Gait & Posture xxx (xxxx) xxx

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Multi-segment models for kinetic analysis of women during pregnancy: A systematic review[1]

Jie Chen [a,*], Xin Li [b], Patria A. Hume [a,c,d,e], Hannah Wyatt [c,f,g], Julie Choisne [a]

[a] Auckland Bioengineering Institute, The University of Auckland, Auckland, New Zealand
[b] Faculty of Engineering, University of Pannonia, Veszprém, Hungary
[c] Sports Performance Research Institute New Zealand (SPRINZ), Faculty of Health and Environmental Science, Auckland University of Technology, New Zealand
[d] Traumatic Brain Injury Network (TBIN), Auckland University of Technology, Auckland, New Zealand
[e] Technology and Policy Lab - Law School, The University of Western Australia, Perth, Australia
[f] Sport, Health and Rehabilitation Research Cluster, Faculty of Health, The University of Canterbury, Christchurch, New Zealand
[g] Biomolecular Interaction Centre, University of Canterbury, Christchurch, New Zealand

ARTICLE INFO

Keywords:
Multi-segment model
Musculoskeletal model
Kinetic analysis
Pregnant women

ABSTRACT

Background: During pregnancy, significant physiological, morphological, and hormonal changes profoundly affect women's biomechanics, increasing the risk of falls and musculoskeletal complaints, especially in the third trimester. To understand movement adaptations and musculoskeletal disorders in pregnant women, kinetic analysis using pregnant-specific multi-segment or musculoskeletal models is essential. This review aims to evaluate the development, applications and limitations of such models intended for kinetic analysis in pregnancy.

Methods: Following the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement, PubMed, Web of Science, Scopus, and IEEE Xplore databases were searched systematically for kinetic studies involving the pregnant-specific multi-segment models. Quality assessment was completed to assess the methodological quality of the selected studies.

Results: A total of 14 different pregnant-specific multi-segment models (including musculoskeletal models) used within 19 kinetic studies were included in this review. Currently, most scaling methods are marker-based and limited by pregnancy-related soft tissue artifacts. Segment inertial parameter estimations were largely based on regression models, which may not adequately capture the high degree of individual variability among pregnant women. Most existing models focus on analyzing lower-limb or lumbar kinetics during daily activities, yet many remain unvalidated and lack detailed lumbopelvic representations. Pregnant-specific musculoskeletal models are scarce and primarily rely on static optimization for lumbar muscle force estimation, which overlooks trunk co-contraction.

Conclusion: Future research should focus on developing more detailed and validated pregnant-specific models, alongside advanced workflows for more accurate model personalization, to more accurately capture the biomechanical changes across different pregnancy stages and support clinically relevant kinetic analysis.

1. Introduction

During pregnancy, women experience substantial changes in their physiology, morphology, and hormonal systems. These changes profoundly impact the musculoskeletal system and consequently the biomechanics of the human body [1,2]. The disproportional changes in body mass [3], joint laxity caused by the seven to ten-fold increased relaxin hormone [4], and altered postural control and movement patterns [5] of pregnant women all have the potential to influence the stresses placed on the musculoskeletal system. As a result, pregnant women face an elevated risk of falls with an estimated incidence of 17 %–39 % [6], and a variety of musculoskeletal disorders [7], such as back pain [8], pelvic pain [9], lower extremity pain [10], muscle cramps and peripheral neuropathies [11], especially during the third trimester

[1] Prospero registration number: CRD420250589467

* Corresponding author.
E-mail address: jche973@aucklanduni.ac.nz (J. Chen).

https://doi.org/10.1016/j.gaitpost.2025.08.082
Received 21 May 2025; Received in revised form 23 July 2025; Accepted 29 August 2025
Available online 30 August 2025

[7].

To better understand the mechanisms of pregnant-related movement adaptation and musculoskeletal disorders from a biomechanical perspective, it is crucial to perform human kinetic analysis. Multi-segment models represent the human body as rigid segments articulated through joints, which are effective and efficient for estimating joint moments during kinetic analysis [12]. Musculoskeletal models are advanced multi-segment models that incorporate muscle-tendon actuators, allowing further estimation of muscle forces and joint contact forces [13–15]. Kinetic analysis based on these models enables the quantification of internal parameters that cannot be measured in vivo non-invasively, and has proven to be a versatile and effective method for studying a wide range of biomechanical and clinical conditions [13].

For instance, in gait pathology research, assessments of bilateral asymmetry and center of mass (COM) trajectory have been used to characterize balance impairments that may elevate fall risk [16–18]. In clinical studies of musculoskeletal pain, estimated muscle activations and joint contact forces have provided insights into abnormal loading patterns potentially underlying pain symptoms [19,20]. Given the high prevalence of falls and musculoskeletal disorders during pregnancy, applying multi-segment modeling to pregnant populations holds significant promise for both research and clinical applications. To enhance model accuracy and population representativeness, multi-segment models have been frequently adapted for specific cohorts, such as individuals with limb amputation [21], obesity [21], neuromuscular disorder [22,23], or post-surgical conditions [24]. Likewise, developing pregnant-specific models can further improve the physiological relevance and predictive accuracy of such analyses, providing a deeper understanding of gestational biomechanics and associated health risks. For clinical application, an accurate model may serve as a screening tool to predict pain development or falling risk and guide perinatal rehabilitation or ergonomic interventions for pain management or fall prevention [25].

At present, however, there is a scarcity of studies proposing detailed musculoskeletal or multi-segment modeling methods specifically designed for pregnant women, whether a generic pregnant-specific model to scale, or a workflow to build a subject-specific one [3]. In this study, the term "generic model" refers to a scalable baseline model constructed from averaged anthropometric and anatomical data. Given the increasing need for tailored healthcare in pregnant women, and to provide direction for future modeling, it is crucial to evaluate existing pregnant-specific models. Therefore, this review aims to investigate the characteristics, applications, limitations and challenges of pregnant-specific multi-segment modeling used in prior kinetic analysis, specifically focusing on how these models have been developed for pregnant women.

2. Methods

This study followed a systematic review methodology adhering to PRISMA guidelines [26] (literature search; assessment of study quality; data collection of study characteristics; analysis and interpretation of results; recommendations for practice and further research).

2.1. Search strategy

PubMed, Web of Science, Scopus, and IEEE Xplore databases were searched without any date restriction. We used the following terms: (musculoskeletal model OR computational model OR biomechanical model OR kinetic* OR multi-body OR multi-segment* OR multibody OR multisegment*) AND (pregnan* OR gestation* OR perinatal OR prenatal OR antenatal) AND (women OR woman) search strategy in the field of Full text to search databases. Searching was from inception to 22/08/2024. Manual searching of reference lists and the ‘Cited by’ tool on Google Scholar were used to identify additional articles.

2.2. Study selection

Titles and abstracts of potentially eligible studies were screened by two authors (JC, XL) separately. Full text of all studies that were not excluded after initial title and abstract screening were retrieved and assessed for eligibility by the lead author (JC) and independently checked by a co-author (XL). Disagreements between researchers during full-text screening were resolved through discussion with all other co-authors. Studies were included if multi-segment models were used for kinetic analysis for pregnant women. Papers were excluded if: (i) content was unavailable in English; (ii) content was not peer-reviewed or unavailable in full-text format; (iii) they did not use multi-segment models for the purpose of kinetic analysis for pregnant women; (iv) they did not introduce details of the modeling process of the multi-body model; (v) no pregnant-specific modifications were made to the model beyond general anthropometric scaling. Fig. 1 shows the PRISMA flowchart used in finding relevant studies.

Note that the term ’pregnant-specific model’ in this review refers to models that incorporate modifications directly reflecting pregnant-related anatomical or physiological changes. These may include, but are not limited to, the addition or remodeling of segments such as the uterus or fetus, adjustments to segment inertial properties, or changes to joint definitions or muscle paths that account for pregnancy-induced postural adaptations. Although pregnant-related morphological changes are significant, the skeletal structure is basically the same as regular people [27]. Therefore, scaling alone was considered a subject-specific process rather than a pregnant-specific process, unless the model incorporates new segments such as the uterus or other pregnancy-related anatomical changes.

2.3. Quality assessment

A customized checklist was developed based on previous reviews in the field of biomechanics modeling topics to assess the methodological quality of the selected studies [28–30]. Each question was rated as two (satisfying description or justification), one (limited details) or zero (no information). The 15-item quality checklist used in this review was:

Q1: Are the research objectives clearly stated?
Q2: Is the study design clearly described?
Q3: Is the scientific context clearly explained?
Q4: Is the original multi-segment model clearly described?
Q5: Were the pregnant-specific alterations of the model clearly described?
Q6: Were participant characteristics (including pregnancy trimester) adequately described?
Q7: Were movement tasks, equipment design, and setup clearly defined?
Q8: Was the evaluation strategy appropriately justified?
Q9: Was the joint kinetic analysis methodology clearly described?
Q10: Were the statistical methods justified and appropriately described (other than descriptive statistics)? Q11: Were the direct results easily interpretable?
Q12: Were the main outcomes clearly stated and supported by the results?
Q13: Were the limitations of the study clearly described?
Q14: Were key findings supported by other literature?
Q15: Were conclusions drawn from the study clearly stated?

Two authors (JC, XL) reviewed all included studies independently. Discrepancy between these reviewers was resolved by a meeting in which consensus was found between authors.

