to 1152.)	-0.04	
Midfoot [a]				
Raw score	2.78 (2.69 to 2.87)	2.86 (2.77 to 2.94)	-0.08	0.239
z Score	0.63 (0.47 to 0.78)	0.73 (0.59 to 0.87)	-0.11	
Rearfoot				
Raw score	17.1 (16.52 to 17.67)	17.88 (17.37 to 18.39)	-0.78	0.054
z Score	0.43 (0.25 to 0.62)	0.69 (0.52 to 0.85)	-0.26	
Modified arch index [b]				
Raw score	0.35 (0.34 to 0.36)	0.36 (0.34 to 0.37)	-0.01	0.437
z Score	0.41 (0.26 to 0.56)	0.51 (0.38 to 0.65)	-0.10	
Maximal force (N)				
Forefoot				
Raw score	331.32 (317.36 to 345.27)	306.54 (293.94 to 319.15)	24.78	**0.012**
z Score	0.06 (-0.13 to 0.24)	-0.27 (-0.44 to -0.1)	0.33	
Midfoot [a]				
Raw score	7.83 (7.5 to 8.16)	7.77 (7.47 to 8.07)	0.07	0.774
z Score	0.31 (0.19 to 0.43)	0.27 (0.16 to 0.38)	0.04	
Rearfoot				
Raw score	231.4 (218.8 to 244.)	221.55 (210.15 to 232.95)	9.85	0.254
z Score	-0.24 (-0.47 to -0.01)	-0.42 (-0.62 to -0.21)	0.18	
Force-time integral (N/S)				
Forefoot				
Raw score	229.49 (209.92 to 249.05)	207.6 (190.04 to 225.16)	21.89	0.117
z Score	0.63 (0.35 to 0.92)	0.32 (0.06 to 0.57)	0.32	
Midfoot [a]				
Raw score	6.14 (5.81 to 6.47)	6.11 (5.81 to 6.41)	0.03	0.898
z Score	0.59 (0.36 to 0.82)	0.47 (0.27 to 0.68)	0.12	
Rearfoot				
Raw score	1.76 (1.57 to 1.95)	1.74 (1.57 to 1.91)	0.02	0.865
z Score	0.49 (0.15 to 0.84)	0.17 (-0.14 to 0.49)	0.32	

CI = confidence interval; n=sample size; N=Newton.
[a] Outcome normalized through square root.
[b] Outcome normalized through Neperian logarithm.
A one-way analysis of covariance (ANCOVA) was used to test raw and z-score differences between the intervention and control group at the post-intervention, adjusting for basic pre-intervention values. Adjusted means and confidence intervals of the

mean are represented. Differences between groups are presented as: post-intervention mean minus pre-intervention mean. Significant differences (p < 0.05) are highlighted in bold.

Figure 3 provides a schematic overview of the main significant changes in plantar pressure characteristics. Similar anthropometric growth (i.e., weight, height, BMI and foot length) was recorded for both groups after the 13-week intervention period (all p>0.05). Compared to the CG participants, the EG participants showed a significantly smaller increase in plantar surface area (small effect size: -0.25 SDs; p=0.015). The forefoot and midfoot surfaces, as well as the modified arch index, remained unaltered for both groups after the study period (all p>0.05). A border-line difference was seen between the groups after the intervention period in terms of the rearfoot surface area, with the EG participants showing a slightly smaller increase (small effect size: -0.26 SDs; p=0.054). After the intervention period, the EG participants showed a significantly greater increase in maximum force (small effect size: 0.33 SDs; p=0.012) applied beneath the forefoot area, specifically beneath the lateral and medial forefoot than observed for the CG participants (See **Figure 4**, differences in maximum force between EG and CG beneath the three regions of the forefoot**)**.

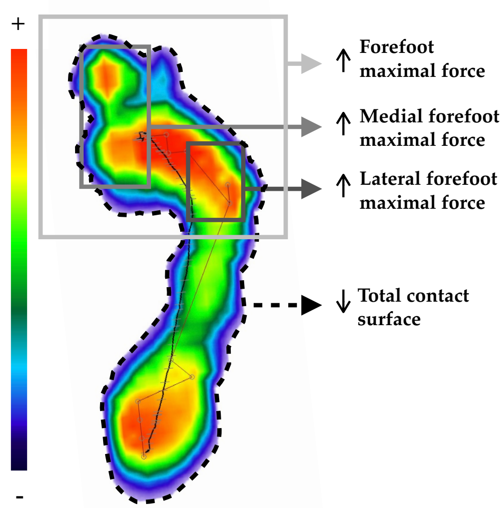

Figure 3. Changes (all p<0.05) in plantar pressure during walking experienced by the EG and CG participants.

ANCOVA was used to examined the differences in maximum force and contact surface area between EG and CG groups, adjusting for pre-intervention values. The colored bar provides a qualitative representation of the pressure values, from lower (black-blue) to higher (orange-red) pressure.

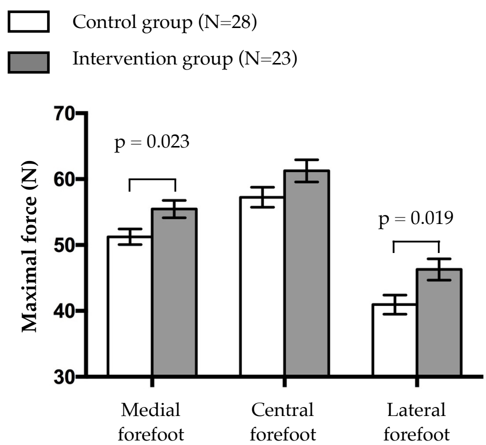

Figure 4. Differences in maximum force between the intervention and control groups beneath the three regions of the forefoot.

A one way analysis of covariance (ANCOVA) was used to test differences in maximum force on the three regions of forefoot between intervention and control groups, adjusting for pre-intervention values. Adjusted means and standard error of the mean are represented.

These significant differences in total plantar surface area and forefoot maximum force results remained significant after adjusting for subject maturational stage (data not shown). No significant differences were seen between the groups for any remaining maximum force variables (all p>0.05). No differences in force-time integrals were seen between the EG and CG participants at the end of the intervention period (p>0.05). Both the EG and CG participants reported reduced foot pain (from 37 and 19% at pre-intervention, to 26 and 7% at post-intervention respectively), although no change was significant (both p>0.05).

Table 3 (effects on plantar pressure in the whole sample) shows the intention-to-treat analysis. Briefly, all significant results found in the per-protocol analysis disappeared. On the contrary, the increase in the maximum force supported by the EG participants beneath the rearfoot was greater than that observed for the CG participants (p=0.025).

DISCUSSION

By the end of the intervention period, the EG participants showed no significant change in total plantar surface area during walking, whereas the CG participants experienced a significant increase. The maximum force supported beneath the forefoot (specifically beneath the lateral and medial forefoot) increased in the EG participants more than in the CG participants, while the force-time integrals changed similarly in both groups.

To our knowledge, only two previous studies have reported on the effects of exercise interventions on plantar pressures in children with OW/OB during walking [13, 14]. Steinberg et al. [14] reported significant reductions in total plantar surface area, maximum force and force-time integrals in children who took part in an obesity management/locomotion-emphasis program, while no reductions were seen among those who took part in obesity management alone. In the present study, no change in plantar surface area was seen for the EG participants, but it increased in the CG participants. It is important to remember that children's feet grow, thus, a reduction in plantar surface area might be deemed unlikely to occur [4]. Unlike Steinberg et al. [14], no reduction was seen in maximum force or force-time integrals for the present EG participants; rather, an increase in maximum force was recorded beneath the forefoot. The fact that the exercise program proposed by Steinberg et al. [14] was twice as long as the present intervention might could indicate that longer intervention programs are necessary for force reductions to be detected.

The findings of Riddiford-Harland et al. [13] contrast with those of Steinberg et al. [14]; they detected no change in foot anthropometric measurements induced by their exercise program, and an increase in the force-time integrals for the medial and lateral regions of the forefoot in those who followed it [13]. In the present work, the force-time integrals increased similarly in both groups, but the change in the maximum force applied beneath the forefoot in the EG participants was greater than that seen in the CG participants. It should be noted that the children examined by Steinberg et al. [14] wore shoes, while those examined by Riddiford-Harland et al. [13], and the present children, were barefoot. Shoe-wearing is known to impact the biomechanics of gait (i.e., impact forces, contact surface and plantar pressure distribution) [25]; the present findings are therefore more comparable with those of Riddiford-Harland et al. [13].

A greater plantar surface area has been related to pediatric obesity - partially explained by the greater prevalence of pes planus in this population [4, 26]. It is therefore reasonable to assume that the present plantar surface area values for the EG group imply positive changes in the morphology and functionality of their feet [26]. This finding cannot be attributed to different foot growth between the groups, since foot length had changed similarly in both the EG and CG groups by the end of the intervention period, suggesting exercise related adaptation to be the cause. Neither can these changes be explained by differences in maturation between the groups, since the results remained similar after taking into account subject maturational stage at pre- and post-intervention.

The maximum force increase under the medial and lateral forefoot recorded for the EG participants might indicate a change towards a more normal foot rollover pattern, specifically during the push-off phase during which forces shift from the lateral (5th and 4th metatarsal) to the medial (1st metatarsal and hallux) regions of the forefoot [27, 28]. In fact, studies in adults with normal foot functionality during walking reveal that the medial and lateral forefoot are the regions that support the greatest forces; they are therefore the structures best prepared to absorb mechanical stress [28]. However, it could also be that the EG participants had begun to acquire a more adult gait pattern. The literature records a shift towards forefoot forces in children with increasing age, and in adults compared to children [4, 29]. This increase in maximum force in the EG participants cannot, however, be attributed to changes in anthropometric measures; both groups experienced similar changes in weight, height and BMI.

Some authors have suggested that an increase in the forces supported by the foot while walking - as observed for the forefoot maximum force in the EG participants - could be a risk factor in the development of foot pain [3, 13]. However, it has also been suggested that force-time integrals are more important than maximum force when assessing risk factors of foot structural damage, since the former take into account the accumulation of forces being applied in a certain region of the foot over time [30]. In this regard, the force-time integrals recorded for both the EG and CG participants had increased similarly by the end of the intervention period, which might be attributable to the natural maturation of their gait [29]. The children of both groups reported the presence of less foot pain at post-intervention, although the difference was not statistically significant in either group. It is important to note that children with OW/OB normally experience lower limb pain (e.g., foot pain) during sports or physical activities, and have an injury risk per exposure of >35% [31]. The reason underlying the reduced foot pain in the CG participants (though this did not reach significance) might be that the pre-intervention assessment was conducted in February; Spanish children typically practice greater physical activity in February than in July (when the academic year and after-school activities have ended). Interestingly, the EG participants also reported a reduced presence of foot pain prevalence even though the children exercised more intensely during last phase of the intervention. However, the foot pain reported in the present work was mostly mild or moderate, and did not limit the daily physical functioning or physical activity of any subject. Follow-up studies might determine whether physical exercise helps in the prevention of more severe foot pain in children with OW/OB.

