

Original Article

Three-dimensional gait quantitative analysis in postoperative rehabilitation of lumbar degenerative diseases: a self-controlled before-after study

Chao Zhou, Haipeng Xia, Jun Yin, Yanping Zheng

Department of Spine Surgery, Qilu Hospital of Shandong University (Qingdao), Qingdao, Shandong Province, China

Received January 28, 2021; Accepted February 24, 2021; Epub June 15, 2021; Published June 30, 2021

Abstract: Objective: To evaluate the efficacy of three-dimensional (3-D) gait quantitative analysis in the surgical treatment and postoperative rehabilitation in patients with lumbar degenerative diseases. Methods: This is a prospective study with self-control before -after. A total of 48 patients with lumbar degenerative diseases and treated in our hospital were enrolled in the observation group, 40 healthy individuals were included in the control group. Gait analysis was carried out with 3-D motion acquisition and analysis system. The 3-D gait quantitative parameters of the two groups were compared preoperatively. These include time-distance parameters (gait speed, stride frequency, stride length, support phase), hip joint flexion angle and gait deviation index (GDI). The 3-D gait quantitative parameters in the observation group were analyzed post operation and during rehabilitation. Pearson correlation coefficient was used to evaluate the correlation between 3-D gait quantitative parameters and the patient's visual analog score (VAS), Japanese Orthopedic Association (JOA) score and Oswestry Disability Index (ODI). Results: Compared with the healthy group, the time-distance parameters and the kinematics parameters of lower extremity joints in the observation group were significantly decreased (both $P < 0.001$). The gait index indicated that there were significant gait abnormalities in the observation group ($P < 0.001$). Two weeks after operation, the patient's VAS score, JOA score and ODI were significantly improved compared to the results preoperatively, as well as the 3-D gait quantitative parameters (all $P < 0.05$). Further improvement was then observed after 12 weeks of rehabilitation training (all $P < 0.05$), and the patient's gait was close to normal. Pearson correlation analysis showed that the improvement of the 3-D gait quantitative parameters positively correlated with VAS score, JOA score and ODI (all $P < 0.001$). Conclusion: The 3-D gait quantitative analysis can effectively evaluate the effect of operation and rehabilitation training.

Keywords: Lumbar degenerative disease, 3-dimensional gait, gait analysis, rehabilitation, correlation

Introduction

Lumbar degenerative disease is one of the most common types of spine diseases, which include lumbar disc herniation, spinal stenosis, lumbar spondylolisthesis, and degenerative scoliosis, etc. [1]. Statistically, lumbar degenerative diseases account for about 30% in orthopedic operations and are currently one of the largest sources of pain, disability and social medical burden in the world [2, 3]. Therefore, the treatment efficacy and rehabilitation have attracted much clinical attention. How to accurately evaluate the clinical efficacy and the effectiveness of rehabilitation training is also the focus of orthopedics surgeons and rehabilitation physicians [4].

Currently, relevant functional scales are mainly used as evaluation indicators for the assessment of treatment efficacy of spinal disease, such as the internationally accepted VAS score and ODI, which are widely used all over the world [5-7]. However, given the subjectivity of these assessment methods, it is often difficult to be accurate and comprehensive. Therefore, it is still necessary to explore objective and quantifiable measurement methods clinically.

Gait analysis is a technology that uses a variety of sensor technologies to obtain kinematics and electromyography signals of human lower limbs, and to study human gait movement function by analyzing its temporal and spatial characteristics [8]. Gait analysis can provide a wide

3-D gait analysis in postoperative rehabilitation

range of gait characteristics, including spatio-temporal parameters, dynamic joint range of motion, neuromuscular activity and dynamic joint reaction force, etc. These parameters can be evaluated in two-dimensional (2-D) or 3-D planes to assess the characteristics of a specific anatomical plane [9, 10]. At present, gait analysis has been widely used and studied in hemiplegia, cerebral palsy, knee osteoarthritis, etc., and has been highly recognized clinically [8, 11]. However, there is still a lack of sufficient research about its application in spinal degenerative diseases. It also lacks evidence in the application of postoperative rehabilitation. In this study, a total of 48 patients with lumbar degenerative disease were enrolled into the study to analyze and clarify the gait changes in preoperative, postoperative and rehabilitation process as well as its application in rehabilitation evaluation, aiming to provide reference for clinical practice.

