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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Summary

It is known that obesity is associated with biomechanical alterations during locomotor tasks, which is considered a potential risk factor for the development of musculoskeletal disorders (MSKD). However, the association of obesity with biomechanical alterations of walking in the early stages of life have not yet been systematically reviewed. Thus, this review aims to summarise the biomechanical characteristics of walking in children and adolescents with overweight/obesity (OW/OB) versus their normal-weight (NW) counterparts. PubMed and Web of Science were systematically searched until November 2018. We found strong and moderate evidence supporting biomechanical differences in the gait pattern of OW/OB with respect to NW. 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. 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 biomechanical alterations during walking in OW/OB could play a major role in the onset and progression of MSKD.

1. 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 (MSKD) [4–6]. From early childhood, OW/OB has been associated to the development of various MSKD (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 MSKD 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 MSKD 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 (NW), 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 NW.

2. 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.

2.1. 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**.

2.2. Eligibility criteria

Inclusion criteria were defined as follows: 1) participants $\leq$ 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 NW. 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.

2.3. Study selection

The selection process of relevant articles was performed in two stages by two independent researchers (PM-G and AP-F). In the first stage, studies identified in the database search process were introduced to 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.

2.4. 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.

2.5. 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.

2.6. 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 NW 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 NW (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.

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

3.1. 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, NW, 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.

3.2. Quality assessment

Inter-rater reliability for the initial agreement between both researchers (PM-G and AP-F) was high to very high ($\kappa = 0.79$). 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.

3.3. Biomechanical characteristics of OW/OB

A summary of the evidence of gait biomechanics differences between OW/OB and NW is presented in **Table 2.** Furthermore, a schematic summary of main results based on strong and moderate evidence reporting gait biomechanical differences between OW/OB and NW 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**.

3.3.1. 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 NW. On the contrary, there was moderate evidence for non-significant differences between OW/OB and NW in the stride length [24,25,28,29,32].

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The remaining spatiotemporal parameters (i.e., gait speed, cadence, double support, swing and single support phases) demonstrated an inconsistent level of evidence.

3.3.2. Upper extremities kinematic and kinetic parameters

Given that only one study investigated differences between OW/OB and NW 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 motion in the frontal plane, while they display less arm and shoulder motion in the sagittal plane [33].

3.3.3. 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 NW peers [34,35]. 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 NW [29,35–38]. Kinetics of transversal plane showed inconsistent evidence, while there was insufficient evidence, with only one study available [39], to determine differences between OW/OB and NW in terms of contact forces acting on the femoral head during walking.

3.3.4. 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 NW [29,40,41]. 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 NW. Regarding kinetic parameters, we found moderate evidence supporting higher knee flexion and extension moments and higher power generation/absorption in OW/OB than in NW [29,36–38,42], as well as moderate evidence supporting higher knee abduction and adduction moments and power generation/absorption [29,36–38,42,43]. Furthermore, we found moderate evidence indicating higher tibiofemoral compressive forces and a more medially loaded distribution in OW/OB compared to NW during the stance phase of gait [44,45]. Lastly, there was insufficient evidence on transverse plane knee kinetics with only one study reporting on this [37].

3.3.5. 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 NW [28,36–38,43]. Differences between OW/OB and NW in frontal plane

kinetics were inconsistent, whereas insufficient evidence was available on transverse plane kinetics [37].

3.3.6. Centre of mass parameters

We identified only one study investigating differences in centre of mass parameters between OW/OB and NW during walking [46], 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 NW. Moreover, during the stance phase, they displaced their centre of mass with lower velocities than NW in vertical and anterior-posterior directions, whereas during the swing phase they demonstrated a greater centre of mass lateral displacement.

3.3.7. 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 NW [47,48]. On the other hand, there was moderate evidence supporting no differences between OW/OB and NW on quadriceps [39,47,49] and hamstring muscle [39,49] activations and forces, respectively. The remaining muscles studied in the gait pattern of OW/OB and NW were inconsistent (i.e., gluteus complex) or insufficient (i.e., psoas, iliacus and tibialis anterior).

4. Discussion

In the present systematic review, we provide an overview of the biomechanical characteristics of gait in OW/OB with respect to NW, 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.

4.1. 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 NW 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 [50]. 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 [28,51,52]. Concerning the remaining spatiotemporal parameters, there were no consistent differences between OW/OB and NW. 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.

