

RESEARCH

Open Access



Kinematic difference and asymmetries during level walking in adolescent patients with different types of mild scoliosis

Run Ji^{1,3}, Xiaona Liu², Yang Liu⁷, Bin Yan^{4,5,6,7}, Jiemeng Yang^{1,3}, Wayne Yuk-wai Lee⁸, Ling Wang^{9,10}, Chunjing Tao^{1*}, Shengzheng Kuai^{4,5,6,7*} and Yubo Fan^{1*}

*Correspondence:
chunjingtao@buaa.edu.cn;
kkzh2008@126.com;
yubofan@buaa.edu.cn

¹ School of Biological Science and Medical Engineering, School of Engineering Medicine, Beijing Advanced Innovation Centre for Biomedical Engineering, Beihang University, Beijing 100191, China

⁴ Department of Spine Surgery, Shenzhen Second People's Hospital, Shenzhen 518039, China

Full list of author information is available at the end of the article

Abstract

Background: Adolescent idiopathic scoliosis (AIS), three-dimensional spine deformation, affects body motion. Previous research had indicated pathological gait patterns of AIS. However, the impact of the curve number on the walking mechanism has not been established. Therefore, this study aimed to compare the gait symmetry and kinematics in AIS patients with different curve numbers to healthy control.

Results: In the spinal region, double curves AIS patients demonstrated a smaller sagittal symmetry angle (SA) and larger sagittal convex ROM of the trunk and lower spine than the control group. In the lower extremities, the single curve patients showed a significantly reduced SA of the knee joint in the frontal plane, while the double curves patients showed a significantly reduced SA of the hip in the transverse plane.

Conclusion: The curve number indeed affects gait symmetry and kinematics in AIS patients. The double curves patients seemed to adopt a more "careful walking" strategy to compensate for the effect of spinal deformation on sensory integration deficits. This compensation mainly occurred in the sagittal plane. Compared to double curves patients, single curve patients unitized a similar walking strategy with healthy subjects.

Keywords: Adolescent idiopathic scoliosis, Gait symmetry, Curve number, Kinematics

Background

Adolescent idiopathic scoliosis (AIS) is a common three-dimensional deformation of the spine, which has been reported to be prevalent in 1–3% [1–3] of the population aged 10–16 years. To date, the etiology of AIS remains unclear. However, there are several hypotheses regarding the genetic, biomechanical, neurological, and muscular factors. From the view of biomechanics, previous studies have found that AIS could alter postural orientation and induce abnormal gait patterns [4–9]. As a result, the investigation of the walking pattern between healthy subjects and AIS patients may help better understand AIS's etiology.

Since the AIS is a kind of spinal deformity, the trunk motion could be affected directly. It was found that AIS patients had a smaller spinal range of motion (ROM) [4]. Recent



© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>. The Creative Commons Public Domain Dedication waiver (<http://creativecommons.org/publicdomain/zero/1.0/>) applies to the data made available in this article, unless otherwise stated in a credit line to the data.

studies have even exhibited the variation of trunk motion according to the severity and type of scoliosis [10–13]. In specific, trunk motion parameters were correlated with Cobb angle at 0.82. In Nishid's study, the AIS patients with a single thoracic curve showed asymmetrical trunk movement in the transverse plane, and patients with a single lumbar curve showed asymmetrical trunk movement in the coronal plane. However, in Pesenti's study, the AIS patients with a single thoracic or lumbar curve presented no difference in the transverse plane. Apart from the trunk motion, the postural adjustment of AIS patients during level walking also involved the pelvis, upper extremities, and lower extremities. Wu et al. [14] found that the kinematics of the trunk, pelvis, and lower extremities differed between concave and convex sides at different gait events in severe thoracic AIS. Also, the AIS patients demonstrated reduced ROM in the upper body and lower extremities [9, 15]. However, the previously observed differences were inconsistent, and most studies were limited to single curve AIS or mixed up all curve types and Cobb angles. Moreover, the trunk was regarded as a rigid body and the relative motion between spinal vertebrae was omitted.

This study aimed to investigate the symmetry and kinematics of the multi-spine and lower extremities among healthy subjects, single curve AIS patients, and double curves AIS patients during a stance phase of gait. Our first hypothesis was that AIS patients might demonstrate more kinematic asymmetry than healthy subjects. The second hypothesis was that the kinematic characteristics of multi-spine and lower extremities in three planes might vary with the type of AIS.