Materials and methods

Patients

A total of 48 patients with lumbar degenerative diseases treated in our hospital from September 2018 to December 2019 were enrolled into this prospective self-controlled before-after study as observation group.

Inclusion criteria: ① There were clinical symptoms of lumbar degeneration, such as lumbar and leg pain, lumbar discomfort, intermittent claudication, etc. [1]; ② ≥ 18 years old; ③ Computerized tomography (CT), magnetic resonance imaging (MRI) and other imaging examinations showed lumbar disc herniation, spinal stenosis or lumbar spondylolisthesis, etc. in all patients; ④ After conservative treatment for 3 months, the disease was still hard to alleviate.

Exclusion criteria: ① Patients who have previously undergone lumbar operation; ② Patients diagnosed with congenital lumbar deformities or tumors in the lumbar spinal canal; ③ Patients with sequelae of cerebrovascular disease, knee arthritis, meniscus injury and other lower limb diseases affecting walking posture; ④ Patients with incomplete clinical data.

In addition, 40 healthy subjects were recruited as normal controls (healthy group) in the same period.

Ethics statement

This study followed the principles of the Declaration of Helsinki and was approved by the Ethics Committee of our hospital. All patients and their families were informed of this study and signed informed consents.

Treatment

All patients underwent minimally invasive transforaminal interbody fusion performed by the same senior spine surgeon. A unified staged rehabilitation training was carried out postoperatively [12]. In the first week after operation, bed rest and passive activities were the main focus. In the next week, active activities in bed were carried out. Active spine stretching exercises and gradual stretching exercises of lower back muscles were conducted at Week 3-6 to relieve symptoms and to increase muscle flexibility. After 6 weeks, core muscle intensive training and force walking mode training were carried out, including: ① training for the waist and hip muscles, such as bridge-style movement, supine arching exercises, "sit and reach", etc. ② training for the abdominal muscles, such as upper limb support exercises in the lying position, supine leg raise exercises, and modified Yanfei exercises, etc. ③ training for pelvic and lower limb functions, such as lateral pelvic strengthening exercises in the lying position, alternating pronation movement of the pelvis and crawling training in the lying position.

3-D gait analysis

The Italian BTS (G-WALK) 3D Motion Capture System was adopted for gait analysis. The equipment included 6 cameras, multiple markers, software (motion), etc., and the specific test methods were as follows.

At each evaluation, the patient was equipped with a set of whole-body reflection markers, which was primarily used for kinematic data collection. Participants were asked to perform a series of ground walking tests at a normal and natural speed on a 10-meter-long flat ground for 5 times. From the middle of the fifth trial, the whole gait cycle was taken for kinematics analysis. The 3-D gait quantitative parameters were recorded and analyzed, including time-distance parameters (gait speed,

3-D gait analysis in postoperative rehabilitation

Table 1. Baseline information (n (%), $\bar{x} \pm sd$)

Items	Observation group (n=48)	Healthy group (n=40)	P
Gender [n (%)]			0.659
Male	22 (45.83)	16 (40.00)	
Female	26 (54.17)	24 (60.00)	
Age (years old)	55.3±13.5	54.9±12.8	0.887
Weight (kg)	67.00±14.52	65.50±9.12	0.557
Height (cm)	167.8±7.8	168.5±8.5	0.691
Course of disease (year)	0.8-16		
Site of lesion (n)			
L4-5 segments	27 (56.25)		
L5-S1 segments	21 (43.75)		
Straight leg raise test positive	48 (100.00)		

Table 2. Differences in gait parameters ($\bar{x} \pm sd$)