2.4. Data extraction

A customized data extraction form was developed to extract key

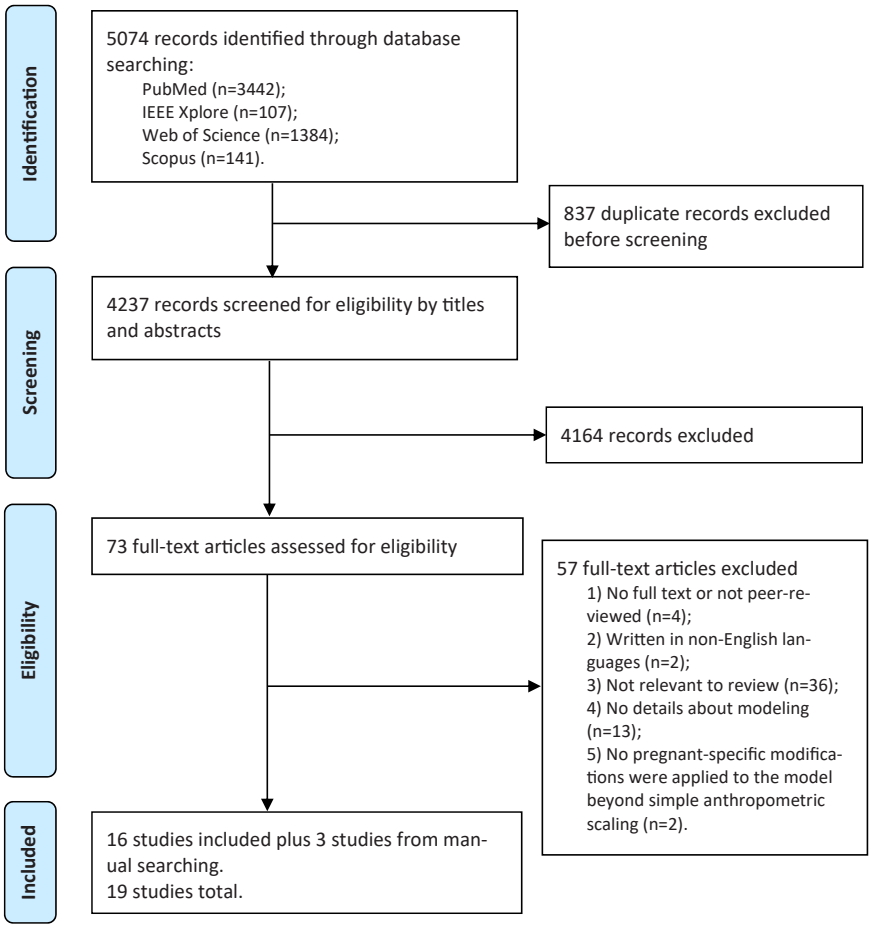

Fig. 1. The PRISMA flowchart of identification, screening, eligibility, and study inclusion of previously published studies.

details from each selected study. The lead author (JC) extracted data from included studies; data were checked by a co-author (XL), and conflicts were resolved after discussion with all other co-authors. Data extraction included the first author's name, year of publication, study focus, pregnant trimester simulated, original model characteristics (model type, software and included segments), pregnant-specific modifications (segment geometric parameters, segment inertial parameters, muscle parameters), evaluation of new model, kinematic and kinetic input, simulation workflow and kinetic outcomes measured.

2.5. Data analysis

A descriptive summary and analysis were performed. Results were categorized and reported based on the general and specific characteristics outlined in the previous section (author's name, year of publication, study focus, pregnant trimester simulated, original model characteristics, pregnant-specific modifications, evaluation of model, kinematic and kinetic input, simulation workflow and kinetic outcomes).

3. Results

3.1. Search strategy yield

Of 5074 studies identified, 837 were duplicates. A further 4164 studies were removed after screening by title and abstract. After the eligibility assessment of 73 full-text articles, 57 additional studies were excluded due to: 1) full text not available or not peer-reviewed (n = 4); 2) full text written in languages other than English (n = 2); 3) did not use multi-segment models for the purpose of kinetic analysis for pregnant women (n = 36); 4) contained no details about modeling process of the multi-body model (n = 13); 4) made no additional pregnant-specific modifications to the model beyond scaling (n = 2). Quality assessment results and data extraction are reported (Supplementary Table S1, S2 and Table 1).

3.2. Quality assessment

The selected studies were of high quality, with scores ranging between 80 % and 100 % and a mean score of 91 % (Supplementary Table S1). However, several questions were only partially answered, for example:

1. Validation of the model was not explicitly mentioned in most research;
2. Detail of the original model was not always explicitly mentioned in certain research;
3. Pregnant-specific alterations were not adequately mentioned in certain research;
4. Some selected studies reported descriptive statistics other than statistical methods (i.e. mean, standard deviation, root mean square error, correlation).

All noted limitations were reflected in the quality assessment scores.

3.3. Original multi-segment model characteristics

In the 19 included studies that met selection criteria, there were 14 different pregnant-specific multi-segment models used for kinetic analysis. Most models (11 out of 14, Fig. 2) were developed since 2010, and

Table 1
Overview of pregnant-specific multi-segment models, modeling methods and biomechanical research questions to address.

Study	Research Focus & Focused Trimester	Original Model		Pregnant-specific Modifications			Evaluation of Model	Kinematic and Kinetic Input	Simulation Workflow & Kinetic Outcomes Measured
		Model Characteristics	Included Segments	Pregnant-specific Segment Geometry	Pregnant-specific Segment Inertial Parameters	Pregnant-specific Muscle Parameters			
Haddox et al. [3] (2020)	Changes in body segmental mass and inertia during pregnancy Trimester: 1–3 T	Software: OpenSim 3D / Dynamic / full-body musculoskeletal model	12 segments (92 muscles [31])	No	Yes Details: BSIPs calculated by an elementary shape model built based on anthropometric data of military women [32]	No	Yes	Stance phase of gait of a healthy person from OpenSim dataset [31] (gait2354)	ID Joint moments of the ankle, knee, hip, and lumbar
Nakashima et al. [33,34] (2010 & 2014)	1. Muscle load of the erector spinae during standing and sitting tasks during pregnancy [33] (2010) Trimester: 3 T	Software: AnyBody 3D / Static&Dynamic / full-body musculoskeletal model	21 segments (464 muscles)	Yes Details: Modeling of an extra segment of the uterus [35,36] & Manual modification of other segments [35,37].	Yes Details: COM of uterus estimated in the center of enlarged abdomen [35]. Increased weight of breast added to thorax, increased weight of other body parts added to abdomen, arms and legs [35,38].	Yes Details: Modeling of stretched abdominal muscles [35,39]	Yes	Standing straight, bending forward and bending backward; Sitting on a seat with a backrest	ID, SO Muscle force of the erector spinae
	2. Muscle load of the erector spinae during chair-rise for pregnant women [34] (2014) Trimester: 3 T		25 segments (581 muscles)					Sit-to-stand with comfortable, fast and slow speeds	IK, ID, SO Muscle force of the erector spinae
Michnik et al. [40] (2022)	Effect of the growing fetus on lumbopelvic loads during standing Trimester: 1–3 T	Software: AnyBody 3D / Static / full-body musculoskeletal model	69 segments (1000 muscles)	Yes Details: Manual modification based on anthropometric data [41,42].	Yes Details: A force vector representing increased weight of uterus added to abdominal area [43].	Yes Details: Modeling of stretched abdominal muscles [43]	No	Standing with pregnant-specific anterior pelvic tilt [41,42]	SO Muscle forces of erector spinae, transversus abdominis, biceps femoris longum and iliopsoas; resultant, compression, and shear forces in L5-S1 and hip joint
Morino et al. [44,45] (2017 & 2020)	1. The co-contraction of trunk muscles during chair-rise for pregnant women [45] (2017) Trimester: 3 T	Software: Biomechanics of Bodies in Matlab 3D / Dynamic / full-body musculoskeletal model	36 segments (666 muscles)	Yes Details: Manual modification based on anthropometric data [37].	Yes Details: Adding weight gain of breast, abdomen, arms, and legs, and estimating COM of lower trunk [33,46] based on the model with female mass distribution [46].	Yes Details: Modeling of stretched abdominal muscles [35,39]	Yes	Sit-to-stand	IK, ID, Genetic algorithm Muscle torque of the rectus abdominis and erector spinae
	2. Relationships between motion, muscle load, and the severity of LBP during chair-rise [44] (2020) Trimester: 3 T								
Schröder et al. [47] (2016)	Impact of pregnancy on back pain and spinal posture Trimester: 1–3 T, PP	Software: NA 3D / Static / Spinal biomechanic model with musculus erector spinae [48]	Probably 7 segments	Yes Details: Modification of trunk length measured by Video raster stereography and vertebral body heights [49].	Yes Details: Vertebral body mass derived from literature [50].	No	No	Isometric trunk flexion, extension, lateral flexion, and rotation	Static equilibrium-based analysis methods (Formula) Muscle force of the erector spinae
Aguiar et al. [51,52] (2014 & 2015)	1. The gait pattern during the 2 T of pregnancy [51] (2014) Trimester: 2 T	Software: Visual 3D 3D / Dynamic / lower-limb model	7 segments	Yes Details: Scaled by markers.	Yes Details: Calculated by regression equations based on anthropometric data [53].	NA	No	Walking	IK, ID Joint moments of the ankle, knee, and hip

(*continued on next page*)

Table 1 (*continued*)

Study	Research Focus & Focused Trimester	Original Model		Pregnant-specific Modifications			Evaluation of Model	Kinematic and Kinetic Input	Simulation Workflow & Kinetic Outcomes Measured
		Model Characteristics	Included Segments	Pregnant-specific Segment Geometry	Pregnant-specific Segment Inertial Parameters	Pregnant-specific Muscle Parameters			
	2. Gait adaptations related with increased trunk mass during pregnancy [52] (2015) Trimester: 2 T				Yes Details: Calculated by regression equation [36].				
Branco et al. [54–56] (2015 & 2016)	1. Gait kinetics from the beginning of pregnancy until the postpartum [54] (2015) Trimester: 1–3 T, PP 2. Differences of gait kinetics between 2,3 T and non-pregnant group [56] (2015) Trimester: 2–3 T 3. Relationships between maternal anthropometry, body composition and gait kinetics [55] (2016) Trimester: 1–3 T, PP	Software: Visual 3D 3D / Dynamic / lower-limb model	7 segments	Yes Details: Scaled by markers.	Yes Details: Calculated by anthropometric data [57].	NA	No	Walking	IK, ID Joint moments and powers of the ankle, knee, and hip
Catena et al. [58] (2021)	Biomechanical costs of gestational lumbopelvic curvature change during standing and walking Trimester: 2–3 T	Software: Cortex v8 3D / Static & Dynamic / full-body model	13 segments	Yes Details: Scaled by markers.	Yes Details: Calculated by regression equations based on anthropometric data [59–61].	NA	No	Standing & walking	IK, ID Joint moments and powers of the ankle, knee, and hip, mechanical energy requirements and balance control of walking and standing
Hemmerich et al. [62] (2018)	Pelvic loads of dynamic movements during childbirth Trimester: 3 T	Software: Visual 3D 3D / Dynamic / lower-limb model	7 segments	Yes Details: Scaled by markers.	Yes Details: Calculated by digitized body segments guided by the reflective markers [63]	NA	No	Childbirth movements (including squatting, all-fours and supine)	IK, ID Joint moments of hip and lumbosacral joint
Howard et al. [27] (2012)	Compare three different physics-based posture prediction formulations for the prediction of seated postures of pregnant women Trimester: 3 T	Software: SNOPT [64] 3D / Dynamic / full-body model	28 segments	Yes Details: Manual modification of the size of the abdomen sphere segment based on anthropometric measurements. Other segments are scaled by markers.	Yes Details: COM of uterus as a point force applied at the center of the abdomen segment; Mass, COM of other segments are computed by regression equations [65]. Moments of inertia are ignored.	NA	No	Target-reaching tasks while sitting	IK, ID Average torque in each spinal joint
Jensen et al. [36] (1996)	Changes in body segmental mass and inertia during pregnancy Trimester: 2–3 T	Software: NA 2D / Dynamic / full-body model	16 segments	Yes Details: Not mentioned	Yes Details: Calculated by digitized body segments orthogonal front	NA	No	Sit-to-stand	Intersegmental dynamic analysis Hip moments