Methods

Subjects

From January 2022 to September 2022, 36 mild AIS patients and 18 control teenagers were recruited for this study. The criteria for the inclusion were as follows: (1) diagnosed as AIS through radiological examination, (2) Cobb's angle ranges from 10 to 25 degrees, and (3) aged 8–16 years. The scoliosis patient was further divided into PUMCI (single curve) and PUMCII (double curves) according to the PUMCI classification [16] (Fig. 1), and those patients that did not belong to the two groups were excluded from the study. Specially, the PUMCII patients with identical primary and secondary Cobb angles were also excluded. Moreover, any subject who has metabolic or oncological or chronic respiratory system diseases, central nervous system disorders, injuries, and fractures within the previous 6 months was also excluded. The control group included teenagers aged 8–16 years without systemic diseases and with an angle of ATR less than 5°. The general information of these participants is shown in Table 1. The study was approved by the Ethics Committee of Shenzhen Second People's Hospital and conducted according to the Declaration of Helsinki. All participants and their parents signed an informed consent form before the experiment.

Procedure

Before the experiment, 56 reflective markers were placed on the landmarks according to the definition of Fig. 2. In the spinal region, the markers were placed on the jugular notch where the clavicles meet the sternum (clavicle, CLAV), the xiphoid process of the sternum (sternum, STRN), the spinous process of the first, third, fifth, seventh,

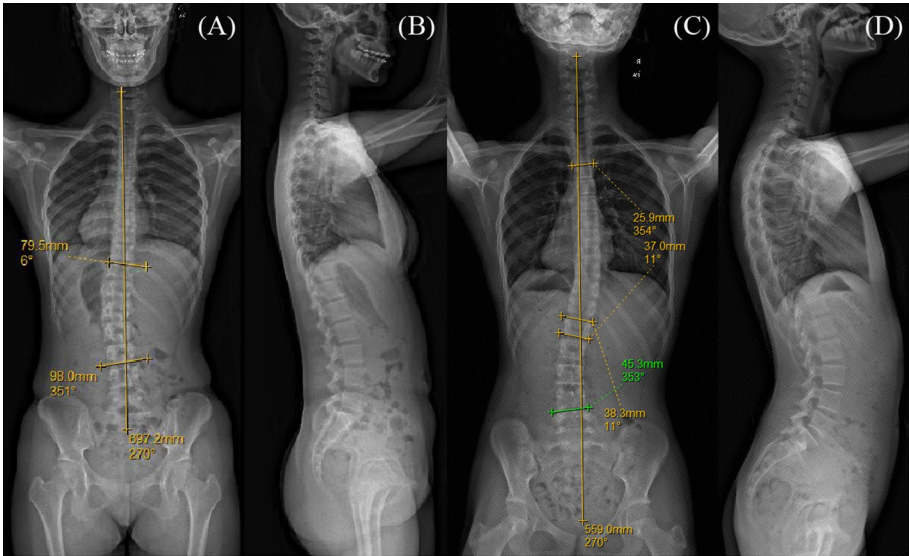


Fig. 1 Frontal and lateral radiographic images of one PUMCI patient (A, B), frontal and lateral radiographic images of one PUMCII patient (C, D)

Table 1 Demographics of participants

Group	Age (Year)	Height (cm)	Weight (kg)	Cobb Angle (°)
Control	11.27 ± 2.03	150.16 ± 13.97	40.44 ± 11.57	–
PUMCI	12.66 ± 2.63	155.16 ± 15.74	42.55 ± 11.28	15.66 ± 2.54
PUMCII	13.61 ± 1.37	159.94 ± 6.84	42.50 ± 7.84	16.11 ± 2.21