Items	Observation group (n=48)	Healthy group (n=40)	P
Gait speed (m/s)	0.46±0.12	1.08±0.17	<0.001
Stride frequency (step/s)	1.10±0.24	1.62±0.26	<0.001
Stride length (cm)	115.37±6.20	141.87±7.60	<0.001
Ratio of left and right support phase	0.78±0.06	0.99±0.03	<0.001
Maximum hip joint flexion Angle (°)	19.50±2.10	29.42±2.23	<0.001
GDI on the affected side	86.93±12.42	100.02±10.23	<0.001

Note: GDI for Gait Deviation Index.

stride frequency, stride length, support phase), hip joint flexion Angle and GDI. When calculating GDI, the standardized gait cycle of the legs of the healthy controls was first input to calculate a reference GDI, and then the GDI of both legs of the observation group was calculated separately. The data was analyzed with supporting software. Only one complete test was carried out in health controls, while patients in the observation group underwent 3 complete tests pre-operation, 2 weeks post operation and 12 weeks post operation, respectively, to analyze the gait changes during rehabilitation.

Evaluation of rehabilitation

Pain assessment: VAS score was used to assess the improvement of the patient's pain, which was graded from mild to severe (0-10 points) based on patient's subjective pain degree [13]. The higher the score, the more intense the pain.

Low back pain assessment: JOA score was used for assessment of 4 aspects, including

subjective symptoms (low back pain, leg pain and/or tingling, gait), clinical signs (straight leg raise test, sensory impairment, movement disorder), limitation of daily activities and bladder function [14]. The highest score for subjective symptoms was 9 points, for daily activities was 14 points, for bladder function was 6 points, and the total score was 29 points. The lower the score, the more severe the patient's dysfunction.

ODI: The ODI score was used to evaluate the pain [6], single functions and individual comprehensive functions. There were 9 items in the scale, with 0-5 points in each item, and the total score was 45 points. The higher the score, the more severe the dysfunction.

Determination of the cross-sectional area of the torn muscle: Achieva 1.5T nuclear magnetic resonance (NMR) scanner manufactured by Philips Company in the Netherlands was used to perform T2-weighted MRI on axial intervertebral space of lumbar operation segment. Select the cross-sectional boundary of multifidus muscle by freehand and calculate its area [15].

Observation indicators

In this study, the gait changes in patients with lumbar degenerative diseases were firstly analyzed. The 3-D gait parameters of the observation group and the healthy group were mainly compared, including gait speed, stride frequency, stride length, left and right support phase, maximum hip joint flexion Angle and GDI.

In the observation group, the indicators of operation and rehabilitation and the changes of 3-D gait parameters were further analyzed, specifically including ① VAS score, JOA score, ODI score, and changes in multifidus cross-sectional area preoperatively and postoperatively; ②

