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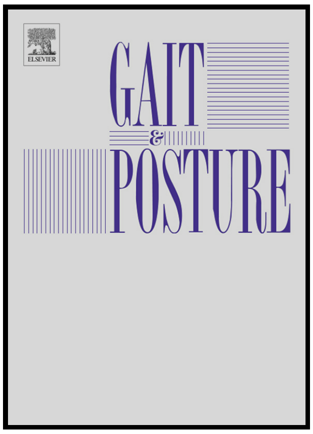

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Barycentremetry, spine disorders, posture and motion analysis☆

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Structured abstract

Purpose of the research

Prevention of spine disorders and their management require better understanding of related biomechanical issues. While tremendous progress has been performed for musculoskeletal modelling of the spine, subject specific modelling of the gravitational loads and their effects on the spine is still an issue.

Recently, 3D reconstruction of the skeleton from biplanar head to feet X-rays in erect position has been completed by the external body envelope. An approach named "barycentremetry" based on density models to estimate the mass and centre of mass of each body segment, yielding a force plate less estimation of the gravity line, together with the estimation of the gravitational loads and the associated lever arm at each vertebral level.

Principal results

Due to vertebral pose, gravitational loads effect on intervertebral disc shows wide variation. Studies exploring barycentremetry clinical relevance were analysed, particularly for adolescent idiopathic scoliosis, adult spinal deformities and osteoporosis. They progressively yield a better comprehension of the potential vicious circles linking postural disorder to increase of spine loads to increase of postural disorder.

Barycentremetry was also explored within gait and motion analysis research, allowing to estimate subject specific body segments inertial parameters for patient specific dynamic analysis. Indeed, 3D

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musculoskeletal modelling of posture and motion could benefit from subject specific dynamic analysis based on barycentremetry.

major conclusions

Such approaches progressively provide a better understanding of the stability of this complex system and compensation strategies that could be useful for early detection of disorders that are responsible of a biomechanical cascade.

Keywords

Barycentremetry / Spine disorders / Posture / motion / Adult spinal deformity / Adolescent idiopathic scoliosis / osteoporosis.

Introduction

Spine deformities can occur at any age, even in very young children (early onset scoliosis). Adolescent idiopathic scoliosis (AIS) may affect up to 4% of the population (Cheng *et al.* 2015). With ageing, spine evolves with postural changes and alteration of the constitutive tissues and the whole neuromusculoskeletal system, yielding disorders that affect up to 32% in adults and 68% in elderly (Ames et al 2016). Spine pathologies represent a growing human and socioeconomic burden. In 2017, the health economic cost of fragility fractures due to osteoporosis was estimated at 37.5 billion in Europe (Burden of Osteoporosis | International Osteoporosis Foundation). Moreover, it is estimated that under-diagnosis of vertebral fracture is a worldwide problem. Indeed, spine deformities may both result from or increase the risk of vertebral fractures and may be responsible for disabling pain and loss of autonomy (Hu *et al.* 2018).

When conservative treatment fails, surgery is an option with a well-documented impact on quality of life (McCarty et al 2014, Riley *et al*. 2018). However, mechanical complications represent a real issue that is associated with increased costs, both on the human and economic level (McCarty et al 2014, Lafage et al 2024). Mechanical complications may occur in the implants, such as rod or screw breakage. They may also be due to spine degradation, (adjacent disc, secondary fracture, or deformity such as postoperative junctional kyphosis (PJK)), or implant spine connection (screw loosening, pull out). Complications may be due to specificity of instrumented spine structure (geometry mechanobiology of the tissues, implant strategy), or to gravitational loads that could yield overstress in the construct.

Prevention of mechanical complications requires better understanding of the biomechanical mechanisms underlying both intact and instrumented spine disorders.

In clinical biomechanics, the analysis of sagittal alignment has gained attention, as it is well established that malalignment is a crucial issue when considering spine condition, quality of life and mechanical complications of surgery (Glassman *et al.* 2005, Smith et al 2015). Duval-Beaupère and Legaye described fundamental parameters of spinopelvic alignment in the sagittal plane i.e., pelvic incidence (PI), sacral slope, pelvic tilt, lumbar lordosis (LL) and thoracic kyphosis (TK) (Legaye *et al.* 1998). An increasing number of complementary radiographic parameters, in both the frontal and sagittal planes, have been proposed to describe the erect position and its evolution with age (Schwab *et al.* 2005, Schwab *et al.* 2009, Diebo *et al.* 2019). The three-dimensional aspects and deformities in the horizontal plane were also shown to be crucial (Perdriolle, Vidal 1987, Dubousset 1994). The development of the low dose biplanar X-Rays imaging (Dubousset *et al.* 2005) allowed 3D head.to-feet analysis in load bearing position (figure1a). Particularly, we found a quasi-invariant parameter for a wide range of volunteers and patients with spine disorders (Amabile *et al.* 2016, Alzakri *et al.* 2018, Hu *et al.* 2022, *Langlais et al.* 2024), except those with the most severe deformities (Ferrero *et al.* 2021): figure 1-b illustrates the axis joining OD (upper tip of the odontoid, close to the head center of mass) to HA (middle of the line formed by the two femoral heads). OD-HA angle has a mean value of 2° and a standard deviation (SD) of 2°, indicating that the neurocentral and muscular system act to maintain the head above the pelvis, independently of local or global disorders, leading to compensatory mechanisms at different levels.

