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Full length article

The impact of femoral rotation on sacroiliac articulation during pregnancy. Is there evidence to support Farabeuf's hypothesis by finite element modelization?

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ABSTRACT

Background: Counter-nutation movement is deemed crucial during the management of the birth process. It is a combination of lateral ilia expansion and backward displacement of the promontory resulting from the external rotations of the femurs producing an enlargement of the pelvic inlet. However, since its description by Farabeuf, this mechanism has never been challenged and analyzed in a dynamic finite element study.
Methods: Based on a female pelvic mesh and sacroiliac ligaments, we simulated external rotations of both femurs with imposed rotation of the two acetabulum centers. We hypothesize that lateral ilia expansion generates a sacrum movement resulting in a backward displacement of the promontory and a pelvic inlet enlargement.
Results: Finite element simulation confirms our hypothesis and reveals that ilio-sacro-transverse and axile ligaments play an essential role in this mechanism. Indeed, the increase in stiffness (ranging from 500 MPa to 750 MPa) of these ligaments accentuates the counter-nutation movement and the opening of the inlet. Instead of the anatomic congruence between the ilium and the sacrum, the sacroiliac ligaments may explain the counter-nutation. After a 6° of femur rotation, the inlet area increases to 11 cm^2 (141 cm^2 vs. 130 cm^2). This enlargement could be noteworthy in case of obstructed labor or shoulder dystocia. Moreover, the association between external rotation and flexion of the femurs could be more efficient for opening the pelvic inlet.
Conclusions: Our result did not support the original assumption of Farabeuf. By revealing how postural adjustment increases the bony birth canal, this study provides essential information for the clinical management of the delivery.

In obstetrics, we face a "dilemma" resulting from the tight fit between the fetus and maternal pelvis [1,2]. This obstetrical dilemma is present in modern humans because the human childbirth results from an evolutionary trade-off between two conflicting pressures resulting from bipedal gait, and encephalization [3]. The space between the fetal cranium and the human mother's birth canal is more constricted than in non-human primates, where the birth process is relatively quick and easy [4], but see [5].

Because of this constriction, the dimensions of the mother's pelvis have been hypothesized to predict potential issues during labor [6,7]. But some authors have argued that the dimensions of the pelvis alone [8] or associated with neonatal dimensions [9,10] are insufficient to accurately predict difficulties during the birth process (i.e., dystocia). Several confounding factors, such as the strength of uterine contractions,

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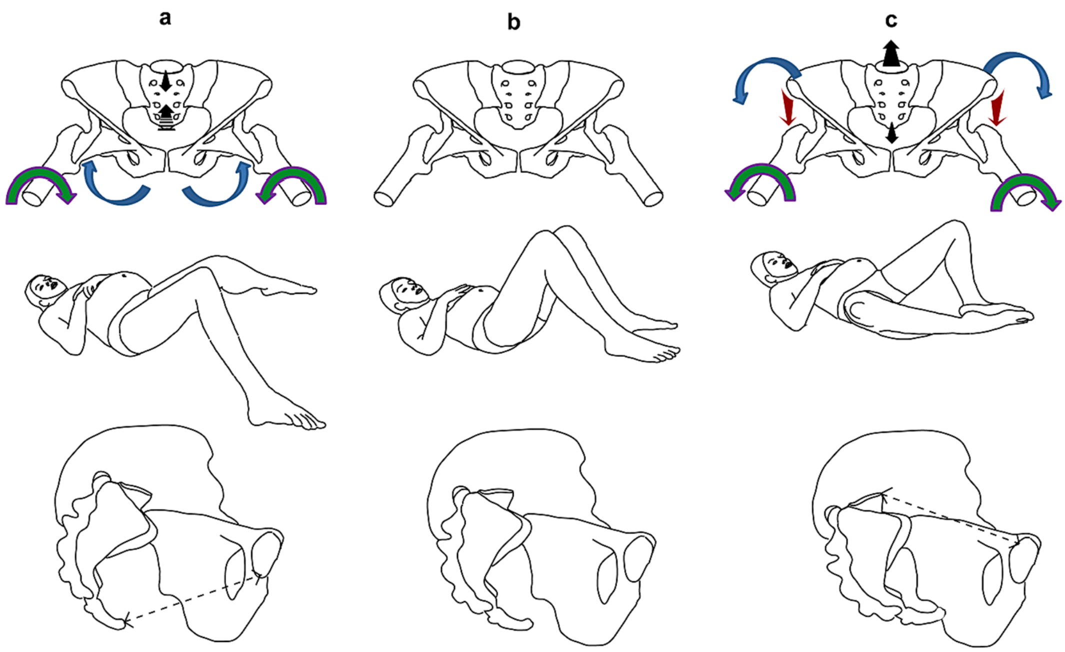