3-D gait analysis in postoperative rehabilitation

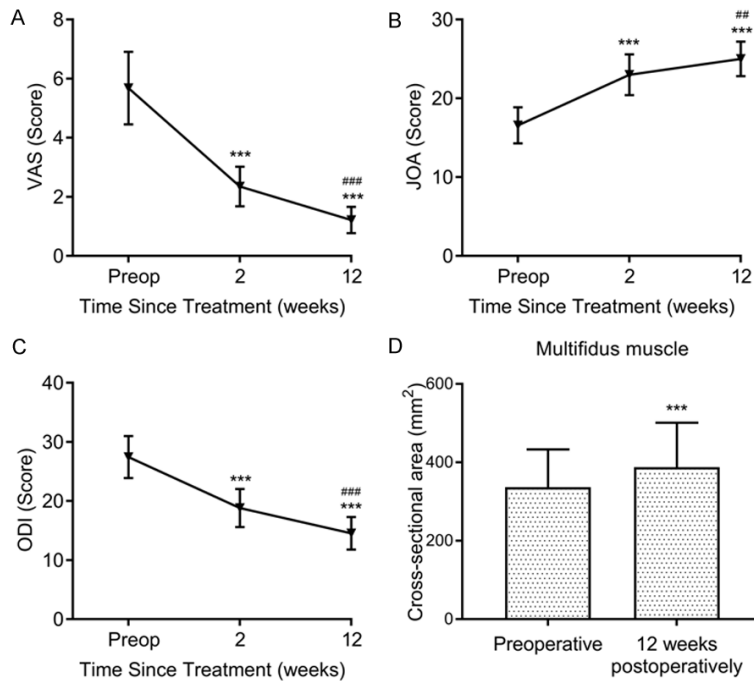


Figure 1. Significant improvement of postoperative rehabilitation indicators. A: VAS score; B: JOA score; C: ODI score; D: Multifidus cross-sectional area (mm²). Compared with pre-operation, ***P<0.001; compared with 2 weeks post operation, **P<0.01, ###P<0.001. VAS: Visual analogue scale; JOA: Japanese Orthopedic Association; ODI: Oswestry disability index.

the changes of 3-D gait parameters preoperatively and postoperatively in the observation group; ③ correlation between 3-D gait quantitative parameters and rehabilitation.

Statistical methods

SPSS 23.0 (SPSS, Inc., Chicago, IL, USA) was used for statistical analysis. The count data was expressed as the number of cases (percentage) (n (%)), and chi-square test was performed. The measurement data conformed to the normal distribution were expressed as mean \pm standard deviation ($\bar{x} \pm sd$). Independent sample t-test was used between groups, and paired t-test was used within groups. Pearson correlation coefficient was used to evaluate the correlation between 3-D gait parameters and the patient's rehabilitation. All statistical tests were two-sided using $\alpha=0.05$. P<0.05 was considered statistically significant.

Results

Baseline information

Compared with the healthy controls, there were no significant differences in gender, age, weight, height and other general demographic

characteristics in the observation group (all P>0.05). In the observation group, the shortest course of disease was 0.8 years and the longest was 16 years. More lesions in the L4-5 segment (56.25%) were identified. All patients were positive for straight leg raise test. See **Table 1**.

Gait differences

The gait differences between patients with lumbar degenerative diseases and healthy controls were compared preoperatively. Compared with the healthy controls, the gait speed, stride frequency, stride length, ratio of left and right support phase, maximum hip joint flexion Angle and GDI on the affected side in the observation group were significantly decreased (all P<0.001). See **Table 2**.

Evaluation of postoperative rehabilitation

VAS score, JOA score, ODI and multifidus cross-sectional area were used to evaluate the quality of postoperative rehabilitation. The postoperative VAS score and ODI showed a decreasing trend (**Figure 1A**), while the JOA score showed an opposite trend (**Figure 1B, 1C**). VAS score and ODI were significantly lower than those of pre-operation 2 weeks post operation (both P<0.001), while JOA score was significantly increased (P<0.001). Further improvements in VAS, JOA, and ODI were observed at 12 weeks postoperatively (all P<0.01). At 12 weeks postoperatively, the multifidus cross-sectional area was significantly increased compared with that pre-operation (**Figure 1D**; P<0.001).

Postoperative 3-D gait quantitative analysis

The time-distance parameters (**Figure 2A-D**), the kinematics parameters of lower extremity joints (**Figure 2E**) and GDI (**Figure 2F**) all increased post operation. Compared with pre-operation, patients showed higher gait speed, stride frequency, stride length, ratio of left and right support phase, maximum joint hip flexion Angle and GDI on the affected side (all

