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Multi-Segments Kinematic Model of the Human Spine during Gait

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***Abstract*—The complex biomechanical structure of the human spine requires a deep investigation to properly describe its physiological function and its kinematic contribution during motion. The computational approach allows the segmentation of the human spine into several rigid bodies connected by 3D joints. Despite the numerous solutions proposed by previous literature studies based on both inertial and stereophotogrammetric systems, the modelling of the human spine is characterized by some limitations such as the lack of standardization. Accordingly, the present preliminary study focused on the development of a multi-segments kinematic model of the human spine and its validation during gait trials. Three-dimensional spinal angular patterns and ranges of motion of one healthy young subject were considered as outcomes of interest. They were obtained by applying the YXZ Euler angles convention to the custom model. First, results were compared with those of the standard Plug-in-Gait full-body model, which segments the human spine into pelvis and trunk segments. Then, outcomes of the multi-segments model were compared with those obtained using the Tilt-Twist method. Overall, results stressed the importance of the spine segmentation, the major angular contributions of spinal regions during gait (Medium-Lumbar segments for lateral bending and flexion-extension, Thoracic-Medium segments for axial rotation), and the reliability of the proposed custom model (differences between Euler angles method and Tilt-Twist method lower than 0.5° in most cases). Future analysis on a larger healthy population and in the clinical context might be implemented to optimize, standardize and validate the proposed human spine model.**

Keywords*—*human spine, multibody modelling, kinematics, gait analysis, stereophotogrammetric system, Tilt-Twist method, Euler angles

I. Introduction

The human spine is a complex mechanical structure composed of different musculoskeletal components: bones, joints, muscles, and ligaments [1]. Vertebrae are the main rigid bodies of the spine. Considering their regional position along the spinal cord, vertebrae can be classified into different groups: 7 cervical vertebrae, 12 thoracic vertebrae, 5 lumbar vertebrae, 5 sacral vertebrae, and 4 coccygeal vertebrae. The different shapes and orientations of each vertebral body contribute to defining the range of motion in the three different anatomical planes. Vertebrae characterize several physiological curves (cervical and lumbar lordosis, thoracic and sacral kyphosis) that accommodate the different pelvic orientations during motion and contribute to maintaining balance [1]. Intervertebral discs keep separated the vertebrae and act as shock absorbers. A complex architecture of muscles dynamically controls the motion and supplies torques across joints [2].

The human spine has different physiological functions, strongly correlated to human motions. During static postures, such as standing and sitting, the trunk oscillations allow to maintain balance and control, and to support human body parts [3]. The human spine is also involved in different dynamic tasks, such as walking and lifting. During gait, the spine considerably contributes to regulating the oscillations in the 3D anatomical directions, and consequently to achieving the locomotion [4]. When lifting external heavy objects, the human spine plays a fundamental active role in terms of generating joints forces and moments and transferring the weight of the upper body to the human pelvis [5]. The human spine can be involved in structural and non-structural alterations, such as scoliosis and Pisa's Syndrome [6]. Moreover, the low-back pain is the most common musculoskeletal disorder affecting the population of workers [7]. All these disturbs can negatively affect the human movement during daily activities. Concerning the range of motions (ROMs), the spine movements can be described as the sum of lateral bending (LB), flexion-extension (FE), and axial rotation (AR). Different ROMs can be achieved based on the spine region [8]. Due to the multibody structure of the vertebral column and to the difficulties of the biomechanical analysis, a deep investigation of the spine could be crucial in several applications, such as gait analysis, clinics, sports, rehabilitation, but also industrial environments.

