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ORIGINAL ARTICLE

3D postural balance with regard to gravity line: an evaluation in the transversal plane on 93 patients and 23 asymptomatic volunteers

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Abstract Relevance of posture assessment has been reported in case of spine disorders. This study explores the interest in quantifying posture using 3D reconstruction from biplanar X-rays in free standing position and a force plate. 93 patients consulting for spine disorders were divided ('3D deformity', 'sagittal imbalance' and 'mild deformity') and compared with 23 asymptomatic volunteers. Registration of the gravity line (GL) in reconstruction yielded transversal position of the center of acoustic meati (CAM) T1, T4, T9, L3, S1 and hip axis (HA) with regard to GL. Transversal position of CAM and L3 appeared as relevant parameters to discriminate patients from volunteers. Sagittal inclination of the axis linking the CAM to HA was correlated with position of the CAM to GL ($r = 0.92$ for patients). In conclusion, observing posture in 3D with regard to GL provides clinical relevant information. CAM-HA inclination may improve postural evaluation without force plate.

Keywords Postural balance · Alignment · Spine disorders · Gravity line · 3D reconstruction

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Introduction

The importance of posture when dealing with spinal pathologies has been underlined in several articles [1, 2]. It is commonly assessed dropping a vertical plumb line from C7 vertebral body center and quantifying the distance of other anatomical landmarks from this vertical. In particular, sagittal offset of the sacral plate from C7 plumb line, known as sagittal vertical axis, has been reported to quantify balance [3, 4]. Alternatively, Jackson et al. [5] evaluate the distance between C7 plumb line and the middle of both centers of femoral heads (hip axis, HA).

However, no correlations were found between gravity line (GL) and C7 position by patients [6, 7]. Gangnet et al. [8] showed that the center of acoustic meati (CAM) remains near GL and proposed evaluating the distance from CAM to HA to quantify sagittal balance. Besides, Vital and Senegas [9] underlined the proximity of this landmark to the center of gravity of the head, which role in 3D posture should be essential because of its weight, its distal location and the willing to keep a horizontal sight.

Antero-posterior (AP) and lateral (LAT) radiographs are commonly done but most studies evaluate posture only in the sagittal plane [10, 11] although some authors report frontal values [6, 12]. Simultaneous use of coronal and sagittal information was not found but in few studies [8, 13].

Objectives

This study explores the interest in quantify posture in 3D with regard to GL using stereoradiography in combination with a force plate and proposes in clinical routine usable parameters and representations.

Patients and methods

Patients and control group

EOS^{TM} exams with GL record between April and July 2008 were systematic processed. 93 patients (female 70%) were included in the study. Patients with spondylolistheses were excluded. The mean age was 44 (from 12 to 78, divided into 82 adults and 15 children under 18). In addition, a control group of 23 asymptomatic patients (13f/9m), aged from 9 to 34 (mean 18) was build using data from former studies using the EOS^{TM} system. These studies were approved by the local Institutional Review Board and informed consent was retrieved from all volunteers.

Data acquisition

Concerning the patients, all data were acquired on the EOS^{TM} system of Bordeaux CHU (France). The Radiographs of the EOS^{TM} exams were completed with GL location, recorded by a force plate on the floor. Each exam was driven following the standardized operating procedure (SOP) of the service of radiology:

- For adults, radiographs were made from the CAM to the medial tibia, whereas for children under 15, the inferior limit should only include the femoral heads.
- Each patient was asked to stand comfortably on the force plate in the position described by Faro et al. [14]. In order to limit the confusion caused by the hands in the lower cervical spine, some patients were asked to extend the wrist, setting their hands on the mandibles as shown in Fig. 1 (SRS modified free standing position).
- A mirror placed at eye's level helped the patient keep a horizontal sight.

Sex, birth year of the patient, clinical indication (pre-op planning, post-op control or follow up) and pathology were recorded when available.

Data processing

From the EOS^{TM} biplanar images, a 3D patient-specific model of the thoracic and lumbar spine, from T1 to L5, and the pelvis was obtained using previously described reconstructions techniques [15, 16]. Two stereocorresponding points localizing the acoustic meati were added to each reconstruction to compute their center (CAM). Reproducibility was assessed on 20 patients and two operators who repeated three times each the CAM localization. Finally, the center of pressure issued from the force plate's measurements was merged with the reconstruction as shown in Fig. 1. To assess the GL evaluation's precision, a 5 kg cylindrical weight was set on the force plate, X-rayed and its position recorded using the force plate. This procedure was repeated at five different positions. The comparison between the force plate recordings and the weight's position on the radiographs yielded the registration's parameters.