A recent systematic review reported that children with OW/OB experience biomechanical (i.e., spatiotemporal, kinetic, kinematic and muscle activation) alterations of the lower limbs that could play a role in the development of musculoskeletal disorders [10]. These alterations are commonly connected. For example, foot dysfunctions during walking in children have been shown linked to lower limb malalignment such as dynamic knee valgus [32]. The improvement in foot dynamics observed in the EG participants might not, therefore, be occurring in isolation, but in combination with other biomechanical changes. Although the evidence is limited, physical exercise and gastrectomy weight-loss interventions have been shown effective in counteracting the biomechanical malalignments of the lower extremities experienced by children with OW/OB [33, 34]. Future research should test whether positive effects of exercise on foot loading patterns are related to other lower limb biomechanical changes (e.g., kinetics or kinematics) in this population group.

Four explanations may be contemplated for the plantar pressure changes induced by the exercise program. The first derives from the logical assumption that any weight-loss induced would reduce the forces supported by the foot while walking [13]. This idea must be rejected, however, since neither the EG participants nor the CG experienced any fall in body weight. The second suggests a strengthening of key muscles involved in raising the foot arch, such as the tibialis posterior or flexor hallucis longus [35, 36]. The third is related to the "movement quality" work of the session. Performed barefoot, this could have helped in the activation of the flexor digitorum brevis and abductor hallucis muscles, with positive adaptations in the bone and ligament configurations of the foot [35, 36]. Finally, there may have been an improvement in the capacity to generate power through explosive tasks (such as jumping or sprinting) performed in the "multigames" work; this could have led to more optimal balance and functioning of the ankle and foot muscles [37]. A combination of the last three possibilities would seem the most plausible.

Exercise interventions are an effective treatment for childhood obesity, with positive benefits for the overall health of children [38]. The fact that the present intervention improved foot functionality during walking shows that exercise interventions based on "movement quality" and "multigames" may be an effective means of treating dysfunctional foot dynamics in this population. However, caution should be exercised when drawing conclusions; further research is needed if the present results are to be reliably interpreted.

The present findings add to those reported by Riddiford-Harland et al. [13] and Steinberg et al. [14], and provide yet more reasons to promote physical exercise as a means of preventing foot discomfort and pain, especially at this critical stage of life when the feet are still developing [29]. Traditionally, in-shoe orthoses have been the most-used conservative treatment for foot dysfunction, but a recent systematic review has highlighted the limited evidence of their effectiveness [39]. Future studies should try to confirm whether physical exercise offers an alternative way of preventing - or even reversing - dysfunctional foot dynamics in children with OW/OB, or whether it should be seen as a complementary treatment.

The present work suffers from three main limitations. First, no foot anthropometric measurements were taken via imaging (such as X-ray or magnetic resonance imaging) which would have allowed the impact of the intervention on foot bone structural changes to be determined. Second, the pressure platform used was of medium range resolution, which could have influenced the plantar pressure results. Third, assignment to the EG or CG was ethically determined rather than via a randomization process; consequently, pre-intervention differences between the groups existed. Although these were subject to statistical control (adjustment for the pre-intervention values of the study variables), they may have had some influence on the primary outcomes.

Conclusion

This study shows that a 13-week exercise program, based on "movement quality" and "multigames" work, maintained the total plantar pressure surface and increased the maximum force supported beneath the forefoot (specifically beneath the lateral and medial forefoot) in a sample of children with OW/OB. These results suggest the exercise program led to positive functional changes in foot dynamics during walking. However, the increased maximum force supported beneath the forefoot - even though it might indicate a change towards a normal foot rollover pattern and a more mature gait - has the potential to cause foot pain and discomfort. Further work should attempt to confirm whether (and how) physical exercise can used as an effective means of preventing, and even reversing, foot dysfunctions in children with OW/OB.

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SECTION 3

Study 7

Effects of a 13-week exercise program on the gait biomechanics of children with overweight and obesity

Draft

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INTRODUCTION

Overweight/obesity (OW/OB) in childhood has risen alarmingly in the last decades in most countries around the world with severe consequences on the overall health of children [1, 2]. Among other consequences, OW/OB impairs daily locomotor activities of children, even one as fundamental as walking. A recent systematic review revealed biomechanical alterations during gait in this population, which could lead to the development of musculoskeletal disorders and an energetic inefficiency during walking [3].

It is evident that the excess of body mass in these children plays a major role in the force parameters of gait (e.g., joint moments and contact forces), but some spatiotemporal and joint angle (i.e., kinematics) parameters have also been demonstrated to be affected [3]. Based on a strong level of evidence, children with OW/OB walk with longer stance time, a wider step and a more accentuated genu valgum position during the stance phase compared with their normal weight peers [3]. Exercise interventions have been proposed as a promising treatment to combat these biomechanical alterations through three main mechanisms [4–6]: 1) weight loss, 2) muscle strengthening and 3) neuromuscular reeducation of movement patterns. However, to date we are only aware of three previous studies testing the effect of exercise on biomechanical gait parameters in children and adolescents with OW/OB.

An 8-week high intensity aerobic program had positive effects on gait speed and energetic efficiency in adolescents with obesity, but authors did not study improvements in additional spatiotemporal parameters such as stance time [7]. Two previous exercise programs, one involved strength and neuromuscular training, and the other one involved a yoga intervention (12 and 8 weeks of duration respectively), found a reduction in the genu valgum position during the stance phase of walking in children and adolescents with OW/OB [8, 9]. Given the scarce literature on this research topic, further studies are needed to continue investigating whether exercise per se, and different exercise modalities, can be an effective treatment to diminish the gait biomechanical alterations from childhood obesity. Thus, the main aim of the present study was to analyze the effect of a 13-week exercise program, based on movement quality and multi-games, on spatiotemporal and kinematic parameters of gait in children with OW/OB. As a secondary aim, we studied the effect of the exercise program on the presence of lower limb musculoskeletal pain in children with OW/OB.

METHODS

Study design and participants

This study belongs to the MUBI (MUévete BIén in Spanish; Move Well in English) project, a non-randomized controlled trial carried out in Granada (Spain) from February to July 2017. A subsample of 50 children between 8 and 12 years old (25.85 ± 3.58 kg/m2, 62% girls) from the MUBI project participated in this particular study after meeting inclusion/exclusion criteria previously published [10]. For ethical reasons, the EG of this study was composed of children who had participated in the ActiveBrains study as a control group, and who had not yet had the opportunity to take part in an exercise program because of the randomization procedure [11]. The CG was recruited from primary schools in Granada (Spain) following the same inclusion/exclusion criteria, and we also offered them to participate in the exercise program the following year. All 50 children were included in the intention-to-treat analysis and 42 in the per-protocol analysis (**Figure 1**).

Three-dimensional gait kinematics

Three-dimensional gait kinematics was evaluated using a motion capture system composed of eight high-resolution cameras (Optitrack Prime 41, Corvallis, Colorado, USA)

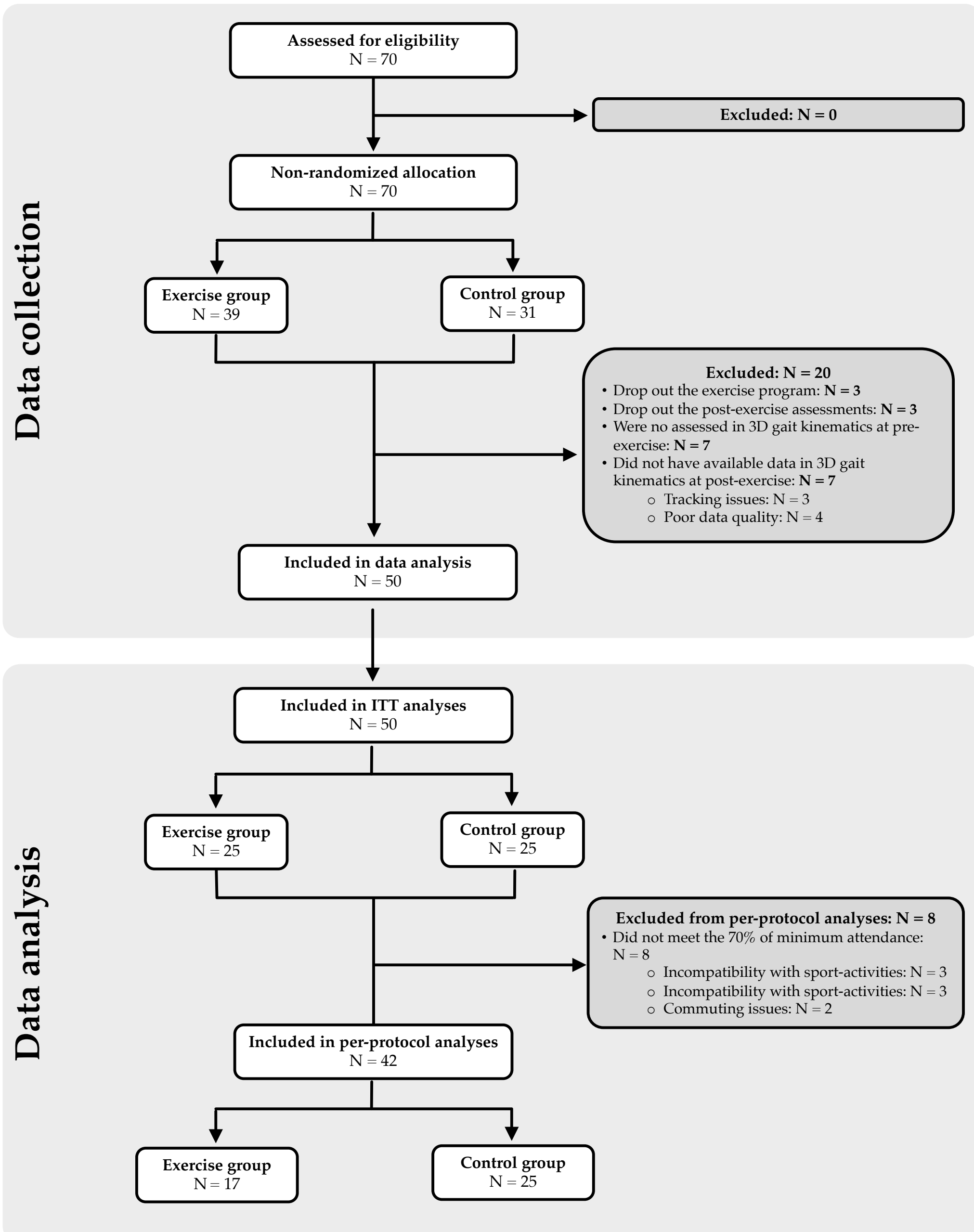

Figure 1. Flow diagram describing the data collection and data analysis processes.