However, alignment analysis on X-Rays only considers geometric static configuration, thus providing a partial view of the patient’s condition:

- In standing erect position, alignment is different from balance, the latter resulting from gravitational loads and muscle permanent regulation yielding natural oscillations to maintain the body within what Jean Dubousset called the “cone of economy,” with minimal energy expenditure (Dubousset 1994).
- Quantitative movement analysis (QMA) allows a better understanding of daily life functional activities. While dynamic analysis based on QMA has been extensively performed in sports biomechanics, in ergonomics, or in specific disorders involving mainly the lower limbs, QMA used to investigate spine disorders is still mainly focused on the kinematic spatiotemporal parameters (Pesenti *et al.* 2019, Boulcourt *et al.* 2023).

Beyond geometric (alignment) or kinematic (movement) assessment, biomechanical analysis (static or dynamic) would be essential, both to better understand the mechanisms responsible for spine deformities and their evolution, and to provide a deeper insight into the causes of mechanical complications of surgery. However, such biomechanical analysis is particularly complex: despite a huge effort in spine biomechanics research (1000 PubMed publications each year in the last ten years), there are no biomechanical models that are routinely used in clinics. While *in vitro* biomechanical analysis of intact, injured, or instrumented spine segments has been extensively investigated, with some numerical models that replicate these *in vitro* tests and complement the experimental approach, *in vivo* biomechanical modelling is much less investigated and still raises scientific bottlenecks.

Indeed, numerical models could be highly valuable, providing they incorporate subject-specific geometry, material properties and mechanical loads. The latter point, of crucial importance, is the most difficult to tackle, because loads that apply to the spine result from gravitational loads that act all along the spine and that are regulated by the muscles activated by the Central Nervous System (CNS) based on the sensory system (vision, vestibular system, mechanoreceptors located in the skin, in muscles, tendons, and joint capsules, …).

Various muscular regulation models have been proposed, either in static or dynamic analysis, particularly in sports biomechanics and in ergonomics. They require estimation of gravitational loads and of body segment inertial parameters (BSIPs), i.e., mass, center of mass and moments of inertia along the axes associated to each segment. Estimation of these parameters is generally performed using statistical data (Dempster et al 1955, De Leva 1996, …). Nevertheless, subject specificity is of paramount importance in clinical biomechanics as patients may be far from the young volunteers generally considered in these databases.

Recent efforts tend to progressively bridge the gap between neuro-musculo-skeletal biomechanical models, often based on typical subjects, and clinical issues that concern those non-typical spines with neuro-musculo-skeletal disorders.

In this global context, barycentremetry can be of particular interest, constituting a piece in the collective effort. Barycentremetry is the measurement of the center of mass (or barycentre) of a multi-components object. In spine biomechanics, it applies to the measurement of the center of mass of the human body from the centers of mass of the different body segments, and the analysis of their relative locations. Duval-Beaupère first introduced this term (Duval Beaupère *et al*, 1987, 1992), using a gamma-ray scanner to estimate the mass on successive body scans, and the coordinates of the centres of these masses. The latter were then transferred from the coordinate system (CS) of the gamma ray system to full radiographs CS, thus yielding an estimation of the gravitational load on each specific vertebra. However, the process was too cumbersome and therefore not used in practice. Our group has revisited barycentremetry by using calibrated biplanar X-Rays (BPXR) and 3D reconstruction both of the skeleton and of the external envelope, together with density modelling of each body segment (Pokorski, Skalli 2007). The method was progressively refined and validated (Sandoz *et al.* 2010, Amabile *et al.* 2016), and used both in children and adults. Various publications explored the potential relevance of the technique on various focused topics.

The aim of the current review is to present the biomechanical bases of such measurement, the synthesis of the work conducted, and to discuss the importance of this measurement and what it could bring for the functional evaluation in patients with spinal deformity.

Barycentremetry from Biplanar X-rays:

General principle

Assessing the mass and the barycentre (or center of mass, CoM), of a body requires the volume and the density of each of the body segments.

For a given individual, BPXR allows using validated methods to get the external envelope of both the longitudinal skeleton (Gajny *et al.* 2019, Mitton *et al.* 2006, Chaibi *et al.* 2012) and the external envelope (Nerot *et al.* 2015, Hernandez *et al.* 2018), as illustrated in figure 2. A skeleton related coordinate system is used for body segments location in relation to bone components. This coordinate system is anatomo-gravitational, i.e., Z is the vertical (gravitation) axis, XY being the horizontal plane, oriented by the centers of femoral heads. The external envelope provides volume computation.

Each body segment is nonhomogeneous, as density of bone, muscles, fat, and other tissues are different. The thorough cadaveric measurements performed by Dempster (Dempster 1955, Dempster & Gaughan 1967) provided estimation of a mean density for each body segment. This database is still widely used, except for the thorax where the air in the lungs was not considered. Recently, a detailed nonhomogeneous model of the thorax was proposed, accounting for the different tissues (heart, lung, bone, …) in order to quantify thorax mass, and to validate the relevance of homogenization, thus yielding an improved mean thorax density (Amabile et al 2016).

Considering n body segments (BS), each of them with a mass m_i and a center of mass coordinates x_i, y_i, z_i, global mass is $M = \sum_1^n mi$.