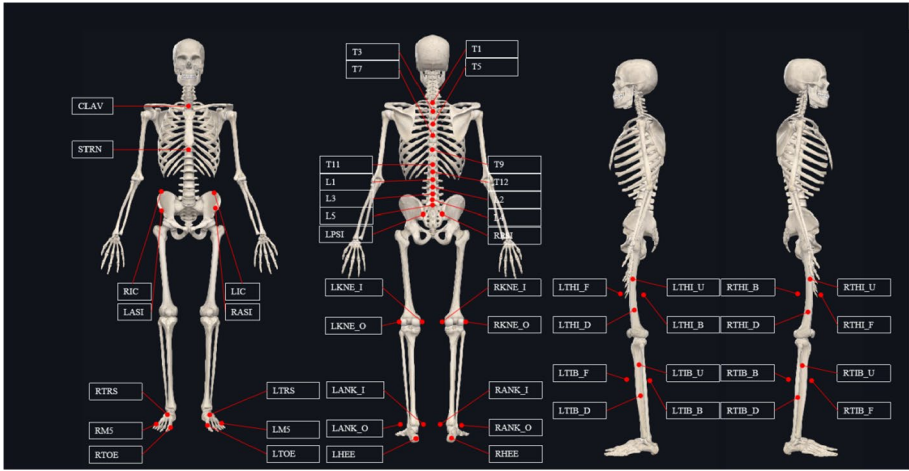


Fig. 2 The schematic of the marker set definition in this study

ninth, eleventh and twelfth thoracic vertebrae (T1, T3, T5, T7, T9, T11, T12), of the first, second, third, fourth, fifth lumbar vertebrae (L1, L2, L3, L4, L5). In the pelvic region, the markers were placed on the left and right anterior superior iliac (LASI, RASI), left and right posterior superior iliac (LPSI, RPSI), and left and right iliac crest

(LIC, RIC). In the thigh region, two markers were placed on the medial and lateral condyle of the femur (KNE_I, KNE_O), and non-collinear four markers were placed on the surface of the thigh (THI_U, THI_D, THI_F, THI_B). In the shank region, two markers were placed in the medial and lateral malleolus, and non-collinear four markers were placed on the surface of the shank (TIB_U, TIB_D, TIB_F, TIB_B). In the foot region, the markers were placed on the first and third metatarsal head (Toe, M5), calcaneus (HEE), and superior surface of the cuneiform bone (TRS).

After marker placement, participants assumed an anatomical pose for 1 min to get a standing reference trail, then they were asked to walk through a 10 m walkway at their self-selected speed for several minutes to adapt to this experiment. Subsequently, participants walked naturally for data collection. During level walking, a ten-camera three-dimensional (3D) motion capture system (MotionAnalysis Corp., USA) and two force platforms (AMTI Inc., Watertown, MA, USA) embedded in the walkway were used to collect three-dimensional markers' trajectories and ground reaction force (GRF) with a sampling frequency of 100 Hz and 1000 Hz, respectively.

Musculoskeletal model and simulation

A generic MoCap_FullBody model in the AnyBody modeling system (version 6.0.6, Aalborg, Denmark) was selected, and the upper extremities were removed for this study. Therefore, the musculoskeletal model contained the spine, pelvis, and lower extremities. The spinal model consisted of five lumbar vertebrae and one lumped thoracic segment. The pelvis was one lumped segment. The lower extremities were composed of the thigh, shank, and foot. These segments were linked by joints with 35 degrees of freedom (DOFs). In specific, two spherical hip joints (with 3 DOFs) that linked pelvis and thigh, two spherical knee joints (with 3 DOFs) that linked thigh and shank, two revolute ankle joints (with 1 DOF) that linked the shank and foot, six spherical intervertebral joints (with 3 DOFs) that linked the spinal segments, and one spherical sacroiliac joint (with 3DOFs) that linked the spine and pelvis. The positions of these joints were pre-defined in the MoCap_FullBody model, which were based on the work by Pearcy and Bogduk [17]. A detailed overview and validation of the model were given in the literature [18–20].

For each participant, the standing reference trial was utilized to identify the parameters of segment lengths and the (virtual) marker positions of the musculoskeletal model. Then, inverse kinematics was applied to minimize the errors between captured markers and virtual markers, driving the musculoskeletal model to simulate the participant walking.

In general, a minimum of three markers was essential to determine the segmental motion. For pelvis and lower extremities, the markers attached to these segments were enough to drive the motion of these segments. However, there were insufficient markers to determine the vertebral bodies. Consequently, the spine model followed a spine rhythm that distributed the trunk motion over the vertebral bodies in AnyBody modeling system. In this study, the spine rhythm was removed and each vertebral body was independently driven by captured markers referred to the previous studies [21]. In specific, the thorax was driven by CLAV, STRN, T1, T3, T5, T7, T9, T11 and T12. The first lumbar vertebra was driven by T12, L1, and L2, while other spinal vertebrae were driven using a similar method.

