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Review article

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Methods and Criteria for Assessing Dynamic Sagittal Body Balance (Non-systematic Review)

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Abstract

Radiography of the spine makes it possible to assess disorders in the global sagittal balance of the spine only in statics. Therefore, the assessment of the dynamic sagittal balance according to the data of three-dimensional (3D) gait analysis including the balance of the trunk in general (in the sagittal and frontal planes) and the lumbosacral area, in particular, and determination of the compensatory mechanisms employed by the patient while walking due to the body segments and limbs, is getting more topical. Foreign publications on these topics in the last decade in the search resources of PubMed, e-Library, Cochrane Library and Scholar Google are not numerous, and there are no domestic ones at all, that, in turn, requires an independent detailed study. **Purpose** Primary analysis of the literature with the identification of methods and criteria for assessing the dynamic balance of the body. **Materials and Methods** In preparation of the review, the search and information resources of PubMed, eLibrary, Cochrane Library and Scholar Google were used. In the resources of the scientific e-Llibrary, there are no publications on the sagittal dynamic balance, that, in turn, requires an independent detailed analysis. **Results and Discussion** The postural model that considers the trajectory of movement of the center of mass (CoP) below foot was used to assess the dynamic sagittal balance. It is possible to evaluate the compensatory mechanisms for maintenance of dynamic sagittal balance basing only on the data of three-dimensional (3D) analysis of gait motions. Compensated / decompensated condition of the dynamic balance was defined according to the data of the ground reaction in 3 planes, the motions of the chest with regards to the pelvis, and according to the evaluation of the frontal vertical alignment (CVA-G) and sagittal vertical alignment (SVA-G). **Conclusion** The standard medical block for 3D gait analysis allows to perform quantitative estimation of compensatory mechanisms for sagittal imbalance, such as in-phase / antiphase coordination pattern of the trunk with regards to the pelvis; the compensated / decompensated condition of the dynamic balance according to the Ground Reaction data in three planes; and compensatory mechanisms, manifested in the parameters of the kinetics and kinematics of the lower limb joints. Assessment of dynamic sagittal balance is carried out in laboratories, where there is a software with an additional calculation option. Two main directions were proposed for its formation, taking into account either the maximum approximation to the X-ray criterion, or to the anatomical position of the center of mass.
Keywords: spine, dynamic sagittal balance, assessment criteria, video gait analysis, gait analysis platform

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INTRODUCTION

The transition to upright posture in humans was carried out through morphological adaptation of the skeleton in ontophylogenesis, in particular, of the lower extremities, pelvis and spine [1]. The pelvis acts as a free base and is subjected to gravity force from the spinal column, the force of the support reaction transmitted through the femoral heads [2]. Spinal curves allow maintaining neutral vertical alignment of the spine in the sagittal plane to reduce stress loads on the musculo-ligamentous structures - sagittal balance [3, 4, 5].

Maintaining the correct position of the spine in the sagittal plane is critical to ensure a horizontal gaze and direction of gravitational forces through the projection of the common center of pressure between the supporting surface of the feet without additional compensatory mechanisms [6, 7, 8, 9, 10]. Spine alignment is postural radiographic information currently assessed on static radiographs, which serve as the basis for preoperative and postoperative evaluation of patients.

From the standpoint of assessing the sagittal balance by the method of 3D video analysis of movements, two aspects of the biomechanics of the spine are considered: the problems of the balance of the trunk in general (in the sagittal and frontal planes) and the lumbosacral region in particular. There are not many international publications on these topics in the last decade in the PubMed, e-Library, Cochrane Library, Scholar Google, and there are no Russian publications at all, which, in turn, requires an independent detailed analysis.

The primary analysis of the literature with the identification of methods and criteria for assessing the dynamic balance of the body determined the purpose of the study.

MATERIALS AND METHODS

When preparing this review, the following information sources were used: the scientific search portal PubMed, e-Library, Cochrane Library, Scholar Googl, the Wiki site of the C-motion company, the resources of the scientific electronic library e-library from 1980 to 2021 inclusive.

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RESULTS AND DISCUSSION

The parameters of the global spine balance are usually considered in the context of the "cone of economy" (COE) proposed in 1994 by J. Dubousset [11]. According to this concept, the optimal balance of the spinal column allows you to maintain the position of the trunk within the boundaries of the base of support (BOS), the designated cone (with apex at the feet) without additional energy consumption. An increase in sagittal imbalance leads to a position of the trunk closer to the periphery of the cone, which leads to increased muscle effort and energy consumption causing pain, fatigue and disability. This condition is regarded as a compensated imbalance of the spine. If the body is displaced outside the cone, maintaining balance is impossible without the use of assistive supporting devices, and a decompensated imbalance occurs.