The coordinates of the CoM are:

$$xCoM = \frac{1}{M}\sum_1^n mi * xi$$

$$yCoM = \frac{1}{M}\sum_1^n mi * yi$$

$$zCoM = \frac{1}{M}\sum_1^n mi * zi$$

Considering the whole body, the mass corresponds to the mass of the individual, and the vertical passing through the CoM is the gravity line (GL).

Because the computation of each body segment CoM is difficult to evaluate, the global evaluation was performed using a force plate calibrated in the Biplanar X-ray coordinate system and used as a reference. Table 1 shows the comparison between the estimated GL projection on the platform and the measured mean center of pressure. Both for asymptomatic adults and for adolescents with idiopathic scoliosis, the difference between estimated and measured GL location was less than 1 cm.

Even if this evaluation was limited to 24 subjects and did not consider adults with spinal deformities, it appeared that an average density for each body segment was sufficient, and that the volume differences between individuals played the major role in interindividual variations.

Other limitations were underlined in various studies: for some patients, the anterior part of the external envelope was extrapolated because it exceeded the size limit of the X-ray detector. Also, the free-standing position requires moving the arms to put hands on the cheeks or on the clavicles to allow visibility of the spine on the sagittal X-ray. This does not affect posture but has an impact on the global CoM (Legaye and Duval Beaupère 2017). However, this artefact can be partially corrected by virtually repositioning the upper limbs along the body, as was done in recent investigations (Heidsieck *et al.* 2022). Nevertheless, the current method appears robust and has been used in research for more than 300 patients.

Associated output in basic biomechanical analysis

In addition to the estimation of the gravity line, the CoM of each body part can be computed. Figure 3 illustrates the typical location of the global CoM, the head COM, and the body segment above the femoral heads. On a population of 157 asymptomatic adults (68F, 89M, mean age 37 years old, SD 21), the coordinates of the global body centre of mass with regard to the centre of the femoral heads appears quite stable, they are respectively -1 cm (SD 1) in the X axis (posteroanterior), -0 cm (SD 1) in the Y axis (lateral), and 7 cm (SD 2.5) in the Z axis (caudocranial), quite close to the centre of sacral endplate whose coordinates in the x, y, z axes are respectively -2 cm (SD 1), 0 cm (SD 0.5) and 11cm (SD1).

The advantage of this numerical barycentremetry method is the ability to compute the CoM location for various body parts: body slices were defined considering the horizontal plane passing through each centre of the intervertebral discs in order to investigate the mechanisms to maintain the global balance of the body. Computing the barycentre of all the body segments above a given vertebral level yields gravitational loads that apply at this level (Figure 4). The CoM distance to the considered vertebra is called lever arm. Gravitational loads can be further introduced in more or less sophisticated muscle regulation models to estimate muscle forces and spine loads (Schultz *et al.* 1981).

Considering simultaneously gravitational loads, lever arms and the inclination of the vertebra of interest is of particular importance because of gravitational loads decomposition in vertebral plane. Spine segments do not react similarly to compression loads on a horizontal endplate or in case of inclination yielding shear forces. Also lever arm may induce flexion, lateral bending or torsion, as underlined in (Thenard *et al.* 2018). As this point could be crucial for better understanding of the relation between gravitational loads, posture and spine disorders analysis, a complementary theoretical analysis is performed here after. A validated finite element model of an L3-L4 spine functional unit (Badaoui *et al.* 2024) was used, in which the bottom of the vertebral segment was fixed, and a 400 N vertical load was applied to the upper L3 vertebral endplate, that could correspond to gravitational loads. Three conditions were considered (figure 5):

1. Vertebra located so that the vertical load is centred regarding the L3 upper endplate, which is horizontal; in this case, as expected, vertical displacement is observed, and the forces in intervertebral disc fibers do not exceed 2N
2. Vertebra deviated laterally (4 cm) regarding the vertical load with no change in vertebral segment orientation; this condition induces a 16 Nm lateral bending moment, inducing frontal plane inclination and lateral deviation, with an increase of fiber forces.
3. Same as 2, while changing the spine segment sagittal orientation to get a 50° sagittal inclination of the upper L3 endplate. In this case, the projection of the gravitational force has a component that generates a 12 Nm axial torque, thus yielding an axial rotation, and associated drastic increase in the intervertebral disc fiber forces (figure 5c).

Increase of disc fibers forces could in turn result in disc degradation and a vicious circle with an increase of the deformity. Indeed, these results confirm that the spine segments are very well built to withstand centred compression, while they are more vulnerable in case of deviated loads (Skalli *et al.* 2007).

In case of high loads, muscles should be considered. Numerous spine control models are proposed in literature, with muscle activation either driven by optimization, generally to minimize an energy criterion (Delp *et al.* 2007, Burkhart *et al.* 2018,) or by a control approach to regulate spine loads (proprioceptive control models, Pomero *et al.* 2004, Van Den Abbeele *et al.* 2018). In economic erect posture, only minimal muscle activation is required to maintain the position. When spinal loads increase, due to spine malalignment as shown above, muscles activate for spine loads regulation, inducing energy expenditure and thus a non-economic posture. However, in ASD with severe malalignment, muscle regulation could be less efficient because of muscles alteration such as fat infiltration (Ferrero *et al.* 2020). Non-regulated spine loads could be considered as a worst-case scenario, which could induce a biomechanical cascade of tissue degradation and deformity increase.