operating at 180 Hz, the SIMI motion software (SIMI Motion 5.0 Reality Motion Systems, Unterschleissheim, Germany) and a twenty-one marker model according to the International Society of Biomechanics (ISB) standard [12]. Before gait recording, an upright static trial in anatomic position was recorded to calibrate the motion trials. Children walked barefoot during 15 s on a treadmill (Woodway Pro XL, Waukesha, WI, USA) at a self-selected speed, which was determined in a prior familiarization trial. The same speed was used at post-exercise to not influence gait kinematics based on changes in walking speed [13, 14]. Upright static trials and a minimum of seven valid gait cycle motions were exported for subsequent analysis in Visual 3D software 4.96.11 (C-Motion, Inc., Germantown, MD, USA).

First, an upright static trial was used to create the lower limbs segment (i.e., pelvis, femur, shank and foot) and the joint centers (i.e., pelvis, hip, knee and ankle) posteriorly used in the motion trials. Second, marker trajectories were filtered using a low-pass Butterworth filter with a cut-off frequency of 7 Hz. We selected this filter frequency after performing a residual analysis with different cut-off frequencies (i.e., 3 to 10 Hz) and considering previous literature in this population [15, 16]. Third, joint angular displacements of pelvis, hip, knee and ankle in all three planes (sagittal, frontal and transversal) were calculated as the relative orientation of the distal segment to the proximal segment. After verify that there were no overall kinematic asymmetries between both lower limbs, we decided to analyze the right lower limbs for all participants. Fourth, gait events (heel contact and toe off) were automatically calculated in Visual 3D based on the kinematic data using previously described algorithm in gait analysis [17]. Fifth, based on these events the gait cycle was divided in stance phase (from right heel contact to right toe off) and weight acceptance phase (from right heel contact to left toe off), and subsequently spatiotemporal parameters were calculated considering the gait speed and height of participants [18]. Sixth, range of motion (ROM) and maximum displacement angles were calculated in key joints, plane and gait phases previously reported in the literature of this population [3, 8]. Seventh, we detected the most representative stride out of the seven strides we captured in each participant using the approach of Sangeux and Polak [19]. From this representative stride we selected the above-mentioned spatiotemporal parameters, ROM, maximum displacement and kinematics curves normalized to 100% of the stance phase. We focused on the stance phase because a recent systematic review reported gait biomechanical alterations in this phase but not in swing phase for children with OW/OB [3].

Musculoskeletal pain

The Pediatric Pain Questionnaire™ was used to identify self-reported musculoskeletal pain [20]. Children were instructed to highlight on a body map the areas where they usually feel pain, and 4 different colors were used to indicate the intensity of this pain (i.e., low, mild, moderate and severe). Before the children filled in the questionnaire, an instructed evaluator explained the type of pain the children should report, and immediately after, each questionnaire was reviewed to discard non-related musculoskeletal pain (i.e., head or stomach pain). Based on this questionnaire, children were categorized as follows: 1) presence of pain (“yes” or “no”) in any body area of lower limbs (e.g., knee pain), and 2) overall presence of pain in lower limbs (i.e., feet, knees, hips and lumbar spine).

Potential confounders

Body height and weight were measured to the nearest 0.1 kg and 0.1 cm respectively (SECA Instruments, Germany), and body mass index (BMI, kg/m^2) was calculated. The maturational stage of the children was determined by calculating the peak height velocity with the Moore's equations, which use participants' age and standing and sitting height [21].

Exercise program

The exercise program was undertaken at the Sport and Health University Research Institute (iMUDS) between the 1st of March and the 29th of May of 2017. Group sessions were offered from Monday to Friday, and participants were asked to attend minimum three sessions per week. Sessions lasted 90 min and were divided into two different parts: 30 min of movement quality work and 60 min of multi-games. During the movement quality part children acquired awareness in their movements (e.g., anterior and posterior pelvic tilt) and body posture (e.g., optimal spine position), they trained joint mobility (e.g., hip flexion mobility) and stability (e.g., core stability) to gain muscular strength over a functional range of motions (e.g., bilateral lower limb push strength), and they learned fundamental movement patterns (e.g., squat pattern). The multi- games part of the exercise program aimed to reach a moderate-to-vigorous intensity of aerobic exercise, to teach children a wide range of fundamental movement skills (e.g., sprinting, hopping or throwing), and to make physical exercise an enjoyable activity. Further information about the exercise program can be found elsewhere (http://profith.ugr.es/pages/investigacion/proyectos/rationaleexerciseprogram).

Statistical analysis

Baseline differences between the EG and the CG in all included outcomes were investigated by performing t-tests for continuous outcomes and chi-squared tests for categorical outcomes. The exercise program effects were tested according to the per-protocol analysis. Firstly, outcomes were checked for normal distributions through histograms. Secondly, pre-exercise z-scores were calculated, and post-exercise z-scores were based on this according to the following formula: (participant raw score at post-exercise – sample's mean raw score at pre-exercise) / sample's standard deviation at pre-exercise. Thirdly, a one-way Analysis of Covariance (ANCOVA) was used to examine differences in gait biomechanical outcomes between the EG and the CG at post-exercise, and including pre-exercise values as a covariate. Differences between the pre- and post-exercise were presented in raw and z-scores, the latter which can be interpreted as the change from pre-exercise in standard deviations (SDs) and used as effect size indicator: 0.2 – 0.5 SDs = small effect size; 0.5 – 0.8 SDs = medium effect size; and ≥ 0.8 = large effect size [22]. Additional confounders such as gender, age, maturational status and anthropometric measures were discarded after verifying that they did not influence the ANCOVA models (all $p > 0.05$). Intention-to-treat analyses are presented in the supplementary material and followed the same process as explained above for the per-protocol analysis. All analyses were performed using the SPSS software (version 24.0, IBM Corporation), and the level of significance was set at $p<0.05$.

Additionally, Statistical Parametric Mapping one-dimension (SPM1D) package available for Matlab (v.0.4, http://www.spm1d.org) was used to investigate the effects of exercise on the entire gait kinematic curves. SPM1D is a statistical tool using the random field theory and allows one to conduct conventional statistical tests on one-dimensional data (e.g., kinematic curves). Firstly, a two-way mixed ANOVA was performed to test the interaction effect between groups (EG vs CG) and assessment time (pre- and post-exercise). Secondly, a post-hoc analysis were performed in those outcomes demonstrating an interaction effect, which consisted of paired SPM t-tests comparing pre- and post-exercise gait kinematics in each group (EG and CG). Considering the exploratory nature of this kinematic analysis, no corrections for multiple testing were performed to avoid overly conservative interpretations.

RESULTS

Baseline characteristics of the subjects are presented in **Table 1**.

Table 1. Pre-exercise characteristics of the total sample and divided by intervention and control group for the per-protocol analysis.

	All (N = 42)	Intervention (N = 17)	Control (N = 25)	*P*
	Mean ± SD	Mean ± SD	Mean ± SD	
Age (years)	10.86 ± 1.26	11.40 ± 1.10	10.50 ± 1.25	**0.021**
Weight (kg)	57.75 ± 12.43	64.79 ± 7.58	52.96 ± 12.91	**0.002**
Height (cm)	148.70 ± 8.63	152.49 ± 5.98	146.12 ± 9.29	**0.017**
Body mass index (kg/m^2)	25.85 ± 3.58	27.85 ± 2.81	24.48 ± 3.43	**0.002**
Gender N (%)				**0.003**
Girls	26 (62)	6 (35)	20 (80)	
Boys	16 (38)	11 (65)	5 (20)	
Spatiotemporal parameters				
Cadence (steps/min)	122.54 ± 12.00	119.95 ± 7.87	124.3 ± 14.03	0.254
Stance time (cs)	66.68 ± 56.19	67.34 ± 5.06	66.23 ± 6.03	0.537
Single support time (cs)	32.94 ± 2.56	33.39 ± 2.01	32.64 ± 2.87	0.357
Double support time (cs)	33.74 ± 3.87	33.95 ± 3.79	33.59 ± 3.99	0.772
Step length (cm)	51.38 ± 8.42	56.10 ± 4.50	48.17 ± 9.00	**0.002**
Stride width (cm)	13.95 ± 3.21	13.59 ± 2.88	14.19 ± 3.46	0.555
Kinematics: stance phase (º)				
Pelvis ROM sagittal	4.53 ± 1.07	4.51 ± 1.15	4.54 ± 1.03	0.946
Pelvis ROM transversal	8.69 ± 3.49	9.71 ± 3.54	8.00 ± 3.34	**<0.001**
Knee ROM frontal	5.95 ± 3.58	6.48 ± 4.91	5.59 ± 2.34	0.438
Ankle max. plantarflexion	60.22 ± 9.68	62.53 ± 10.3	58.65 ± 9.1	0.206
Kinematics: weight acceptance (º)				
Pelvis max. elevation	3.65 ± 2.63	3.96 ± 2.88	3.44 ± 2.49	0.539
Hip ROM frontal	3.71 ± 2.15	4.24 ± 2.52	3.35 ± 1.83	0.192
Knee ROM sagittal	14.37 ± 5.51	16.11 ± 5.46	13.18 ± 5.32	0.091
Ankle max. abduction	13.76 ± 9.41	15.78 ± 10.38	12.38 ± 8.63	0.254

SD = standard deviation; N = sample size;
Values are presented as mean ± SD or percentages. For continuous variables, p value was obtained by an independent samples T-test, whereas for categorical variables, p value was obtained by chi-square test.
Significant differences ($p < 0.05$) are highlighted in bold.