Fig. 1 Subject standing in free standing position (mandibles variation) and associated 3D subject specific model (acoustic meati, spine, pelvis and inferior limbs) with gravity line

3D parameters

After registration, the 3D position of each element of the followings was calculated with regard to GL:

- CAM, center of both acoustic meatus as defined in Gangnet et al. [8].
- HA, middle of the line joining the centers of both acetabula as defined in Jackson et al. [2].
- Vertebral body center of T1, T4, T9 and L3 vertebrae.
- Center of the sacral plate (S1).

Each position was quantified using both the 3D distance to GL and the offsets in the transversal plane (postero-anterior and right to left, Fig. 2). Sagittal vertical axis was estimated using the sagittal distance of T1 to the center of the sacral plate.

The CAM–HA inclination was quantified using the angle from the vertical of the line connecting the CAM to

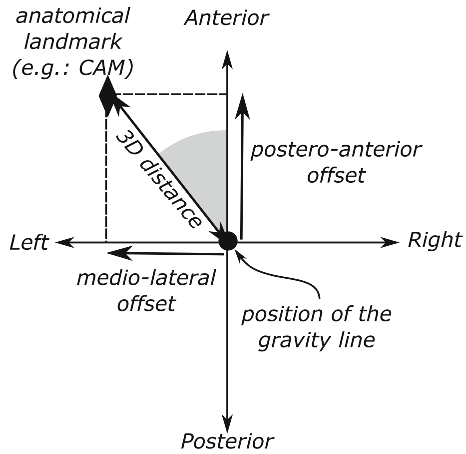


Fig. 2 Quantification of the 3D position of an anatomical landmark with regard to the gravity line (GL)

the HA. In the sagittal plane, the angle was chosen positive when the CAM was anterior from HA. Reconstruction output includes spine curvatures and pelvic parameters which were also recorded for comparison with literature.

Statistical analysis

Groups of patients

Patients are divided according to their deformity into groups, named '3D deformity', 'sagittal deformity', and 'mild deformity'. To be included in the '3D deformity' group, the patient should have at least 20° of Frontal Cobb angle or should have been operated for scoliosis. This group was composed of 42 patients (37 females/5 males) among whom 11 were operated. The 'sagittal Imbalance' group is composed of ten patients with T1 more than 5 cm ahead of S1 and three patients that underwent surgery for sagittal imbalance correction. 38 patients (22 females/16 males) who cannot be included in the other groups compose the 'mild deformity' group.

Description of the groups using GL

Mean and standard deviation (SD) of 3D and sagittal distance from each element to GL are assessed for each group. Each pathological group is compared against the asymptomatic volunteers using Student *t* test and Snedecor *F* test ($\alpha < 0.05$). Correlations between the sagittal CAM–GL offset and CAM–HA inclination are assessed using scatterplot matrix and Pearson's coefficient for patients and asymptomatic volunteers.

For each level, position of each landmark with regard to GL in the transversal plane is calculated for each patient. Distribution of the position with regard to GL for a given group is then described using an elliptic model (Fig. 7).