As a conclusion of this basic part, barycentremetry yields estimation of the gravitational loads and their distribution, together with the vertebrae position and angulation in space. It provides an estimation of gravitational loads and the lever arms of the CoM of segments above each intervertebral level, which could be of high clinical relevance.

Potential clinical relevance for spine disorders investigation

In the following part, clinical relevance of barycentremetry will be considered, with a focus on scoliosis and osteoporosis. Most investigations were retrospective, performed on existing databases of biplanar

X-Rays of asymptomatic volunteers and patients, all in respect of the ethical procedures, detailed in each reference.

Analysis for Adolescent Idiopathic Scoliosis (AIS)

A preliminary investigation was performed on 27 non scoliotic adolescents and 53 AIS patients with a mean Cobb angle of 32° varying from 10° (very mild scoliosis) to 76° (very severe). For non-scoliotic subjects, CoM calculated for the slices in the frontal plane were close to the gravity line, with a mean value of 0.4 cm and a 95% corridor of 0.8 cm. Scoliotic patients, even with large deformities, maintained the maximum distance of the slice CoMs to a mean value of 0.6 mm, (max < 1.3 cm) (Thenard *et al.* 2019). Figure 6 illustrates this phenomenon: despite the large deformity of the spine, this patient maintains the CoM of each body slice of the trunk very close to the gravity line. This may be obtained by rotating the trunk and explains why lateral deviation and axial rotations are strongly interrelated, in a compensation mechanism that could be mutual: rotating a slice is necessary in case of deviation to maintain the slice CoM close to the GL, but in case of slice rotation, the CoM-GL distance also increases and deviation is necessary to reduce it.

However, the consequence of the vertebrae lateral deviations is the increase of the lever arm of upper body segment load on some of the vertebrae. Particularly, when computing the resulting axial torques, maximal values were 2.1 Nm for asymptomatic subjects, while they could reach 8.9 Nm at the junctions of the scoliotic curves.

These results on AIS were confirmed for 41 asymptomatic subjects and 60 AIS (Langlais *et al.* 2021), while defining a 95% confidence interval (CI) for torques in asymptomatic subjects. Indeed, the high axial torque values may yield disc degradations that could in turn yield an increase of the deformity in a vicious circle.

In fact, this axial torque only represents a worst-case scenario, and fortunately the muscles activate to protect the spine from overloading. Several investigations regarding muscles in scoliosis underlined asymmetry of the deep apical paraspinal muscles particularly at the apex of the curve, as well as modification of their volume and structure compared to controls *(*Berry *et al.* 2021, Duncombe *et al. 2023*). Paraspinal muscles probably play an important role to reinforce the strength of the spine when overloaded, at the price of an increased compression, impacting the mechanobiology of the components (bone, cartilaginous endplates, discs). Indeed, ultrasound elastography of the intervertebral discs at lower junction of scoliosis curve has shown that disc stiffness increases compared to normal discs (Langlais *et al.* 2018).

As this altered condition could play a role in the mechanical cascade responsible for aggravation of mild scoliosis, the role of barycentremetric parameters was also explored to improve the predictive performance of a severity index used at a very early stage to differentiate progressive from non-progressive scoliosis (Skalli *et al.* 2017). The BPXR barycentremetry was performed on 162 mild AIS patients at their first exam showing that for thoracic curves, the use of barycentremetric parameters could potentially improve the specificity and positive predictive value of this severity index (Langlais *et al.* 2024a).

The potential clinical relevance of barycentremetric parameters was also investigated for surgical evaluation in 29 AIS patients (Langlais *et al.* 2024b). It was confirmed on the pre-operative data that 90% of patients had higher axial torque values than the 95% reference corridor at the upper and lower junction levels (i.e. ends of the scoliotic curve). The surgical procedure reduced the Cobb angle as expected, resulting in a decrease of the axial torques at the junctions, even if postoperatively, up to 62% of patients still had higher torque than the 95% reference corridor, particularly at the upper junction. There is still a need for large scale analysis and longer-term follow-up to understand the effect of correction strategies on the resulting barycentremetric parameters, and to assess the relationship between these parameters and the clinical outcome. Nevertheless, the potential use of the numerous retrospective data allows such investigations, since barycentremetry does not require additional data to the Biplanar X-rays, providing they are performed in standardized free-standing position.