(*continued on next page*)

Table 1 (*continued*)

Study	Research Focus & Focused Trimester	Original Model		Pregnant-specific Modifications			Evaluation of Model	Kinematic and Kinetic Input	Simulation Workflow & Kinetic Outcomes Measured
		Model Characteristics	Included Segments	Pregnant-specific Segment Geometry	Pregnant-specific Segment Inertial Parameters	Pregnant-specific Muscle Parameters			
					and right side photographs [66].				
Lou et al. [67] (2001)	Kinetics of chair-rise at different periods of pregnancy Trimester: 1–3 T	Software: laboratory-developed software 2D / Dynamic / full-body model	4 segments	Yes Details: Scaled by markers.	Yes Details: Calculated by anthropometric data [68].	NA	No	Sit-to-stand	IK, ID Moments of ankle, knee, and hip joints
Paul et al. [69] (1996)	Effect of a standing task on hip kinetics during pregnancy Trimester: 1–3 T	Software: NA 2D / Static / full-body model	9 segments	Yes Details: Manual modification of the segment length based on the proportion of measured bone length [68, 70].	Yes Details: Segment masses were estimated by volumes calculated from body dimensions based on regression [71]. Pregnant-specific mass increase was divided among all segments [72], and segment COMs were estimated [68,70, 73].	NA	No	Bolt-winding tasks while standing	Static equilibrium-based analysis methods (Free body diagram) Hip joint moments
Sunaga et al. [39] (2016)	Inertial parameters of the lower trunk in pregnant women Trimester: 1–3 T	Software: Body Builder 3D / Dynamic / full-body model	15 segments	Yes Details: Scaled by markers.	Yes Details: BSIPs of lower trunk were estimated by 3D motion capture system; other segments refer to literature [74].	NA	No	Sit-to-stand, picking up plates, turning to the right, and walking a few steps	IK, ID Lower trunk moment

The definition of the abbreviations: T (trimester), PP (postpartum), LBP (low back pain), BSIP (body segment inertial parameter), COM (center of mass), IK (inverse kinematic), ID (inverse dynamic), SO (static optimization). A detailed table of extensive information is provided in Supplementary Table S2.

only three models were developed before 2010 [36,67,69].

3.3.1. Software

A variety of software packages were utilized across the reviewed studies to develop pregnant-specific multi-segment models (Fig. 2). Motion analysis software was the most frequently used tool, including four models developed in Visual 3D [51,54,62], one developed in Body Builder [39], and one developed in Cortex v8 [58]. Musculoskeletal models were developed using specialized biomechanical software such as OpenSim (one model) [3] and AnyBody (two models) [33,40]. Additionally, mathematical and optimization software like Matlab (one model) [45] and SNOPT (one model) [27] were also used. One model was based on laboratory-developed software [67]. Three studies did not report the software that was used for model development [36,47,69].

3.3.2. 3D/2D

The majority (11 out of 14) are 3-dimensional models [3,27,33,39, 40,45,47,51,54,58,62], with only three models being 2-dimensional [36,67,69].

3.3.3. Static/dynamic

Most models (11 out of 14) were used to simulate dynamic conditions [3,27,33,36,39,45,51,54,58,62,67], and three models were only used to simulate static conditions [40,47,69].

3.3.4. Segments

The number of segments in the multi-body models ranged from four to 69. Most models (10 out of 14) are full-body models [3,27,33,36,39, 40,45,58,67,69], including segments of the lower limbs, pelvis, trunk and upper limbs. Several models (three out of 14) are lower-limb models, only including the pelvis, thigh, shank, and foot segments [51,54,62]. One model was limited to the torso, which included the rib cage, L1-L5, and pelvis segments [47].

3.3.5. Muscles

Approximately one-third of the models (five out of 14, Fig. 2) are musculoskeletal models, containing musculotendon actuators ranging from 86 to 1000 [3,33,40,45,47].

3.4. Pregnant-specific modifications

3.4.1. Body segment lengths

Most models (eight out of 14) [27,39,51,56,58,62,67,69] utilized marker-based scaling to custom segment geometry for pregnant women. Three models were manually scaled based on anthropometric data from the pregnant-related literature [33,40,45]. One model applied a combination of scaling methods with some parameters from the literature and some from experimental measurements [47]. One model did not incorporate pregnant subject-specific scaling [3], and another did not document details of scaling [36].

3.4.2. Body segment inertial parameters

All included models made pregnant-specific modifications to the body segment inertia parameters (BSIPs), although the degree of detail

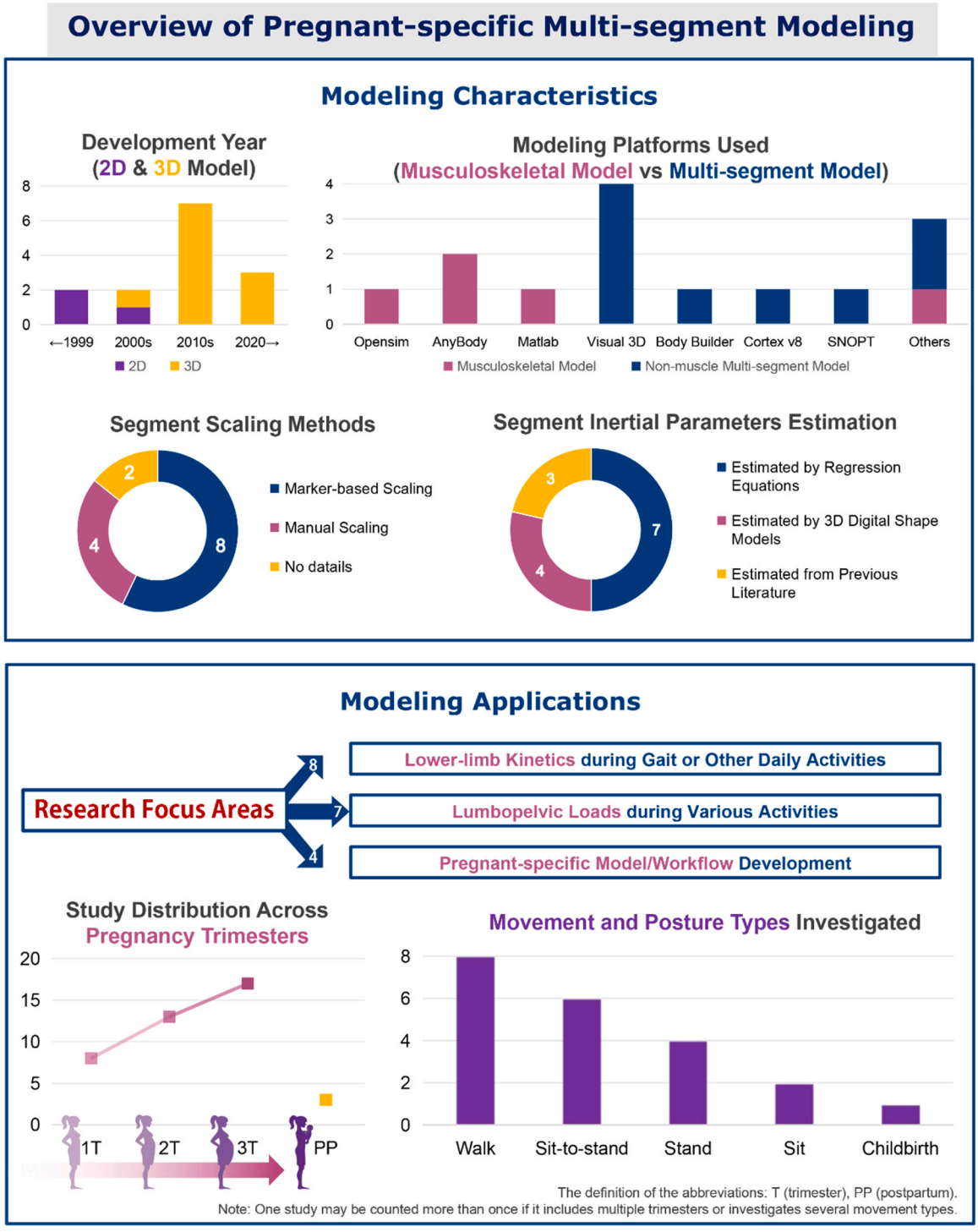

Fig. 2. Visual summary of pregnant-specific multi-segment modeling methods and applications.

provided varied widely. BSIPs of many models (seven out of 14) were estimated by regression equations, which may require anthropometric data as input [27,51,52,54,58,67,69]. Some models (four out of 14) were numerically computed by 3D digital shape models [3,36,39,62]. Others were estimated roughly based on anthropometric data from relevant literature [33,40,45].

3.4.3. *Muscle paths and musculotendon parameters*

To avoid confusion, we use "muscle path" to refer only to the geometric trajectory of the muscle (via points, wrapping surfaces, etc.), and "musculotendon parameters" to refer to mechanical or physiological properties such as optimal fibre length, tendon slack length, and maximum isometric force.

Of the five musculoskeletal models, three made pregnant-specific modifications in musculotendon actuators other than just scaling, by changing the stretched abdominal muscle paths [33,40,45]. None changed the musculotendon parameters.

3.4.4. *Evaluation of new model*

Few (three out of 14) modified pregnant-specific models were evaluated or validated [3,33,45]. Two models were validated for their ability to simulate muscle forces by comparing them with

electromyography (EMG) data [33,45]. Another model was only validated for the rationality of the body segmental mass by comparing it with previous measurements [3].