Fig. 1. Illustration of the nutation (a), counter-nutation (c) movements, and neutral position (b). Top row: pelvis in front view. Middle row: postures with internal and external rotation of the femurs. Bottom row: right lateral view. During nutation (a), the internal rotation (green arrows) of the femurs produces traction of the *quadratus femoris* muscles, resulting in an enlargement of the pelvis outlet (blue arrows, dashed line). During counter-nutation (c), the external rotation (green arrows) of the femurs produces traction of the muscles inserted in the iliac crest (i.e., *gluteus medius and minimus*, red arrows) and generates a downward and outward displacement of the ilia (blue arrows), while the ischia approximate. Simultaneously, the promontory moves backward while the last sacral vertebra moves forward (black arrows and dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maternal weight, pelvic soft-tissue resistance, epidural analgesia, joint hypermobility, or ambulation during labor [9], can explain this.

Among these confounding factors, the maternal position has been a topic of growing interest in obstetrics [11]. Recent research using magnetic resonance imaging (MRI) [12,13] or finite element analysis (FEA) [14] found that birth positions can modify pelvic dimensions. This is due to the change of one position to another, rather than the position itself, which significantly increases the dimensions of the bony pelvis [13]. Postural adjustments and femoral rotations are deemed to modify pelvic dimensions with nutation and counter-nutation movements, as shown in Fig. 1.

The exact mechanism of how the eversion of the ilia generates a forward displacement of the lower sacrum (i.e. counter-nutation) remains unclear. Some authors suggested that superior posterior ligaments of the sacroiliac joints play a crucial role in this mechanism [15]. In a recent study, Toyohara et al. [16] modelized nutation and counter-nutation movements during a simulation of bipedal locomotion: during the stance phase, the ilium was elevated relative to the sacrum, and sacrum nutated, while during the swing phase, the ilium was lower relative to the sacrum which moved in a counter-nutation sense. However, since bipedal locomotion induces a swing and a stance phase at each hemipelvis simultaneously, these results are difficult to interpret solely regarding the movement of the sacrum. Hemmerich et al. [14] analyze the effects of squatting while pregnant on pelvic dimensions. Their computational simulations show that squatting position increases anteroposterior and transverse measurements of outlet and midplane. However, a squat movement implies flexion rather than external rotation of the femur. It is, therefore, difficult to deduce the effects of external rotation of the femurs on pelvic dimensions.

Hence, our objective was to precisely investigate the effect of external rotation of the femurs on the sacroiliac joints and model the counter-nutation movement (assuming the exact opposite mechanism was the nutation). This work explicitly investigates the effect of ilia eversion on the sacroiliac joints. We hypothesized that eversion of the ilia would produce a backward displacement of the promontory and a forward displacement of the lower sacrum. A second objective was to investigate the role of superior posterior ligaments on the effectiveness of counter-nutation. We suggested that these ligaments play a crucial role in the counter-nutation as compared to the sacroiliac junction's anatomical configuration.