Results

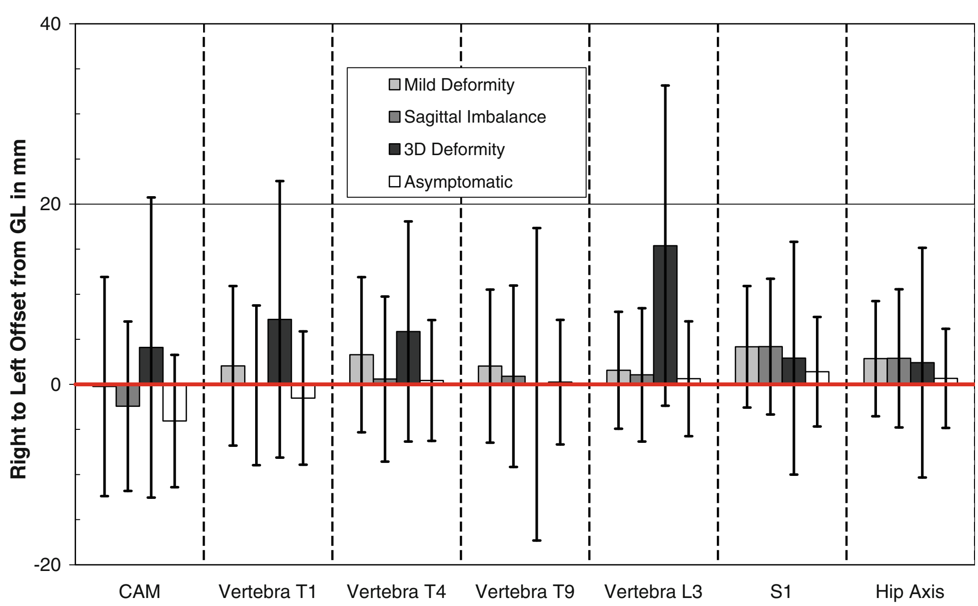
Evaluation of the method

The accuracy of registration of the force plate stays under 5 mm. The reproducibility study quantifies a 95% confidence interval of 4.2 mm for the postero-anterior offset, 3.5 mm for the right to left offset and of 3.4 mm for the 3D distance.

Configuration of the skeleton with regard to the GL

In the frontal plane (Fig. 3), mean CAM distance to GL is inferior to 4 mm. SD remains inferior to 10 mm for the

Fig. 3 Right to left offset evaluated with respect to gravity line (GL). Mean and standard deviation for each group. Positive value indicates that the landmark is left to GL



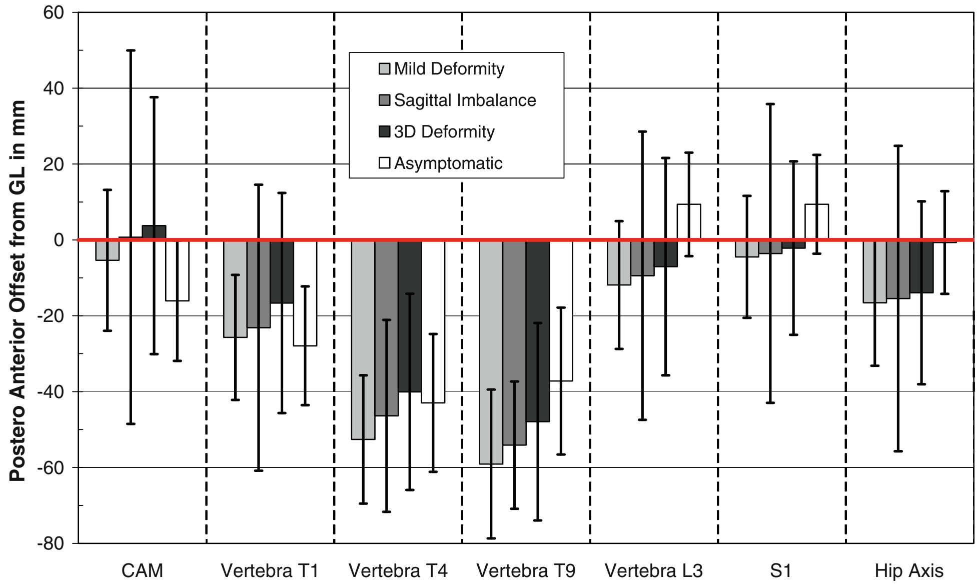


Fig. 4 Postero-anterior offset evaluated with respect to gravity line (GL). Mean and standard deviation for each group. Positive value indicates that the landmark is anterior to GL

'asymptomatic', and 'sagittal deformity' groups and reaches 16 mm for the '3D deformity' group. Vertebral levels' mean deviation from GL remains inferior to 5 mm (SD < 10 mm) except for the '3D deformity' group (L3 is 15 mm right of GL).

In the sagittal plane (Fig. 4), mean CAM offset of the 'asymptomatic' group is 16 mm posterior to GL with SD 16 mm, whereas for 'sagittal deformity' and '3D deformity', mean CAM location is anterior to GL. SD is also greater in both groups. Considering T1, mean position for asymptomatic is 28 mm posterior to GL whereas 17 mm posterior to GL for patients with 3D deformity. SD remains for all levels inferior to 20 mm for asymptomatic volunteers but is greater than 30 mm for patient with sagittal deformity. L3 and S1 are anterior to GL asymptomatic but posterior for patients. In Fig. 5, the CAM–HA inclination is highly correlated with the distance CAM to GL for patients ($r = 0.92$) and less for asymptomatic volunteers ($r = 0.58$).