3.5. Applications of pregnant-specific models for kinetic analysis

3.5.1. Research Focus

Some research (eight out of 19, Fig. 2) utilized pregnant-specific models to explore lower-limb kinetics during gait or other daily activities during pregnancy [51,52,54–56,58,67,69]. Other studies (seven out of 19, Fig. 2) applied pregnant-specific models to evaluate lumbopelvic loads during various activities [33,34,39,40,44,47,52,62]. Two studies specifically examined the mass distribution of body segments in pregnant women and developed models with detailed pregnant-specific BISPs [3,36]. One model was employed to compare different posture prediction formulations for simulating pregnant women with experimentally measured kinematics [27], and another model was employed to evaluate a genetic algorithm (GA) method to estimate the co-activation of abdominal and lumbar muscles [45].

3.5.2. Pregnant trimester

Half of the studies (eight out of 19) encompassed the entire pregnancy period (1st to 3rd trimesters) [3,39,40,47,54,55,67,69]. Six studies focused exclusively on the 3rd trimester [27,33,34,44,45,62]. Three studies investigated both the second and third trimesters [36,56,58], while two studies only examined the second trimester [51,52]. Notably, three studies extended their investigation beyond pregnancy to include the postpartum period [47,54,55] (Fig. 2). In total, most studies (17 out of 19, Fig. 2) included the 3rd trimester of pregnancy.

3.5.3. Simulated movements

More than one-third of these studies (eight out of 19, Fig. 2) included pregnant-related gait analysis [31,39,51,52,54–56,58]. Sit-to-stand movements were also simulated in many studies (six out of 19, Fig. 2) [34,36,39,44,45,67]. Some studies (four out of 19, Fig. 2) examined standing posture [33,40,58], or in conjunction with some specific tasks while standing [33,69]. Several studies (two out of 19, Fig. 2) investigated sitting posture [33], or movements with task-specific activities performed while sitting [27]. Additionally, one study investigated movements associated with childbirth, such as squatting, hands-and-knees (all-fours), and the supine position [62] (Fig. 2). Complex tasks, like picking up items while sit-to-stand and turning right while walking, were included in one study [39].

3.5.4. Simulation Workflow

Most studies (13 out of 19) used inverse kinematics (IK) to calculate joint kinematics during movements [34,44,45,51], while only one study [39] manually modified pregnant-specific static postures based on relevant literature, and three studies used 2D photographic recording [33,36,69]. One study directly imported the gait movements of a non-pregnant individual other than the gait of pregnant women [3].

Most studies (15 out of 19) utilized inverse dynamics (ID) to compute joint moments [3,33,34,39], especially in 3D simulations. Among the 2D simulating studies, one study used equilibrium-based analysis methods to evaluate static conditions [69], whereas the other two studies analyzed dynamic situations using laboratory-developed software [67] or intersegmental dynamic analysis [36]. Three of the five 3D musculoskeletal model studies employed static optimization (SO) to estimate muscle forces [33,34,40], while other studies applied the GA [44,45].

3.5.5. Kinetic outcomes

More than half of the studies (11 out of 19) investigated lower-limb kinetics (ankle, knee, and hip) during pregnancy [3,51,54]. Most of these studies reported joint moments [3,51,52], with some also providing joint power as an output [54,55]. Approximately half of studies (9 out of 19) investigated spinal kinetics, particularly lumbar kinetics, with four studies reporting spinal joint moments [3,27,39,62] and one reporting lumbar joint contact forces [40]. Furthermore, six studies examined muscle forces or torque in the lumbar region [33,34,40,44,45,47]. All six studies included the erector spinae muscles, while three studies also analyzed abdominal muscles [40,44,45].

4. Discussion

4.1. Overall observation

The findings indicated that 14 different pregnant-specific multi-segment models (including five musculoskeletal models) were used across 19 kinetic studies, as some models were utilized in multiple pregnancy-related investigations [33,34,44,45]. The majority of these models were developed after 2010 [3,40], potentially being driven by the developments in biomechanical modeling and simulation platforms and motion capture techniques in recent years. Increased public attention to the health and well-being of pregnant women may also have contributed to the growing interest in developing pregnant-specific models [75]. Motion analysis software like Visual 3D was the most commonly used tool due to its practical focus and suitability for studies without complex modeling [51,52,62]. More complicated musculoskeletal models were developed using OpenSim or AnyBody [3,33,34], which are advanced biomechanical modeling tools with abundant available non-pregnant generic models that can be easily adapted [14,15].

Most included studies utilized 3D modeling [3,33,34], enabling more complex simulations across three spatial planes. Those limited to 2D modeling tended to be earlier research before or around 2000 [36,67,69], likely due to the limited availability and capability of 3D modeling software at the time. Most models were able to simulate dynamic conditions (e.g., walking and sit-to-stand) [3,44,45]. Static analysis has also been conducted in some studies (e.g., standing and bending) [40,47,69], as pregnant-specific postural changes are significant and, when combined with changes in mass distribution, will impact joint kinetics significantly. Lower-limb models were most common for studies which aimed to investigate pregnant-specific gait kinetics [51,54,62]. However, given that changes in trunk mass are significant during pregnancy and some studies explored lumbopelvic loads, full-body models have been most frequently used [3,33,39,45,58], which can provide a more comprehensive representation of the biomechanical changes occurring throughout the body. In total, only five pregnant-specific musculoskeletal models were found [3,33,40,45,47], with most related studies aimed at estimating the lumbar and abdominal muscle loads [33,34,44,45].

4.2. Pregnant-specific multi-segment modeling

Based on non-pregnant generic multi-segment models, pregnant-specific modifications are necessary for biomechanical investigation. Body segment parameters are essential to understanding human biomechanics in multi-segment models, including body segment lengths and body segment inertial parameters (BSIPs) [76]. BSIPs include body segment masses, COM locations with respect to the segment reference frame, and segment moments of inertia about a specific point [76].

4.2.1. Body segment lengths

During pregnancy, the body experiences notable changes in mass distribution, posture, and movement patterns, while the segment lengths may remain relatively unaffected [27]. Therefore, the modification of body segment lengths is, to some extent, a subject-specific rather than a pregnant-specific process. However, given that accurate segment lengths play a crucial role in musculoskeletal model simulations, and considering the significant morphological and postural changes that occur during pregnancy, it is worth exploring whether current scaling methods are appropriate for pregnant populations.

Most pregnant-specific models relied on marker-based linear scaling (proportional scaling of the segment lengths based on the marker placements) to determine body segment lengths [51,52,54–56]. Some studies manually modified the model segment lengths by using anthropometric data from literature or experimental measurements [33,40,45]. The marker-based motion capture system is currently considered the gold standard method of measurement for 3D kinematics measurements [77]. Compared to anthropometric data, marker-based scaling may provide a personalized model and record kinematics efficiently. However, anthropometric data is also useful for calculating BSIPs through regressions in some studies beyond scaling [69].

Given the insignificant body length change during pregnancy, generating a pregnant-specific model using standard marker-based scaling methods, as employed in most studies, is feasible in principle. However, pregnant individuals often experience edema (water retention), particularly in the lower limbs, with this issue becoming more pronounced in the third trimester [78,79]. Excess weight gain is another common occurrence during pregnancy [80]. The added soft tissue may contribute to discrepancies between the real anatomical marker positions and the virtual positions assumed by the model in pregnant women compared to non-pregnant individuals [81,82]. Similar issues have been noted in obese populations, highlighting the importance of population-specific scaling approaches [82]. Some studies have proposed modified pelvic marker placements to reduce errors caused by an enlarged abdomen during pregnancy, while the reliability of this marker set has yet to be validated [83,84]. Future research is warranted to develop and validate marker sets that better fit pregnant women, potentially by learning from the obesity-specific marker protocol [82].

Alternative scaling or modeling approaches may also hold promise for pregnancy applications. While magnetic resonance imaging (MRI) offers a gold-standard and radiation-free method for personalized musculoskeletal modeling, its application during pregnancy has been largely restricted to uterine modeling due to the inconvenient acquisition and complex post-processing [85,86]. With adequate imaging datasets, statistical shape modeling could support nonlinear, pregnant-specific scaling [87,88]. Additionally, 3D body scanning provides a radiation-free, efficient method for capturing external body shape, presenting another promising solution for scaling during pregnancy [89]. Optimization-based scaling is another approach that is safe for the pregnant population, relying on dynamic trials to adjust the model's geometry by minimizing the error between experimental and model marker positions [90].

4.2.2. Body segment inertial parameters

Compared with kinematic analysis, BSIPs are required for kinetic analysis of movements, to calculate variables such as the COM location, joint moments, and joint powers. Accurate segmental COM location is crucial for studying balance control and fall risk during pregnancy, while joint moments and powers can help understand pregnancy-related musculoskeletal pain [3]. Some studies emphasized the need for accurate BSIP estimations for estimations of joint kinetics [91,92]. However, the available BSIP estimates used in most existing models are not applicable to pregnant women, who have a distinctively different mass distribution compared to non-pregnant subjects [3].

Half of the pregnant-specific models estimated BSIPs using regression models, which may require anthropometric data as input [51,52,58]. One limitation of these studies is that some of the regression models used are not designed specifically for pregnant women [65,71]. One study compared the accuracy of two sets of regression equations in estimating inertia parameters for pregnant individuals, and surprisingly, found that the regression developed for older populations was more accurate than that designed specifically for pregnant women [36,60]. This discrepancy may be due to the coarse predictive capability of the pregnant-specific regression [36], which relied on limited anthropometric input, or it may reflect the high degree of individual variability among pregnant women [60]. These findings highlight the potential limitations of estimating BSIPs using regression models, even those tailored for pregnancy.

In other pregnant-specific models, BSIPs have been estimated using 3D digital shape models derived from anthropometric data [3,52,93] or image-based modeling techniques (e.g., projecting and digitizing of 2D images) [36,62]. Assuming constant segmental density, the BSIPs of each segment can be computed based on the closed triangular surface mesh using the divergence theorem [3,36]. In this situation, the accuracy of 3D shape models determines the accuracy of the estimated inertial parameters to a large extent. However, the generalizability of these models may be limited by the source population. For example, the shape modeling data of Haddox et al. came from the average anthropometry of military pregnant women, which means the estimated inertial data may not be representative of non-military groups and lack subject specificity [3].

Using the 3D motion capture system is another way to estimate BSIPs with no undesirable effects on the mother or fetus [39]. It can be regarded as a simplified method by establishing 3D digital shape models, but with limited accuracy since it relies solely on markers as geometric vertices for polyhedral shape modeling.