The results of the one-way ANCOVA analyses can be found in **Table 2**. In the spatio-temporal gait parameters there was a significant group difference at post-exercise in stance and single support times (medium effect size: -0.55 and -0.73 SDs; p = 0.036 and 0.014 respectively), with the EG maintaining similar values whereas the CG increasing them . The remaining spatio-temporal parameters did not present significant differences between groups (all $p > 0.05$). In gait

Table 2. Per-protocol intervention effects on gait biomechanics

	Adjusted post-exercise mean (95% CI)			
Total sample = 42	Exercise group (N = 17)	Control group (N = 25)	Groups difference (EG – CG)	*P*
Spatiotemporal parameters				
Cadence (steps/min)				
Raw score	119.82 (115.57 to 124.07)	115.02 (111.52 to 118.51)	4.80 (-0.74 to 10.34)	0.088
z Score	-0.23 (-0.58 to 0.13)	-0.63 (-0.92 to -0.34)	0.40 (-0.06 to 0.86)	
Stance time (cs)				
Raw score	68.10 (65.85 to 70.33)	71.20 (69.37 to 73.04)	-3.11 (-6.00 to -2.10)	**0.036**
z Score	0.25 (-0.14 to 0.65)	0.81 (0.48 to 1.13)	-0.55 (-1.07 to -0.04)	
Single support time (cs)				
Raw score	33.79 (32.7 to 34.9)	35.64 (34.7 to 36.6)	-1.9 (-3.3 to -0.40)	**0.014**
z Score	0.33 (-0.11 to 0.77)	1.06 (0.70 to 1.42)	-0.73 (-1.30 to -0.16)	
Double support time (cs)				
Raw score	34.38 (33.00 to 35.70)	35.52 (34.40 to 36.60)	-1.10 (-2.90 to 0.60)	0.191
z Score	0.17 (-0.18 to 0.51)	0.46 (0.18 to 0.74)	-0.29 (-0.74 to 0.15)	
Step length (cm)				
Raw score	52.85 (50.45 to 55.24)	54.17 (52.24 to 56.10)	-1.32 (-4.57 to -1.92)	0.415
z Score	0.17 (-0.11 to 0.46)	0.33 (0.10 to 0.56)	-0.16 (-0.54 to 0.23)	
Stride width (cm)				
Raw score	14.06 (12.96 to 15.16)	13.38 (12.47 to 14.28)	0.68 (-0.74 to 2.11)	0.337
z Score	0.04 (-0.31 to 0.38)	-0.18 (-0.46 to 0.1)	0.21 (-0.23 to 0.66)	
Kinematics: stance phase				
Pelvis ROM sagittal (°)				
Raw score	4.33 (3.69 to 4.96)	3.91 (3.39 to 4.43)	0.42 (-0.40 to 1.24)	0.308
z Score	-0.19 (-0.78 to 0.41)	-0.58 (-1.07. to -0.09)	0.39 (-0.38 to 1.16)	
Pelvis ROM transversal (°)				
Raw score	8.40 (6.59 to 11.09)	7.85 (6.00 to 9.69)	0.99 (-1.95 to 3.94)	0.499
z Score	0.04 (-0.60 to 0.69)	-0.24 (-0.77 to 0.29)	0.29 (-0.56 to 1.13)	
Knee ROM frontal (°)				
Raw score	8.45 (7.10 to 9.81)	7.65 (6.53 to 8.76)	0.81 (-0.96 to 2.57)	0.361
z Score	0.70 (0.32 to 1.08)	0.47 (0.16 to 0.79)	0.23 (-0.27 to 0.72)	
Ankle max. plantarflexion (°)				
Raw score	56.68 (54.09 to 59.28)	57.21 (55.08 to 59.34)	-0.52 (-3.91 to 2.86)	0.756
z Score	0.37 (0.10 to 0.63)	0.31 (0.09 to 0.53)	0.05 (-0.3 to 0.4)	
Kinematics: weight acceptance				
Pelvis max. elevation (°)				
Raw score	1.96 (0.98 to 2.94)	1.82 (1.01 to 2.63)	0.14 (-1.13 to 1.41)	0.826
z Score	0.64 (0.27 to 1.01)	0.69 (0.39 to 1.00)	0.05 (-0.43 to 0.54)	
Hip ROM frontal plane (°)				
Raw score	3.66 (2.82 to 4.50)	3.31 (2.62 to 4.00)	0.35 (-0.74 to 1.44)	0.521
z Score	-0.02 (-0.41 to 0.37)	-0.19 (-0.51 to 0.13)	0.16 (-0.35 to 0.67)	
Knee ROM sagittal (°)				
Raw score	13.73 (12.00 to 15.46)	14.75 (13.33 to 16.17)	-1.02 (-3.30 to 1.26)	0.371
z Score	-0.12 (-0.43 to 0.2)	0.07 (-0.19 to 0.33)	-0.19 (-0.6 to 0.23)	
Ankle max. abduction (°)				
Raw score	14.37 (12.09 to 16.66)	18.25 (16.37 to 20.13)	-3.87 (-6.86 to 0.89)	**0.012**
z Score	0.06 (-0.18 to 0.31)	0.48 (0.28 to 0.68)	-0.42 (-0.73 to -0.10)	

CI = confidence interval; n = sample size; EG = exercise group; CG = control group; cs= centiseconds.
A one-way analysis of covariance (ANCOVA) was used to test raw and z-score differences between the EG and CG at post-exercise, adjusting for pre-exercise values. Adjusted means and confidence intervals of the mean are represented. Differences between groups are presented as: post-exercise mean minus pre-exercise mean. Significant differences ($p < 0.05$) are highlighted in bold.

kinematics there was a significant group difference in the maximal ankle abduction angle (small effect size: -0.42 SDs; $p = 0.012$), which was due to similar values in the EG against an increase in the CG. No other between-group differences were found in the other kinematic outcomes (all $p > 0.05$). Regarding musculoskeletal pain, there were no changes post-exercise, neither in the presence of pain nor in pain intensity, and that in both groups (all $p > 0.05$).

The two-way mixed ANOVA analysis done with SPM1D showed an interaction between group and intervention effects in the kinematic curves of pelvis sagittal angles e and ankle transversal angles. Subsequently, a post-hoc analysis (i.e., paired t-test in SPM1D) was performed to assess which group showed kinematic changes (**Figure 2**). This post hoc analysis showed no post-exercise differences in the pelvis

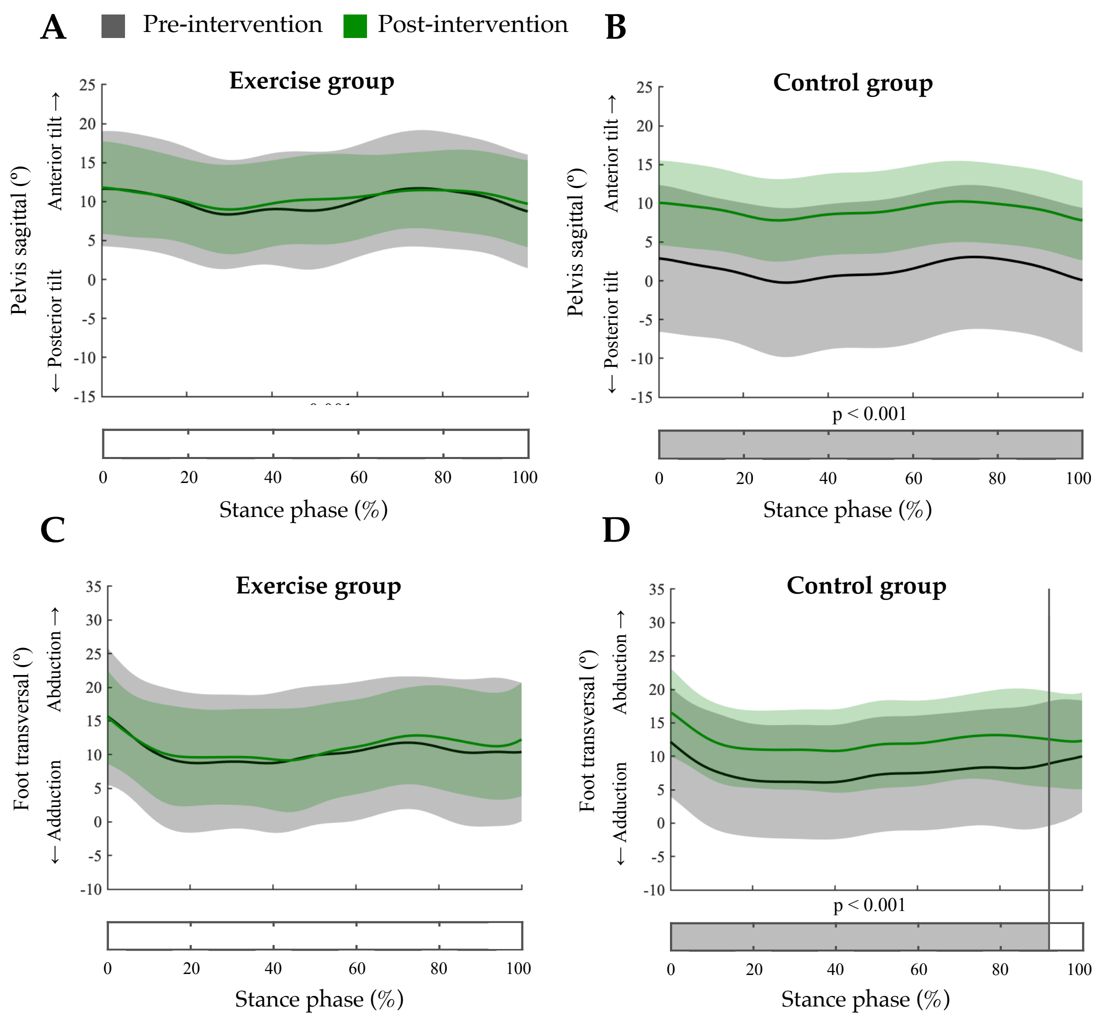

Figure 2. SPM1D-analysis for the comparisons between pre- and post-exercise in gait kinematic curves for each group (exercise and control groups).
Solid lines represent mean and shaded areas standard deviation. Shaded area in the bars indicate significant differences between pre- and post-exercise, which occurs when the SPM{t} values exceeded the alpha level threshold of 0.05..

sagittal angle for the EG, while there was a significantly increase in the CG during the entire stance phase (cluster $p < 0.001$). There were no post-exercise differences in the ankle abduction angle for the EG, while in the CG this was a significant increase from 0 to 92% of the stance phase (cluster $p < 0.001$).