In the transversal plane (Fig. 6), mean distance from CAM to GL is 20 mm (SD 13 mm) for the asymptomatic volunteers and patients with mild deformity. However, mean reaches 30 mm for patients with deformity. Differences are less important at T1. Variability of the S1 distance to GL is smaller than 15 mm except for patients with sagittal deformity. Mean distance of HA to GL is 12 mm for asymptomatic volunteers and greater than 20 mm for patients.

The ellipses describing the position of CAM in the 'sagittal imbalance' and the '3D deformity' group have an important part anterior to GL (Fig. 7). On the other hand, the ellipse describing the position of the CAM in asymptomatic volunteers remains mostly posterior to GL.

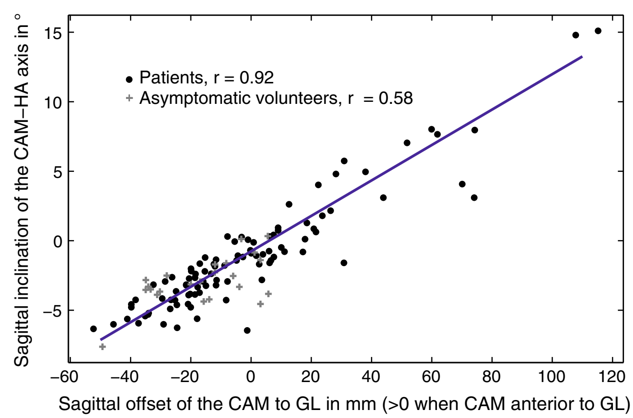


Fig. 5 Correlation between offset from the center of both acoustic meati (CAM) to gravity line (GL) and the inclination of the CAM–HA from the vertical

In Fig. 8a, mean position of the CAM is centered on GL for patients and posterior for asymptomatic volunteers. However, the distribution is more scattered for patients with 3D, sagittal or even mild deformity so that overlapping of the groups remains reduced. Position of T1 (Fig. 8b) differentiates patients with 3D or sagittal deformity but not patients with mild deformity from the asymptomatic volunteers. In Fig. 8e, a majority of asymptomatic volunteers have L3 anterior to GL whereas patients have rather L3 posterior. Overlapping of the ellipses is also low at this level. Position of HA for asymptomatic is centered on GL and do not deviates more than ±10 mm in the frontal plane and ±25 mm in the sagittal plane, but many patients have HA out of this area. On the contrary, important overlapping of the groups is present at levels T4 and T9 (Fig. 8c, d).

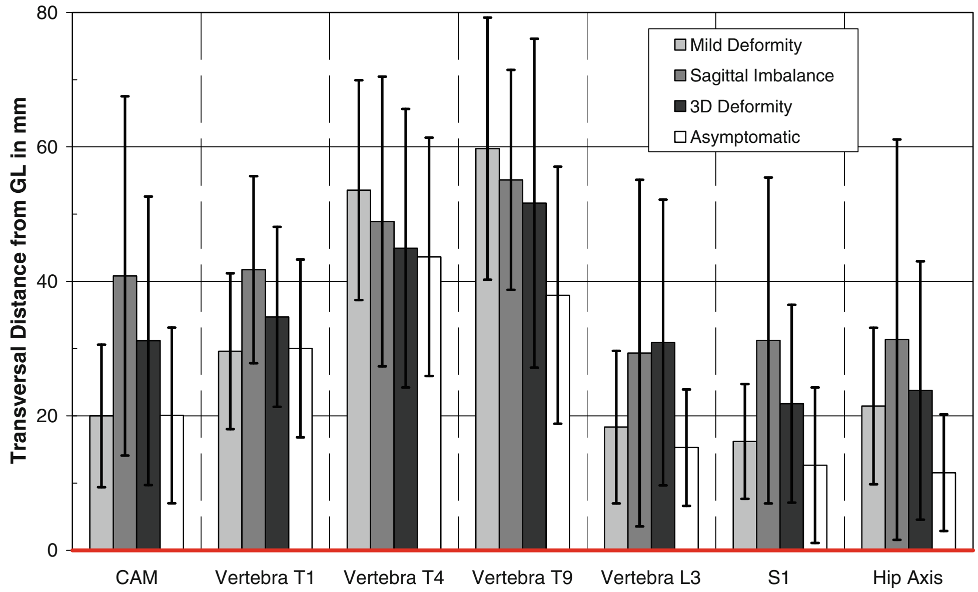


Fig. 6 3D Distance evaluated with regard to gravity line (GL). Mean and standard deviation for each group