3-D gait analysis in postoperative rehabilitation

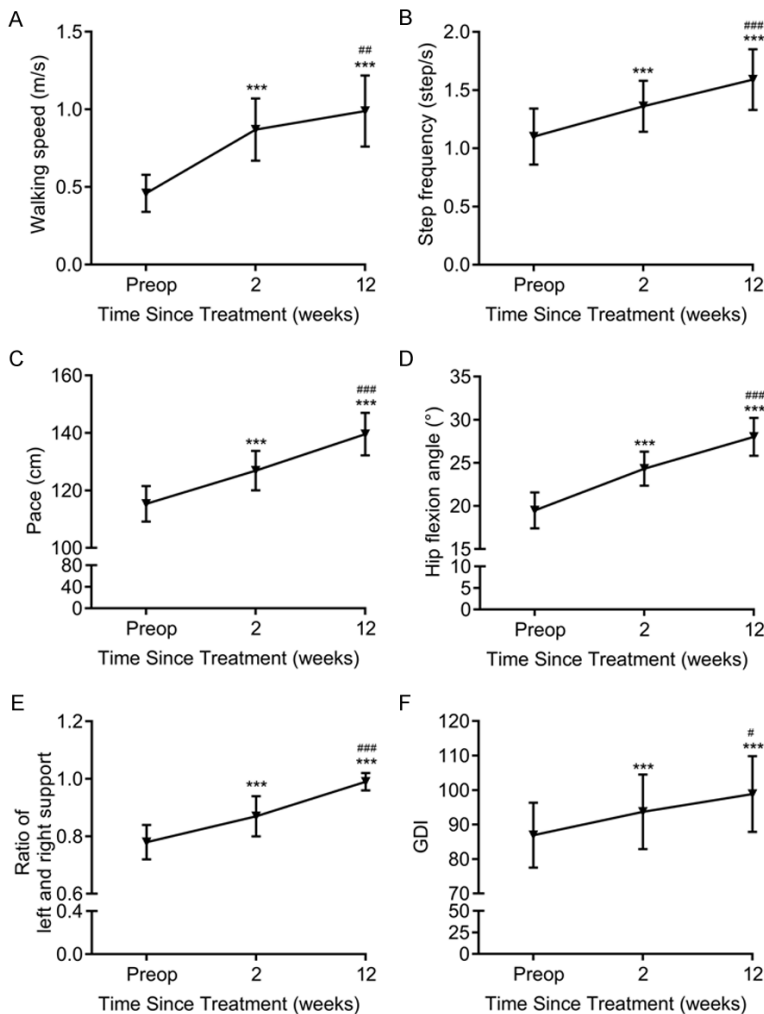


Figure 2. Changes of postoperative 3-D gait quantitative parameters. A: Gait speed (m/s); B: Stride frequency (step/s); C: Stride length (cm); D: Maximum hip joint flexion Angle (°); E: Ratio of left and right support phase; F: GDI. Compared with pre-operation, *** $P < 0.001$; compared with 2 weeks post operation, # $P < 0.05$, ## $P < 0.01$, #### $P < 0.001$; GDI: Gait Deviation Index.

$P < 0.001$) at 2 weeks post operation. In addition, further increases in these 3-D gait indicators were observed at 12 weeks postoperatively (both $P < 0.001$), which were close to normal.

The correlation between 3-D gait parameters and rehabilitation

Pearson correlation analysis showed that the improvement of the 3-D gait quantitative parameters had a significant positive correlation with VAS score, JOA score and ODI (all $P < 0.001$). See **Table 3**.

Discussion

As an advanced research method, 3-D gait quantitative analysis can be used to identify

the cause of dysfunction through the relevant information and evaluate the effectiveness of interventions [9, 10]. However, the data obtained by this method are large and complex. How to accurately use the results of 3-D gait analysis is a clinical problem that needs to be solved urgently [16]. It is still in the early stage of this technology, and thus not much attention has been paid to the field of spinal degenerative diseases [17, 18]. In this study, 3-D gait quantitative analysis in patients with lumbar degenerative disease was investigated so as to clarify the effect of 3-D approach in evaluation of the postoperative rehabilitation of patients with lumbar degenerative disease. The results showed that 3-D gait quantitative analysis could effectively evaluate the effect of operation and rehabilitation training.