Given that the line of gravity must be within the BOS in order to meet the sustainability criteria, the following factors should be considered:

– increasing the boundaries of the base of support (BOS) increases stability (the line of gravity must move a greater distance to go beyond the BOS);

– shifting the center of gravity to the center increases stability (it is unlikely that the line of gravity will go beyond the BOS). Currently, this study is widely performed by the stabilometry method [12, 13, 14, 15, 16].

To maintain a common center of pressure within its base of support (BOS), biomechanical compensatory mechanisms are formed, which are revealed during the analysis of gait kinetics data [17].

In assessing changes in the sagittal balance during walking, a postural model was used that takes into account the trajectory of movement of the common center of pressure (CoP), which normally moves under the foot from the heel to the forefoot and with a medial / lateral deviation (Fig. 1) [18, 19] .

When the trajectory deviates from the norm, the central nervous system tries to counteract gravitational forces by adjusting the alignment of body segments so that any disturbance in this biomechanical system reduces the effectiveness of equivalent responses [20]. There is a significant relationship between body posture, the effectiveness of compensatory responses, and gait quality [21]. In cases of minor deformities, compensatory reactions are formed in the sagittal plane, but with severe abnormal curvature of the spine in the frontal plane – in the form of a change in step variability [22]. It was shown that the severity of the kyphotic and lordotic components is associated with the amplitude of the CoP displacement. The correlation strength of the lordosis angle for the CoP displacement in the sagittal plane is 0.999 and takes a linear value [20].

But this method for assessing the sagittal balance has no common parameters with the assessment of the static sagittal balance according to X-ray data, which is widely used in clinical practice [23, 24, 25] in the form of a deviation of the sagittal vertical axis (SVA) from the gravity vertical line drawn from the center of the body C7 vertebra to the projection of the posterior edge of the superior endplate of the first sacral vertebra (S1) in the horizontal plane. This parameter makes it possible to assess the disturbance of the global sagittal balance of the spine, and according to the definition of the Scoliosis Research Society, a positive sagittal balance is determined when the SVA is displaced anteriorly from the L5–S1 intervertebral disc. In this case, the anterior displacement of the SVA more than 5 cm from the posterior edge of the superior endplate S1 should be regarded as a violation of the sagittal balance [26]. But this radiological parameter does not provide information about the position of the general center of pressure at the base of the support, and there is no correlation with the true gravity line (GL). With age, the true gravity line (GL) in the sagittal plane is located anterior to the spine, but is projected within the base of support, while posterior pelvic tilt (pelvic retroversion) increases and lumbar lordosis disappears. The daily activities and functional aspects of patients are more related to the dynamic status of the pelvic segment. The improvement in dynamic parameters measured by 3D analysis has been shown to be more significant for predicting surgical outcomes than angular measurements performed when using plain radiography [27].

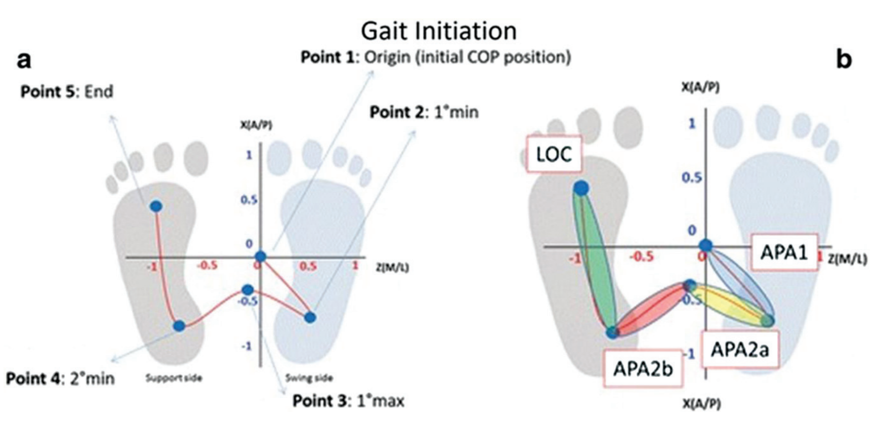

Fig. 1: a – projection of the center of pressure (CoP -) displacement in the antero-posterior and medio-lateral directions during walking. Supporting limb – left foot, non-supporting – right foot; b – separation of the center of pressure trajectory (COP -) for analysis in step cycle time [18]