The motion analysis approach has turned out as a strategical method for the evaluation of musculoskeletal systems [9], body systems [10], human-device interaction [11], and occupational ergonomics [12]. It mainly consists in the acquisition of specific landmarks motion, associated with biomechanical models. The modelling approach allows calculating objective parameters that cannot be measured with experimental and observational analysis. One of the golden standards of motion analysis is the VICON system, and the associated Plug-in-Gait (PiG) full-body model [13], [14]. This presents the human body modelled as multi rigid segments connected by 3D joints. The human spine is represented by two rigid segments: the pelvis and the trunk, connected by the lumbar joint. Moreover, the trunk is linked to the human head by the neck joint. Despite its clinical validation and its wide adoption, the identification of only two spine segments might be too basic and introduce important limits when a characterization of the full spine motion is required and in pathologies where it is necessary to focus on the trunk movement analysis. Previous literature studies proposed a multi-segments model of the human spine to overcome these limitations. In particular, these studies can be grouped based on instruments and algorithms adopted for the development.

In 1997, Crosbie and colleagues analyzed the spinal motion during walking, through the partition of the human spine in four segments [15]. An analog solution was implemented for the analysis of trunk motion, on frontal and sagittal planes, during treadmill walking [16]. In that study, passive markers were positioned in correspondence to vertebrae levels of interest. More recently, Leardini and colleagues used a multi-segments model to investigate trunk motion in elementary daily exercises [17]. To overcome soft tissue artifacts and the precise location of markers on specific vertebrae, Needham and colleagues validated a custom model developed from clusters of markers [18]. All these studies stressed the importance of the human spine segmentation and the different contribution of column regions in several tasks. Nevertheless, the lack of standardization and reference trends represents an important limitation.

Inertial measurement units (IMUs) have been proposed for monitoring human motion in clinical practice and they had been used also to assess the biomechanics of the spine [19], [20]. During the last years, IMU set-ups with a higher number of units have been proposed in the attempt to differently describe the human spine regions [21]–[23]. More recently, a previous pilot study proposed the application of the Tilt-Twist method to IMUs data recorded during gait sessions to assess spinal posture [24]. The Tilt-Twist method was developed by Crawford [25] to calculate the 3D orientations of vertebrae and to obtain relative angles, which were both physically meaningful and mathematically stable. In [24] the algorithm was validated by comparing 3D angles of three rigid segments obtained with IMUs to ones calculated with an optical gold standard. Moreover, the Tilt-Twist method was adopted also for the column segmentation using passive markers triads. Since results demonstrated the suitability of IMUs in estimating relative angles among vertebral segments during gait, the study was amplified by proposing a more detailed assessment of the spinal posture and by considering the influence of gender, walking speed, and imposed cadence on ROMs [26]. Despite the numerous advantages of inertial sensors and their applications in several studies, a robust algorithm needs to be implemented and verified to calculate human kinematics. In particular, their clinical application for the assessment of pathologies may reveal some difficulties and discrepancies. Finally, despite the promising results obtained in the previous analysis, the Tilt-Twist method can be considered a reliable algorithm in the case of small angles, while it might be unsuitable in the case of a larger range of motions.

With the global intent of developing a detailed multibody biomechanical model for clinical applications, the main object of the current study deals with the development and the validation of a multi-segments kinematic model of the human spine. Gait experimental trials were performed by one young healthy subject. The analysis focused on: i) the comparison between the multi-segments spine model and the Plug-in-Gait full-body model, ii) the validation of 3D spine angles obtained with YXZ Euler convention through the Tilt-Twist method.

II. Materials & Methods

A. Participant & Protocol

One female young healthy subject (25 years, 1.72 m, 58 kg) participated in the preliminary experimental test. She declared to be not affected by any musculoskeletal and neurological disease. Tests were conducted in a laboratory setting, in the specialized Movement Disorders Center of “Città della Salute e della Scienza” in Turin. The capture volume of the laboratory was 10 m in length and 5 m in width. The subject first assumed a static standing posture used for the calibration of the models. Then, 5 dynamic gait trials were performed. The participant was asked to walk barefoot back and forth along the path, at a self-selected comfortable speed.

B. Instrumentation

The instrumentation set adopted for the experimental test was a VICON system composed by:

- 2 cameras Vicon VUE for video recording (1080p, 50 Hz);
- 8 infrared-cameras Vicon Bonita 10 for infrared capture (1024x1024 resolution, 120 Hz);
- 39 passive reflective markers (diameter of 14 mm) for the Plug-in-Gait full-body human model (Fig. 1);
- 9 additional passive reflective markers (diameter of 14 mm) for the customized human spine model.