DISCUSSION

In the present study we generally found that children with OW/OB who participated in our 13-week exercise program stopped the progression of some gait biomechanical alterations due to OW/OB, while in children belonging to the CG progressions continued. In the EG the stance and single support times remained the same whereas in the CG both spatiotemporal parameters increased. Furthermore, the EG maintained the same pelvic and foot angles in the stance phase while walking post-exercise, whereas the CG demonstrated an increase in pelvic anterior tilt (pelvic anteversion) and foot abduction (toe-out) angles.

As was mentioned in the introduction, we had only identified three previous studies testing the effects of exercise on gait biomechanics in a pediatric population with OW/OB [7–9]. Unlike Delextrat et al. [7], we could not test changes in walking speed since for post-exercise evaluation we maintained the speed that children had self-selected pre-exercise [13, 14]. However, we found novel and promising results in the stance and single support times, which directly target a gait biomechanical alteration typically experienced by this population [3]. In terms of gait kinematics, both Horsak and Hainsworth's studies suggested positive effects of exercise in children and adolescents with OW/OB through improved lower limb alignment during the stance phase of walking [8, 9]. In the present study, we did not find modifications in our EG towards a more optimal gait pattern, but a stabilization in the progression of some kinematic alterations in comparison with the CG that continued getting worse. A possible explanation for these contrasting findings is that participants from previous studies had already reached a mature gait, since they were over 13 years old on average, while our participants were still consolidating their gait pattern before puberty [23]. Based on these findings, we hypothesized that exercise interventions can revert kinematic alterations derived from OW/OB in young who have reached a mature gait, whereas exercise stops the deterioration in younger children who are still developing their gait pattern. However, there is still little evidence available to draw firm conclusions and further research should confirm these observations.

In a normal gait development process, children consolidate an adult walking speed at approximately 8 years of age [23]. From that point, walking cadence, stance time and step length become the most relevant parameters to determine gait maturity in childhood and adolescence [23]. Stance time and single-support time experience a natural decrease from childhood to adulthood [23]. However, neither our EG nor CG showed this natural phenomenon probably because of the OW/OB, moreover the CG experienced even showed an increase in these two parameters. Compared with healthy normal-weight children of the same age, our sample already presented a longer stance time at pre-exercise (63 centiseconds vs. 67) confirming that an increase in this spatiotemporal parameter represents an alteration in the gait pattern [24]. Walking with relatively longer steps while maintaining similar cadence is associated with lower mechanical efficiency, since it requires a higher force generation to re-accelerate the center of mass in the step-to-step transition via a disruption in the normal stretch-shortening cycle of muscles and tendons [25, 26]. Based on all this evidence, findings from this study seem to indicate positive effects of exercise on the mechanical efficiency of walking in children with OW/OB. In fact, this would be in line with the results of Delextrat et al. [7], who found a reduction in the energy cost of walking ranging from 10% to 20% in adolescents with obesity after participating in a high intensity aerobic program.

Our findings suggested some beneficial effects of our exercise program by stopping the progression of some gait biomechanical alterations such as excessive pelvic anteversion and toe-out positioning. Compared with healthy children with normal-weight, our participants presented excessive values in these two outcomes, which lead us to interpret the increase in the CG as a progression in the gait deterioration [27, 28]. An elevated pelvic anteversion together with a toe-out position are intimately related biomechanical alterations that reinforce each other, and are indicators of a hyperlordotic and pronated gait pattern [27, 29, 30]. Lumbar hyperlordosis has been related with the presence of low back pain in childhood, and its progression through lifespan is considered a risk factor for severe spine pathologies such as herniated disc [31, 32]. An excessive foot pronation is associated with overuse musculoskeletal disorders in adults such as knee pain and structural damage in the medial tibiofemoral cartilage [33, 34]. Furthermore, to increase the toe-out position in early- and mid-stance phases of gait, as observed in the CG, it seems to increase the knee adduction moment, which is considered a major biomechanical factor for the development of knee osteoarthritis later in life [35–37]. Despite the encouraging results of this study, it is important to note that the EG still demonstrated a worrying pelvic anteversion and toe-out position during walking, so future studies should elucidate effective strategies to not only stop but reverse these gait deteriorations.

Findings from this study are in line with those we reported in previous work with the same sample, which suggested positive functional changes in foot biomechanics during walking induced by exercise [10]. Our hypothesis is that the exercise program has induced the strengthening of key foot and ankle muscles (e.g., tibialis posterior and flexor hallucis longus) via barefoot training and the performance of highly dynamic tasks in the multi-games work [38, 39]. Although further study is still needed on this topic, a considerable body of evidence begins to demonstrate that exercise interventions might be a potential treatment to stop and reverse the biomechanical alterations during walking in children and adolescents with OW/OB [8–10, 40–42]. Improvements in biomechanics induced by exercise could have a protective effect on the development of musculoskeletal disorders, and preserve a more optimal mechanical efficiency during walking, but future longitudinal studies should verify this [3, 43]. It is important to mention that exercise is not the only available treatment, since weight loss programs by nutritional modifications and surgical interventions (e.g., subtalar arthroereisis and bariatric surgery) have also demonstrated positive effects on the gait biomechanics of children and adolescents with OW/OB [44–46]. A possible intervention strategy could be to start with more conservative treatments, such as exercise and nutritional interventions, and prescribe surgical interventions only in the most extreme cases.

This study comes with a number of limitations. First, this study only reported gait spatiotemporal and kinematic outcomes, and additional biomechanical parameters such as gait kinetics, joint contact forces or mechanical efficiency would could greatly benefit a deeper understanding of how benefits from exercise come about. However, (reliably) measuring those additional parameters in the target population of children and adolescents with OW/OB comes with considerable challenges that our outside the scope of the current research project. Second, we used a standard marker model in our 3-D analysis of gait, and currently there are more accurate models that are believed to better take into account morphological characteristics of children with OW/OB [15]. Third, our marker model considered the foot as a rigid segment, which means that we could not gain insights into intersegmental foot motions in this population, such as midfoot eversion [47]. Fourth, due to a non-randomized assignment, the EG and CG presented baseline differences that might be influencing the results. However, all statistical analyses were adjusted for baseline values based on the influence of potential confounders (i.e., age, gender, height, maturational stage and BMI), and were discarded after it was verified that none influenced the results.

Conclusions

This study shows that a 13-week exercise intervention, based on "movement quality" and "multigames" work, stopped the progression of some biomechanical alterations during walking derived from childhood obesity. Those children who participated in the exercise program maintained a stable stance time, single support time, pelvic anteversion and foot toe-out position during the stance phase of walking, while their peers who continued their daily life showed an increase of all these biomechanical parameters. Findings of this research suggest that exercise leads to positive effects in the gait biomechanics of children and adolescents with OW/OB, which may ultimately contribute to the prevention of musculoskeletal disorders and the preservation of an optimal mechanical efficiency during walking in this population.

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GENERAL DISCUSSION

MAIN FINDINGS OF THE PRESENT DOCTORAL THESIS

The present doctoral thesis contributes to a better understanding of childhood obesity from a biomechanical perspective, describing its potential implications for the musculoskeletal health of this population and proposing exercise as a possible way to counteract the negative consequences of obesity. To see a summary of the findings of this doctoral thesis, please refer to **Table 1**.

SECTION 1. SYSTEMATIC REVIEWS AND META-ANALYSES: IMPACT OF CHILDHOOD OBESITY ON THE MUSCULOSKELETAL STRUCTURE AND THE BIOMECHANICS OF WALKING

The main findings in this section can be summarized as follow: 1) higher OW/OB degree was associated with the presence of five postural malalignments, namely rounded shoulders, thoracic hyperkyphosis, lumbar hyperlordosis, genu valgum and flatfoot (**Study 1**); 2) children and adolescents with OW/OB had 6.6 times higher risk of presenting genu valgum, 1.5 times higher risk of presenting flatfoot and 1.7 times higher risk of presenting any kind of postural malalignment compared to normal-weight (**Study 1**), and 3) in comparison with normal-weight, children and adolescents with OW/OB walk with greater step width, longer stance phase, a lower limb valgus position, greater force moments at hip, knee and ankle, higher tibiofemoral contact forces and greater calf muscle activation (**Study 2**). These findings reveal the negative impact of childhood obesity on musculoskeletal structure and function, and this in actions that are fundamental to our daily life such as maintaining an upright posture and walking.

The influence of age and gender

The first question that arose in this section was at what age the negative effects of obesity are first observed. In **Study 1**, we found that those articles including new-born children until the age of four did not find associations between OW/OB and postural malalignment. It was not until the age of five and onwards when the existing evidence supports a relationship between childhood obesity and postural alterations. With regard to the walking biomechanics, included articles in **Study 2** only investigated children older than eight years, possibly to make sure that they had already acquired some maturity in the gait pattern [1]. Notably, all studies that included 8-9 years old children found gait biomechanical alterations associated with the presence of OW/OB [2–9]. This makes us believe that, as with the body posture in **Study 1**, the negative effect of childhood obesity had already consolidated in previous stages. Considering findings from **Study 1 and 2** together, the first four years of life seems to be a particularly sensitive period when postural malalignments are developed as a consequence of OW/OB, while in the gait pattern there are no studies in the pre-school population that allow us to determine when biomechanical alterations arise. This situation is particularly worrying, given that the current world prevalence of OW/OB among preschool children (i.e., under five years old) stands at 9% and, therefore, many children are at risk of developing the