Osteoporosis: vertebral strength estimation

Subject specific finite elements (FE) models for vertebral strength evaluation from Computer Tomography (CT) were proposed more than thirty years ago (Faulkner *et al.* 1991), and have reached maturity (Keaveny *et al.* 2023, Choisne *et al.* 2018). However, CT exam is performed in lying position and does not consider the potential effect of gravitational loads and their evolution with ageing. Sensitivity of the lever arm of compressive force has already been underlined from a theoretical point of view (Travert *et al.* 2011). Barycentremetry allowed to investigate this sensitivity in vivo (Heidsieck *et al.* 2022): 117 asymptomatic volunteers were considered, having no major pain in the spine, hips or knees. They were aged between 20 and 83 years and were divided in three age groups: young (20 to 40 years, 62 subjects), intermediate (40 to 60 years, 26 subjects), and elderly (60 years and over, 29 subjects). Biplanar X-rays in free standing position were used to perform barycentremetry and compute the CoM lever arm of the body segment above the L1 vertebra (BS_{L1} lever arm). The gravitational load was applied to a previously validated finite element model of L1 vertebra (Choisne *et al.* 2018) to estimate vertebral strength. To isolate the role of vertebral inclination and gravitational loads with ageing, the same vertebral model (with same geometry and material properties) was used for all the subjects. While mean BS_{L1} sagittal lever arm was - 0,1 cm for young adults, it increased to 1 cm and 2.4 cm, respectively, for the intermediate and elderly group. Vertebral strength decreased from 2527 N for the young group to 1820 N for the elderly group, i.e. 27% decrease. Indeed 2.4 cm increase of the lever arm may appear minor (approximatively the diameter of a quarter of a 2 Euros coin), but its effect is high!

Looking at inter-individual variations, the effect was even higher since the vertebral strength values varied from 860 N to 4066 N due to BS_{L1} lever arm variation. Even if these simulations did not consider muscles regulation, they underline the importance of considering posture and not only bone mineral density and vertebral geometry when considering osteoporosis strength estimation in elderly, and more generally on spine disorders with the objective of their potential prevention.

Analysis for adult spines

The same core database increased to 124 asymptomatic volunteers was used to explore gravitational loads in relation with age, spinopelvic parameters and morphologic changes (Khalifé *et al.* 2024). The barycentremetric analysis highlighted the interrelations between the spine curvatures and the CoM location above key vertebrae (at thoracic apex and at the thoracolumbar inflexion point), and the role of the pelvic tilt to rebalance the masses distribution according to the specificities of the subject. Particularly an increased abdominal volume yielded a more anterior location of the whole-body centre of mass associated with increased thoracic kyphosis and decreased lumbar lordosis, resulting in compensation through hip extension.

The same core database was also used to investigate the evolution of gravitational loads in the cervical spine (Muth Seng *et al.* 2022). Average computed mass of the head-neck segment above C6C7 was 5.0 kg (SD 0.7), with no age effect. Ageing did not affect the lever arm (mean 2.3 cm, SD 1.4), while vertebral sagittal inclination increased with age, thus increasing postero-anterior shear in the intervertebral discs. A preliminary investigation was performed on 46 patients operated with cervical spine instrumentation to investigate gravitational loads at the upper adjacent level after surgery.

These examples show the diversity of the potential use of barycentremetry : indeed, the method appears robust and has been successfully used for more than 300 subject. The two main current limitations concern subjects whose external envelope is out of the Xray field and cannot be extrapolated, which may be the case particularly for obese persons. Also, the major current limitation is the time to perform the 3D reconstruction, both for the spine and for the external envelope. Work is in progress towards full automation, for a routine clinical use.

Nevertheless, research activity is compatible with a 20mn reconstruction time, and work is in progress to tackle various issues in relation with barycentremetry, particularly with the investigation of the impact of gravitational lever arms at the limits of the instrumentation after surgery, in relation with postoperative junctional failures and more generally mechanical complications of surgery.

In conclusion, there is still a lot to do to understand the neuromuscular control and postural adaptation to local disorders. Barycentremetry provides an original information complementary to the generally considered alignment analysis. Such analysis conducted at a large scale could help building musculoskeletal control model for basic research and clinical impact.

Barycentremetry, gait and posture

From kinematic to dynamic analysis

The principles of barycentremetry can be used for direct dynamic approaches in 3D gait and motion analysis, from the external envelope. These subject-specific segmental masses and CoMs could be used in dynamic posture and motion analysis. Indeed, attempts have been made with simplified envelope geometric modelling (Pillet et al 2010), showing that centres of pressure could be estimated during the whole gait cycle. While quantitative motion analysis has a widely recognized clinical value, there is a need for simple accurate quantitative tools to extend its use to a larger scale. Marker less motion capture systems are in rapid development, and get more and more accurate (bae *et al.* 2024, Vafadar *et al.* 2022). Progress in 3D scanning of the external envelope makes it possible to use currently available modelling methods to get barycentremetric data to complement kinematic analysis. A first attempt has been performed in the field of ergonomics to quantify intersegmental forces in L5-S1 in a lifting task, using a non-constrained environment, marker-less and platform-free (Jang *et al.* 2024). In clinical applications, BPXR is more and more available and provides access to the gravitational loads regarding vertebrae position and orientations, while in more general applications, the vertebrae positions could be estimated using relationship between external and internal parameters (Nerot *et al.* 2018).

Further investigations could yield routinely usable tools for a wide range of applications where human body dynamic modelling is necessary. Current research in clinical biomechanics or the spine uses more and more combination of BPXR and gait analysis using marker-based gait and motion analysis (Otayek *et al.* 2020, Severijns *et al.* 2021). Performing BPXR acquisition with passive skin markers in place allows data fusion between radiologic and kinematic data (Rebeyrat *et al.* 2022, Assi *et al.* 2023). This approach provided novel insight in kinematic investigations for the spine and hips : among the findings it is interesting to note that the dynamic ODHA angle appeared quasi-invariant too, except for patients with worst condition. Head and pelvis appeared as the key segments recruited by adult spinal deformity patients during daily life activities (Ayoub *et al.* 2024). Complementing these studies with barycentremetric parameters and muscular models would probably help progressing in the comprehension with the underlying mechanisms.