Passive markers were positioned on anatomical landmarks of the subject through adhesive tape.

C. Model development

The custom multi-segments spinal model was developed with Vicon Nexus and Vicon Procalc software. A graphical representation of the model is depicted in Fig. 1.

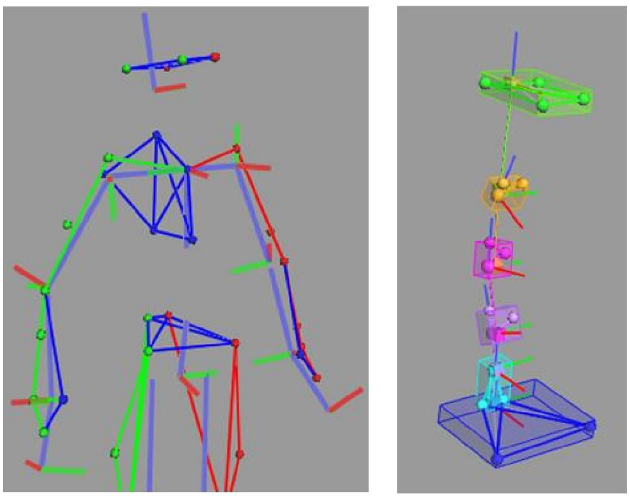

Fig. 1. The graphical schematization of Vicon PiG full-body human model and custom multi-segments spinal model.

A total of 19 markers were used to identify 6 rigid segments connected by 3D joints. In agreement with the PiG full-body model, four markers were used to register head and pelvis segments, respectively. Then, markers triads were positioned in correspondence of anatomical curvatures of the spine to define different segments: Cervical (C7-T6), Thoracic (T6-T12), Medium (T12-L3), Lumbar (L3-Midpoint between LPSI-RPSI). Fig. 2A shows the positioning and labelling of markers on the human spine, while Fig. 2B depicts the spinal segmentation.

For each rigid segment, a proper local coordinate system was defined with the x-axis oriented in the same direction of gait, y-axis pointing to the left side of the participant, and z-axis pointing upward (Fig. 2C). The convention of YXZ Euler rotations was adopted to define relative angles of each segment with respect to its inferior adjacent one.

D. *Signal processing and data analysis*

Signal processing and data analysis were conducted with both Vicon Nexus and Matlab custom routines.

In detail, relative angles of adjacent segments were calculated on the three planes. The upright standing posture was assumed to be the neutral one. Angles were calculated with respect to the neutral position. Gait events were detected through the PiG full-body model and used to segment consecutive gait cycles, identifying stance and swing phases. A total number of 15 gait cycles (30 steps) was considered. Angular curves were first averaged among gait cycles, then expressed to the percentage of the right gait cycle. For each gait cycle, angular ROMs were estimated for all vertebral levels. Subsequently, mean and standard deviation values of ROMs were obtained among gait cycles.

The procedure was then repeated to calculate relative angles and correspondent ROMs using the Tilt-Twist method, as presented in [24], for the comparison and verification of the custom model.

III. Results

Fig. 3 shows 3D kinematic results for the human trunk obtained with the PiG full-body model. In detail, angular trends are depicted both as relative to the human pelvis segment (Spine) and the global coordinate system (Thorax) defined in the laboratory.

Fig. 4 shows 3D kinematic results for the human spine calculated with the custom multi-segments model based on YXZ Euler angles convention (solid line) and compared to the angular trends obtained with the application of the Tilt-Twist method (dashed line). In particular, in both approaches, five relative angles were estimated in the three planes (LB, FE, AR) by relating each superior spine segment to its inferior adjacent one: Head-Cervical (Head-Cer), Cervical-Thoracic (Cer-Tho), Thoracic-Medium (Tho-Med), Medium-Lumbar (Med-Lum), Lumbar-Sacral (Lum-Sac).