Dynamic sagittal balance can only be assessed using three-dimensional (3D) gait analysis. This makes it possible to understand and evaluate the compensatory mechanisms involved by the patient when walking using the segments of the body and limbs [28]. Today, 3D Gait Analysis 3DGA is the gold standard for quantifying the kinematics (angles) and kinetics (strength) of joints during walking and is widely used in various groups of patients with gait disorders.

Any abnormal change in the curvature of the spine results in compensation, first at the level of the pelvis through rotation, then in the lower limbs through flexion of the knee. This mechanism maintains the gravity line within the base of support (BOS), but is not ergonomic. When the line of gravity goes beyond this support base, various compensatory mechanisms are registered [29]:

– contraction of m. erector spinae lifts the trunk vertically, requiring painful abnormal forces from the back muscles to prevent falling forward;

– retroversion of the pelvis around the femoral heads;

– hip hyperextension, however, has a limit, known as extension reserve, which is usually 10°;

– knee flexion in severe forms; controlled by the quadriceps muscle.

Using patients with idiopathic scoliosis as an example, Varghese et al. [30] demonstrated an increase in frontal displacement (gravity vertical line C7 [C7–GL] more than 30 mm) to the right with the formation of compensatory mechanisms of the lower limbs during walking, leading to a significant limitation of ipsilateral hip abduction, and a decrease in the range of flexion of the hip and knee ($p < 0.05$). In assessing the sagittal balance, the authors propose to take into account the complex of parameters and their deviations from the norm, but do not determine which values and how reflect the degree of disturbance of the sagittal balance (Table 1) [28]. The compensated / decompensated state of the dynamic balance was determined from the Ground Reaction data in 3 planes. Kramers-de Quervain et al. [31] and Schizas et al. [32] reported that the magnitude of asymmetries in the vertical component of the support reaction force in patients with adolescent idiopathic scoliosis did not exceed 4 %, which was comparable to the norm published by Herzog et al. [33]. However, Chen et al. [34] recorded violations of postural stability in patients with scoliosis with an increase in the amplitude of oscillations in the frontal and sagittal planes. Similar data were noted by the authors of this work (Fig. 2).

Movement of the chest relative to pelvis (thoraco-pelvic coordination) can be classified as in-phase (pathological), if 2 segments turn together in the same direction, or antiphase (normal), if there is turning of 2 segments in opposite directions (Fig. 3) [35].

Table 1

Walking strength parameters (kinetics) in the study of patients with spinal pathology

Parameters	Definition and notes	Measurement plane
Ground reaction force (BW)	Positive value of the support reaction force, normalized to the body mass	Anterior/posterior Medial/lateral Vertical
Joint moments (Hm/kg)	Hip, knee, ankle joints	Sagittal, frontal, horizontal
Power peak (W/kg) (*positive peak*)	The product of the internal joint moment and the angular velocity of the joint	Sagittal, frontal, horizontal
Work *Summed area W/kg* (*positive + negative W/kg*)	The total power is integrated over time; a negative value (negative W/kg) indicates energy absorption (through the eccentric musculature)	Sagittal, frontal, horizontal

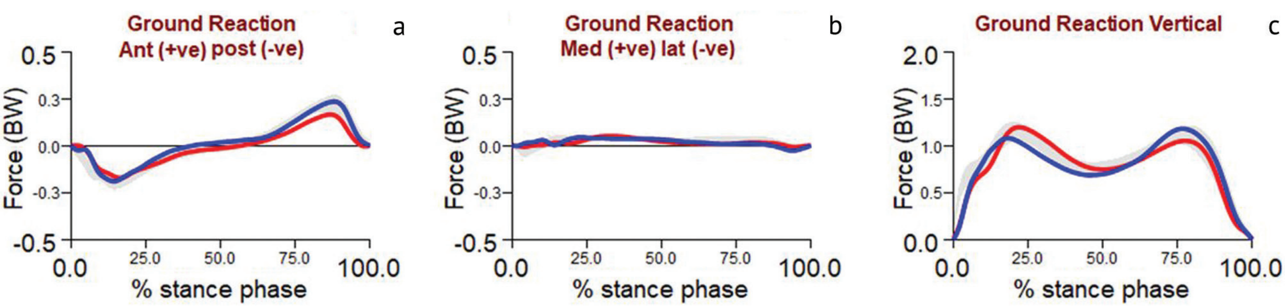

Fig. 2 Data of ground reaction of a 9-year old patient with idiopathic scoliosis of the 4 degree (Lenke I). Assymetric ground reaction is observed: a – sagittal plane – 23 %, b – frontal plane – 3 %, c – vertical component – 14 %