4.2.3. Muscle paths and musculotendon parameters

Most existing pregnant-specific musculoskeletal models have modified abdominal muscle paths to accommodate an enlarged uterus in pregnant women [33,40,45]. This is understandable, as the geometric changes in abdominal muscles are the most pronounced during pregnancy. Among existing musculoskeletal models, none have adjusted musculotendon parameters for pregnant women, primarily due to the lack of research that has quantitatively or systematically investigated changes in muscle active or passive properties throughout pregnancy, considering the ethical sensitivity of the pregnant population.

Most existing pregnant-specific musculoskeletal models have attempted to investigate the loads on the lumbar and abdominal muscles as the most significant biomechanical changes during pregnancy occur in the lower trunk [40,44,45], and lumbar pain is the most common musculoskeletal complaint reported during pregnancy [2,9,94]. Notably, one study utilized personalized lumbar musculoskeletal models to evaluate changes in erector spinae muscle maximum strength during pregnancy based on different trunk isometric maximum force [47]. This is currently the only study we have found that assessed muscle strength during pregnancy, due to the risk of requiring pregnant women to perform maximum voluntary contractions.

4.3. Applications of pregnant-specific models

Pregnant-specific multi-segment models can be used to address a wide range of biomechanical questions during pregnancy.

4.3.1. Research focus

Few studies have focused primarily on developing detailed pregnant-specific models, and these models were generally modified to incorporate pregnant-specific BSIPs, which are crucial for kinetic analysis [3,36]. In these studies, kinetic analysis has primarily served as a means to evaluate the models rather than to address specific pregnancy-related kinetic questions.

Most studies focused on exploring lower-limb kinetics during gait [51,52,54–56,58,93] or other daily activities (e.g., chair-rise [36,39,67]) or some pregnant-specific postures (e.g., childbirth [62]) using pregnant-specific models. These studies have aimed to understand movement adaptations during pregnancy, which could be a potential factor contributing to the high risk of falls and pain. Some studies focused on evaluating lumbopelvic loads during a variety of activities [33,34,40,44,45], given that lumbopelvic pain is the most common musculoskeletal complaint during pregnancy. Understanding lumbopelvic biomechanics provides insights into pregnancy-related lumbopelvic pain. However, most pregnant-specific models used for such

investigations are modified from existing non-pregnant generic models, often lacking modeling details, and the predictive capability of these adapted models is rarely validated [54,67].

A few studies focused on proposing and evaluating simulation methods suitable for pregnant populations, such as using GA to estimate co-activation of abdominal and lumbar muscles [45]. One study evaluated several physics-based posture prediction formulations to better predict the seated postures of pregnant women [27]. In these studies, kinetic data primarily serve as inputs for computational processes. These approaches could help develop more accurate and personalized simulation tools for pregnant populations.

4.3.2. Pregnant trimester

Most models focused on third-trimester pregnancy [33,45,62], mainly due to the most significant changes and higher incidence of falls and musculoskeletal pain during that period. Modeling in the first two trimesters, pre-pregnancy and postpartum could help better understand the progression of kinetic changes during pregnancy, which may be beneficial for pain and falls prevention.

4.3.3. Simulated movements

Numerous models have been used to investigate the mechanical effects of daily activities for pregnant women, such as walking [51,54,58], transitioning from sitting to standing [34,39,44], and performing simple tasks (e.g., gentle bending, extending, or picking up objects) while standing or sitting [33,39,69]. Walking is the most common physical activity modality and is commonly featured in physical activity recommendations for pregnant women [95,96]. Sit-to-stand and picking up objects are among the most difficult common tasks identified by women in their third trimester by interviews [97]. Among the daily activities studied, the most intense movement is fast sit-to-stand [34]. These low-load activities, which are both highly relevant and experimentally feasible for pregnant women, serve as a primary focus in biomechanical simulations. Additionally, one study specifically explored childbirth-related postures, which are relevant for full-term pregnant women, including squatting, hands-and-knees (all-fours), and the supine position [62]. These computed joint torques can be used to understand childbirth kinetics, and serve as inputs for a pelvic finite element model to explore its kinematics during different birthing positions, thereby identifying a wider birth canal [98].

It is worth noting that during pregnancy, the lumbopelvic alignment undergoes significant changes for most women, such as increased pelvic tilt and lumbar lordosis, which may have a substantial impact on movement dynamics [5,99]. However, most full-body musculoskeletal models lack a flexible lumbar spine, which may lead to inaccurate simulations of lumbopelvic kinematics and kinetics. Some studies have considered altered lumbopelvic alignment in pregnant women and demonstrated its significant impact on gait kinetics [58] and loading of lumbopelvic joints or muscles [40,100].

While low-load activities are widely recognized as being more appropriate for pregnant women due to their reduced physical demands, it is important to acknowledge that many pregnant individuals participate in moderate or even high-intensity exercises [101]. Activities like fast walking, jogging and resistance exercise are often part of their routine, either for health, fitness or personal preference [96,102]. Future research could consider integrating higher-intensity movements into experimental designs, exploring their potential influence during pregnancy. Additionally, mind–body exercises such as prenatal Yoga, Pilates and Tai Chi have been shown to benefit maternal health outcomes [103,104]. These practices include movements that may help alleviate pain and improve balance [105,106], making their underlying biomechanical mechanisms a valuable direction for future investigation.

4.3.4. Simulation workflow

The majority of studies relied on inverse kinematics (IK) to determine individual joint kinematics during movement [34,45,51]. Some other studies utilized 2D photographic recordings or manual modification based on literature to simulate static posture [33,36,40,69]. Inverse Dynamics (ID) remains the predominant method for computing joint moments, especially in dynamic situations [3,33,39]. The ID simulation calculates joint moments necessary to generate the simulated movement with kinematic data as input. Few studies that simulated 2D static postures used equilibrium-based analysis methods to compute joint moments, like free body diagram (FBD) [69].

Based on joint moments estimated by ID, the musculoskeletal model can further calculate the muscle force and joint contact force. The vast majority of published musculoskeletal models relied on static optimization (SO) for muscle force calculations [33,34,40]. SO addresses the muscle redundancy problem by optimizing each time frame sequentially to satisfy equilibrium conditions, typically by minimizing the sum of squared muscle forces or activations. Apart from SO, the Genetic Algorithm (GA) method has been proposed to predict trunk muscle co-activation (rectus abdominis and erector spinae) in pregnant women [44,45], as alterations in muscle co-activation during pregnancy remain insufficiently understood and deserves exploration. The co-contraction can be estimated from the joint moment and EMG data using GA. One advantage of GA is that it can estimate the muscle torque of some movement without requiring muscle-tendon modeling. Moreover, it does not rely on maximum voluntary contraction (MVC) tests to normalize EMG signals for validation. Instead, leave-one-out cross-validation can be performed based on repeated EMG measurements.

4.3.5. Kinetic outcomes

Most studies investigated lumbopelvic or lower-limb kinetics during pregnancy, including joint moments or joint power [3,51,54,62]. Pregnant-related weight gain and altered movement patterns significantly impact joint moments and power, particularly in the lumbar spine, pelvis, and lower limbs [60]. Abnormal joint moments or power may indicate compensatory strategies that compromise balance and increase fall risk, or reflect muscle fatigue and soft tissue stress, which could contribute to musculoskeletal pain [60].

Some studies applied musculoskeletal models to examine muscle forces and joint contact forces, with a primary focus on the lumbar region [33,40,44]. Unlike joint moments and power, which reflect the combined effect of all soft tissues around a joint, muscle force analysis allows for identifying specific muscles contributing to abnormal joint mechanics. Results of muscle force also facilitate the calculation of joint contact forces, providing essential insights into the mechanisms of pregnancy-related joint pain.

4.4. Limitations and challenges in pregnancy modeling

Several limitations have been identified across the range of pregnant-specific models, along with the challenges associated with addressing them, and potential solutions have been proposed.

4.4.1. Lack of validation

Validated models can help to gain valuable insights into biomechanically or clinically relevant load cases. Although many models were developed from generic models that have been validated on the general non-pregnant population, most pregnant-specific models included in this review were not revalidated after adaptations. It remains unknown whether the model with abundant pregnant-specific modifications can reliably simulate the actual musculoskeletal loads. The main pregnant-specific modifications focus on the BSIPs, which have a significant impact on simulated joint kinetics [91]. Therefore, it is necessary to revalidate these pregnant-specific models in the future.

4.4.2. Limitations in body segment scaling during pregnancy

Most pregnancy-related studies adopt standard marker-based linear scaling with general marker placement [51,56,58], which may not account for pregnancy-induced changes such as edema and soft tissue

accumulation [21]. While alternative marker placements have been explored, their validity remains uncertain [83]. More advanced pregnant-specific marker protocols, and other scaling/modeling methods like MRI-informed modeling, statistical-shape scaling or optimization-based scaling deserve to be explored in the future.

4.4.3. Challenge of pregnant-specific muscle modeling and limitation of static optimization

Muscles play a significant role in pain, yet pregnant-specific musculoskeletal models are still limited [33,40,45]. No musculoskeletal models have adjusted musculotendon parameters for pregnant women due to the lack of research about muscle properties in this sensitive population. However, studies have shown evidence of changes in muscle strength and passive properties during pregnancy [47,107–110]. The absence of pregnant-specific musculotendon parameter modeling inevitably affects the simulation results.

Currently, most pregnant-specific musculoskeletal models rely on SO for muscle force calculations [33,34,40]. However, the SO approach overlooks muscle co-contraction, which involves the simultaneous activation of antagonist and agonist muscles. Most existing models focus on analyzing muscle forces in the lumbopelvic region, where muscle co-contraction plays a critical role in maintaining trunk stability and cannot be ignored [111]. This limitation of SO highlights the need for alternative methods that accurately account for muscle co-contraction. Fortunately, an alternative GA method proposed by Morino et al. requires only joint moment results and EMG data as inputs, bypassing the need for modeling pregnant-specific muscle properties or conducting MVC tests with participants [44,45]. This method shows promise for future research on pregnant women, as it could provide a more realistic representation of muscle function during pregnancy without requiring risky experimental data collection.