Table 1. Main findings of the present Doctoral Thesis

SECTION 1	Study 1	• Higher overweight/obesity degree was associated with the presence of rounded shoulders, thoracic hyperkyphosis, lumbar hyperlordosis, genu valgum and flatfoot. • Children and adolescents with overweight/obesity had 6.6 times the risk of presenting genu valgum, 1.5 times the risk of presenting flatfoot and 1.7 times the risk of presenting any kind of postural malalignment compared to normal-weight
	Study 2	• Based on strong evidence, children and adolescents with overweight/obesity walk with greater pelvic rotation motion, a lower limb valgus position and greater force moments in hip flexion-extension and abduction-adduction, and in knee abduction-adduction. • Based on mdoerate evidence, children and adolescents with overweight/obesity walk with greater step width, longer stance phase, higher tibiofemoral contact forces, higher ankle plantarflexion force moments and greater gastrocnemius and soleus activation.
SECTION 2	Study 3	• Fatness indicators are negative whereas physical fitness components positive associated with the fundamental movements quality of children with overweight/obesity. • Physical fitness seems to have a protective effect against adverse consequences of fatness in fundamental movements quality in children with overweight/obesity.
	Study 4	• Physical fitness components and fundamental movements were overall associated with a more aligned posture of the head, lumbar and thoracic spines, and lower limb of children with overweight/obesity. • BMI was the best predictor of head and lumbar spine posture, cardiorespiratory fitness and speed-agility of lower limb, and fundamental movements of thoracic spine posture.
SECTION 3	Study 5	• The exercise group developed a more vertical alignment of head and pelvis complex in the sagittal plane and improved their lower limb alignment in frontal plane with respect to the control group. • The exercise group improved their overall performance in fundamental movements, and they obtained better results in several muscular strength indicators (i.e., 1RM arm, handgrip strength, and standing long jump) compared with the control group.
	Study 6	• The exercise group maintained stable the total plantar surface area during walking, while the control group increased it. • The exercise group experienced a greater increase in the maximum force supported beneath the forefoot (specifically beneath the lateral and medial forefoot than the control group.
	Study 7	• The exercise group maintained stable the stance and single support times during walking whereas the control group increased both spatiotemporal parameters. • The exercise group maintained the same pelvic and foot angles while walking whereas the control group demonstrated an increase in pelvic anterior tilt (pelvic anteversion) and foot abduction (toe-out) angles in the stance phase.

above-mentioned biomechanical alterations. An urgent need to diagnose these structural and functional alterations from early ages is evident, in order to intervene as soon as possible and prevent them from continuing to progress.

Moving to the last stage of childhood and the beginning of adolescence, both **Study 1** and **Study 2** show that the detrimental effect of OW/OB on posture and gait biomechanics is already consolidated. What is not clear is whether this detriment is similar in boys and girls, since puberty is when differences in the musculoskeletal system between sexes become more evident [10, 11]. Girls tend to demonstrate more lumbar hyperlordosis and genu valgum whereas boys show more thoracic hyperkyphosis and flatfoot [10, 12]. This influences not only their body shapes but also the way they move [10]. We hypothesized that the impact of OW/OB in the musculoskeletal structure and function could be manifesting differently in girls and boys, probably aggravating postural dimorphisms that naturally occur in both genders. However, we have barely been able to find evidence that supports our hypothesis. In **Study 1**, only a few authors studied the effects of OW/OB on body posture in boys and girls separately, while in **Study 2** no study considered sex-differences in the biomechanical gait analyses. Thus, the present doctoral thesis cannot answer whether the impact of childhood obesity on body posture and gait biomechanics differs between genders, and further research in this regard is warranted.

Is it just a matter of excess mass?

Given that the vast majority of articles in **Study 1 and 2** used BMI to determine the presence of OW/OB, it seems evident that excess of body mass is playing a major role in structure and function of the musculoskeletal system. In **Study 1**, we discuss that excess body mass could be altering the mechanical stability of the spine as well as collapsing lower limbs into a valgus and flatfoot position [13, 14]. Moreover, a greater difficulty decelerating and reaccelerating their heavier body mass for the next step was considered as the most plausible explanation for the biomechanical compensations found in **Study 2** [15]. Given the relevance of body mass from a biomechanical perspective, it seems logical to assume that recovering an adequate (age dependent) body mass should have positive consequences to body posture and gait biomechanics. In fact, previous intervention studies based on weight loss programs by nutritional modifications and bariatric surgery found positive effects on the gait biomechanics of adolescents with OW/OB [16, 17].

In this section we provide additional evidence suggesting that the biomechanical alterations observed in this population are not only explained by the presence of excessive body mass. In **Study 1**, some authors reported that fat mass and muscle mass were independently associated with a hyperlordotic posture in children, which could be indicating differentiated roles in the onset of these postural malalignments [13]. They argued that fat mass accumulation might have a greater implication in the spinal imbalance, while a consequent increase in muscle tone is necessary to restore spinal balance [13]. Something similar was found in **Study 2**, in which several authors reported that children and adolescents with OW/OB still presented alterations in their gait biomechanics after taking into account body mass [18, 19]. These findings reveal that biomechanical alterations in this population go beyond having to support and transport a greater body mass, and point to modifications in the neuromuscular pathways involved in controlling the body positioning and the gait pattern.

Apart from body composition indicators, in this section we have discovered some other factors likely influencing the posture and gait of these children and adolescents. It is important to bear in mind that children and adolescents with OW/OB spend more time in sedentary behaviours and less practicing physical activity, and these lifestyle factors seem to be affecting their musculoskeletal structure and function. One article from **Study 1** found in adolescents that an increased television use was associated with a thoracic hyperkyphosis posture during sitting [20]. Moreover, we highlighted in **Study 1** and **Study 2** that higher levels of physical activity in childhood and adolescence was related to a more aligned body posture and less foot pronation during walking [21, 22]. Having all this in mind, it seems that promoting less time in sedentary behaviours and more in physical activity could be a strategy to fight against all these biomechanical alterations, but the level of evidence found in our systematic reviews remains limited. This is a question that we will address in **SECTION 3** with the intervention effects.

Implications of an altered posture and gait

The major implication of an altered posture and gait that we discuss in this section focuses on the onset and progression of musculoskeletal disorders. In both **Study 1** and **Study 2** we provide ample arguments supporting that the biomechanical alterations found in children and adolescents with OW/OB could have harmful implications on their musculoskeletal system. In **Study 1**, five articles analysed the relationship between postural malalignments and musculoskeletal pain, and four of them observed significant associations [20, 23–25]. For instance, a non-neutral position of the spine in the sagittal plane (i.e., hyperkyphosis and hyperlordosis) and an overall poor posture were associated with a higher incidence of pain in the cervical spine and low back of children and adolescents. Furthermore, the progression of this hypercurved spine through lifespan is considered a risk factor for severe spine pathologies such as herniated disc [26, 27]. Focusing on the lower limbs, the genu valgum position in static and dynamic situations reported in **Study 1** and **Study 2** is considered a risk factor for the development of knee osteoarthritis in adulthood through a progressive degeneration of the tibiofemoral and patellofemoral cartilage [28–30]. The presence of flatfoot (**Study 1**) and a pronated pattern during walking (**Study 2**) were recently identified in a systematic review as risk factors for patellofemoral pain, Achilles tendinopathy and non-specific lower limb overuse injuries, although evidence is still very limited [31]. In **Study 1** we also reported that higher contact forces applied on the hip and knee joints during walking could lead to long-term mechanical damage. Besides, it has been demonstrated that the skeletal structures of these children and adolescents are not adapted to support the greater mechanical stresses in their joints [7]. Although there are serious reasons for considering biomechanical alterations as a potential factor in the development of musculoskeletal disorders in children and adolescents with OW/OB, the truth is that there is currently no longitudinal evidence supporting it. Prospective cohort studies should determine whether these biomechanical alterations are associated with the future presence of musculoskeletal disorders.

Mechanical inefficiency during walking and a subsequent increase in the energetic cost have also been proposed in **Study 2** as a potential implication of an altered gait pattern in this population. Children and adolescents with OW/OB have demonstrated between 22 and 25% higher energetic cost (also called net metabolic cost) than their normal-weight peers walking at the same speed [32, 33]. While the initial impression is that an elevated walking energy cost might be beneficial, with obesity being an energy imbalance between calories consumed and expended, it also comes with a relatively greater effort for walking. This extra effort for walking has been suggested as an important limiting factor for these children and adolescents to be physically active [34]. Now that we have defined the gait biomechanical characteristics of these children and adolescents in **Study 2**, we can begin to get an idea of how biomechanics is influencing the high energy cost during walking. For instance, a longer and wider step, greater joint force moments and muscle overactivation observed in this population are factors associated to an increased energetic cost in walking [33, 35, 36]. However, most of these associations have been reported in adults, and future studies should still determine the real influence of these biomechanical alterations on the energetic cost of walking in children and adolescents with OW/OB.

SECTION 2. CROSS-SECTIONAL STUDIES: ROLE OF PHYSICAL FITNESS IN THE BIOMECHANICS OF CHILDHOOD OBESITY

Overall, the main finding of the present section is that physical fitness components (i.e., cardiorespiratory fitness, muscular strength, and speed-agility) are positively related to the body posture configuration and fundamental movements quality (Functional Movement Screen ™) in children with OW/OB. Particularly, in **Study 3** we examined the associations between BMI, physical fitness components and fundamental movements quality with body posture (whole body 2D photogrammetry). Moreover, **Study 4** shows the associations between some fatness indicators (i.e., BMI, waist circumference, body fat percentage and fat mass index) and physical fitness components with the fundamental movements quality. In **SECTION 1**, we already evidenced that OW/OB is associated with postural and gait biomechanical alterations in children and adolescents, and in the present **SECTION 2** this was confirmed in our own sample. The higher the BMI is, the more pronounced are some postural alterations such as head protraction, thoracic hyperkyphosis, lumbar hyperlordosis and genu valgum (**Study 3**). Through **Study 4**, we further evidenced that a greater BMI is related to biomechanical alterations in more complex patterns than posture or gait, such as fundamental movements. Only three previous studies had investigated the relationship between fatness and fundamental movements in children [37–39], and **Study 4** is the first to do it in a homogenous sample of children with OW/OB. Furthermore, we found that BMI was the strongest fatness indicator related to a worsened fundamental movements quality, which reiterated that the mechanical factor of carrying additional mass is the primary biomechanical constraint.

The positive effects of physical fitness in the biomechanics of childhood obesity

Study 3 revealed for the first time that physical fitness and fundamental movements quality were overall associated with a better aligned posture of the head, thoracic spine, lumbar spine and lower limbs. Concretely, cardiorespiratory fitness was related to a better aligned position of head and lower limbs. Upper-extremity muscular strength (i.e., 1RM arms and handgrip) was associated with a better aligned thoracic spine, while lower-extremity muscular strength (i.e., 1RM legs and long jump) was associated with better aligned lower limbs. Lastly, speed-agility was related to a better aligned lower limb posture. Something similar was found in **Study 4**, where most of physical fitness measures, with the exception of 1RM arms, were associated with a better overall fundamental movements quality (i.e., total Functional Movement Screen™ score). Among the physical fitness components, cardiorespiratory fitness, long jump and speed-agility were most consistently associated with fundamental movements quality, even after adjusting by participants' BMI that already demonstrated to be a relevant factor. A possible explanation we provided is that fundamental movements quality could be associated with locomotor activities that require both power generation and efficiency during long distance running, rather than absolute muscle activities such as 1RM or handgrip [40, 41].