Material and method

Participant

MRI was carried out at the end of the third trimester of pregnancy on a 30 years old woman 165 cm tall and weighed 60 kg before the pregnancy. The patient had no obstetrical history, orthopedic pathologies or muscular diseases. The MRI was performed in a supine position at 39th week of amenorrhea and did not confirm any morphological anomaly. At this time, the BMI was c.a. 25 kg.m^{-2}. Using the data of this MRI we obtained 224 consecutive slices running the entire height of the pregnant pelvis and uterus, and with an acquisition step of 2 mm. As this study aimed to create a model of the pelvis with ligaments, we did not assess the impact of counter-nutation on pelvic diameters by comparing different positions with MRI. Furthermore, this type of study requires a specific MRI setup [17].

Model construction

Based on MRI slices, we generated the surface of the pelvis with automatic contouring of the bony elements. After extracting the fetus and soft-tissues, the finite element model of the pelvis was composed of 68,183 tetrahedral elements: the sacrum and coccyx comprised 24,402 and 992 elements; the two coxal bones and the ligaments were composed of 30,546 and 12,243 elements, respectively.

Boundary and loading condition

Finite element analyses (FEA) generate simulated counter-nutational

Table 1
Material properties of pelvic ligaments.

Component	Young's modulus (MPa)	Anatomical description	Reference
Ilio-sacro-transverse ligament	E1 = 500 E2 = 750	Powerfull and very thick, it is inserted from the most caudal point of the iliac crest to the transverse tubercle of the first sacral vertebra.	[15]
Axile ligament	E1 = 500 E2 = 750	This is the most potent joining structure between the sacrum and ilium, from the iliac crest to the first conjugate tubercle.	[15]
Sacro-spinous ligament	E = 500	This small ligament contributes to the stability of the sacroiliac junction; it is inserted from the fourth and fifth sacral vertebrae to the sciatic spine.	[19]
Zaglas ligament	E = 150	From the posterosuperior iliac spine to the second conjugate tubercle, this is a small and weak ligament	[19]
Third ilio-transverse conjugate ligament	E = 150	From the posterosuperior iliac spine to the third conjugate tubercle, this is a small and weak ligament.	[19]
Fourth ilio-transverse conjugate ligament	E = 150	From the posterosuperior iliac spine to the fourth conjugate tubercle, this is a small and weak ligament	[19]
Anterior sacroiliac ligament	E = 150	Large, thin, and weak, it is more likely to tear	[15]
Pubic symphysis ligament	E = 150	This fibro-cartilaginous structure is similar to the intervertebral disc (i.e. flexible)	[15]

movements using Radioss 11.0 (https://www.altair.com). Counter-nutation is defined as the ilia eversion (i.e. the iliac crests separate), ischia inversion (i.e. the ischial tuberosities gets closer) and would produce a backward movement of the promontory (Fig. 1). To test this hypothesis, we induced external rotations of the ilia (as an imposed trajectory) and analyzed the simulated movement of the sacrum.

The rotational movement of the paired ilia was based on two pivot points at the center of the two acetabula. External rotation was simulated as shown in Fig. 1: rotational movement was an imposed trajectory, with a homogenous speed of rotation of 0.25°/s, and was limited to the y-axis (i.e., frontal plane). We considered the iliac bones and the sacrum as rigid bodies. The tendon's and ligaments' stiffness ranges between 20 and 1200 MPa depending on factors such as the proportion of collagen [18]. The pelvic ligaments may have different mechanical properties according to their contribution to pelvic stability. Based on the previously described mechanical properties of pelvic ligaments [19] and their anatomical descriptions of the pelvic ligaments [15], we decided to apply Young's modulus as listed in Table 1. Since the posterior-superior ligaments were supposed to play a role in the counter-nutation movement, we attributed two Young's moduli to the ilio-sacro-transverse and axile ligament (E1 = 500 MPa and E2 = 750 MPa) in separate FE simulations to evaluate the role of the stiffness of these ligaments for the counter-nutation efficiency. We considered all ligaments (Fig. 2) as isotropic material for simplification.

