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Assessment of stability during gait in patients with spinal deformity—A preliminary analysis using the dynamic stability margin

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ABSTRACT

Daily living activities are dynamic, requiring spinal motion through space. Current assessment of spinal deformities is based on static measurements from full-spine standing radiographs. Tools to assess dynamic stability during gait might be useful to enhance the standard evaluation. The aim of this study was to evaluate gait dynamic imbalance in patients with spinal deformity using the dynamic stability margin (DSM). Twelve normal subjects and 17 patients with spinal deformity were prospectively recruited. A kinematic 3D gait analysis was performed for the control group (CG) and the spinal deformity group (SDG). The DSM (distance between the extrapolated center of mass and the base of support) and time-distance parameters were calculated for the right and left side during gait. The relationship between DSM and step length was assessed using three variables: gait stability, symmetry, and consistency. Variables' accuracy was validated by a discriminant analysis. Patients with spinal deformity exhibited gait instability according to the DSM (0.25 m versus 0.31 m) with decreased velocity (1.1 m s^{-1} versus 1.3 m s^{-1}) and decreased step length (0.32 m versus 0.38 m). According to the discriminant analysis, gait stability was the more accurate variable (area under the curve AUC = 0.98) followed by gait symmetry and consistency. However, gait consistency showed 100% of specificity, sensitivity, and accuracy of precision. The DSM showed that patients with spinal malalignment exhibit decreased gait stability, symmetry, and consistency besides gait time-distance parameter changes. Additional work is required to determine how to apply the DSM for preoperative and postoperative spinal deformity management.

1. Introduction

From degenerative scoliosis and kyphosis secondary to osteoporosis in the elderly to spondylolisthesis and scoliosis in young and active individuals, spinal deformities are common and require significant societal resources for treatment. The usual gold standard when quantifying alignment in patients with spinal deformities is based on two-dimensional full-length standing radiographic measurements. The key parameters are numerous and include both spinal and pelvic reference points in the coronal and sagittal planes [1]. However, radiographs do not assess the consequences of such deformities on dynamic balance during gait. Tools to assess the role of dynamic motion and stability are needed to guide clinical treatment. Dynamics in spinal deformities have been reported using data from conventional gait analysis. Patients with scoliosis exhibit modifications of time-distance parameters by reduced velocity and step length as well as asymmetrical ground reaction forces, but no particular modifications of trunk range of motion [2–5]. Dynamic assessment has been recently reported for elderly adults with kyphosis secondary to osteoporosis [6,7]. They showed increased medio-lateral sway and decreased antero-posterior movement of the center of mass (CoM) during gait which is correlated with fall risk [8]. De Groot et al. recently showed similar results according to trunk acceleration smoothness, which was increased in the antero-posterior direction and decreased in the medio-lateral direction [6]. Dynamic balance during gait has not been reported in Scheuermann's disease nor in dysplastic or degenerative spondylolisthesis.

Dynamic stability during gait depends on control of the CoM position and velocity, and on base of support (BoS) displacement combined with proper foot placement [8–10]. On the basis of an inverted pendulum model, Hof et al. suggested a complementary measure for dynamic stability during gait: the extrapolated center of mass (xCoM) [8,9]. Using the xCoM, they defined a dynamic stability margin (DSM) to quantify gait dynamic balance. The DSM represents the shortest distance from the xCoM to the BoS at all times during the

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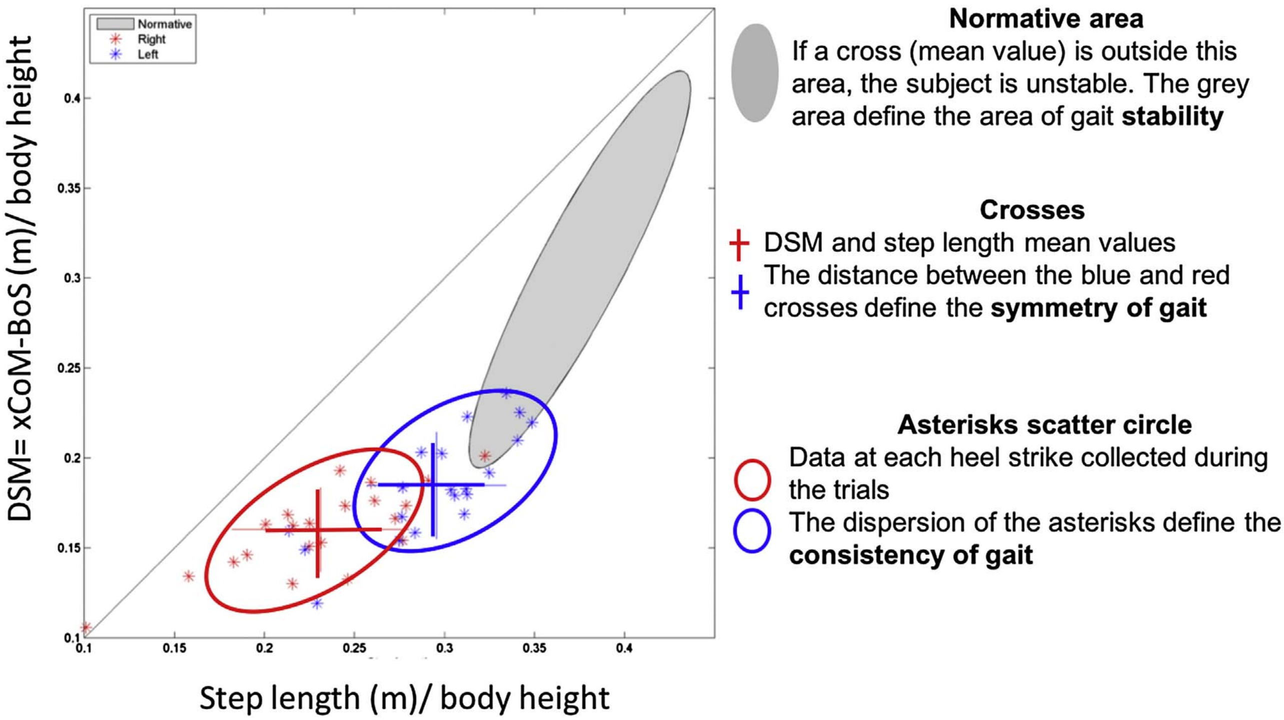