Curves in Fig. 3 and Fig. 4 were expressed to the percentage of the right gait cycle. Moreover, the separation between stance and swing phases is stressed in all graphs through a dashed vertical line representing the toe-off of the right foot.

Finally, Table I highlights the mean and standard deviation values of 3D ROMs calculated for all spinal segments with both methods (Euler angles and Tilt-Twist method).

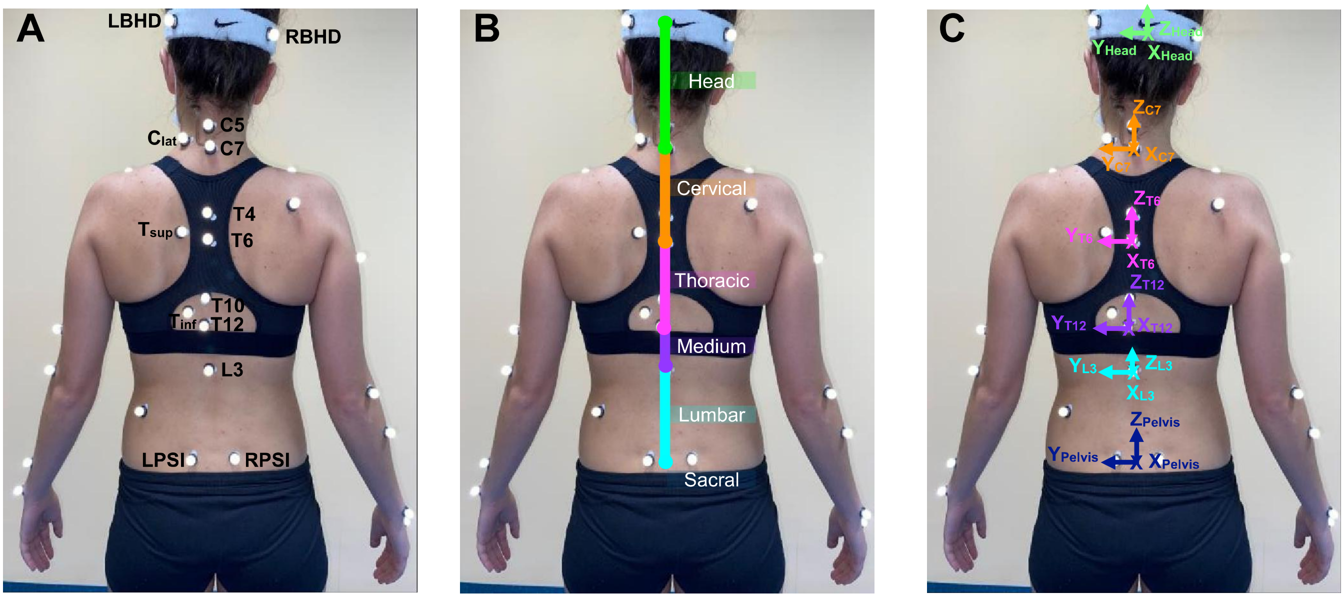

Fig. 2. Spine model: (A) Markers positioning for the development of the custom multi-segments spinal model, (B) Segmentation of the spinal cord in five regions, (C); Definition of the local coordinate systems of the different spinal regions.