Measured parameters

This study assessed the resultant displacement of the sacrum relative to the pelvis and the equivalent stress distribution (Von Mises Stress) on the sacroiliac junction cartilage. We considered the following pelvimetric dimensions: the obstetric conjugate, anteroposterior outlet diameter, bi-iliac breadth, and bi-spinous diameter. The distance between the promontory and the symphysion was defined as the obstetric conjugate. The distance between the inferior border of the pubic symphysis and the ventral edge of the fifth sacral vertebra marked the anteroposterior outlet. The maximum distance between the two iliac crests characterized the bi-iliac breadth. The bi-spinous diameter was defined as the distance between the sciatic spines. All variables were reported in one decimal place. To evaluate the variation of the inlet opening, we measured the change in the surface of the inlet plane (in cm^2).

Validation of the model

Previous clinical studies reported pelvimetric changes when women move from squatting to a supine position [13,17]. When MRI is analyzed, this changing position generates inlet enlargement and outlet

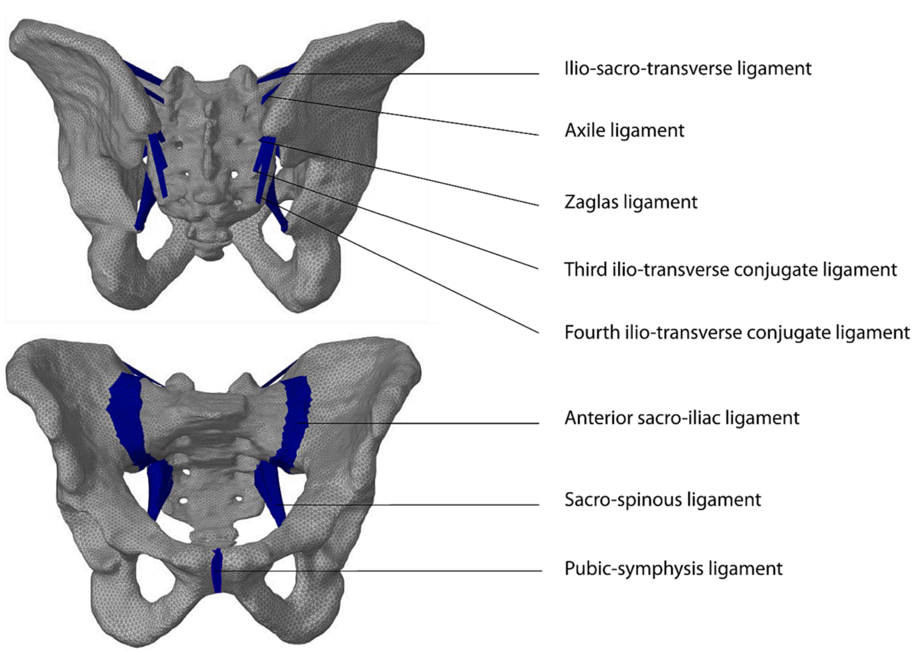

Fig. 2. Ligaments in the Finite Element model.