Data analysis

After walking simulation, the joint angles of lower extremities and multi-spine were the output of the musculoskeletal model. The convex angular ROM of the multi-spine and lower extremities were computed for the stance phase of gait, defined from convex heel strike to convex toe-off. The concave ROM was calculated similarly. The term "convex" refers to the side of the major scoliosis curve in both PUMCI and PUMC II, while "concave" refers to the opposite side. The degree of symmetry between the convex and concave ROM was assessed using the symmetry angle (SA) [22], with a score of 0% indicating perfect symmetry and 100% indicating perfect asymmetry.

The results of the Shapiro–Wilk tests indicated that the majority of demographics, convex ROM and SA did not follow a normal distribution. As a result, Kruskal–Wallis's test was applied to compare the demographics, SA, and convex ROM across the three groups. All statistical analyses were conducted using a custom MATLAB program (The Math Works, Natick, MA, USA). The level of statistical significance was set at $p < 0.05$.

Result

Table 1 shows that there is no significant difference in age, height, weight, and cobb angle among the three groups. Figures 3 and 4 demonstrate the symmetry and convex kinematics of the lower extremities and multi-spine in the three planes during a stance phase of gait.

In the sagittal plane, no significant differences in symmetry and convex ROM of lower extremities were observed among the three groups. However, a significant reduction in SA of L1L2 between control and PUMCII ($p < 0.05$), of L4L5 between control and PUMCI ($p < 0.05$), between control and PUMCII ($p < 0.01$), of L5S1 between control and PUMCII ($p < 0.05$), of Thorax_Pelvis between control and PUMCII ($p < 0.05$). In addition, the convex ROM of L4L5, L5S1, and Thorax_Pelvis increased significantly in PUMC II patients.

In the frontal plane, the knee SA decreased significantly and convex L5S1 ROM on the convex side increased significantly.

In the transverse plane, a reduced SA of the hip was found between the control and PUMCII ($p < 0.01$).

Discussion

The main objective of this study was to compare the kinematic symmetry and convex kinematics of multi-spine and lower extremities between healthy adolescents and two types of mild AIS patients. Contrary to our first hypothesis, the AIS patients exhibited a smaller SA of ROM, suggesting more symmetry in spinal and lower extremities motion during level walking. In addition, no significant differences in convex ROM were found between the control and PUMCI, and a significant increase in convex ROM was observed between the control and PUMCII, which supports the second hypothesis.

In the sagittal plane, no significant difference in the SA and convex ROM was found in the lower extremities during level walking among the three groups, indicating mild AIS did not affect the sagittal movement of the lower extremities. The finding of no symmetry difference among groups was in agreement with previous studies [5, 9, 23].