Fig. 1. DSM- step length relationship for a 59-year old female with a proximal junctional kyphosis secondary to a T2-S1 fusion for degenerative lumbar scoliosis.

gait cycle. An xCoM located within the BoS during gait indicates gait dynamic stability [10]. Gait instability is therefore defined by an xCoM located outside the BoS.

The aim of this preliminary study was to use the DSM to evaluate the dynamic balance of patients with sagittal and/or coronal spinal deformity. The hypothesis was that patients with spinal deformity would demonstrate reduced gait dynamic stability as shown by the DSM, with greater asymmetry, as evidenced by DSM and step length mean variation between sides, and inconsistency, as evidenced by greater step variability, in their gait when compared to healthy young adults.

2. Materials and methods

2.1. Patient recruitment and selection

To assess the consequences of spinal deformities on gait dynamic stability, patients undergoing primary or revision spinal surgery were prospectively enrolled between 2011 and 2014 and represent the spinal deformity group (SDG). Patient data were obtained prior to surgery and postoperative evaluation was not available. Inclusion criteria were ambulatory patients with spinal deformity in either the coronal or sagittal plane (scoliosis, kyphoscoliosis, lytic spondylolisthesis, and postoperative flatback). Twelve healthy young adults without spinal deformity constituted the control group (CG). Exclusion criteria for both groups, that might bias the consequences on gait of spinal deformity, included 1) any neurological disease, 2) abnormal gait due to lower limb pathology or injury, and 3) inability to cooperate with gait study. All data were collected after the subject signed an informed consent approved by the Institutional Review Board.

2.2. Radiographic parameters

Full-spine bi-planar standing radiographs were performed for the SDG patients. Measurements were performed using Surgimap Spine 2.0 (Nemaris Inc., New York, NY, USA). Sagittal plane measures included pelvic incidence, L1-S1 lordosis, T1-T12 kyphosis, and the sagittal T1 spino-pelvic inclination (T1-SPI). T1-SPI corresponds to the angle between the center of the first thoracic vertebra to the middle of the bicoxo-femoral axis and the vertical reference line [11]. Frontal plane measures the C7-plumbline, which is the angle between the center of the seventh cervical vertebra to the center of the first sacral plate and the vertical reference line [12].

2.3. Dynamic measures

Subjects were instructed to walk barefoot at a self-selected comfortable speed along an 8-m walkway. The three-dimensional (3-D) motion of 43 markers placed over bony landmarks was tracked using a ten-camera motion capture system operating at 120 Hz (Motion Analysis Inc, Santa Rosa, CA, USA). Marker-data were low-pass filtered with a fourth order Butterworth filter at a cut-off frequency of 8 Hz. The step length, BoS, and xCoM were computed from the position of the reflective markers. Calculation of the xCoM required an estimation of the position and the velocity of the whole-body CoM. A 13-segment rigid body model was used to calculate the weighted-sum of the whole-body CoM (Matlab 8.1 R2013a, Mathworks, Natick, MA, USA) [13]. The boundaries of the BoS were defined using four markers placed on each foot [10]. Clinical measurements used for the DSM calculation were: patient height, trochanteric height, foot length, and width. In accordance with observations that the maximum DSM occurs immediately prior to heel strike, the DSM was calculated from two complete and consecutive heel strikes, separately on the left and right side during three consistent trials [14]. The 3-D coordinates marker data were input into Visual 3D (C-Motion Inc., Rockville, MD, USA) to calculate joint kinematics.

2.4. Data analysis

The relationship between the DSM and step length was evaluated (Fig. 1). Both values were normalized to body height. The grey elliptical area represents normative values, which contains all the values collected from the CG.

Three dependent variables were identified for each patient based on the relationship between the DSM and step length: stability, symmetry, and consistency. Patients were classified as positive (stable, symmetric,