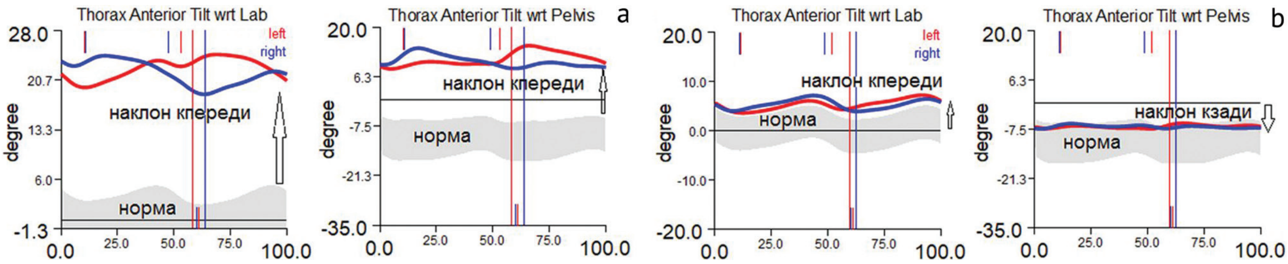

Fig.3: A – **in-phase coordination pattern** – the chest has anterior tilt relative to the floor and pelvis; B – **antiphase coordination pattern** – the chest has anterior tilt relative to the floor, posterior tilt - relative to the pelvis

Studying in-phase or antiphase coordination in static sagittal balance disorders, Park et al. [36] found that patients with adolescent idiopathic scoliosis demonstrated significantly higher in-phase and lower antiphase coordination ($p < 0.05$), resulting in less instability during walking compared to healthy controls.

Measurement of the posture profile in static and walking is done according to the assessment of the frontal vertical alignment (CVA-G) and sagittal vertical alignment (SVA-G). They are defined as the horizontal distance from S2 to the vertical line drawn from C7 in the frontal and sagittal planes, respectively, at the moment of initial contact with each step with support on the right or left limb. These criteria were proposed as being as close as possible to the previously described CVA-R and SVA-R radiographic parameters. The values at the start of the support are taken into account.

To analyze compensatory mechanisms in case of imbalance, it was proposed to consider the dynamic balance during walking [37, 38] as a relationship between the common center of mass (CoM) and the distance from it of the common center of pressure (CoP). The common center of mass (CoM) is the point equivalent of the total mass of the body in the global reference frame, the common center of pressure (CoP) is the location of the vector of the vertical support reaction force. It has been described that CoP fluctuates on either side of CoM, where the amplitude of the CoP displacements always exceeds the amplitude of the CoM displacements.

CoM is located around the S2 vertebra [39], so information from the S2 marker was used to estimate CoM-related moments, as shown by the following equation:

Net Moment (M) =
Fx(Perpendicular distance (Z) between CoP and S2) +
Fz (Perpendicular distance (X) between CoP and S2).

The variables used in this study are the maximum and minimum displacement of the CoP projection relative to the projection of the S2 vertebra to the floor level. The overall center of pressure (CoP) was estimated using the following equations:

$$CoP_{AP} = M_{ML}/Fz \text{ u } CoP_{AP} = -M_{AP}/Fz,$$

where M_{ML} and M_{AP} – moments around the mediolateral (ML) and anterior-posterior components (AP), and Fz – vertical force [39].

The maximum and minimum displacement of CoP is determined by the maximum and minimum CoP coordinates in the mediolateral and anterior-posterior axis of the foot. Dynamic gait imbalance was assessed using the calculated dynamic stability margin (DSM – distance between the extrapolated center of mass and the base of the support).

Changes in the distance parameters in the step cycle were calculated for the right and left sides [40] with the definition of the symmetry index (SI) using the formula:

$$SI = [(X1 - X2)/0{,}5 \times (X1 + X2)] \times 100,$$

where X1 is the CoP displacement amplitude on the right limb, X2 is the CoP displacement amplitude on the left limb [37]. The symmetry index equal to "0" indicates that the power parameter is the same on both legs.