4.4.4. Lack of detailed modeling of lumbopelvic region

Low back pain and pelvic pain are prevalent in pregnant women, but models with detailed and advanced lumbar spine and/or pelvic modeling are rare. More developed modeling of lumbopelvic region in the future will facilitate a deeper understanding of pregnancy-related lumbopelvic pain. For example, lumbar models with more degrees of freedom to simulate lumbar lordosis and the introduction of pubic symphysis or sacroiliac joint to explore the pelvic joint contact forces are needed.

4.4.5. Lack of subject-specific modeling

Pregnancy is a highly individualized process [36,60], with gestational weight gain varying widely across populations and influenced by a range of factors [112]. Thus, generic pregnant-specific models built from "average" geomatic and inertial parameters may not provide sufficient accuracy for kinetic analysis. More advanced workflows (e.g., incorporating MRI or 3D body scanning, either as modeling inputs or validation tools) to build personalized pregnant-specific models with accurate body segment parameter estimates are essential in future research.

4.5. Limitations of the review

Some modeling studies may not have clearly specified pregnancy-related modifications in their titles or abstracts [62,69], particularly when such modifications were minor. As a result, despite the use of a comprehensive search strategy, some relevant studies may have been missed during the initial screening process. For instance, certain studies emphasized how they addressed pregnancy-related biomechanical issues but did not mention modeling explicitly in the title or abstract, making them less likely to be captured in database searches [62,69]. Additionally, certain studies may have underreported modeling details [54,67], limiting our ability to fully assess the extent of pregnant-specific adaptations.

Due to the limited number of existing studies on pregnant-specific multi-segment modeling, and the wide heterogeneity in model complexity [40,67] (e.g., from simplified multi-segment models to detailed muscle path modifications), it was challenging to perform a comprehensive synthesis across studies. Nevertheless, this review aimed to go beyond merely describing model characteristics by synthesizing both their applications and modeling approaches, offering important guidance for future modeling efforts in this field.

5. Conclusions

Kinetic analysis using multi-segment or musculoskeletal models is a powerful approach to gain insight into the human musculoskeletal biomechanics. To understand biomechanics during pregnancy, models intended for the general population have been modified to incorporate pregnant-specific features, including adjustments to body segment parameters and muscle paths. However, most existing scaling methods are marker-based and limited by pregnancy-related soft tissue artifacts. Segment inertial parameters are often estimated using regression models, which may fail to capture the considerable individual variability among pregnant women. Most models are used to explore lower-limb or lumbar kinetics during daily activities, but the majority of them lack validation and detailed lumbopelvic modeling. Existing pregnant-specific musculoskeletal models are limited and mainly rely on static optimization for lumbar muscle force calculation, which neglects trunk co-contraction. Future research should prioritize the development of more detailed and validated modelling methods with more accurate model personalization, to better account for the biomechanical changes during pregnancy, enhancing our understanding of pregnant-related movement adaptations and musculoskeletal disorders.

CRediT authorship contribution statement

Jie Chen: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julie Choisne:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Hannah Wyatt:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Hume Patria:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Xin Li:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

None declared.

Acknowledgements

We would like to acknowledge the scholarship from China Scholarship Council for funding this research.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.08.082.

References

[1] V. Pennick, G. Young, Interventions for preventing and treating pelvic and back pain in pregnancy, Cochrane Database Syst. Rev. 18 (2007) CD001139, https://doi.org/10.1002/14651858.CD001139.pub2.

[2] P. Kristiansson, K. Svärdsudd, B.V. Schoultz, Back pain during pregnancy: a prospective study, Spine (Philos. Pa 1976) 21 (1996) 702–709, https://doi.org/10.1097/00007632-199603150-00008.

[3] A.G. Haddox, J. Hausselle, A. Azoug, Changes in segmental mass and inertia during pregnancy: a musculoskeletal model of the pregnant woman, Gait Posture 76 (2020) 389–395, https://doi.org/10.1016/j.gaitpost.2019.12.024.

[4] M.L. Marnach, K.D. Ramin, P.S. Ramsey, et al., Characterization of the relationship between joint laxity and maternal hormones in pregnancy, Obstet. Gynecol. 101 (2003) 331–335, https://doi.org/10.1016/s0029-7844(02)02447-x.
[5] K.K. Whitcome, L.J. Shapiro, D.E. Lieberman, Fetal load and the evolution of lumbar lordosis in bipedal hominins, Nature 450 (2007) 1075–1078, https://doi.org/10.1038/nature06342.
[6] K. Dunning, G. LeMasters, A. Bhattacharya, A major public health issue: the high incidence of falls during pregnancy, Matern Child Health J. 14 (2010) 720–725, https://doi.org/10.1007/s10995-009-0511-0.
[7] S. Kesikburun, Ü. Güzelküçük, U. Fidan, et al., Musculoskeletal pain and symptoms in pregnancy: a descriptive study, Ther. Adv. Musculoskelet. Dis. 10 (2018) 229–234, https://doi.org/10.1177/1759720X18812449.
[8] N. Salari, A. Mohammadi, M. Hemmati, et al., The global prevalence of low back pain in pregnancy: a comprehensive systematic review and meta-analysis, BMC Pregnancy Childbirth 23 (2023) 830, https://doi.org/10.1186/s12884-023-06151-x.
[9] C.A. Weis, J. Barrett, P. Tavares, et al., Prevalence of low back pain, pelvic girdle pain, and combination pain in a pregnant ontario population, J. Obstet. Gynaecol. Can. 40 (2018) 1038–1043, https://doi.org/10.1016/j.jogc.2017.10.032.
[10] V.J. Vullo, J.K. Richardson, E.A. Hurvitz, Hip, knee, and foot pain during pregnancy and the postpartum period, J. Fam. Pr. 43 (1996) 63–68.
[11] J. Borg-Stein, S.A. Dugan, Musculoskeletal disorders of pregnancy, delivery and postpartum, Phys. Med Rehabil. Clin. N. Am. 18 (2007) 459–476, https://doi.org/10.1016/j.pmr.2007.05.005.
[12] R.L. Huston, C. Passerello, On multi-rigid-body system dynamics, Comput. Struct. 10 (1979) 439–446, https://doi.org/10.1016/0045-7949(79)90019-1.
[13] M. Abdullah, A.A. Hulleck, R. Katmah, et al., Multibody dynamics-based musculoskeletal modeling for gait analysis: a systematic review, J. Neuroeng. Rehabil. 21 (2024) 178, https://doi.org/10.1186/s12984-024-01458-y.
[14] S.L. Delp, F.C. Anderson, A.S. Arnold, et al., OpenSim: open-source software to create and analyze dynamic simulations of movement, IEEE Trans. Biomed. Eng. 54 (2007) 1940–1950, https://doi.org/10.1109/TBME.2007.901024.
[15] M. Damsgaard, J. Rasmussen, S.T. Christensen, et al., Analysis of musculoskeletal systems in the AnyBody modeling system, Simul. Model Pr. Theory 14 (2006) 1100–1111, https://doi.org/10.1016/j.simpat.2006.09.001.
[16] M. Hou, J. He, D. Liu, et al., Bilateral lower limb symmetry during sit-to-stand and stand-to-sit tasks in stroke patients with hemiplegia, Front. Neurol. 16 (2025) 1494133, https://doi.org/10.3389/fneur.2025.1494133.
[17] Y. Osada, N. Motojima, Y. Kobayashi, S. Yamamoto, Abnormal gait movements prior to a near fall in individuals after stroke, Arch. Rehabil. Res. Clin. Transl. 3 (2021) 100156, https://doi.org/10.1016/j.arrct.2021.100156.
[18] G.F. Devetak, R.C.D. Bohrer, A.L.F. Rodacki, E.F. Manffra, Center of mass in analysis of dynamic stability during gait following stroke: a systematic review, Gait Posture 72 (2019) 154–166, https://doi.org/10.1016/j.gaitpost.2019.06.006.