4.2. Pelvis and hip kinematics and kinetics

Pelvis and hip kinematics of OW/OB only showed differences with respect to NW 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 [53]. 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 [27,54]. With regard to kinetics, OW/OB generated higher hip extension and abduction power, possibly to prevent lower-limb collapse and maintain an upright posture [28,38]. 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 [36].

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 [55]. Only studies of Briggs et al. [42], Lerner et al. [39,45] 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 [39]. Lerner et al. [39] found that OW/OB are exposed to higher femoral head forces in compressive and anterior-posterior directions compared to NW 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.

4.3. 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 [37]. 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 NW 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 [29,36]. We did not find consistent evidence of knee kinematic and kinetic differences in the sagittal plane of OW/OB with respect to NW, 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 [34,37].

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 [45,48]. To further explore how obesity affects knee contact forces relative to the skeletal structure, Lerner et al. [45] 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 NW peers, but also that their skeletal structure is not adapted to supporting the greater mechanical stresses [45].

4.4. 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 NW. Some authors have acknowledged this compensation as a need to decelerate and propel their heavier body mass into the next step [28,38]. 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. [56] 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.

4.5. Muscle activation and forces

This systematic review evidences a higher activation and forces of the gastrocnemius and soleus complex in OW/OB than NW during the whole gait cycle, which is in agreement with the higher ankle plantarflexion moment and power generation previously mentioned [45]. 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 [47,57]. 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 [47,48].

On the other hand, quadriceps and hamstring muscles have demonstrated a similar activation and forces profile in both OW/OB and NW, results which seem to not be consistent with the abovementioned 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 NW are meaningfully different.

4.6. Clinical implications

4.6.1. *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 MSKD, 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 MSKD 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 [39,58].

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 [59,60]. 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 MSKD. The gait patterns of OW/OB suggested in this review present similarities with other populations suffering from MSKD. For instance, some authors have reported that patients undergoing low back pain present increased pelvis transverse plane motion during walking [61], whereas patients present with knee osteoarthritis also walk with higher knee adduction moments than healthy-patients [62].

Among other possible consequences, the development of MSKD 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 [63], but has also major implications for mobility and quality of life during adulthood and old age [8,64]. It is important to highlight that all associations between biomechanical alterations and MSKD 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 MSKD.

4.6.2. *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 NW [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 [11,65]. For instance, a greater step width, as has been evidenced in OW/OB, is related to an increased energetic cost in human walking [11,66]. 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 [27,67].

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 [68], 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.

4.7. 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 MSKD 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.

5. Conclusion

Findings from this review reveal strong and moderate evidence supporting biomechanical differences in the gait pattern of OW/OB with respect to NW. 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 MSKD and could be a key factor to understanding the energetic inefficiency experienced by this population during walking.

6. Supporting information

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

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

Table S3. Summary of study characteristics of articles included in review.

Table S4. Quality assessment of included articles.

Table S5. Summary of the main gait biomechanical differences between children and adolescents with overweight/obesity and normal-weight divided by key gait phases.

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8. Tables and figures

9. **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

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 24–28,30,32,33,44	2 26,27	3 30,33,44	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 24,26,27,31,32,46	2 26,27	2 31,46	1 24	1 32	67	Inconsistent
Swing phase	6 24,26,29–31,46	2 26,29	1 31	1 24	2 30,46	50	Inconsistent
Single support phase	3 27,30,32	1 27	1 32	-	1 30	67	Inconsistent
Upper extremities							
Kinematics	1 33	-	1 33	-	-	100	Insufficient
Pelvis and hip							
Kinematics							
Sagittal	7 24,28,29,34,37,39,41	4 28,34,39,41	-	3 24,29,37	-	57	Inconsistent
Frontal	8 28,29,34,37,39–41,47	4 28,34,40,47	-	4 29,37,39,41	-	50	Inconsistent
Transversal	2 28,34	2 28,34	-	-	-	100	Strong diff.
Kinetics							
Sagittal	6 28,29,36–38,69	5 28,29,36–38	1 69	-	-	100	Strong diff.
Frontal	4 29,36–38	4 29,36–38	-	-	-	100	Strong diff
Transversal	2 36,38	1 38	-	1 36	-	50	Inconsistent
Contact force	1 39	1 39	-	-	-	100	Insufficient
Knee							
Kinematics							
Sagittal	9 24,28,29,34,37,41,45,47,70	5 28,29,34,41,47	1 70	3 24,37,45	-	66	Inconsistent
Frontal	4 29,37,40,41	3 29,40,41	-	1 37	-	75	Strong diff.
Transversal	1 34	1 34	-	-	-	100	Insufficient
Kinetics							
Sagittal	7 29,32,36–38,42,70	5 29,36–38,42	-	-	2 32,70	71	Moderate diff.
Frontal	7 29,36–38,42,45,70	5 36–38,42,45	1 70	1 29	-	86	Strong diff.
Transversal	1 37	1 37	-	-	-	100	Insufficient