The authors found no correlation between static radiographic data (CVA-R and SVA-R) and walking 3D analysis data (CVA-G and SVA-G) for the frontal and sagittal planes. However, a positive correlation was found between SVA-R – SVA-G in the sagittal plane ($p < 0.05$) and CVA-R – CVA-G in the frontal plane ($p < 0.01$) when recording radiographic parameters in statics and 3D kinematics – video analysis of gait [41].

The COG parameter is variable because in anatomical position the common center of mass (CoM) or common center of gravity (COG) lies roughly anterior to the S2 vertebra, and the exact location of the COG is constantly changing with each new position of the body and limbs. The proportions of a person's body will also affect the location of the COG. The spatial orientation of the pelvis is a key area for load transfer from the trunk [42]. The common center of gravity (COG) was determined by magnetic resonance imaging together with a video motion capture system as a point with a 4 cm offset in the anterior-posterior direction from the midpoint between the ASIS points - the anterior superior iliac spines [43]. It is proposed to determine the normal position of the center of gravity in the plane of the pelvis (perpendicular to the main axis of the body) at the average distance of the segment of the corresponding axis (Fig. 4).

When walking, the common center of mass (COG) has an amplitude of oscillation relative to the midpoint between the ASIS (marker points of the anterior superior iliac spine) in the anterior / posterior direction of approximately 4 cm, in the upper / lower - more than 5 cm and the minimum - in the right / left direction during the step cycle [44].

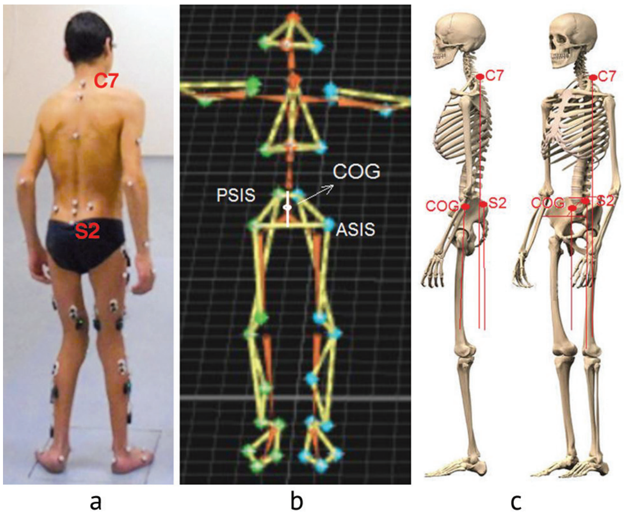

Fig.4: a – placement of markers during the study of 3D gait analysis (3DGA); b – scheme of marker placement for determining the plane of the pelvis and the calculated common center of gravity (mass) – COG; c – scheme for determining the distance between the projections of the common center of pressure (CoP), S2 vertebra and the common center of gravity

CONCLUSION

The standard medical block of 3D gait analysis allows assessing compensatory mechanisms in disorders of sagittal balance of the body, such as:

– pattern of in-phase / antiphase coordination of the trunk relative to the pelvis;

– compensated / decompensated state of dynamic sagittal balance according to ground reaction data in three planes;

– compensatory mechanisms, manifested in the parameters of the kinetics and kinematics of the joints of the lower limb.

Assessment of dynamic sagittal balance requires formation of a program for an additional calculation option. In the laboratories of clinical biomechanics, two main directions for assessing dynamic sagittal balance have been proposed:

1. Calculation of deviations and range of motion in 3 planes of the projection of a point from the C7 vertebra relative to the projection of a point from the S2 vertebra on the reference plane. This indicator in statics is as close as possible to the radiographic criterion of sagittal imbalance in statics, but there is no correlation between radiographic data and 3D analysis data when walking.

2. Calculation of deviations and range of motion of the projection of the point from the C7 vertebra relative to the projection point of the COG (common center of mass) located in the projection of the pelvic plane, with an offset to the center relative to the coordinate system from the midpoint of the ASIS line (anterior superior iliac spines) on the reference plane. COG (common center of mass) was determined according to magnetic resonance imaging data together with a video motion capture system and is as close as possible to the anatomical position of the common center of mass, but there is no correlation with the radiological criterion of sagittal imbalance, not only when walking, but also in statics.

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