[19] J. Hu, X. Li, P. Zheng, et al., The impact of neck pain and movement performance on the interarticular compressive force of the cervical spine: a cross-sectional study based on OpenSim, J. Neuroeng. Rehabil. 22 (2025) 26, https://doi.org/10.1186/s12984-025-01559-2.
[20] Z. Zhang, J. Zou, P. Lu, et al., Analysis of lumbar spine loading during walking in patients with chronic low back pain and healthy controls: an OpenSim-Based study, Front. Bioeng. Biotechnol. 12 (2024) 1377767, https://doi.org/10.3389/fbioe.2024.1377767.
[21] Z.F. Lerner, W.J. Board, R.C. Browning, Pediatric obesity and walking duration increase medial tibiofemoral compartment contact forces, J. Orthop. Res. 34 (2016) 97–105, https://doi.org/10.1002/jor.23028.
[22] G. Davico, C. Pizzolato, D.G. Lloyd, et al., Increasing level of neuromusculoskeletal model personalisation to investigate joint contact forces in cerebral palsy: a twin case study, Clin. Biomech. 72 (2020) 141–149, https://doi.org/10.1016/j.clinbiomech.2019.12.011.
[23] K. Veerkamp, M.M. van der Krogt, N.F.J. Waterval, et al., Predictive simulations identify potential neuromuscular contributors to idiopathic toe walking, Clin. Biomech. 111 (2024) 106152, https://doi.org/10.1016/j.clinbiomech.2023.106152.
[24] J. Pataky, C.L. Graves, J. Heitzenrater, et al., Development of a breast reconstruction-specific computational model to predict shoulder function in breast cancer survivors, Support Care Cancer 33 (2025) 390, https://doi.org/10.1007/s00520-025-09454-1.
[25] A. van der Have, S. Van Rossom, I. Jonkers, Musculoskeletal-Modeling-Based, Full-Body Load-Assessment tool for ergonomists (MATE): method development and proof of concept case studies, Int J. Environ. Res. Public Health 20 (2023), https://doi.org/10.3390/ijerph20021507.
[26] M.J. Page, J.E. McKenzie, P.M. Bossuyt, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ 372 (2021) 71, https://doi.org/10.1136/bmj.n71.
[27] B. Howard, A. Cloutier, J. Yang, Physics-based seated posture prediction for pregnant women and validation considering ground and seat pan contacts, J. Biomech. Eng. 134 (2012) 071004, https://doi.org/10.1115/1.4007006.
[28] A. Peters, B. Galna, M. Sangeux, et al., Quantification of soft tissue artifact in lower limb human motion analysis: a systematic review, Gait Posture 31 (2010) 1–8, https://doi.org/10.1016/j.gaitpost.2009.09.004.
[29] F. Moissenet, L. Modenese, R. Dumas, Alterations of musculoskeletal models for a more accurate estimation of lower limb joint contact forces during normal gait: a systematic review, J. Biomech. 63 (2017) 8–20, https://doi.org/10.1016/j.jbiomech.2017.08.025.
[30] H. Kainz, C.P. Carty, L. Modenese, et al., Estimation of the hip joint centre in human motion analysis: a systematic review, Clin. Biomech. 30 (2015) 319–329, https://doi.org/10.1016/j.clinbiomech.2015.02.005.
[31] S.R. Hamner, A. Seth, S.L. Delp, Muscle contributions to propulsion and support during running, J. Biomech. 43 (2010) 2709–2716, https://doi.org/10.1016/j.jbiomech.2010.06.025.
[32] T.C. Perkins, S.U. Blackwell. Accommodation and Occupational Safety for Pregnant Military Personnel (Technical Report), U.S. Air Force Research Laboratory, 1998.
[33] M. Nakashima, T. Komura, An analysis of muscle load on the erector spinae of a pregnant woman, J. Biomech. Sci. Eng. 5 (2010) 357–367, https://doi.org/10.1299/jbse.5.357.
[34] M. Nakashima, Y. Mori, Effect of mechanical unbalance induced by pregnancy on the muscle load of the erector spinae during a sit-to-stand motion, J. Biomech. Sci. Eng. 9 (2014) 14-00035, https://doi.org/10.1299/jbse.14-00035.
[35] Y. Mori, E. Kioka, Basic study on designing maternity wear corresponding to change of body form in the later stage of pregnancy (Part 1), J. Home Econ. Jpn. 45 (1994) 137–149, https://doi.org/10.11428/JHEJ1987.45.137.
[36] R.K. Jensen, S. Doucet, T. Treitz, Changes in segment mass and mass distribution during pregnancy, J. Biomech. 29 (1996) 251–256, https://doi.org/10.1016/0021-9290(95)00042-9.
[37] "Human Characteristics Database"Life and Welfare Technology Center(Accessed 6 June 2017),⟨http://www.tech.nite.go.jp/human/indexeng.html⟩2017 .
[38] O. Tsutsumi, M. Sadatsuki, Itemized discussions of maternal nursing (in Japanese), IgakuShoin (2008) 38–95.
[39] Y. Sunaga, N. Kanemura, M. Anan, et al., Estimation of inertial parameters of the lower trunk in pregnant Japanese women: a longitudinal comparative study and application to motion analysis, Appl. Erg. 55 (2016) 173–182, https://doi.org/10.1016/j.apergo.2016.02.010.
[40] R. Michnik, H. Zadoń, K. Nowakowska-Lipiec, et al., How does the lumbopelvic complex cope with the obstetrical load during standing? Ergonomic aspects of body posture in pregnant women, Appl. Sci. 12 (2022) 4330, https://doi.org/10.3390/app12094330.
[41] W. Forczek, Y. Ivanenko, M. Salamaga, et al., Pelvic movements during walking throughout gestation - the relationship between morphology and kinematic parameters, Clin. Biomech. 71 (2020) 146–151, https://doi.org/10.1016/j.clinbiomech.2019.11.001.
[42] W. Forczek, Y. Ivanenko, M. Curyło, et al., Progressive changes in walking kinematics throughout pregnancy-A follow up study, Gait Posture 68 (2019) 518–524, https://doi.org/10.1016/j.gaitpost.2019.01.004.
[43] K.K. Whitcome. Obstetric lOad and the Evolution of Human Lumbopelvic Sexual Dimorphism (PhD Dissertation), The University of Texas at, Austin, Texas, 2006.
[44] S. Morino, M. Yamashita, F. Umezaki, et al., Assessment of motion and muscle activation impacts on low back pain during pregnancy using an inertial measurement unit, Appl. Sci. 10 (2020) 3690, https://doi.org/10.3390/app10113690.
[45] S. Morino, M. Takahashi, Estimating Co-Contraction activation of trunk muscles using a novel musculoskeletal model for pregnant women, Appl. Sci. 7 (2017) 1067, https://doi.org/10.3390/app7101067.
[46] A. Matsuo, T. Fukunaga, K. Funato, et al., Examination of mass and location of the center of gravity of segment of the body in Japanese women (in Japanese), Proc. Dep. Sports Sci. Coll. Arts Sci. Univ. Tokyo 24 (1990) 37–54.
[47] G. Schröder, G. Kundt, M. Otte, et al., Impact of pregnancy on back pain and body posture in women, J. Phys. Ther. Sci. 28 (2016) 1199–1207, https://doi.org/10.1589/jpts.28.1199.
[48] A. Bergmark, Stability of the lumbar spine. A study in mechanical engineering, Acta Orthop. Scand. Suppl. 230 (1989) 1–54, https://doi.org/10.3109/17453678909154177.
[49] J.L. Berry, J.M. Moran, W.S. Berg, S. AD, A morphometric study of human lumbar and selected thoracic vertebrae, Spine (Philos. Pa 1976) 12 (1987) 362–367, https://doi.org/10.1097/00007632-198705000-00010.
[50] G. Duval-Beaupère, G. Robain, Visualization on full spine radiographs of the anatomical connections of the centres of the segmental body mass supported by each vertebra and measured in vivo, Int. Orthop. 11 (1987) 261–269, https://doi.org/10.1007/BF00271459.
[51] L. Aguiar, R. Santos-Rocha, M. Branco, et al., Biomechanical model for kinetic and kinematic description of gait during second trimester of pregnancy to study the effects of biomechanical load on the musculoskeletal system, J. Mech. Med. Biol. 14 (2014) 1450004, https://doi.org/10.1142/S0219519414500043.
[52] L. Aguiar, R. Santos-Rocha, F. Vieira, et al., Comparison between overweight due to pregnancy and due to added weight to simulate body mass distribution in pregnancy, Gait Posture 42 (2015) 511–517, https://doi.org/10.1016/j.gaitpost.2015.07.065.
[53] E.P. Hanavan, A mathematical model of the human body, Aerosp. Med. Res. Lab. 32 (1964), https://doi.org/10.1037/e400822004-001.
[54] M. Branco, R. Santos-Rocha, F. Vieira, et al., Three-Dimensional kinetic adaptations of gait throughout pregnancy and postpartum, Scientifica 2015 (2015) 580374, https://doi.org/10.1155/2015/580374.
[55] M. Branco, R. Santos-Rocha, F. Vieira, et al., Influence of body composition on gait kinetics throughout pregnancy and postpartum period, Scientifica 2016 (2016) 3921536, https://doi.org/10.1155/2016/3921536.
[56] M. Branco, R. Santos-Rocha, F. Vieira, et al., Kinetic analysis of gait in the second and third trimesters of pregnancy, J. Mech. Med. Biol. 16 (2015) 20, https://doi.org/10.1142/S021951941650055X.