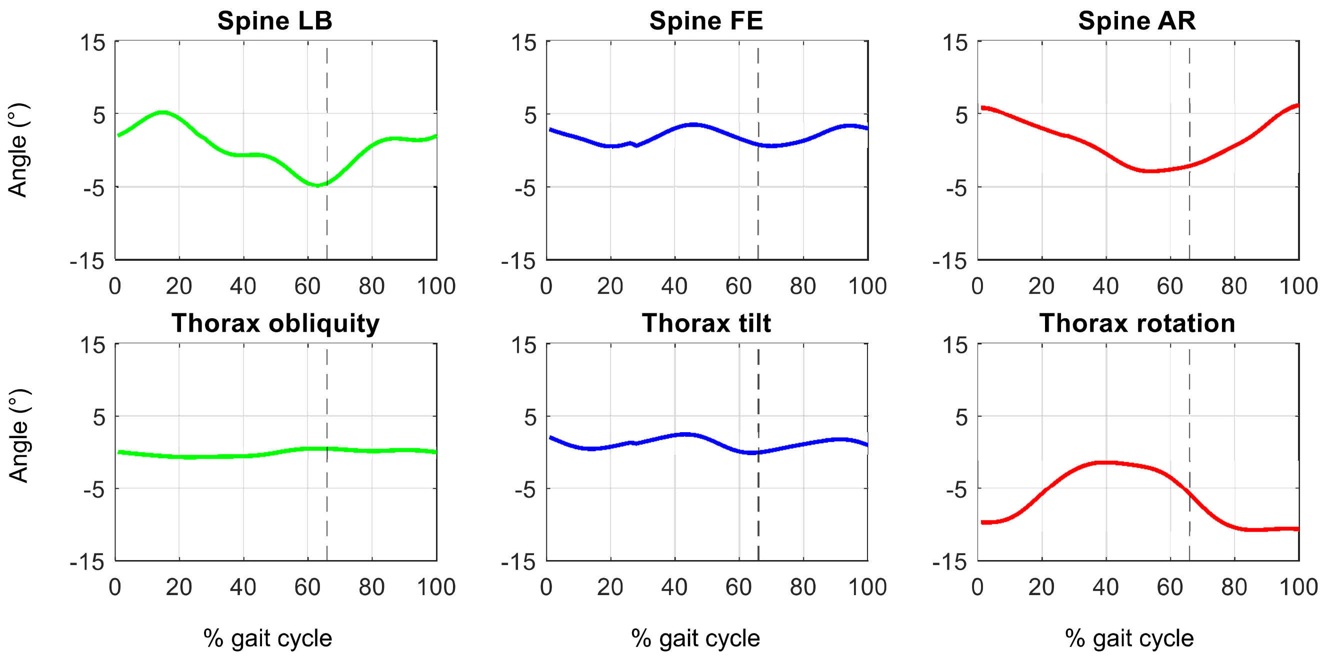

Fig. 3. 3D kinematic angles of spine and thorax obtained from the PiG full-body model in the frontal (LB), sagittal (FE), and transverse (AR) planes.

IV. Discussions

The current pilot study concentrated on the development of a multi-segments model of the human spine and its preliminary validation during gait performed by one healthy subject. Relative angles between adjacent segments were evaluated in all three planes with i) PiG full-body model, ii) custom multi-segments model with YXZ Euler convention, iii) custom multi-segments model with Tilt-Twist method.

Considering LB motion in the frontal plane (green lines), in the PiG model (Fig. 3), the thorax obliquity does not highlight a significant contribution during gait. On the other hand, if related to the pelvis segment, the LB of the spine shows two peaks (one positive and one negative) occurring approximately at 15% and 65% of the gait cycle. These coincide with the early swing phase [15]. Considering the multi-segmented model that divides the spine into more regions (Fig. 4), different angular trends can be observed during gait phases. Indeed, according to [15], [16], [18], the displacement of thoracic and medium segments occurs towards the weight-bearing limb, while the displacement of the lumbar-sacral segments is towards the swinging leg. The pattern of the head segment depicts a trend comparable to one of the lumbar-sacral segments [26].

Considering FE patterns in the sagittal plane, a double bump of the spine is highlighted by both the thorax tilt and relative spine angle obtained from the PiG full-body model (Fig. 3). This two-phases movement corresponds to one flexion-extension cycle per step [15], [16]. With the separation of the five spinal segments in the custom model, it is possible to identify the spinal region of medium and lumbar segments like the ones mainly involved in the movement.

Considering AR patterns in the transverse plane, a rotation peak occurs in correspondence of 50% of the gait cycle, both in relative and absolute angles of the trunk (Fig. 3). With the detailed multi-segments models (Fig. 4), as expected, the major kinematic contribution results from the thoracic region.