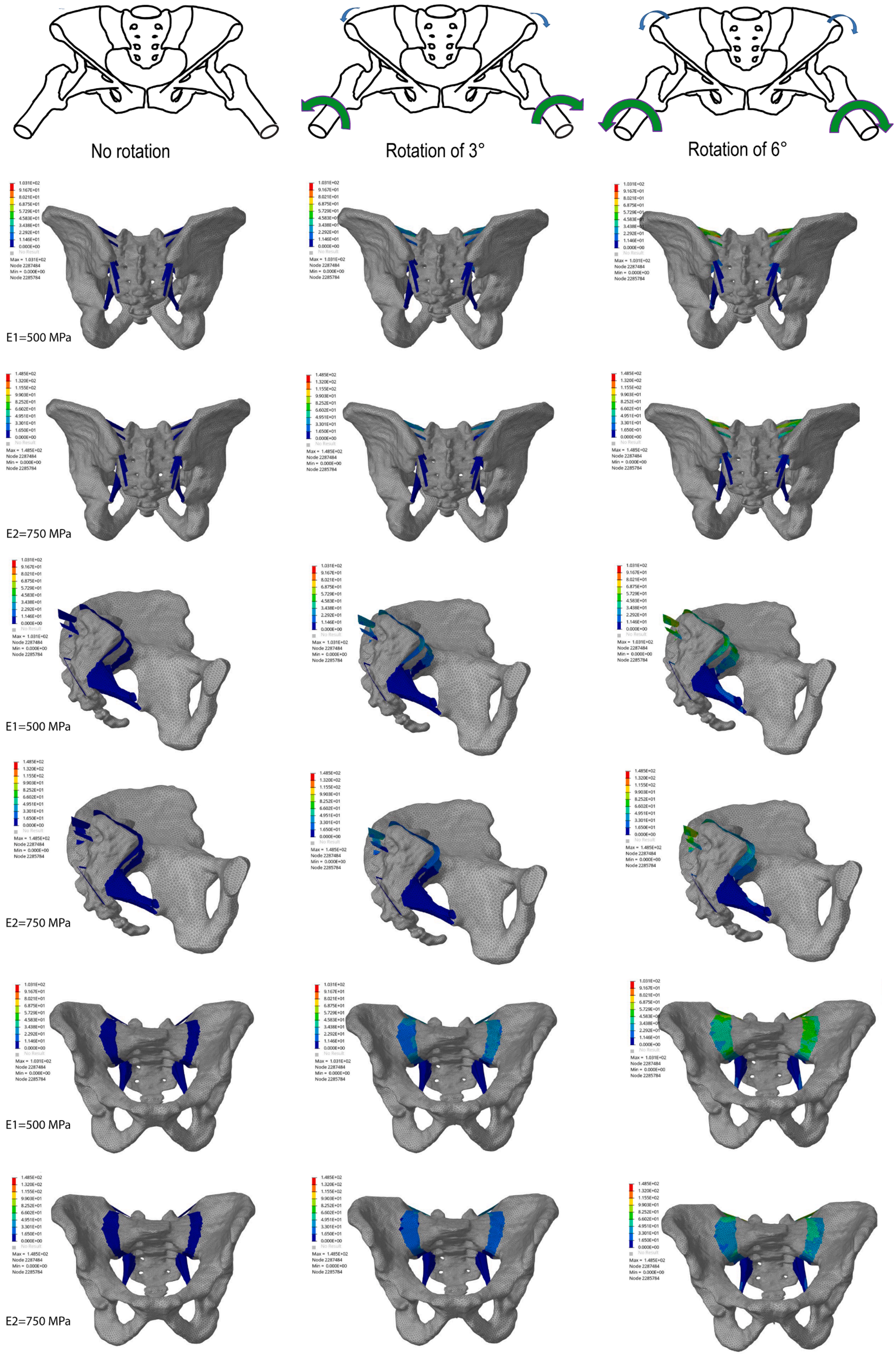

Fig. 3. Von Mises stresses in the sacroiliac ligaments and sacroiliac kinematics resulting from external iliac rotation.