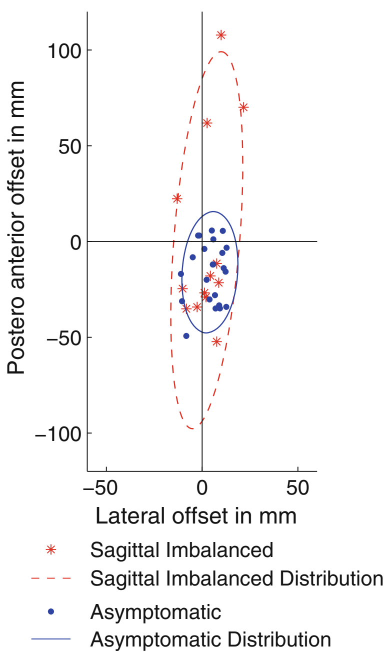


Fig. 7 Position of center of acoustic meati (CAM) with regard to gravity line (GL) for each patient of the 'sagittal imbalanced' group or the 'asymptomatic' group. Elliptic models of the spatial distribution for each group in the transverse plane

Comparison of the asymptomatic control group with the literature

Three studies already published reference values concerning the position of vertebrae and the femoral heads evaluated with regard to GL on asymptomatic cohorts. Figure 9 presents the mean and SD of the values already published and those evaluated in the present study. The 3D reconstructions in Gangnet et al. [8] yielded reference values for the frontal and the sagittal planes and allowed the calculation of the 3D distance.

Discussion

Position of the patient during the acquisition was standardized. We used either Faro et al. [14] 'clavicle' position or a slightly modified position, where the only difference with the former is an extension of the wrist, setting the hands on the mandibles. This variation allowed a better visualization of the lower cervical spine.

Acquisition protocol was implemented in clinical routine and enabled to quantify posture in three dimensions, using the calibrated EOS™ X-ray device [17] in combination with a force plate. This protocol can now be used routinely.

Previously reported positions of elements with regard to GL on asymptomatic volunteers that adopted similar positioning of the patient during the acquisition [8, 10, 11] were analyzed. From HA to T9, the results of the present study are consistent with the study of Gangnet et al. [8]. T4, T1 and the CAM are more posterior in our study, which can be a consequence of the particular positioning of the patient (hand leaning on handle fixed at eyes' level). On the frontal plane, the corridors of the calculated parameters are included in the corridors published by Gangnet et al. but mean coronal distance of the spine to GL is lower in the present study. The studies of Schwab et al. [10] and Lafage et al. [10, 11] are consistent with each other but described more posterior references points than the present study. The position of the center of L3 is described to be posterior