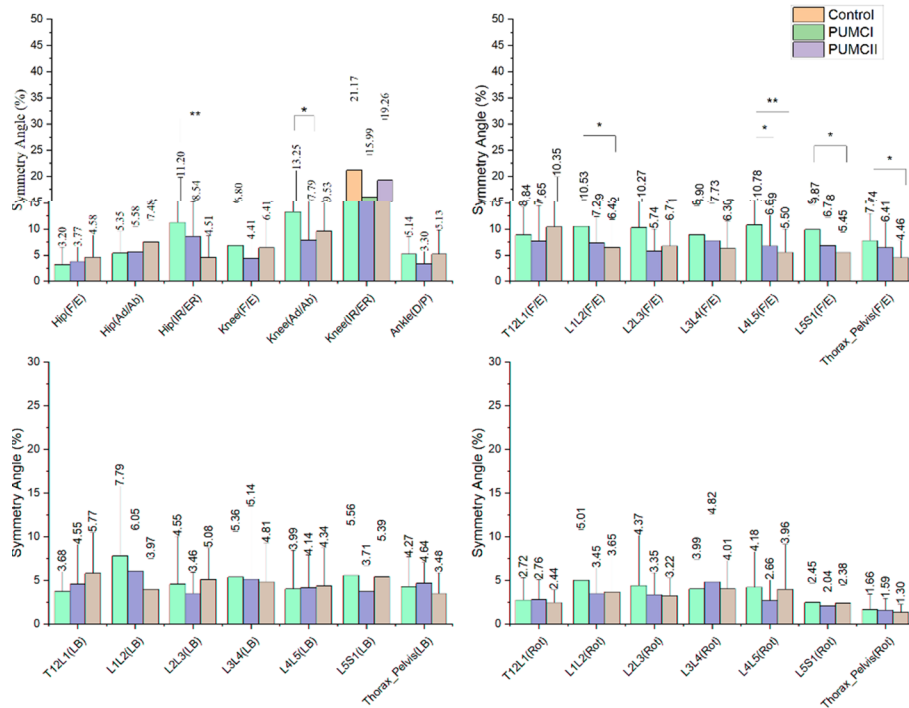


Fig. 3 SA scores for the joint angle of lower extremities and multi-spine. ** indicates $p < 0.001$; * indicates $p < 0.05$ (F/E: flexion/bending; Ad/Ab: adduction/abduction; IR/ER: internal rotation/external rotation; D/P: dorsiflexion/plantarflexion; LB: lateral bending; Rot: rotation; Thorax_Pelvis: thorax with respect to pelvis; Thorax_Pelvis: thorax with respect to Pelvis; T12/L1: thorax with respect to first lumbar vertebra; L1/L2: first lumbar vertebra with respect to second lumbar vertebra; L2/L3: second lumbar vertebra with respect to third lumbar vertebra; L3/L4: third lumbar vertebra with respect to forth lumbar vertebra; L4/L5: forth lumbar vertebra with respect to fifth lumbar vertebra; L5/S1: fifth lumbar vertebra with respect to sacrum)

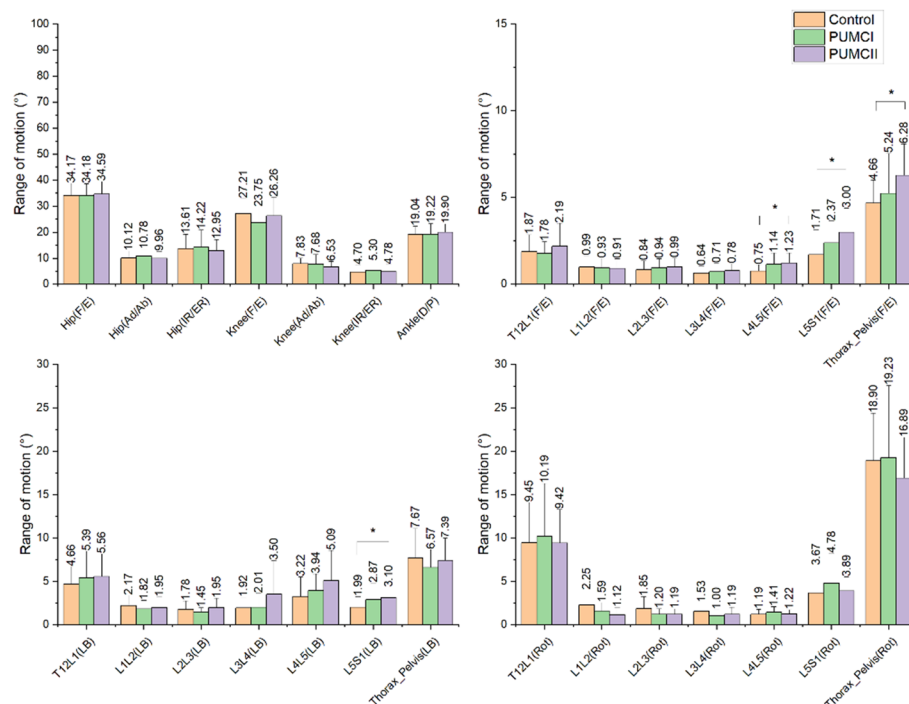


Fig. 4 ROM of the joint angle of lower extremities and multi-spine in the convex side. * $p < 0.05$