Contact force	2 44,45	1 45	1 44	-	-	100	Moderate diff.
Ankle and foot							
Kinematics							
Sagittal	7 24,28,29,34,37,41,56	4 24,28,41,56	-	3 29,34,37	-	57	Inconsistent
Frontal	6 29,34,37,40,41,56	3 34,40,56	-	3 29,37,41	-	50	Inconsistent
Transversal	3 34,37,56	2 34,56	-	1 37	-	67	Inconsistent
Kinetics							
Sagittal	7 28,29,32,36–38,70	4 28,36–38	1 70	1 29	1 69	71	Moderate diff.
Frontal	2 29,37	1 37	-	1 29	-	50	Inconsistent
Transversal	1 37	1 37	-	-	-	100	Insufficient
Centre of mass							
Velocity/acceleration	1 46	-	1 46	-	-	100	Insufficient
Lateral displacement	1 46	-	1 46	-	-	100	Insufficient
Muscle Activation							
Psoas and iliacus	1 39	-	-	1 39	-	100	Insufficient
Gluteus complex	2 39,47	1 47	-	1 39	-	50	Inconsistent
Quadriceps	4 39,44,47,49	-	1 44	3 39,47,49	-	75	Strong no diff.
Hamstring	3 39,44,49	-	1 44	2 39,49	-	67	Moderate no diff.
Gastrocnemius/soleus	2 44,47	1 47	1 44	-	-	100	Moderate diff.
Tibialis anterior	1 49	-	-	1 49	-	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 ($\geq$ 75% of results showed significant or no significant differences). N studies: number of studies reporting a biomechanical parameter; diff: difference between children and adolescents with overweight/obese vs their normal-weight peers.

Identification

Records identified through databases searching

PubMed = 1138 articles
Web of Science = 1566 articles
N total = 2704 articles

Duplicated excluded

N = 353 articles

Screening

Records screened by title and abstract

N = 2351 articles

Records excluded

N = 2304 articles

Elegibility

Full-text articles assessed for eligibility

N = 47 articles

Full text excluded for different reasons

N total = 22 articles

- Not original paper (N = 9)
- Irrelevant outcomes (N = 4)
- Adult population (N = 3)
- Only overweight/obese population (N = 2)
- Wrong study design (N = 4)