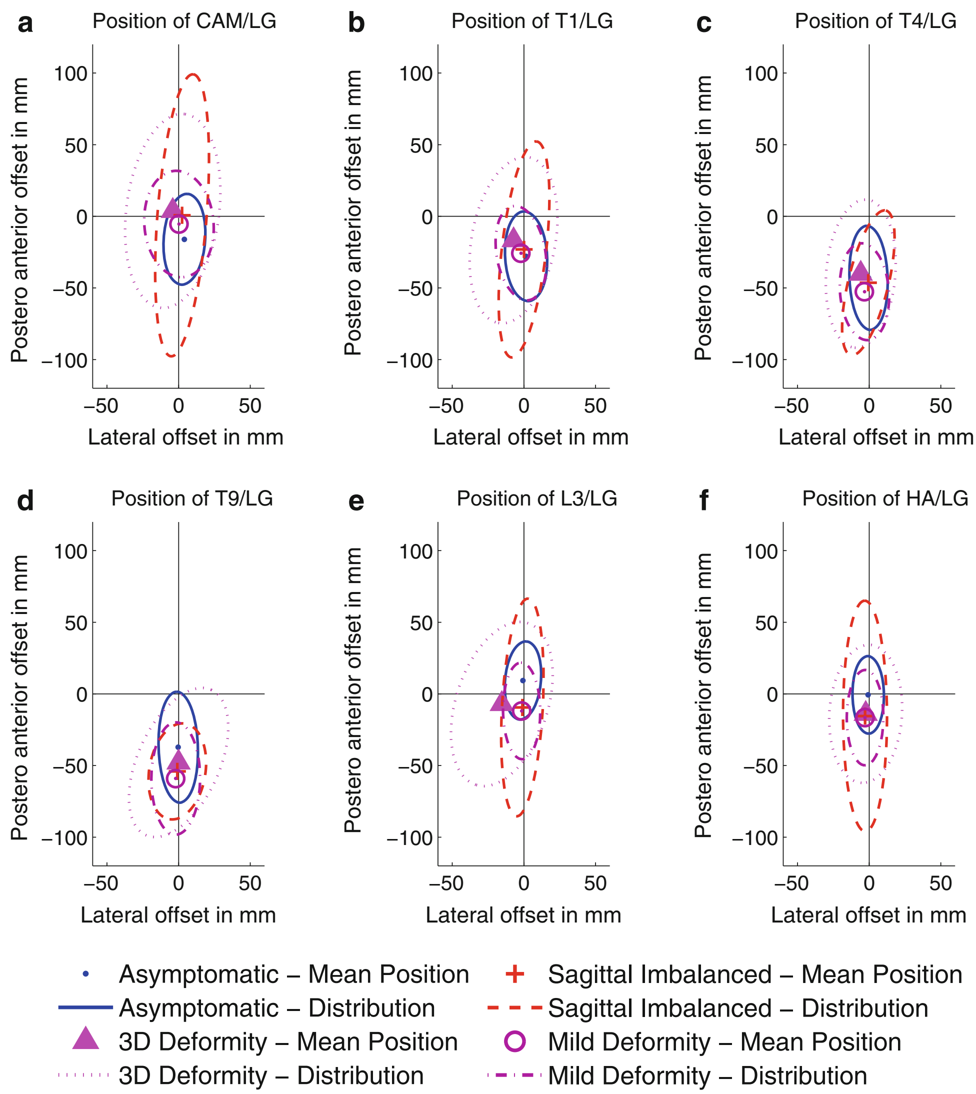


Fig. 8 Spatial distribution and mean position of the position of several landmarks in the transverse plane with regard to gravity line (GL) using an elliptic model to regroup patients and volunteers

to GL in both studies but is found anterior in the asymptomatic and pathological cohorts of our study. Mean distance of vertebra from GL in the sagittal plane is also greater than in the present study. These differences could be explained by the specificity of the samples which may not stand for the same population. Another reason could be the divergence of the ray, since Schwab et al. [10] and Lafage et al. [11] used direct measurements on the films, whereas measurements of Gangnet et al. [8] and the present study are made in a calibrated 3D space.

Relevance of the CAM and L3 levels for analysis with respect to GL could be inferred from Fig. 4 (sagittal plane analysis) and Fig. 8 (transversal plane analysis). According to Fig. 4, CAM anterior to GL or L3 posterior to GL can be considered as sub-normal. Distance from T1 to GL differentiates less our groups. Paradoxically, the 'mild deformity' group is the most different from the control group at the T4 and T9 levels. However, this group is quite heterogeneous and further study should be carried out.

Link to symptoms was made by Glassman et al. [4, 12] who stated that people with C7 anterior to sacrum were symptomatic. In our study, no asymptomatic volunteer but several patients followed up for sagittal imbalance or scoliosis presented T1 anterior to GL. Nevertheless, observing the CAM instead of T1 provides more acute differences between the patients groups and the group 'asymptomatic' (Fig. 8a, b).