In this study, the gait differences between patients with lumbar degenerative disease and healthy controls were compared at first. The results showed that the indicators of gait speed, stride frequency, stride length, ratio of left and right support phase, maxi-

mum joint hip flexion Angle and GDI on the affected side were significantly decreased. The gait speed, stride frequency, stride length and joint hip flexion Angle on the affected side can directly reflect the gait stability of patients, and the results showed that above four indicators would be reduced to maintain the stability of the gait in the case of motor dysfunction. These results are consistent with previous studies [19, 20]. The length of Supporting phase is a commonly used evaluation indicator for gait analysis, but literature showed that this indicator is sometimes affected by individual difference, resulting in decreased accuracy of evaluation [21]. However, this individual difference can be eliminated to a certain extent with the application of ratio of left and right support

3-D gait analysis in postoperative rehabilitation

Table 3. The correlation between 3-D gait parameters and rehabilitation

Items	Δ Gait speed	Δ Stride frequency	Δ Stride length	Δ Ratio of left and right support phase	Δ Maximum hip joint flexion Angle	Δ GDI on the affected side
ΔVAS score						
r	0.584	0.620	0.494	0.633	0.596	0.652
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
ΔJOA score						
r	0.532	0.483	0.509	0.615	0.593	0.642
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
ΔODI value						
r	0.482	0.522	0.494	0.538	0.492	0.613
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: Δ Refer to the absolute value of the difference of each indicator preoperatively and 12 weeks postoperatively; GDI for Gait Deviation Index; VAS: Visual analogue scale; JOA: Japanese Orthopedic Association; ODI: Oswestry disability index.

phase. The decrease of the ratio of left and right support phase indicated that the stability of gait can be elevated by increasing the support phase of both feet [21].

GDI is a composite indicator of gait abnormalities derived from the range of motion of the lower extremity joints, including data of coronal, sagittal and horizontal plan of pelvis and hip joint, flexion and extension of knee, ankle plantar dorsiflexion and step angle [22]. In a variety of pathological gait studies, such as cerebral palsy, muscle atrophy in children and Parkinson's disease, GDI value has shown high validity [23-27]. This study indicated that GDI of patients with lumbar degenerative diseases was significantly different from those of healthy controls. Study also showed that GDI of patients with spinal degenerative diseases was significantly lower than that of healthy people, which was consistent with this study. VAS, JOA, ODI and multifidus cross-sectional area are effective indicators for evaluation of patients with lumbar degenerative diseases [28]. In this study, above four indicators showed significant improvement 2 weeks postoperatively and 12 weeks after rehabilitation, indicating the effectiveness of operation and rehabilitation training.

The postoperative 3-D gait quantitative analysis showed that, with the improvement of the patient's condition, the gait speed, stride frequency, stride length, ratio of left and right support phase, maximum hip joint flexion Angle and GDI on the affected side all increased. Similarly, results of previous study comparing

the stride length, gait speed and Angle of hip joint motion of patients with degenerative scoliosis pre- and post-operation showed that the three indicators increased significantly post-operation [29], which was consistent with the result of this study. Further correlation between 3-D gait parameters and rehabilitation suggested that the improvement of the 3-D gait quantitative parameters correlated well with VAS, JOA and ODI, and thus further explained that 3-D gait quantitative analysis can be used for evaluation of postoperative rehabilitation of patients with spinal degenerative diseases, and has high application value.

This study may have some limitations. Firstly, due to the limited sample size, not all types of patients with lumbar degenerative diseases were included in current study. Secondly, there lacked a subgroup analysis of included disease types, which might lead to different results in 3-D gait parameters of different types. In addition, considering the difficulty of follow-up, there was no detailed tracking record of the data changes during the rehabilitation, and the 3-D gait analysis during the rehabilitation could not be displayed in more detail either.

In conclusion, our results support that 3-D gait quantitative analysis could effectively evaluate the surgical efficacy and rehabilitation training effects for patients with lumbar degenerative diseases. It can also provide references for effective training evaluation of patients, and contribute to the development of more individualized and accurate rehabilitation strategies in the future.

3-D gait analysis in postoperative rehabilitation

Acknowledgements

This work was supported by Research on the Kinematics and Time-Spatial Parameters of Lumbar Degenerative Diseases Based on Three-dimensional Gait Analysis and Its Clinical Significance (QDKY2019RX08).