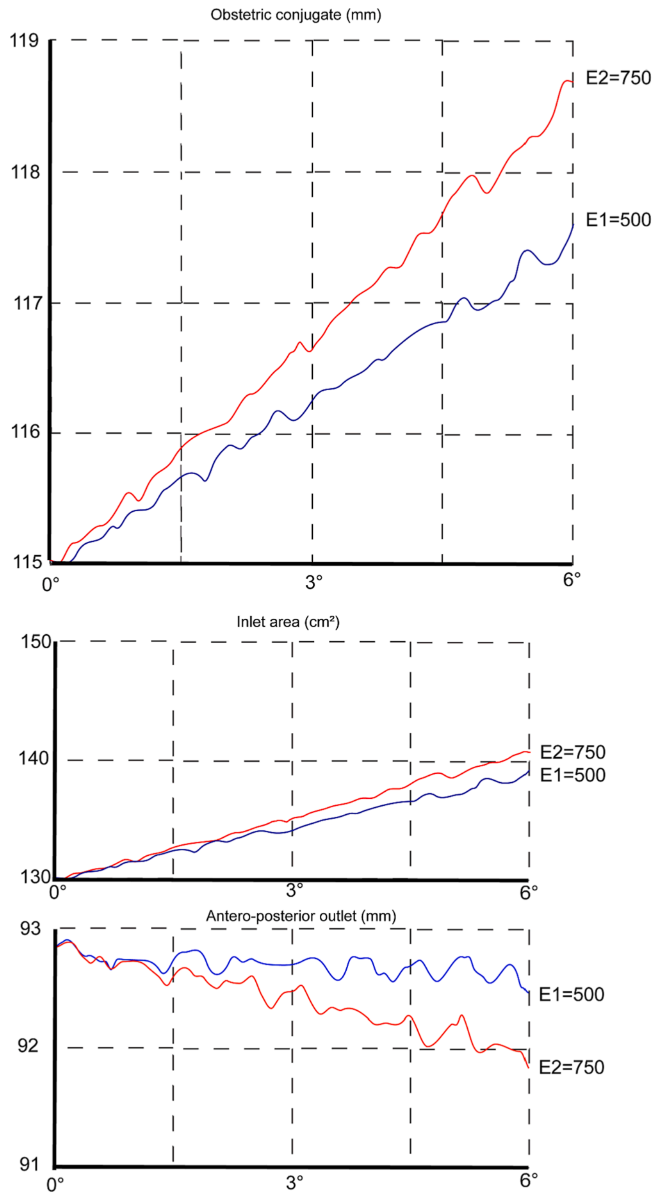

Fig. 4. Quantitative changes of the obstetric conjugate, inlet area and anteroposterior outlet during the simulations: Young modulus of the ilio-sacro-transverse and axile ligaments is E1 = 500 MPa (in blue) and E2 = 750 MPa (in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

constriction, similar to the counter-nutation. Therefore, our results were compared with those published by Reitter et al. [13] and Michel et al. [17]. We also considered the movement of pelvic bones and associated clinical measurements during squatting movements resulting from a computational simulation study [14].

Results

Changes in the different pelvimetric diameters during the simulation

Fig. 3 shows the sacrum's movement according to the iliac bones' external rotation. While the bi-iliac breadth increases with external rotation, the promontory shows a backward displacement. Meanwhile, the lower part of the sacrum is displaced forward, resulting in a general decrease in the size of the pelvic outlet and an increase in the dimension of the pelvic inlet plane.

Fig. 4 shows the changes in the different pelvimetric diameters and inlet areas during the simulation. The quantitative analyses reveal that the pelvis has an upper area of the pelvic inlet of 130 cm^2 at the onset of the simulation. This level can increase up to 141 cm^2 after 6° of external rotation, resulting in an expansion of 11 cm^2, with E2 = 750 MPa. When applying Young's modulus of E1 = 500 MPa on the ilio-sacro-transverse and axile ligaments, the opening of the inlet is estimated at 139 cm^2. The obstetric conjugate is 115,0 mm at the onset of simulation and 117,6 mm at the end (i.e., after 6° of external rotation) with E1 = 500 MPa, and 118,7 mm with E2 = 750 MPa. The anteroposterior outlet diameter decreases by 0,3 mm (from 92,8 mm to 92,5 mm) with E1 = 500 MPa, while this diameter decreases by 1 mm (from 92,8 to 91,8) with E2 = 750 MPa. External rotation produces a linear approximation of the sciatic spines: bi-spinous is 99,5 mm at the onset and 93,5 mm at the end of simulations (Fig. 4, Fig. 5). The paired ilia separate, and the bi-iliac crest increases by 22 mm (from 262,5 mm to 284,9 mm).