Stability, cone of economy and posture analysis

The use of a force platform has been widely used in Posturology to investigate balance in erect position (balance test, or stabilometry). The work of Winter (Winter *et al.* 1995) positions the problem: in quiet standing, the centre of pressure (CoP) variation is measured during a few seconds by the force platform. The mean CoP location is located at the projection of the subject's overall CoM, defining the GL location. When the subject is in equilibrium, GL projection is located inside the support envelope formed by the two feet, with a postural sway yielding CoP variation around the GL. The trajectory of the CoP positions (stabilogram) can be described with numerous parameters (Quijoux *et al.* 2021), and its alteration may be due to the musculoskeletal system, to the sensory system, and/or to the central nervous system (CNS). Stabilometry is widely used in motor control, particularly for fall issues. It is also important for spine disorders investigation and has been performed by a balance test either in combination with X-Rays, (Lafage *et al.* 2008, Segi *et al.* 2023) or with a motion capture system (Haddas *et al.* 2018, 2021) reminding the Cone of Economy (CoE) proposed in 1975 by Jean Dubousset.

CoE is in relation with the simplified model of the erect posture by an inverted pendulum. In this classical control model, angulation and position of the pendulum are permanently controlled with slight adjustments to maintain equilibrium. With this model, the global body reduced to its CoM is rigidly linked to the axis of the ankles, with a rotational spring representing the ankle stiffness K_{ankle}. The stiffness of the ankle joint, and its ability to regulate the dynamic equilibrium by slight muscle activation, allow maintaining a stable posture (Morasso & Schieppati 1999). With balanced erect position and a harmonious spine, sway is limited thus requiring a minimum muscle energy expenditure. Patients with ASD have a larger CoM sway and expend more muscle activity to maintain standing position (Haddas *et al.* 2018). Moreover, with ageing and spine deformities, it appears that the control strategy is no more solely on ankle-foot control, while it also involves hip joint, evolving toward a double pendulum or even more (Kilby *et al.* 2015, Haddas *et al.* 2020), with a more challenging stability issue.

Thus, 3D musculoskeletal modelling based on posture and motion analysis enriched by the mass distribution of the different body segments should provide a better understanding of the stability of this complex system for a better understanding of compensation strategies and early detection of disorders that could cause a biomechanical cascade.

Conclusion

This review is based on BPXR barycentremetry as a new methodology to estimate mass and CoM of various body segments, from the external envelope 3D reconstruction and density models. The method appears robust with preliminary investigations that illustrate the potential clinical relevance of barycentremetry in a wide range of applications in volunteers but also in patients with spinal pathologies. Extensive retrospective evaluations with existing BPXR in free-standing position could allow to progress to a more mechanical analysis complementing the geometric alignment analysis.

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Captions

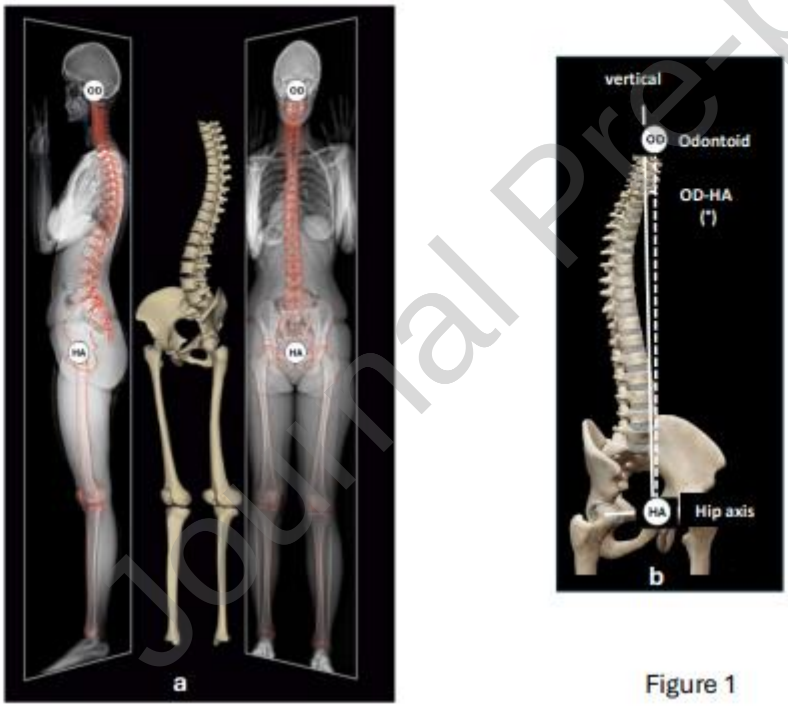

Figure 1

Figure 1 - a) 3D reconstruction of the longitudinal skeleton from calibrated biplanar X-rays; b) illustration of the OD-HA angle, between the vertical and the line joining the tip of the odontoid (OD) to the hip axis (HA).