In all three planes, it is evident that the head segment has a greater ROM compared to the spinal regions. Finally, comparing the custom model based on YXZ Euler angles convention and the one based on the Tilt-Twist method, the strong similarity of angular trends and values verifies the reliability of the model, except for the head segment. In this last case, indeed, some discrepancies can be underlined. This is due to the fact that the Tilt-Twist method performs better when the angles are small, while it may provide some discrepancies in the case of larger ROMs. This problem of larger mobility is highlighted by the head segment compared to spinal segments.

As regards ROMs of all vertebral segments (Table I), except for the head, mean values result in a range of 1-12°, confirming previous literature findings [17], [18], [27]. Similar accordance can be pointed out for standard deviations [27], with a maximum value of 3° registered at the thoracic-medium segments. From the comparison between the Euler angles convention and the Tilt-Twist method, similar ROMs were obtained, except for the lumbar-sacral LB. For the head segment, greater mean values are displayed with both Euler and Tilt-Twist methods, with maximum values of 8.79° and 15.19° for AR ROM, respectively. Concerning the standard deviation, both methods produced values higher than 3°. From the comparison between methods for the head segment, some discrepancies were found in the mean and standard deviation values of all three planes.

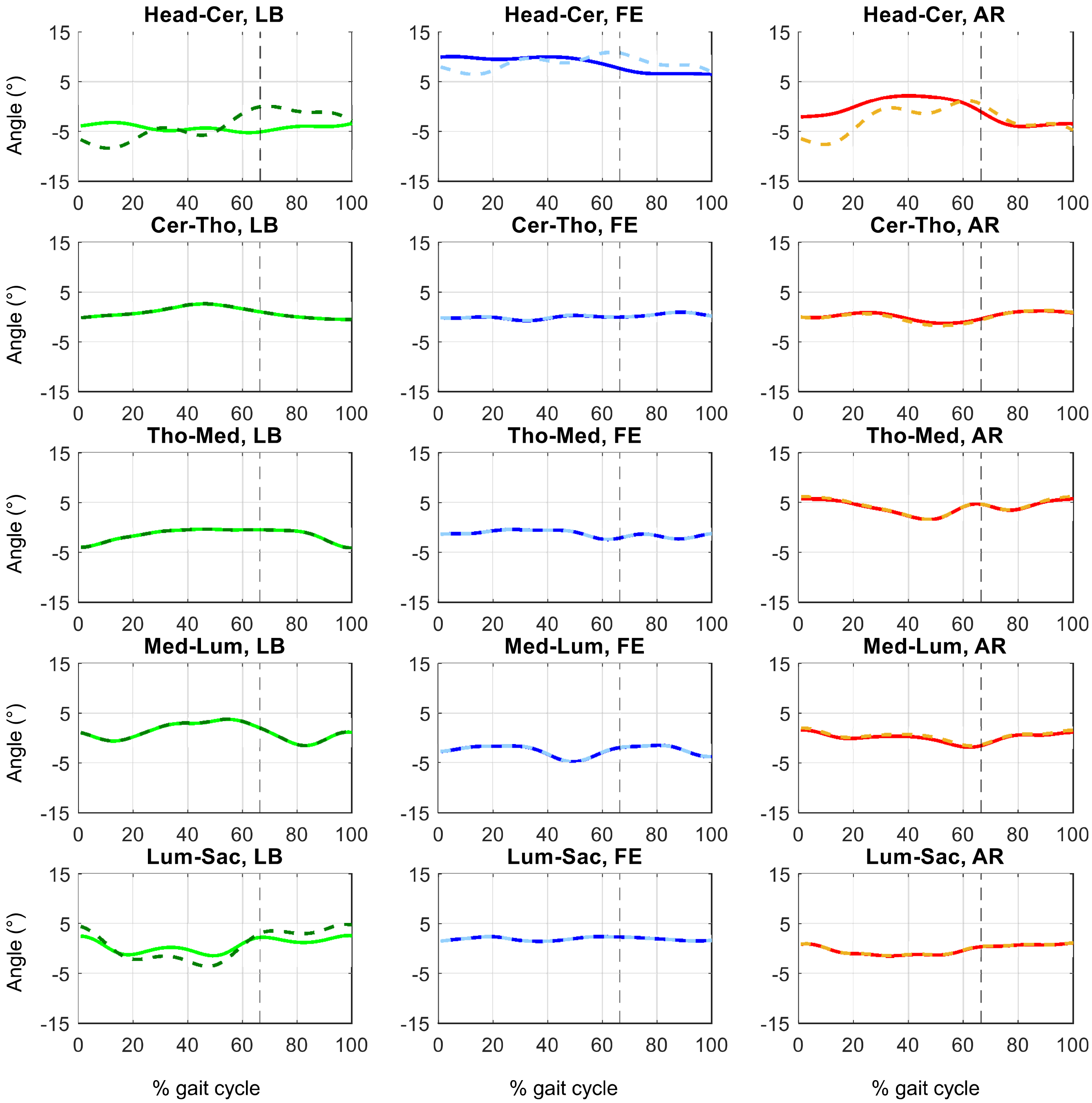

Fig. 4. 3D kinematic angles of all vertebral segments from the custom model in the frontal plane (LB), sagittal plane (FE), and transverse plane (AR). The solid line and dashed line represent angles obtained with the Euler angles convention and the Tilt-Twist method, respectively.

TABLE I. ROMS OF ALL VERTEBRAL SEGMENTS IN CUSTOM MODELS

	3D ROMs during gait Mean (std)					
	LB (°)		***FE (°)***		***AR (°)***	
	Euler angles	***Tilt-Twist***	***Euler angles***	***Tilt-Twist***	***Euler angles***	***Tilt-Twist***
Head-Cervical	5.06 (3.11)	14.56 (7.45)	7.37 (5.20)	10.73 (7.02)	8.79 (3.17)	15.19 (6.07)
Cervical-Thoracic	4.65 (1.51)	4.76 (1.54)	3.71 (1.64)	3.69 (1.60)	4.75 (1.22)	5.02 (1.39)