[57] A. Stewart, M. Marfell-Jones, T. Olds, J.D. Ridder. International Standards for Anthropometric Assessment, International Society for the Advancement of Kinanthropometry, Lower Hutt, 2011.
[58] R.D. Catena, W.C. Wolcott, Self-selection of gestational lumbopelvic posture and bipedal evolution, Gait Posture 89 (2021) 7–13, https://doi.org/10.1016/j.gaitpost.2021.06.022.
[59] M.J. Pavol, T.M. Owings, M.D. Grabiner, Body segment inertial parameter estimation for the general population of older adults, J. Biomech. 35 (2002) 707–712, https://doi.org/10.1016/S0021-9290(01)00250-0.
[60] R.D. Catena, C.P. Connolly, K.M. McGeorge, N. Campbell, A comparison of methods to determine center of mass during pregnancy, J. Biomech. 71 (2018) 217–224, https://doi.org/10.1016/j.jbiomech.2018.02.004.
[61] D. Flores, C.P. Connolly, N. Campbell, R.D. Catena, Walking balance on a treadmill changes during pregnancy, Gait Posture 66 (2018) 146–150, https://doi.org/10.1016/j.gaitpost.2018.08.035.
[62] A. Hemmerich, E. Geens, T. Diesbourg, G.A. Dumas, Determining loads acting on the pelvis in upright and recumbent birthing positions: a case study, Clin. Biomech. 57 (2018) 10–18, https://doi.org/10.1016/j.clinbiomech.2018.05.011.
[63] R.K. Jensen, Estimation of the biomechanical properties of three body types using a photogrammetric method, J. Biomech. 11 (1978) 349–358, https://doi.org/10.1016/0021-9290(78)90069-6.
[64] P.E. Gill, W. Murray, M.A. Saunders, SNOPT: an SQP algorithm for Large-Scale constrained optimization, SIAM Rev. 47 (2006) 979–1006, https://doi.org/10.1137/S0036144504446096.
[65] R. Dumas, L. Chèze, J.P. Verriest, Adjustments to McConville et al. And young et al. Body segment inertial parameters, J. Biomech. 40 (2007) 543–553, https://doi.org/10.1016/j.jbiomech.2006.02.013.
[66] R.K. Jensen, P. Fletcher, Distribution of mass to the segments of elderly males and females, J. Biomech. 27 (1994) 89–96, https://doi.org/10.1016/0021-9290(94)90035-3.
[67] S.Z. Lou, Y.L. Chou, P.H. Chou, et al., Sit-to-stand at different periods of pregnancy, Clin. Biomech. 16 (2001) 194–198, https://doi.org/10.1016/s0268-0033(00)00114-5.
[68] W.T. Dempster, Space requirements of the seated operator: geometrical, kinematic, and mechanical aspects of the body, with special reference to the limbs (technical report), University of Michigan, Ohio, 1955. https://doiorg/10.21236/AD0087892.
[69] J.A. Paul, H. Sallé, M.H. Frings-Dresen, Effect of posture on hip joint moment during pregnancy, while performing a standing task, Clin. Biomech. 11 (1996) 111–115, https://doi.org/10.1016/0268-0033(95)00049-6.
[70] D.B. Chaffin, G.B.J. Andersson, B.J. Martin. Occupational Biomechanics, Forth ed., Wiley, New York, 2006.
[71] J.W. Young, R.F. Chandler, C.C. Snow, K.M. Robinette, Anthropometric and mass distribution characteristics of the adult female, PsycEXTRA Dataset (1983), https://doi.org/10.1037/e465662008-001.
[72] M.I. Ellis, B.B. Seedhom, V. Wright, A comparison of knee joint and muscle forces in women 36 weeks pregnant and four weeks after delivery, Eng. Med. 14 (1985) 95–99, https://doi.org/10.1243/emed_jour_1985_014_019_02.
[73] P. Hummel, Changes in posture duringpregnancy [PhD thesis]. Vrije Universiteit. (1987).
[74] M. Ae, H. Tang, T. Yokoi, Estimation of inertia properties of the body segments in Japanese athletes, Biomechanisms 11 (1992) 23–33, https://doi.org/10.3951/BIOMECHANISMS.11.23.
[75] D. Barker, M. Barker, T. Fleming, M. Lampl, Developmental biology: support mothers to secure future public health, Nature 504 (2013) 209–211, https://doi.org/10.1038/504209a.
[76] P. Kudzia, E. Jackson, G. Dumas, Estimating body segment parameters from three-dimensional human body scans, PLOS One 17 (2022) e0262296, https://doi.org/10.1371/journal.pone.0262296.
[77] E. Ceseracciu, Z. Sawacha, C. Cobelli, Comparison of markerless and marker-based motion capture technologies through simultaneous data collection during gait: proof of concept, PLOS One 9 (2014) e87640, https://doi.org/10.1371/journal.pone.0087640.
[78] G. Larciprete, H. Valensise, B. Vasapollo, et al., Body composition during normal pregnancy: reference ranges, Acta Diabetol. 40 (1) (2003) 225–232, https://doi.org/10.1007/s00592-003-0072-4.
[79] H.C. Lukaski, W.A. Siders, E.J. Nielsen, C.B. Hall, Total body water in pregnancy: assessment by using bioelectrical impedance, Am. J. Clin. Nutr. 59 (1994) 578–585, https://doi.org/10.1093/ajcn/59.3.578.
[80] M.G. Dalfra', S. Burlina, A. Lapolla, Weight gain during pregnancy: a narrative review on the recent evidences, Diabetes Res. Clin. Pr. 188 (2022) 109913, https://doi.org/10.1016/j.diabres.2022.109913.
[81] A.J. Ramme, N.D. Fisher, J. Egol, et al., Scaling marker position determines the accuracy of digital templating for total hip arthroplasty, HSS J. 14 (2018) 55–59, https://doi.org/10.1007/s11420-017-9578-0.
[82] Z.F. Lerner, W.J. Board, R.C. Browning, Effects of an Obesity-Specific marker set on estimated muscle and joint forces in walking, Med. Sci. Sports Exerc. 46 (2014) 1261–1267, https://doi.org/10.1249/MSS.0000000000000218.
[83] J.J. Bagwell, N. Reynolds, M. Walaszek, et al., Lower extremity kinetics and muscle activation during gait are significantly different during and after pregnancy compared to nulliparous females, Gait Posture 81 (2020) 33–40, https://doi.org/10.1016/j.gaitpost.2020.07.002.
[84] J.J. Bagwell, N. Reynolds, J.A. Smith, et al., An exploratory analysis of gait biomechanics and muscle activation in pregnant females with high and low scores for low back or pelvic girdle pain during and after pregnancy, Clin. Biomech. 97 (2022) 105705, https://doi.org/10.1016/j.clinbiomech.2022.105705.
[85] M. Fernandez, M. House, S. Jambawalikar, et al., Investigating the mechanical function of the cervix during pregnancy using finite element models derived from high-resolution 3D MRI, Comput. Methods Biomech. Biomed. Engin. 19 (2016) 404–417, https://doi.org/10.1080/10255842.2015.1033163.
[86] M. House, R. McCabe, S. Socrate, Using imaging-based, three-dimensional models of the cervix and uterus for studies of cervical changes during pregnancy, Clin. Anat. 26 (2013) 97–104, https://doi.org/10.1002/ca.22183.
[87] D. Bakke, P. Ortega-Auriol, T. Besier, Shape-model scaling is more robust than linear scaling to marker placement error, J. Biomech. 160 (2023) 111805, https://doi.org/10.1016/j.jbiomech.2023.111805.
[88] J. Zhang, T.F. Besier, Accuracy of femur reconstruction from sparse geometric data using a statistical shape model, Comput. Methods Biomech. Biomed. Engin. 20 (2017) 566–576, https://doi.org/10.1080/10255842.2016.1263301.
[89] G. McConnochie, A. Fox, C. Bellenger, D. Thewlis, LiDAR-based scaling of OpenSim musculoskeletal human models is a viable alternative to marker-based approaches - a preliminary study, J. Biomech. 179 (2025) 112439, https://doi.org/10.1016/j.jbiomech.2024.112439.
[90] K. Werling, N.A. Bianco, M. Raitor, et al., AddBiomechanics: automating model scaling, inverse kinematics, and inverse dynamics from human motion data through sequential optimization, PlOS One 18 (2023), https://doi.org/10.1371/journal.pone.0295152.
[91] M.K. Lee, N.S. Le, A.C. Fang, M.T. Koh, Measurement of body segment parameters using dual energy X-ray absorptiometry and three-dimensional geometry: an application in gait analysis, J. Biomech. 42 (2009) 217–222, https://doi.org/10.1016/j.jbiomech.2008.10.036.
[92] G. Rao, D. Amarantini, E. Berton, D. Favier, Influence of body segments' parameters estimation models on inverse dynamics solutions during gait, J. Biomech. 39 (2006) 1531–1536, https://doi.org/10.1016/j.jbiomech.2005.04.014.
[93] X. Li, Z. Lu, X. Cen, et al., Effect of pregnancy on female gait characteristics: a pilot study based on portable gait analyzer and induced acceleration analysis, Front. Physiol. 14 (2023) 1034132, https://doi.org/10.3389/fphys.2023.1034132.
[94] H. Ostgaard, G. Andersson, K. Karlsson, Prevalence of back pain in pregnancy, Spine (Philos. Pa 1976) 16 (1991) 229–234, https://doi.org/10.1097/00007632-199105000-00011.
[95] H. Syed, T. Slayman, K.D. Thoma, ACOG committee opinion no. 804: physical activity and exercise during pregnancy and the postpartum period, Obstet. Gynecol. 137 (2021) 375–376, https://doi.org/10.1097/AOG.0000000000004266.
[96] K.R. Evenson, F. Wen, National trends in self-reported physical activity and sedentary behaviors among pregnant women: NHANES 1999-2006, Prev. Med. 50 (2010) 123–128, https://doi.org/10.1016/j.ypmed.2009.12.015.
[97] N. JA, G. DW, Performance of physical tasks in pregnancy - PubMed, Ergonomics 35 (1992), https://doi.org/10.1080/00140139208967815.
[98] A. Hemmerich, T. Bandrowska, G.A. Dumas, The effects of squatting while pregnant on pelvic dimensions: a computational simulation to understand childbirth, J. Biomech. 87 (2019) 64–74, https://doi.org/10.1016/j.jbiomech.2019.02.017.
[99] J. Chen, P.A. Hume, H. Wyatt, et al., Understanding the effect of lumbar lordosis angle on vertebral load distribution during walking, Comput. Method Biomec. (2025), https://doi.org/10.1080/10255842.2025.2530658.
[100] A. Liebetrau, C. Puta, D. Schinowski, et al., Is there a correlation between back pain and stability of the lumbar spine in pregnancy? A model-based hypothesis (in German), Schmerz 26 (2012) 36–45, https://doi.org/10.1007/s00482-011-1125-1.
[101] H.E. Wyatt, K. Sheerin, P.A. Hume, K. Hebert-Losier, Prevalence and risk factors for musculoskeletal pain when running during pregnancy: a survey of 3102 women, Sports Med. 54 (2024) 1955–1964, https://doi.org/10.1007/s40279-024-01994-6.
[102] N. Keating, C. Coveney, F.M. McAuliffe, M.F. Higgins, Aerobic or resistance exercise for improved glycaemic control and pregnancy outcomes in women with gestational diabetes mellitus: a systematic review, Int. J. Environ. Res. Public Health 19 (2022) 10791, https://doi.org/10.3390/ijerph191710791.
[103] I.J. Liang, The wonders of mind-body practices during pregnancy: a topical review, Taiwan J. Obstet. Gynecol. 63 (2024) 486–491, https://doi.org/10.1016/j.tjog.2024.04.007.
[104] E.A. Oyarzabal, B. Seuferling, S. Babbar, et al., Mind-Body techniques in pregnancy and postpartum, Clin. Obstet. Gynecol. 64 (2021) 683–703, https://doi.org/10.1097/GRF.0000000000000641.
[105] R.F. Martins, J.L. Pinto e Silva, Treatment of pregnancy-related lumbar and pelvic girdle pain by the yoga method: a randomized controlled study, J. Alter. Complement Med. 20 (2014) 24–31, https://doi.org/10.1089/acm.2012.0715.
[106] N. Ma, J.P.C. Chau, Y. Deng, K.C. Choi, Effects of a structured tai chi program on improving physical activity levels, exercise self-efficacy and health outcomes among pregnant women: study protocol for a randomised controlled trial, BMJ Open 13 (2023) e065640, https://doi.org/10.1136/bmjopen-2022-065640.
[107] W. Gilleard, J.M.M. Brown, Structural changes to the rectus abdominis during pregnancy and immediate post-pregnancy, J. Biomech. 25 (1992) 728, https://doi.org/10.1016/0021-9290.
[108] A. Żelaźniewicz, B. Pawłowski, Maternal hand grip strength in pregnancy, newborn sex and birth weight, Early Hum. Dev. 119 (2018) 51–55, https://doi.org/10.1016/j.earlhumdev.2018.03.004.
[109] E. Atay, F.B. Iz, Investigation of the effect of changes in muscle strength in gestational age upon fear of falling and quality of life, Turk. J. Med. Sci. 45 (2015) 977–983, https://doi.org/10.3906/sag-1404-9.

[110] M.Ld.S. Santos, S.G.G.F. Macêdo, J. Fernandes, et al., Muscle strength during pregnancy and postpartum in adolescents and adults, PLOS One 19 (2024) e0300062, https://doi.org/10.1371/journal.pone.0300062.
[111] J. Borghuis, A.L. Hof, K.A. Lemmink, The importance of sensory-motor control in providing core stability: implications for measurement and training, Sports Med. 38 (2008) 893–916, https://doi.org/10.2165/00007256-200838110-00002.
[112] C. Kowal, J. Kuk, H. Tamim, Characteristics of weight gain in pregnancy among Canadian women, Matern Child Health J. 16 (2012) 668–676, https://doi.org/10.1007/s10995-011-0771-3.