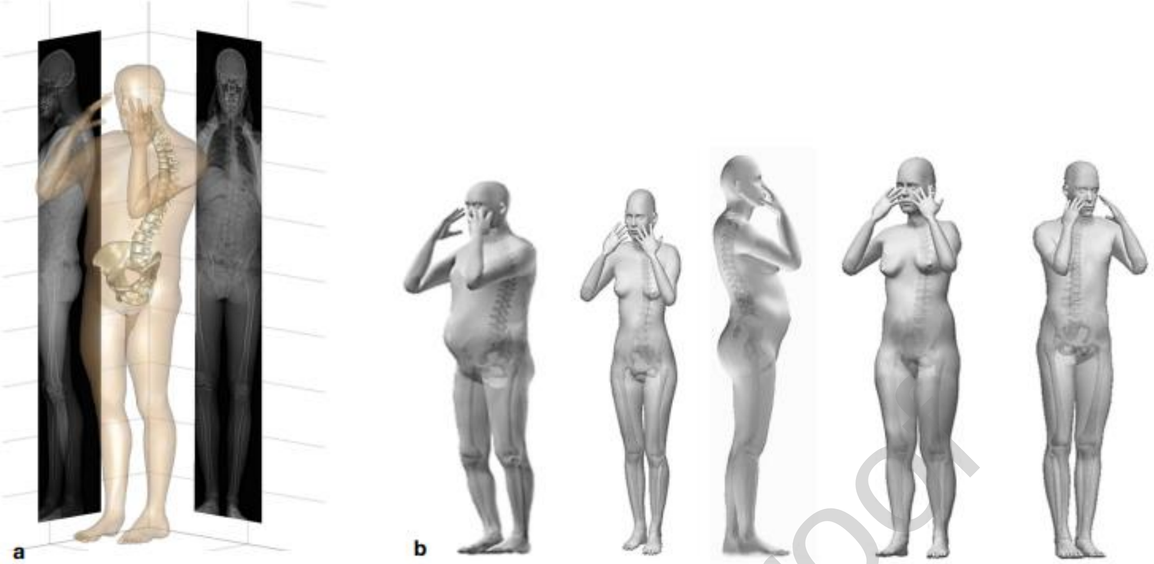

Figure 2

Figure 2 - a) 3D reconstruction spine, pelvis and external envelope from biplanar X-Rays ; b) illustration of the interindividual variations for asymptomatic subjects.

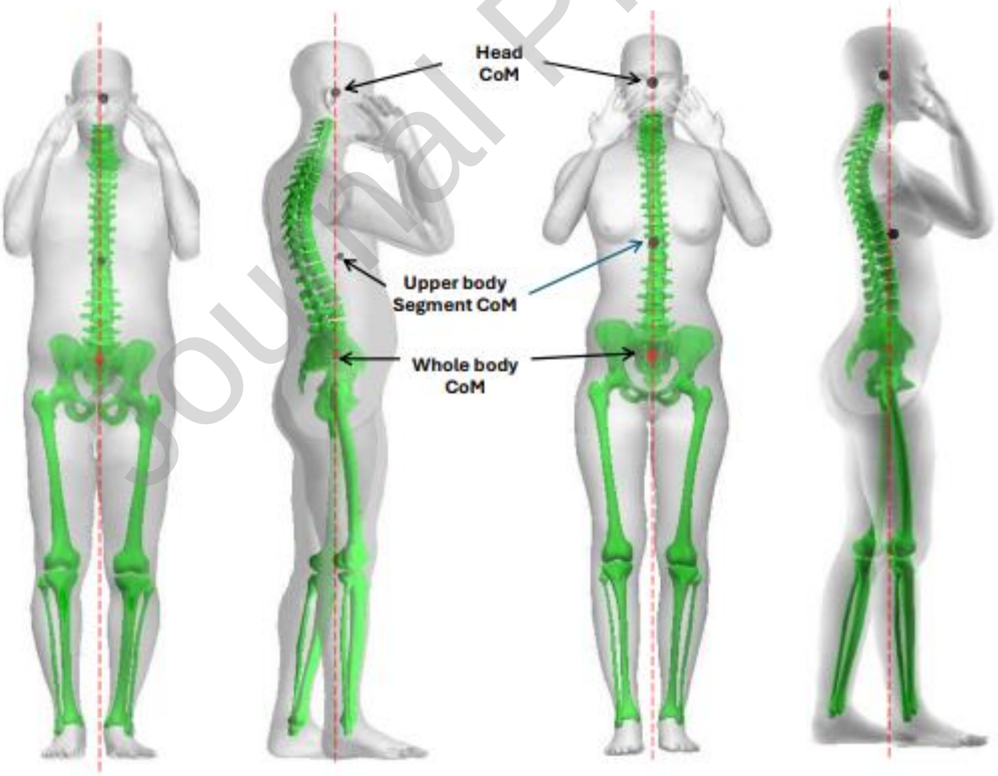

Figure 3

Figure 3 - typical location of the gravity line and Centre of mass (CoM) of the whole body CoM, the head CoM and the CoM of the upper body segment above the femoral heads. Red dotted lines represent the gravity line

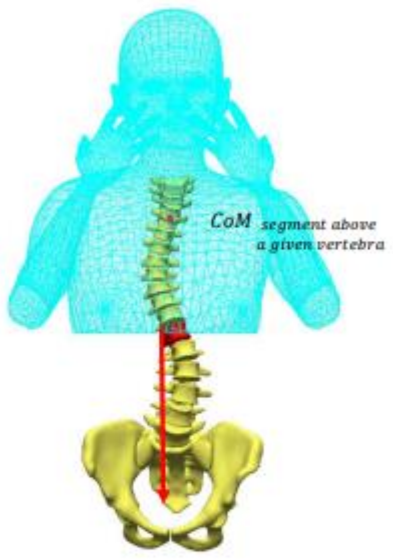

Figure 4

Figure 4 - From body envelope, horizontal slicing at the head-neck and at each vertebral level, barycentre of the segment above a given vertebra yields segmental gravitational load and CoM location.