Model validation results

We compared our simulation results with data in the literature corresponding to clinical situations of postural adjustment from squatting position to supine position [13,17] (Fig. 5). These postural changes are associated with an increase in transverse inlet diameter of 1 mm [17] a decrease in bispinous of 2 cm [13], and a decrease in the bi-ischiatic diameter of 4 mm [17] and 8 mm [13] suggesting a mechanism of similar effect as counter-nutation. Moreover, Hemmerich et al. [14] found a decrease in the bi-ischiatic diameter of 11 mm when passing from squatting to supine position. Obstetric conjugate consistently increases for both simulation and published data except for the *in vitro* obstetric conjugate data presented by Hemmerich et al. [14]. The AP outlet consistently decreases for both simulation and published data. Inlet area increases for both simulation studies: the inlet area increases by 2% [14] and between 6 and 8% in our study.

Changes in stress in the sacroiliac ligaments

Among the different pelvic ligaments, the most significant stresses were observed at the ilio-sacro-transverse and axile ligaments. Specifically, a Von Mises Stress of 148,5 MPa was simulated near the insertion of the ilio-sacro-transverse ligaments on the transverse tubercle of the first sacral vertebra (Fig. 3). The anterior sacroiliac ligaments show a maximum stress of 88,6 MPa. The maximum stress generated into the sacro-spinous ligaments was 34,3 MPa (Suppl video 1–3).

Discussion

According to Farabeuf's hypothesis, the morphology of the auricular surface plays a crucial role in the sacroiliac movement: the auricular surface has an L-shape and two parts with different axis orientations. The upper part of the auricular surface is nearly vertical and the lower part is longer and horizontally aligned. These two axes act biomechanically as two « railroads» and the sacrum combines an anteroposterior displacement with a vertical displacement explaining the nutation/counter-nutation movements. However, a radiological study did not confirm Farabeuf's theory [20]. In this study, we show that from a biomechanical perspective, the sacroiliac junction's anatomical configuration is not as essential as the ligaments' role. While ilio-sacro-transverse and axile ligaments indicate a higher stress value in the simulation, their orientation is crucial in the counter-nutation movement. Indeed, the efficiency of the counter-nutation (i.e., inlet opening) movement increases with the stiffness of the ilio-sacro-transverse and axile ligaments. These ligaments are oriented posteriorly and cranially and are attached to the posterior extremity of the iliac crest. The external rotation of the ilia displaced the iliac crest laterally and pulled the ilio-sacro-transverse and axile ligaments posteriorly. This traction generated a backward displacement of the first sacral vertebra and backward

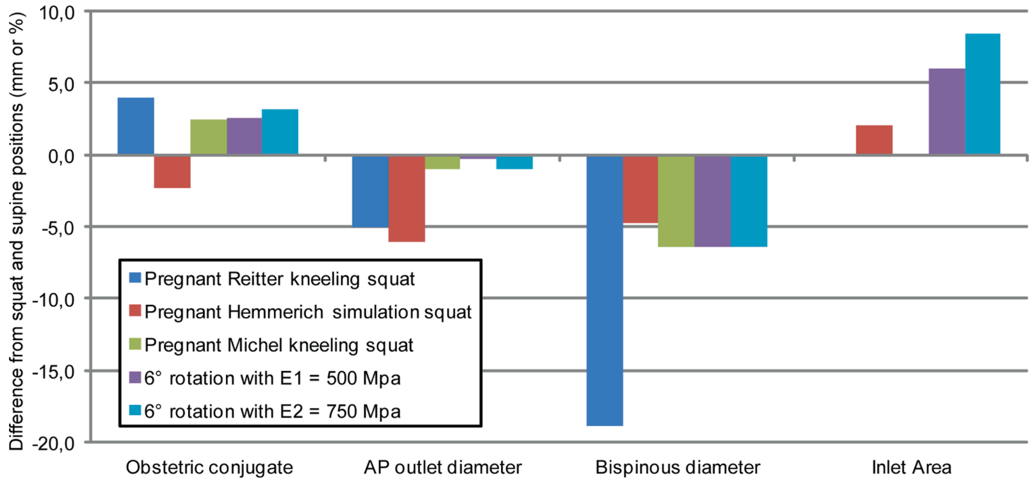

Fig. 5. Simulation results compared with data in the literature [13,14,19], in which mean differences in measurements are between kneeling squat or squatting positions and supine position.

tilting of the sacrum. The sacrospinous ligaments attached the sacrum to the ilia at a lower level, restricting sacrum elevation. Thus, an axial rotation of the sacrum increased the obstetric conjugate and decreased the anteroposterior outlet diameter.