Therefore, the AIS patients seemed to utilize the same sagittal symmetric walking strategy as the control group in previous studies and our studies. As for the spine, the SA of Thorax_Pelvis showed a significant reduction in PUMC II. Further, our multi-spine model clarified that the reduction was found in L1L2, L4L5, and L5S1 in detail. Although no significant reduction of SA was observed in Thorax_Pelvis between PUMCI and control, the PUMC I demonstrated a significant SA reduction of L4L5, which provided new insight into the symmetry between groups. The convex ROM of Thorax–Pelvis was found to increase in PUMCII. In specific, the increase occurred at the L4L5 and L5S1. However, No significant difference was found between PUMC I and control. These findings were in contrast with previous studies that no difference between control and AIS patients was observed in sagittal trunk motion [5, 9], which might be due to the simple trunk model and mix-up classification of AIS. Similarly, this study mixed up the different apex locations of PUMC I. However, the location of the apex for single curve AIS did not affect the sagittal trunk motion [12]. Therefore, it could be inferred that the two types of AIS patients adopted different walking strategies in the sagittal plane, and the strategy of double curves AIS patients seems to be more careful because of the smaller SA.

In the frontal plane, the PUMCI demonstrated a significant reduction of SA in the knee joint compared to the control, which is inconsistent with previous findings [5, 9]. Mahaudens et al. [5] found that the frontal difference of the lower extremities occurred at the hip joint due to the prolonged electrical activity duration of the related muscles. In contrast, no difference was found in Yang's study [9]. The reduced SA of the knee joints in the single curve patients may be considered abnormal muscle activities of the semitendinosus and lateral heads of Gastrocnemius [24] and a compensation for the alteration of the center of body mass (COM). In the spinal region, no significant difference in SA was found among the three groups, which was in agreement with Yang's research [9]. Moreover, the convex ROM of Thorax_Pelvis also did not show the difference among the three groups, in contrast to findings that scoliosis patients had significantly reduced Thorax_Pelvis in the frontal plane [5, 23]. The patients in this study were mild, and the effect of AIS on the trunk oblique might not be enough to be detected. However, the multi-spine model of this study revealed that L4L5 and L5S1 of PUMCII tended to have a larger convex ROM and the significant difference was observed in L5S1, which was similar to sagittal findings that double curves patients showed larger ROM of the lower spine. Therefore, a multi-spine model was essential when assessing the kinematic characteristics in mild AIS patients and could provide new insights on the AIS patients' kinematics.

In the transverse plane, only a significant reduction of hip SA was found between PUMC II and the control, which agreed with the previous study [5]. However, previous research showed that scoliosis patients had significantly reduced trunk ROM and asymmetric trunk rotation in the transversal plane compared to normal subjects [5, 9, 23]. Lots of previous studies had presented the “torsional offset” in AIS patients and found the torsional motion could be affected by the position of the major curve [5, 11, 25]. This study showed the tendency to be more symmetry in the transverse plane. However, no significant difference was detected since the major curve's position was not considered in this study.

There are several limitations to this study. First, only two types of PUMC were included and the subgroup of PUMC I and PUMCII may affect the result of the kinematic findings. Second, we did not analyze muscle activities and kinetic data such as joint force applied at different spine levels. This is important to understand the AIS mechanism of postural control. Third, the upper extremities were not included in this study since the upper extremities play an essential role in body balance and walking strategy. Fourth, the motion between thoracic vertebrae was omitted in the musculoskeletal model, which might provide new insights into the spinal motion of AIS patients.

Conclusions

The AIS patients adopted a more symmetry gait strategy to compensate for the larger ROM of the multi-spine and lower extremities. The primary compensation occurred in the sagittal plane and lower spine in specific. Compared with PUMC II, the kinematics of PUMCI was closer to the control, suggesting the single curve AIS was more stable than the double curves AIS. The finding of this study may contribute to the understanding of the kinematic characteristics of lower extremities and spinal motion during the progression of AIS and also had the potential to help the development of rehabilitation and treatment plans.

Acknowledgements

The experiments comply with the current laws of China. The authors are thankful for the support of the Shenzhen Second People's Hospital, Beihang University, The Chinese University of Hong Kong, National Research Center for Rehabilitation Technical Aids, and Shenzhen University.

Author contributions

CT, SK and YF contributed to the study conception and design. Data collection was performed by XL, YL, and BY. Data analysis was conducted by RJ and SK. The first draft of the manuscript was written by RJ and SK and was modified by JY, LW, and WYL. All authors commented on previous versions of the manuscript. The authors read and approved the final manuscript.

Funding

This work is supported by the National Key R&D Program of China (Grant No. 2020YFC2005900), the National Natural Science Foundation of China (Grant No. 12072, Grant No. 12102268) and the Innovation Commission of Science and Technology of Shenzhen Municipality (JCYJ20210324103010029).