What is more determinant: fatness or fitness?

Once we analysed the role of fitness in posture and fundamental movements, the next question that arose was: what is more determinant, the fatness or fitness of these children? To answer this, in **Study 3** we identified the best predictor of body posture among BMI, physical fitness and fundamental movements. Results showed that BMI was the best predictor of head and lumbar spine posture, cardiorespiratory fitness and speed-agility of lower limb posture, and fundamental movements of thoracic spine posture. On the other hand, in **Study 4** we investigated the separate and interaction effects in fundamental movements between OW/OB categories (overweight vs obese) and physical fitness groups (fit vs unfit). Our findings suggest that, whereas being fit seems to moderately attenuate the negative influence of fatness, children´s weight status still was more determinant in their fundamental movements quality. Putting all this evidence together, the present section evidences for the first time the important role of physical fitness in presenting a more optimal body posture and fundamental movements quality in children with OW/OB. However, although physical fitness seems even more determinant than OW/OB level in the positioning of some musculoskeletal structures, the excess of body mass plays a major role in the postural malalignment of these children.

Practical implications of this section

Based on findings from this section, the message we send to professionals who work daily with this population (e.g., paediatricians, physical education teachers, physical trainers or physical therapists) is that strategies aimed at reducing BMI together with improving both physical fitness and fundamental movements quality could be a promising treatment to prevent or even reverse the biomechanical alterations normally experienced in children with OW/OB. In this sense, to follow the internationally accepted physical activity guidelines for children could be a good starting point, since it promotes to develop both aerobic and musculoskeletal conditioning [42]. However, we strongly recommend to move towards a more integrative exercise programming that not only focuses on the quantitative aspects of physical activity (e.g., accumulate 60 min of daily moderate to vigorous physical activity) but also considers qualitative aspects such as movement quality acquisition (i.e., fundamental movements and skills) and body posture awareness [43, 44]. However, to date there are hardly any intervention studies in this regard, and therefore our ability to guide practical applications from a scientific basis remains limited. In **SECTION 3** we will give some recommendations based on the outcomes of our own exercise program.

SECTION 3. EFFECTS OF A 13-WEEK EXERCISE PROGRAM ON THE BIOMECHANICS OF CHILDHOOD OBESITY

In this section we include three intervention studies (i.e., **Study 5, 6 and 7**) about the effects of our 13-week exercise program, based on movement quality and multi-games, on the biomechanics of children with OW/OB. In **Study 5**, we found that our exercise program leads to positive effects on several body posture indicators (i.e., 2D photogrammetry), global fundamental movements quality (i.e., Functional Movement Screen™) and some muscular strength components (i.e., 1RM arm and leg press, and ALPHA test battery). Particularly, children who participated in the exercise program developed a more vertical alignment of head, pelvis and lower limbs, improved their performance in the total FMS score, and obtained better results in 1RM arm press, handgrip strength, and standing long jump tests. Our main conclusion from **Study 6** was that the exercise program led to positive functional changes in plantar pressure (i.e., baropodometric analysis) during walking. Children in the exercise group did not continue to increase the total plantar pressure surface, as the control group did, which is an indicator of flatfoot and pronated foot pattern during walking [45, 46]. Furthermore, the maximum force supported beneath the forefoot increased in the exercise group participants more than in the control group participants. This shift toward forefoot forces occurs with the development of a mature gait pattern and is observed in an optimal push-off phase in adults [47, 48]. Lastly, in **Study 7** we found that children in the exercise program maintained a stable stance time, single support time, pelvic anteversion and foot toe-out position during the stance phase of walking (i.e., 3D motion capture analysis), while their peers in the control group increased all these biomechanical parameters. In line with **Study 6**, these results suggest that exercise could have stopped the progression of some biomechanical alterations during walking such as a mechanical inefficiency, excessive foot pronation and lumbar hyperlordosis.

Previous interventions and what this section adds

To our knowledge, there are six previous studies separately investigating the effects of exercise on body posture and gait biomechanics (i.e., plantar pressure and gait kinematics) in children and adolescents with OW/OB [22, 49–52], but no studies on fundamental movements. The only precedent we found concerning body posture is the study of Schwanke et al. [49], in which a 4-month exercise program induced improvements in the thoracic spine posture of adolescents with OW/OB. In contrast with Schwanke's study (35), we could not determine a direct improvement in the thoracic spine alignment in our **Study 5**, but rather we found improvements in the head, pelvis and lower limb alignment. With regard to plantar pressure during walking, Riddiford et al. [22] reported no significant changes after their 8-month physical activity program (10-week face-to-face + 22-week self-imparted training), while Steinberg et al. [50] found a reduction in some foot pressure measures after their 6-month intervention consisting of exercise and diet. Unlike Steinberg's results, in **Study 6** we did not find a reduction but a stabilization in plantar pressure surface, as well as an increase in the peak forces supported beneath the forefoot (i.e., medial and lateral forefoot). It is important to note that growing children increase body mass and foot size, and, thus, reductions in plantar surface and maximum forces are unlikely to occur. Results from Riddiford-Harland's study resemble more what we found in **Study 6**, and it might be because we both examined children in barefoot conditions whereas Steinberg et al. did in in-shoes conditions. In terms of gait kinematics, Horsak and Hainsworth's exercise interventions (12 and 8 weeks of duration respectively), found a reduction in the genu valgum position during the stance phase of walking [51, 52]. In **Study 7** we did not find modifications towards a more optimal gait pattern after our exercise program, but a stabilization in the progression of some kinematic alterations. A possible explanation for these contrasting findings is that their participants had already reached a mature gait, since they were over 13 years old on average, while ours were still consolidating their gait pattern before puberty [1].

Our main contribution in the present section was to demonstrate that a well-designed and supervised exercise program can induce simultaneous positive effects on body posture, fundamental movements quality and gait biomechanics in a population of children with OW/OB. It is noteworthy that we found all these benefits in only 13 weeks of exercise program, four weeks less than the average duration of previous exercise interventions. It demonstrates that it is possible to obtain short-term benefits in the biomechanics of this population through exercise. Moreover, all these biomechanical improvements came together with muscular strength gains, even when our exercise program was mainly focused on movement quality rather than quantity and intensity. This confirms the believe that muscular strength development during childhood is more influenced by neuromuscular stimulus (i.e., learn to execute a movement pattern) rather than changes in the muscular structure via hormonal mechanisms (i.e., testosterone) [43]. It is important to highlight that all these results occurred without significant reductions in weight or BMI, demonstrating that exercise has the capacity to induce biomechanical modifications in this population by mechanisms other than merely body composition. Lastly, another important contribution is that we provided a detailed explanation of our exercise program in an open-access source, our official website (http://profith.ugr.es/pages/investigacion/recursos/mubi?lang=en), in order to be replicated by other researches or put into practice.

How can exercise lead to these improvements?

Three possible explanations were contemplated for biomechanical changes induced by our exercise program [53–55]: 1) weight loss, 2) muscle strengthening and 3) neuromuscular re-education of posture and movement patterns.

We consider that a combination of the last two mechanisms would seem the most plausible. The first comes from the logical assumption that any induced weight loss would induce positive effects on posture, gait biomechanics and fundamental movements. This idea must be rejected, however, since neither the EG participants nor the CG experienced any reduction in body weight. The second is related to the strengthening of key muscles involved in improving the structure and function of the musculoskeletal system, such as deep cervical flexors, intrinsic core musculature or foot invertor muscles. Unfortunately, we could not measure muscle structure (e.g., MRI or echography) but we assessed muscle function through the 1RM leg press and long jump tests (**Study 5**). Possibly, improvements found in the performance of these tasks come both from a better muscle function and more optimal biomechanics that maximizes force transfer between ankle, knee and hip joints [56]. The third explanation suggests that the simple act of gaining postural awareness and learning fundamental movements and skills would make children maintain a better posture and move better. As we mentioned in the description of the exercise program, it includes several aspects (i.e., barefoot training, integrative neuromuscular training and dynamic neuromuscular stabilization) specifically targeting the abovementioned goals.

Practical implications of this section

We have in **SECTION 1** thoroughly discussed the potential implications of altered biomechanics on the onset and progression of musculoskeletal disorders. Hence, it is logical to assume that exercise-induced improvements found in this section could be beneficial for the overall musculoskeletal health of these children. For instance, having a more aligned lower limb posture, as we found in **Study 5**, is associated with less likely suffering knee cartilage damages and the consequent development/progression of osteoarthritis compared to when having incorrect lower limb postures (i.e., varus and valgus positions) [30, 57]. Some authors suggest that an excessive foot pronation during walking is associated with overuse injuries in adults [31, 58]. Therefore, the stop in the progression of excessive foot pronation, as we found in **Studies 6 and 7**, could help prevent these movement-derived musculoskeletal disorders from appearing in the future. With regard to the FMS improvements that we found in **Study 5**, the systematic review and meta-analysis of Bonazza et al. (6) shows that people with optimal total FMS scores had a lower likelihood of injuries than those with non-optimal scores. It is logical that if our participants are now moving better they would reduce the risk getting injured whilst practicing physical activities, which in fact occurs more frequently in children with OW/OB [59]. Despite the promising role of these results in the prevention of musculoskeletal disorders, we must be cautious interpreting them because to date there is still no longitudinal evidence supporting it. Thus, future follow-up studies should determine whether all these biomechanical modifications have an implication for the prognosis of future musculoskeletal disorders.

An additional implication of this section is related with the predisposition of these children for keeping practising physical activity in the future. As we discussed in **SECTION 1**, a mechanical inefficiency contributes to these children experiencing greater effort of walking than their peers with normal-weight, which means an important barrier to be physically active. Results in the spatiotemporal parameters of gait found in **Study 7** seem to indicate positive effects of exercise on the mechanical efficiency of walking in children with OW/OB. This will be in line with a previous exercise-based intervention study that found improvements in the energetic efficiency of walking, ranging from 10% to 20%, in adolescents with obesity [60]. Moreover, in **Study 5** we found that children were stronger and more competent in terms of movement quality after the exercise program, which led us to think that this puts them in a better situation to continue practicing physical exercise. Notably, longitudinal studies have evidenced that movement competence during childhood is predictive of physical activity levels during adolescence [61]. Follow-up studies should investigate whether all these changes in the biomechanics of walking, muscular strength and fundamental movements are predictive of a greater physical activity participation in adolescence and adulthood.