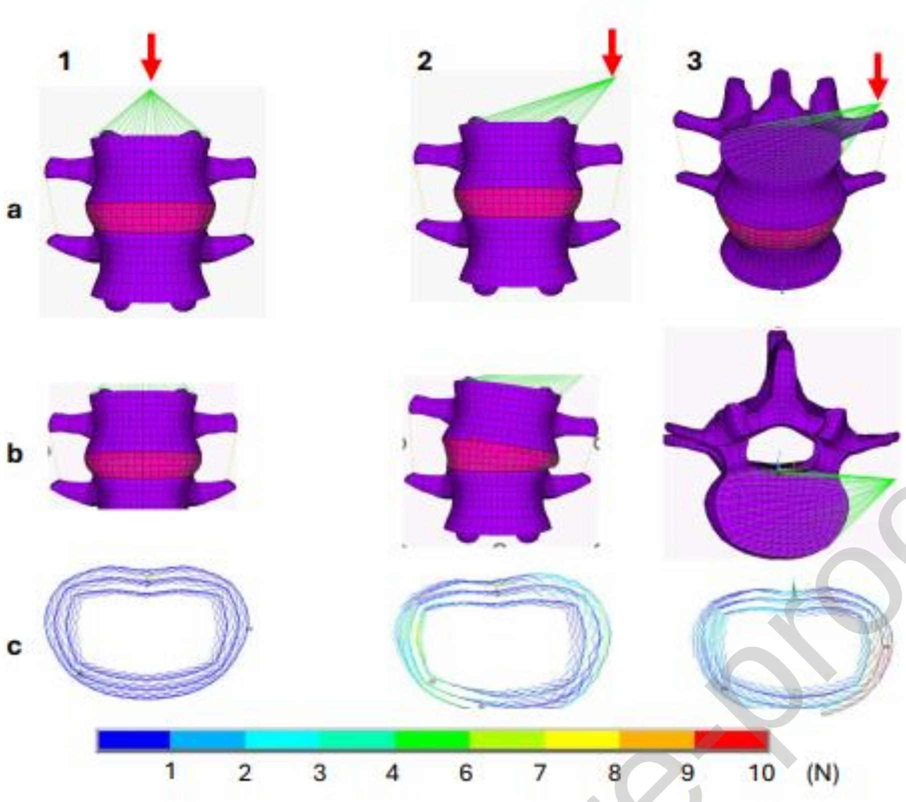

Figure 5

Figure 5 - a)finite element model of the L3-L4 submitted to compression force (400 N) in three conditions: 1/ centered, 2/ with a lateral deviation, 3/ with a lateral deviation on a segment with sagittal inclination; b) resulting displacement highlighting disc deformation in b1 and b2 and axial rotation in b3; c) Resulting intervertebral disc internal forces distribution.

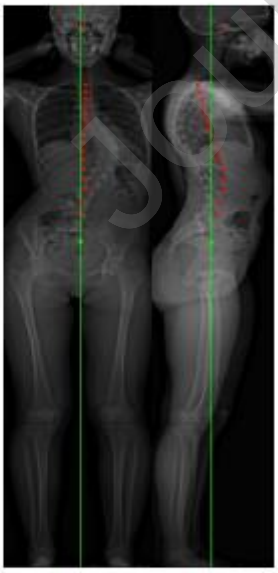

Figure 6

Figure 6 - CoM of each slice (red stars in the figure), resulting from body envelope horizontal slicing at the head and at each vertebral level.

Table 1 : Results for the validation of the determination of the Gravity Line. Δ is the difference between values obtained with force plate and estimated using barycentremetry technique. ΔX and ΔY are the differences between the GL locations , respectively in the antéro-posterior and medio-lateral directions.

Authors	Number of subjects	Characteristics	ΔMass (Kg) Mean (SD)	ΔX (mm) Mean (SD)	ΔY (mm) mediolateral Mean (SD)
Hernandez *et al.* 2019	14 AIS patients (5 M, 9 F),	mean age 14 years old, mean Cobb angle 22° (range 10°-55°)	0.8 (1.2)	0.9 (3.1)	0.5 (1.2)
Amabile *et al.* 2016	10 asymptomatic volunteers (4 M, 6 F):	mean age 27.0 years old	0.3 (1.9)	0.7 (4.9)	1.5 (1.9)

Declaration of interests

☒ 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.

Highlights

- Barycentremetry yields body segments and whole-body mass and centre of mass (CoM).
- Barycentremetry can use biplanar X rays (BPXR) with spine and body envelope models.
- BPXR barycentremetry yield gravitational load on each vertebra and related lever arm.
- Various studies assessed the potential clinical relevance of BPXR barycentremetry.
- Barycentremetry could improve our understanding of posture and motion disorders.