Simulation results were reasonably similar to data presented by previous clinical studies [13,17] suggesting that our simulations represented a confident computational approach to model the counter-nutation. Our results are specifically in line with the clinical findings of Michel et al. [17]. However, the variation in the change of pelvic diameters is still a matter of debate [13,17,21]. Borell and Fernström compared the pelvic size between two distinct birth positions (the lithotomy position, i.e., gynecological position with hyperflexion of the legs, and the Walcher's position, i.e., the legs hanging off the edge of the bed). In this study, the obstetric conjugate increased by 10 mm, and the anteroposterior outlet decreased by 20 mm when they moved from gynecological to Walcher's [22]. This result reveals a significant variation in the amplitude of the obstetric conjugate and suggests that $E2 = 750$ MPa is more realistic than $E1 = 500$ MPa.

Our findings align with other clinical data stating that postural adjustments do not permanently raise a misfit between the fetal head and the mother's pelvis [17]. However, an enlargement of 4 mm could be helpful in case of obstructed labor or shoulder dystocia, where even an opening of a few millimeters of the inlet may resolve the obstruction.

Our study is the first attempt to describe the sacroiliac motion with computational methods when lateral rotation of the ilia is simulated. Our simulation study shows that eversion of the ilia resulted in a backward displacement of the promontory and a forward displacement of the lower sacrum. The association between the change of birth positions and the size of the pelvic planes is challenging to assess in clinical studies given the anatomical variations of the pelvis [23] and the varying levels of relaxin during late pregnancy [24]. For this reason, finite element simulation is a suitable method to understand how postural adjustment may contribute to the optimization of the size of the birth canal. In our study, the lateral rotation of the ilia was considered a proxy of the external rotation of the femurs. Nevertheless, the spine's position relative to the pelvis could also affect the birth canal dimension and was not assessed in our study. Since the flexion of the legs would decrease the lordosis curvature [25], this flexion could increase the sacral expansion, amplifying the counter-nutation movement. Further studies should explore the role of the flexion/extension of the legs.

Predicting birth process issues is still a relevant challenge today [7,26], specifically for estimating the chance of having a vaginal birth after cesarean delivery. In this context, the simulation of the birth process could be a valuable predictor of the progress of the delivery [27]. Nevertheless, taking into account only the pelvis, passenger, and power (i.e., the three "P" s) [28] will not effectively determine the probability of vaginal delivery. Indeed, a birth simulation also requires modeling the sacroiliac motion.

Another expanding subject of interest is paleo-obstetrics. Understanding why humans give birth in a specific manner as opposed to other primates and how evolutionary pressures shaped this process requires birth simulations of hominins [29]. Our work could be replicated in fossil hominins of whom pelvic reconstructions are available. Our results could help us to know if a sacroiliac motion was already present in the past.

Conclusion

In this work, our finite element simulation of the counter-nutation movement shows that a slight external rotation of the femurs of 6° induces an anteroposterior enlargement of the inlet of almost 4 mm. This enlargement could be significant in case of obstructed labor or shoulder dystocia. Our findings confirm the counter-nutation hypothesis and suggest it is based on the elongation of ligaments rather than on the morphology of the auricular surfaces. The most important ligaments in this mechanism are the ilio-sacro-transverse and axile ligaments. Further studies should investigate the external rotation in combination with the flexion of the femurs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ejogrb.2023.08.381.

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