Included

Studies included in the review
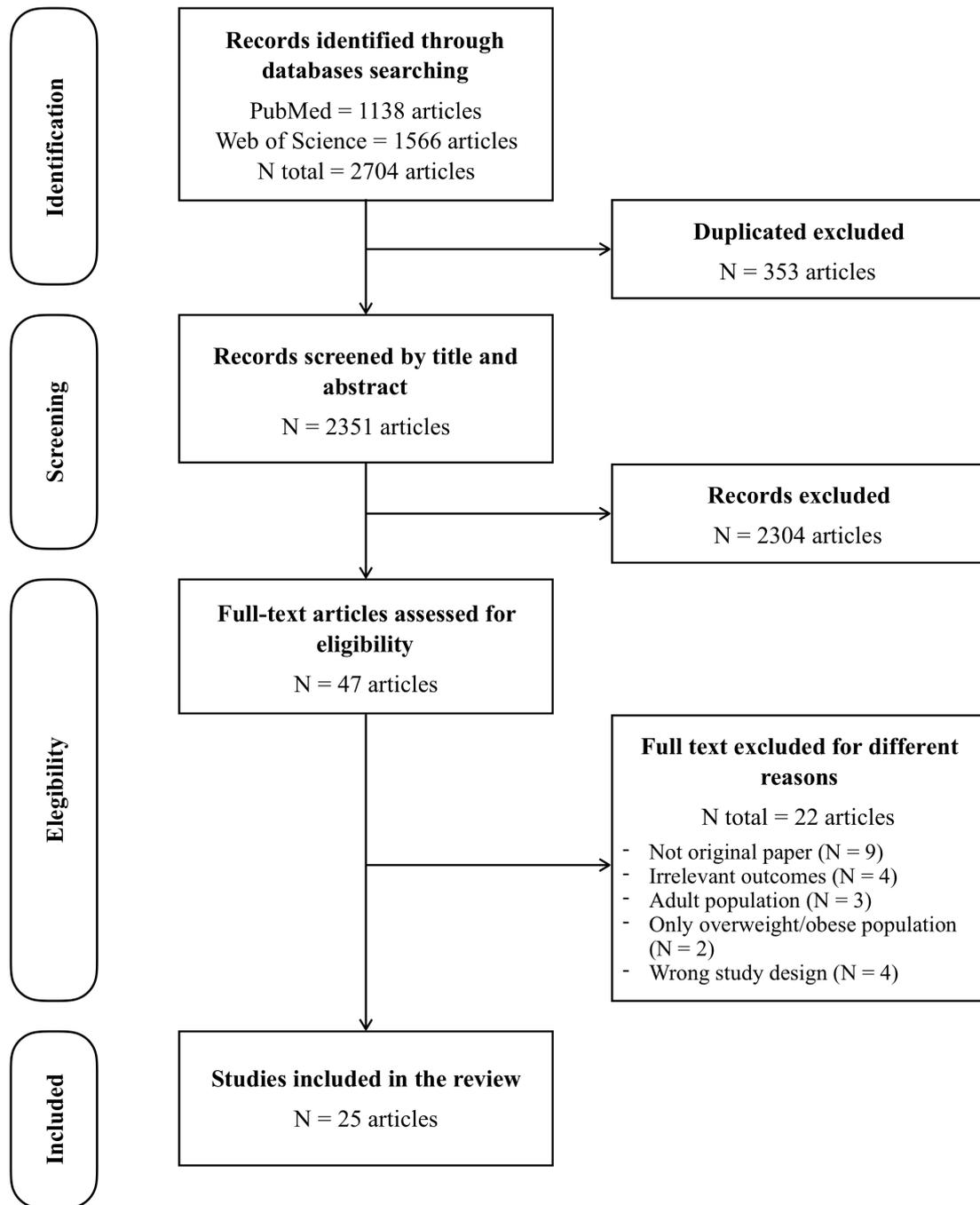
N = 25 articles