OVERALL LIMITATIONS AND STRENGTHS

An integrative view of the general limitations and strengths of the present International Doctoral Thesis can be found in **Table 2**.

Table 2. Overview of the limitations and strengths present in this Doctoral Thesis

	Limitations	Strengths
SECTION 1	• Findings from both **Study 1 and 2** are mainly based on cross-sectional studies and it does not allow to establish firm causality conclusions between childhood obesity and the presence of biomechanical alterations. • A wide variety of assessment protocols were used to measure body posture (**Study 1**) and gait biomechanics (**Study 2**), which restricts inter-study comparisons. • The majority of the included articles in both **Study 1 and 2** did not accounted for potential confounders such as age, maturational stage or gender, which have demonstrated to influence in body posture and gait biomechanics. • There is no current evidence supporting that the biomechanical alterations experienced by this population predict musculoskeletal disorders in adulthood, and therefore, any conclusion around that have a theoretical basis.	• All information included in both systematic reviews were synthesize with standardized protocols, eigther a qualitative evidence synthesis (**Studies 1 and 2**) or a meta-analysis (**Study 1**). • Findings from **Studies 1 and 2** were summarized in graphical and schematic figures to facilitate understanding those readers less experts in the topic. • Both systematic reviews include enough studies (**Study 1:** 68; **Stydy 2:** 25) to draw solid conclusions about the biomechanics of childhood obesity. • **Study 1** synthesis observations from close to 2 million children and adolescents from twenty-three countries around the five continents. • **Study 2** include observations from close to 800 children and adolescents, which is a considerable sample size given the difficulty and complexity of biomechanical analyzes.
SECTI ON 2	• All studies in this section had a cross-sectional design, and therefore, drawing causal associations is not possible.	• All outcomes included in this section (i.e., body posture, fundamental movements and physical fitness) have domenstrated to be valid and

Table 2. Overview of the limitations and strengths present in this Doctoral Thesis

	Limitations	Strengths
	• **Study 3 and 4** did not include gold standard methods for assessing body posture (i.e., X-Ray analysis) and body composition (i.e., dual-energy x-ray absorptiometry), however, two-dimensional photogrammetry and bioimpedance are considered valid and reliable alternatives. • The sample of both **Study 3 and 4** is limited in size and only composed of children with overweight/obesity from a specific re-gion, and thus results may be extrapolated to a general childhood population.	reliable in the childhood population. • The inclusion of different fitness component (e.g., cardiorespiratory fitness, muscular strength and speed-agility) together with fundamentas movements give us a vision of the physical fitness level from both a quantitative and quaalitative perspective. • Functional Movement Screen were evaluated by two certified evaluators with extensive experience, and exercise were videotaped in order to solve any discrepancy between both evaluators.
SECTION 3	• The no-randomized assignment to the exercise or control group led to differences between both groups at baseline. Although these were subject to statistical control (adjustment for the baseline values and/or potential confonders such as sex and maturational stage), they may have had some influence on the results. • Our limited sample size did not allow to detect small changes between groups. • No structutal measurements of the musculoskeletal sysytem were taken via imaging (e.g., X-ray or magnetic resonance imaging) which would have allowed the impact of the intervention on structural changes at for instance the knee or foot. • There is no longitudinal evidence demonstrating whether biomechanical changes found in this section have positive implication on the muskuloskeletal system and, therefore, results should be considered with caution.	• The exercise program was specifically designed to target the biomechanical alterations that children with overweight/obesity normally experience, and it is explained in detail in a open-access source (our official web site) in order to be replicated by other researches or put into practice. • This trial is the first in studying the simultaneous effects of exercise on different biomechanical dimension, such as body posture, fundamental movements and gait biomechanics, in a population of children with overweight/obesity. • The inclusion of Statistical Parametric Mapping allowed us to test the effects of exercise on the entire kinematic curves during walking (**Study 7**).

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CONCLUSION AND FUTURE PERSPECTIVES

CONCLUSIONS

Overall conclusion

Findings from this Doctoral Thesis evidence that childhood obesity is associated with the presence of postural malalignments and biomechanical alterations during walking, which could be playing a major role in the onset and progression of musculoskeletal disorders (**SECTION 1**). Notably, although BMI has demonstrated to be a determining factor for the biomechanics detriments, physical fitness seems to be playing a positive role in the body posture and movement competence of children with overweight/obesity (**SECTION 2**). Finally, results from **SECTION 3** demonstrate that a 13-week exercise program can lead to positive effects on body posture, functional movement quality, muscular strength and gait biomechanics (i.e., plantar pressure and kinematics) in children with overweight/obesity. This suggests that physical exercise could be a promising action against the biomechanical alterations normally experienced in these children.

Specific conclusions

SECTION 1. Systematic reviews and meta-analysis: impact of childhood obesity in the musculoskeletal structure and the biomechanics of walking

- **Study 1:** overweight/obesity is associated with the presence of rounded shoulders, thoracic hyperkyphosis, lumbar hyperlordosis, genu valgum and flatfoot in childhood. Children and adolescents with overweight/obesity have 6.6 times the risk of presenting genu valgum, 1.5 times the risk of presenting flatfoot and 1.7 times the risk of presenting any kind of postural malalignments compared with their NW peers. These postural malalignments might be behind the higher prevalence of musculoskeletal pain in this population and, in if it persists into adulthood, could lead to more severe musculoskeletal disorders.

- **Study 2:** children and adolescents with OW/OB walk with greater step width, longer stance phase, a lower limb valgus position, greater force moments at hip, knee and ankle, higher tibiofemoral contact forces and greater calf muscle activation, all in comparison with their normal-weight peers. These alterations observed in OW/OB could be determinant in the short- and long-term development of musculoskeletal disorders and could be a key factor to understanding the energetic inefficiency experienced by this population during walking.

SECTION 2. Cross-sectional studies: role of physical fitness in the biomechanics of childhood obesity

- **Study 3:** BMI was the strongest predictor of cervical and lumbar spine posture, cardiorespiratory fitness and speed-agility of lower limb posture, and functional movement quality of thoracic spine posture. In view of this, although BMI is a determining factor for body posture detriments, physical fitness and functional movement quality seem to be positively affecting musculoskeletal positioning in children with OW/OB.

- **Study 4:** children with greater fatness indicators demonstrate lower functional movement quality, whereas children with better fitness level (i.e. cardiorespiratory fitness, lower limbs muscular strength, and speed-agility) demonstrate greater functional movement quality. Children´s weight status seems to be more determinant than their fitness level in terms of functional movement quality, whereas being fit seems to moderately attenuate the negative influence of fatness.

SECTION 3. Effects of a 13-week exercise program on the biomechanics of childhood obesity

- **Study 5:** children with OW/OB who participated in the exercise program developed a better alignment of the head and lower limb, improved their performance in functional movement patterns and experienced global muscular strength gains compared with the peers who continued with their usual lives. Among other potential implications, these improvements could contribute to the prevention of musculoskeletal disorders associated with childhood obesity and could increase adherence by positioning these children in a better physical status to keep practicing exercise.
- **Study 6:** the exercise program led to positive functional changes in the plantar pressure during walking of children with OW/OB. The increase in maximum force supported by the forefoot in the exercise group might indicate a change toward a more normal foot rollover pattern and a more adult gait.
- **Study 7:** children who participated in our exercise program stopped the progression of some gait biomechanical alterations (i.e., excessive stance time, toe-out position and pelvic anteversion) compared with peers who continued with their usual lives. These findings could contribute to preventing common movement-derived musculoskeletal disorders in this population, as well as preserving an optimal mechanical efficiency during walking.

FUTURE PERSPECTIVES

- In **SECTION 1** we have demonstrated that OW/OB is associated with biomechanical alterations in two situations as basic as supporting one's body weight and walking, but future research should elucidate whether the biomechanics deterioration also occur in more demanding activities such as running or jumping.
- To date there is no evidence demonstrating that the biomechanical alterations we found in childhood obesity (**SECTION 1**) are related to the development of musculoskeletal disorders in adulthood such as injuries, osteoarthritis, low back pain or disc herniation. Thus, future longitudinal studies are needed in this regards.
- In the present Doctoral Thesis we could not answer whether the impact of childhood obesity on body posture and gait biomechanics (**SECTION 1**) differs between sexes, and further research in this regard is warranted.
- Since the postural malalignments and biomechanical alterations seems to develop at an early age (**SECTION 1**), a premature diagnosis is necessary in order to intervene as soon as possible. Thus, it is necessary to agree on the different health agents involved in this field of knowledge such as paediatricians, orthopaedics, endocrinologist and podiatrists, to create common diagnostic strategies.

- Included articles in **SECTION 1** presented considerably different assessment protocols to analysis the body posture and gait pattern, and a unification of all these protocol is needed to make the results more comparable.
- **SECTION 2** shows the associations of physical fitness with body posture and movement competence, but there are no studies investigating the association of physical fitness with the biomechanics of walking (e.g., plantar pressure or kinematics).
- The main limitation in investigating movement competence in childhood is that available instruments are considerable time-consuming. Fundamental movements, since are more analytic and controlled tasks, are easier and faster to evaluate than Fundamental Movement Skills. We encourage further investigation on Fundamental Movement in childhood, and that new assessment instruments be designed that allow us to have information on movement competence quickly and easily (e.g., mobile apps).
- In our intervention studies (**SECTION 3**), we found several biomechanical changes that could be beneficial for the musculoskeletal health of these children. However, future follow-up studies should determine whether these changes have a real positive effects on the musculoskeletal system of this children.
- Future exercise interventions should additionally include assessment such as MRI (magnetic resonance imaging) and TAC (tomography axial computerized) of the joints to investigate whether biomechanical changes are related to structural changes on the musculoskeletal system.
- We really believe that schools are the ideal place to evaluate several biomechanical dimensions in children and adolescents. Complex motion capture analysis are not feasible since they require since very expensive instruments and a long time of data processing. However, body posture assessment only require one of two photos of each children, which makes it reasonable feasible to be incorporated into schools. Recent studies were able to estimate complex body composition indicators through a simple photo [1, 2], so it is not unreasonable to think that something similar could occur with body posture in a near future. Can you imagine that from a simple photo we could have information on the body composition and posture of a child? This kind of tools will empower physical education teacher to raise red flags on the childhood obesity pandemic and its associated postural malalignments, and furthermore will give them the opportunity to evaluate the effect of possible interventions carried put inside schools.

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