Availability of data and materials

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

¹School of Biological Science and Medical Engineering, School of Engineering Medicine, Beijing Advanced Innovation Centre for Biomedical Engineering, Beihang University, Beijing 100191, China. ²School of Sports Medicine and Rehabilitation, Beijing Sport University, Beijing 100084, China. ³Institute of Biomechanics, National Research Center for Rehabilitation Technical Aids, Beijing 100176, China. ⁴Department of Spine Surgery, Shenzhen Second People's Hospital, Shenzhen 518039, China. ⁵Department of Spine Surgery, First Affiliated Hospital of Shenzhen University, Shenzhen 518035, China. ⁶Shenzhen University School of Medicine, Shenzhen 518060, China. ⁷Shenzhen Youth Spine Health Center, Shenzhen 518035, China. ⁸Department of Orthopedics and Traumatology, The Chinese University of Hong Kong, Hong Kong, SAR, China. ⁹Tianjin Key Laboratory for Advanced Mechatronic System Design and Intelligent Control, School of Mechanical Engineering, Tianjin University of Technology, Tianjin 300384, China. ¹⁰National Demonstration Center for Experimental Mechanical and Electrical Engineering Education, Tianjin University of Technology, Tianjin, China.

Received: 18 July 2023 Accepted: 22 January 2024

Published online: 19 February 2024

References

- Hu M, Zhang Z, Zhou X, Gao R, Wang C, Ma J, Yicheng M, Zhou X. Prevalence and determinants of adolescent idiopathic scoliosis from school screening in Huangpu district, Shanghai, China. *Am J Transl Res*. 2022;14(6):4132–8.
- Penha PJ, Ramos N, de Carvalho BKG, Andrade RM, Schmitt ACB, Joao SMA. Prevalence of adolescent idiopathic scoliosis in the state of Sao Paulo Brazil. *Spine*. 2018;43(24):1710–8. <https://doi.org/10.1097/BRS.0000000000002725>.
- Weinstein SL, Dolan LA, Cheng JCY, Danielsson A, Morcuende JA. Adolescent idiopathic scoliosis. *Lancet*. 2008;371(9623):1527–37. [https://doi.org/10.1016/s0140-6736\(08\)60658-3](https://doi.org/10.1016/s0140-6736(08)60658-3).
- Chen PQ, Wang JL, Tsuang YH, Liao TL, Huang PI, Hang YS. The postural stability control and gait pattern of idiopathic scoliosis adolescents. *Clin Biomech*. 1998;13(1 Suppl 1):S52–s58. [https://doi.org/10.1016/s0268-0033\(97\)00075-2](https://doi.org/10.1016/s0268-0033(97)00075-2).
- Mahaudens P, Banse X, Mousny M, Detrembleur C. Gait in adolescent idiopathic scoliosis: kinematics and electromyographic analysis. *Eur Spine J*. 2009;18(4):512–21. <https://doi.org/10.1007/s00586-009-0899-7>.
- Mahaudens P, Raison M, Banse X, Mousny M, Detrembleur C. Effect of long-term orthotic treatment on gait biomechanics in adolescent idiopathic scoliosis. *Spine J*. 2013;14(8):1510.
- Mahaudens P, Thonnard JL, Detrembleur C. Influence of structural pelvic disorders during standing and walking in adolescents with idiopathic scoliosis. *Spine J*. 2005;5(4):427–33. <https://doi.org/10.1016/j.spinee.2004.11.014>.
- Park HJ, Sim T, Suh SW, Yang JH, Koo H, Mun JH. Analysis of coordination between thoracic and pelvic kinematic movements during gait in adolescents with idiopathic scoliosis. *Eur Spine J*. 2016;25(2):385–93. <https://doi.org/10.1007/s00586-015-3931-0>.
- Yang JH, Suh SW, Sung PS, Park WH. Asymmetrical gait in adolescents with idiopathic scoliosis. *Eur Spine J*. 2013;22(11):2407–13. <https://doi.org/10.1007/s00586-013-2845-y>.