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of study selection, inclusion and exclusion of studies.
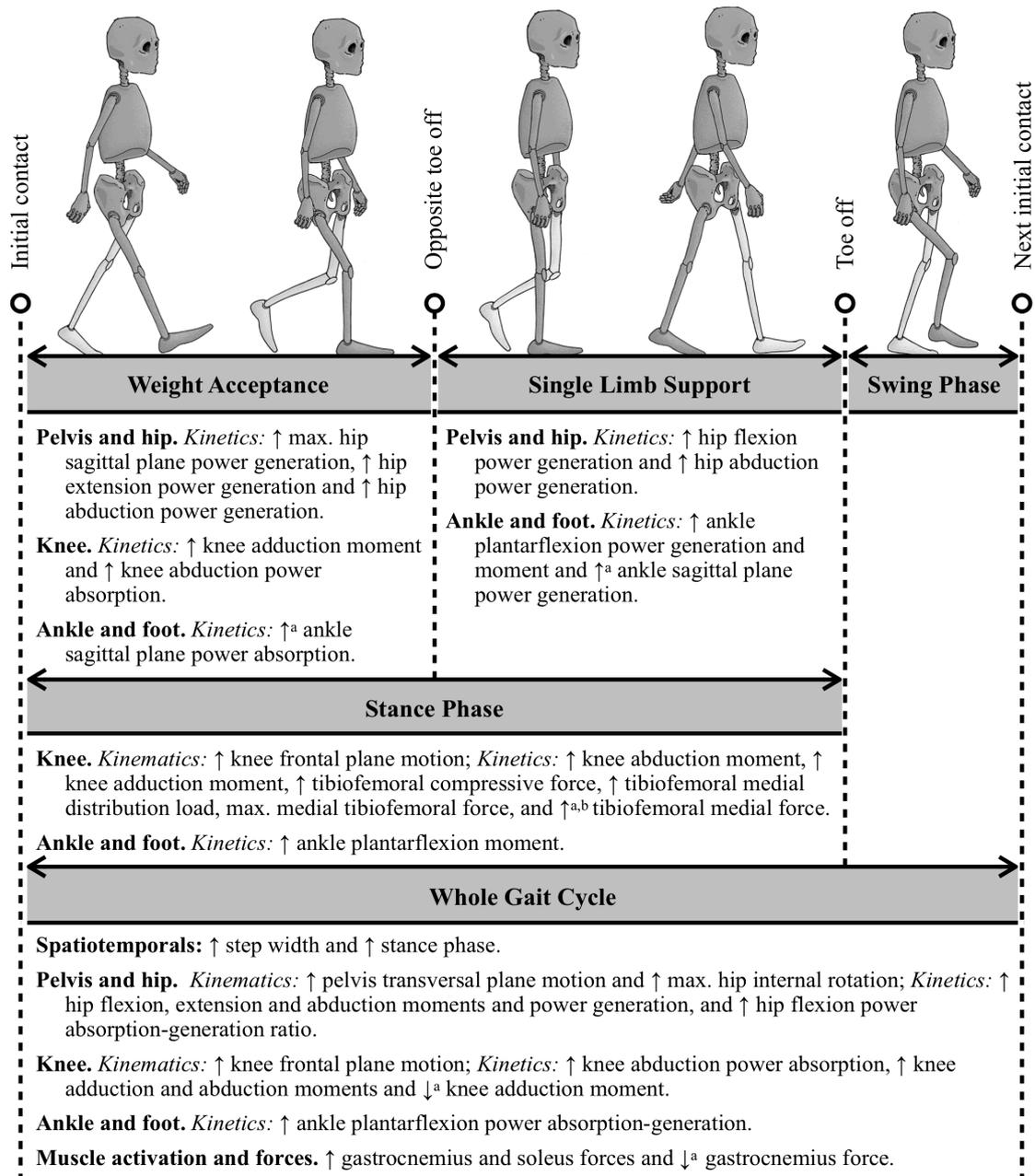
Initial contact · **Opposite toe off** · **Toe off** · **Next initial contact**

| Weight Acceptance | Single Limb Support | Swing Phase |

Weight Acceptance

Pelvis and hip. *Kinetics:* ↑ max. hip sagittal plane power generation, ↑ hip extension power generation and ↑ hip abduction power generation.

Knee. *Kinetics:* ↑ knee adduction moment and ↑ knee abduction power absorption.

Ankle and foot. *Kinetics:* ↑[a] ankle sagittal plane power absorption.

Single Limb Support

Pelvis and hip. *Kinetics:* ↑ hip flexion power generation and ↑ hip abduction power generation.

Ankle and foot. *Kinetics:* ↑ ankle plantarflexion power generation and moment and ↑[a] ankle sagittal plane power generation.

Stance Phase

Knee. *Kinematics:* ↑ knee frontal plane motion; *Kinetics:* ↑ knee abduction moment, ↑ knee adduction moment, ↑ tibiofemoral compressive force, ↑ tibiofemoral medial distribution load, max. medial tibiofemoral force, and ↑[a,b] tibiofemoral medial force.

Ankle and foot. *Kinetics:* ↑ ankle plantarflexion moment.

Whole Gait Cycle

Spatiotemporals: ↑ step width and ↑ stance phase.

Pelvis and hip. *Kinematics:* ↑ pelvis transversal plane motion and ↑ max. hip internal rotation; *Kinetics:* ↑ hip flexion, extension and abduction moments and power generation, and ↑ hip flexion power absorption-generation ratio.

Knee. *Kinematics:* ↑ knee frontal plane motion; *Kinetics:* ↑ knee abduction power absorption, ↑ knee adduction and abduction moments and ↓[a] knee adduction moment.

Ankle and foot. *Kinetics:* ↑ ankle plantarflexion power absorption-generation.

Muscle activation and forces. ↑ gastrocnemius and soleus forces and ↓[a] gastrocnemius force.

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 (cm^2)