Thoracic-Medium	5.51 (1.38)	5.57 (1.40)	4.12 (1.47)	4.11 (1.47)	7.43 (2.95)	7.92 (3.05)
Medium-Lumbar	7.54 (0.96)	7.63 (0.98)	5.10 (1.63)	5.02 (1.63)	5.12 (1.53)	5.26 (1.65)
Lumbar-Sacral	5.90 (0.60)	12.10 (1.08)	2.13 (0.57)	2.13 (0.57)	4.42 (0.79)	4.39 (0.79)

V. Conclusions

The aim of the present study dealt with the development of a three-dimensional multi-segments spinal model and its preliminary verification during walking trials. Relative angles and ROMs of vertebral segments were selected as outcomes of interest. The PiG full-body model and the Tilt-Twist method were adopted as standards of comparison.

Spinal angular trends and ROMs of LB, FE, and AR demonstrated a good correlation with previous literature works. Compared to the PiG full-body model, the differentiation of spinal regions allows stressing the contribution of the singular segments during motion. Moreover, the YXZ Euler convention applied to the custom multi-segments model well reproduced the spinal posture detected with the Tilt-Twist method. Overall, the proposed custom model is reliable and suitable for the investigation of the spinal posture in motion analysis.

Despite these promising results, some limits could be pointed out. Since only one subject performed the test, a larger population should be involved to validate the model. Moreover, only the gait was considered. Additional daily activities and a higher number of movement repetitions could be analyzed to verify the model robustness.

Future plans will consider extending the analysis to a larger population of healthy young and elderly subjects. In addition, a comparison between male and female participants could be performed within the attempt to underline possible differences due to gender. After the validation of the custom model with healthy subjects, clinical applications might be hypothesized to test the reliability of the model in case of a pathological pattern of the motion. Indeed, the spinal segmentation and the estimation of relative angles between adjacent vertebral segments could be strategical in patients with spinal postural disturbs such as the Pisa syndrome.

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