- Dalleau G, Leroyer P, Beaulieu M, Verkindt C, Rivard CH, Allard P. Pelvis morphology, trunk posture and standing imbalance and their relations to the Cobb angle in moderate and severe untreated AIS. *PLoS ONE*. 2012;7(7):6. <https://doi.org/10.1371/journal.pone.0036755>.
- Nishida M, Nagura T, Fujita N, Hosogane N, Tsuji T, Nakamura M, Watanabe K. Position of the major curve influences asymmetrical trunk kinematics during gait in adolescent idiopathic scoliosis. *Gait Posture*. 2017;51:142–8. <https://doi.org/10.1016/j.gaitpost.2016.10.004>.
- Pesenti S, Pomero V, Prost S, Severyns M, Authier G, Roscigni L, Jouve JL. Curve location influences spinal balance in coronal and sagittal planes but not transversal trunk motion in adolescents with idiopathic scoliosis: a prospective observational study. *Eur Spine J*. 2020;29(8):1972–80. <https://doi.org/10.1007/s00586-020-06361-3>.
- Zabjek KF, Leroux MA, Coillard C, Prince F, Rivard CH. Postural characteristics of adolescents with idiopathic scoliosis. *J Pediatric Orthop*. 2008;28(2):218–24. <https://doi.org/10.1097/BPO.0b013e3181651bdc>.
- Wu KW, Wang TM, Hu CC, Hong SW, Lee PA, Lu TW. Postural adjustments in adolescent idiopathic thoracic scoliosis during walking. *Gait Posture*. 2019;68:423–9. <https://doi.org/10.1016/j.gaitpost.2018.12.024>.
- Mahaudens P, Mousny M. Gait in adolescent idiopathic scoliosis. kinematics, electromyographic and energy cost analysis. *Stud Health Technol Inform*. 2010;158:101–6.
- Qiu G, Zhang J, Wang Y, Xu H, Zhang J, Weng X, Lu WW. A new operative classification of idiopathic scoliosis: a peking union medical college method. *Spine*. 2005;30(12):1419–26.
- Pearcy MJ, Bogduk N. Instantaneous axes of rotation of the lumbar intervertebral joints. *Spine*. 1988;13(9):1033–41. <https://doi.org/10.1097/00007632-198809000-00011>.
- Carbone V, Fluit R, Pellikaan P, van der Krogt MM, Janssen D, Damsgaard M, Verdonchot N. TLEM 2.0 - a comprehensive musculoskeletal geometry dataset for subject-specific modeling of lower extremity. *J Biomech*. 2015;48(5):734–41. <https://doi.org/10.1016/j.jbiomech.2014.12.034>.
- Christophy M, Faruk Senan NA, Lotz JC, O'Reilly OM. A musculoskeletal model for the lumbar spine. *Biomech Model Mechanobiol*. 2012;11(1–2):19–34. <https://doi.org/10.1007/s10237-011-0290-6>.
- de Zee M, Hansen L, Wong C, Rasmussen J, Simonsen EB. A generic detailed rigid-body lumbar spine model. *J Biomech*. 2007;40(6):1219–27. <https://doi.org/10.1016/j.jbiomech.2006.05.030>.
- Kuai S, Guan X, Zhou W, Zhang R, Ji R, Liao Z, Wang D. Continuous lumbar spine rhythms during level walking, stair climbing and trunk flexion in people with and without lumbar disc herniation. *Gait Posture*. 2018;63:296.
- Zifchock RA, Davis I, Higginson J, Royer T. The symmetry angle: a novel, robust method of quantifying asymmetry. *Gait Posture*. 2008;27(4):622–7. <https://doi.org/10.1016/j.gaitpost.2007.08.006>.
- Bortone I, Piazzolla A, Buongiorno D, Bizzoca D, Moretti B. *Influence of clinical features of the spine on Gait Analysis in adolescent with idiopathic scoliosis*. Paper presented at the 2020 IEEE International Symposium on Medical Measurements and Applications (MeMeA); 2020.
- Haber CK, Sacco M. Scoliosis: lower limb asymmetries during the gait cycle. *Arch Physiother*. 2015;5:4. <https://doi.org/10.1186/s40945-015-0001-1>.
- Kramers-de Quervain IA, Muller R, Stacoff A, Grob D, Stussi E. Gait analysis in patients with idiopathic scoliosis. *Eur Spine J*. 2004;13(5):449–56. <https://doi.org/10.1007/s00586-003-0588-x>.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.