Transversal distribution with regard to GL helps identifying postural trouble and understanding compensations' mechanisms. Transversal distribution of each group is different at the CAM and T1 levels and at the L3 and HA levels. On the contrary, distribution of T4 is similar for all groups (Fig. 8) and this is still valid in T9 except for patient with 3D deformity. A rotation of the spine around a horizontal axis in the thoracic area [10, 11] would explain the homogeneity of the position of T4 and T9 as well as the differences that occurs above (CAM and T1) and below (L3 and HA) this level. Concerning the HA, inferior limbs

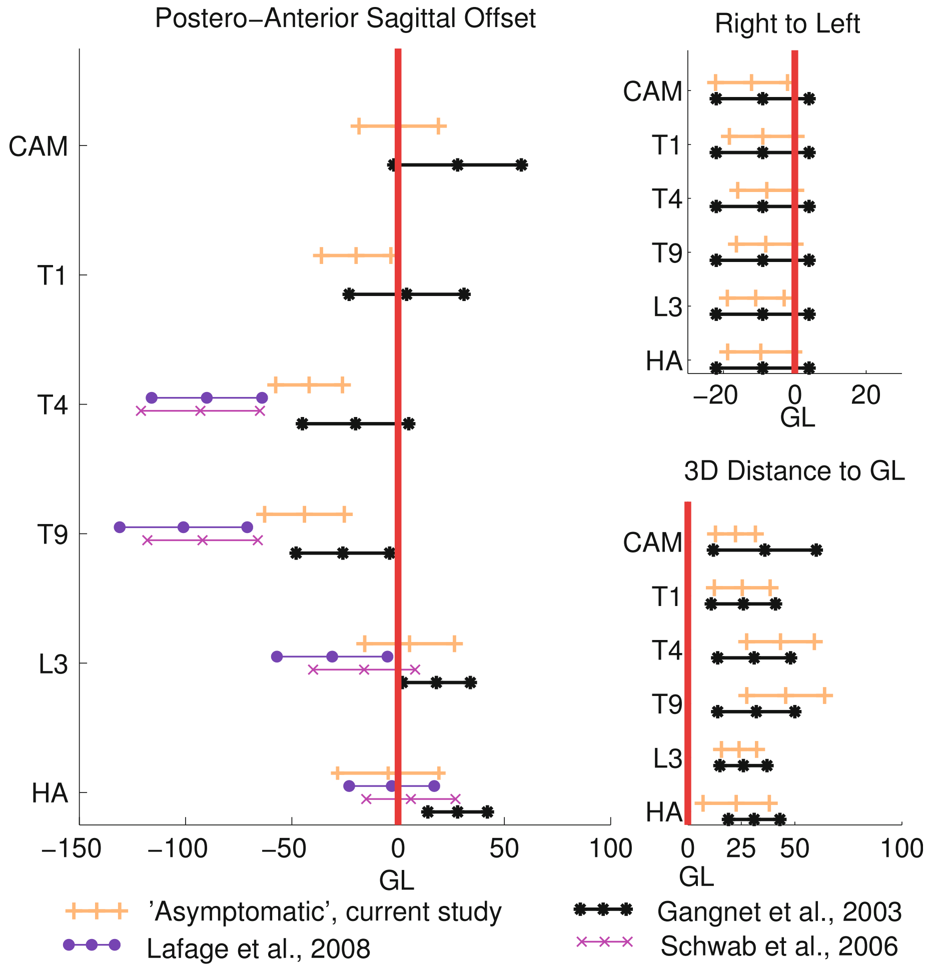


Fig. 9 Position of major landmark evaluated with regard to the gravity line in previous publications and comparison with our asymptomatic cohort

should compensate postural trouble through hip, knee and ankle articulations in order to keep the pelvis forward facing so as to ease walking.

Interest in using the transversal plane instead of the frontal and sagittal planes to analyze posture is highlighted: Considering frontal plane only (Fig. 3), analysis reveals no differences between groups but '3D deformity'. On the contrary, transversal plane analysis, which combines sagittal and frontal information, delivers more relevant information than sagittal only analysis. In particular, the distribution of T9 from patient with 3D deformity is different from the distribution of T9 from asymptomatic volunteers, whereas frontal and sagittal analyses do not provides such distinction. Distribution of L3 (Fig. 8e) is as well different for patients with 3D deformity or sagittal imbalance than for asymptomatic volunteers.

Conclusion and perspectives

This preliminary study underlines advantages in analyzing posture in the transversal plane and with regard to GL. Position of the CAM and L3 with regard to GL seems to be complementary key parameters to evaluate postural trouble.

When force plate measurements are not provided, the inclination of the CAM–HA axis, which is highly correlated with distance CAM–GL, delivers good indication of the postural trouble.

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