Disclosure of conflict of interest

None.

Address correspondence to: Yanping Zheng, Department of Spine Surgery, Qilu Hospital of Shandong University (Qingdao), No. 758 Hefei Road, Shibei District, Qingdao 266000, Shandong Province, China. Tel: +86-0532-66850680; E-mail: zypjizhu@163.com

References

- [1] Harakuni T, Iwai H, Oshima Y, Inoue H, Kitagawa T, Inanami H and Koga H. Full-endoscopic lumbar interbody fusion for treating lumbar disc degeneration involving disc height loss: technical report. *Medicina (Kaunas)* 2020; 56: 478.
- [2] Kim SI, Min HK, Ha KY, Park HY, Cho CH, Cho RK and Kim YH. Effects of restoration of sagittal alignment on adjacent segment degeneration in instrumented lumbar fusions. *Spine (Phila Pa 1976)* 2020; 45: E1588-E1595.
- [3] Abrar DB, Schleich C, Tsiami S, Müller-Lutz A, Radke KL, Holthausen N, Frenken M, Boschheidgen M, Antoch G, Mucke J, Sewerin P, Braun J, Nebelung S and Baraliakos X. Functional MR imaging beyond structure and inflammation-radiographic axial spondyloarthritis is associated with proteoglycan depletion of the lumbar spine. *Arthritis Res Ther* 2020; 22: 219.
- [4] Schleich C, Müller-Lutz A, Matuschke F, Sewerin P, Sengewein R, Schmitt B, Ostendorf B, Wittsack HJ, Stanke K, Antoch G and Miese F. Glycosaminoglycan chemical exchange saturation transfer of lumbar intervertebral discs in patients with spondyloarthritis. *J Magn Reson Imaging* 2015; 42: 1057-1063.
- [5] Suther KR, Hopp E, Smevik B, Fiene AE, Lindberg HL, Larsen S and de Lange C. Can visual analogue scale be used in radiologic subjective image quality assessment? *Pediatr Radiol* 2018; 48: 1567-1575.
- [6] Arpinar VE, Gliedt JA, King JA, Maiman DJ and Muftuler LT. Oswestry Disability Index scores correlate with MRI measurements in degenerating intervertebral discs and endplates. *Eur J Pain* 2020; 24: 346-353.
- [7] Jones T, Miller R, Street JT and Sawatzky B. Validation of the Oswestry Disability Index for pain and disability in arthrogryposis multiplex congenita. *Ann Phys Rehabil Med* 2019; 62: 92-97.
- [8] Chakraborty S, Nandy A and Kesar TM. Gait deficits and dynamic stability in children and adolescents with cerebral palsy: a systematic review and meta-analysis. *Clin Biomech (Bristol, Avon)* 2020; 71: 11-23.
- [9] Haddas R, Ju KL, Belanger T and Lieberman IH. The use of gait analysis in the assessment of patients afflicted with spinal disorders. *Eur Spine J* 2018; 27: 1712-1723.
- [10] Raccagni C, Gaßner H, Eschlboeck S, Boesch S, Krismer F, Seppi K, Poewe W, Eskofier BM, Winkler J, Wenning G and Klucken J. Sensor-based gait analysis in atypical parkinsonian disorders. *Brain Behav* 2018; 8: e00977.
- [11] Apostolopoulos AP, Chronopoulos E, Michos IV, Mastrokalos D, Darras N and Nikolaou VS. Kinematic and kinetic waveform changes of the knee joint following a mobile bearing total knee arthroplasty-gait analysis and single step ascent. *J Knee Surg* 2020; 33: 978-986.
- [12] Xu DS, Walker CT, Godzik J, Turner JD, Smith W and Uribe JS. Minimally invasive anterior, lateral, and oblique lumbar interbody fusion: a literature review. *Ann Transl Med* 2018; 6: 104.
- [13] Chiarotto A, Maxwell LJ, Ostelo RW, Boers M, Tugwell P and Terwee CB. Measurement properties of visual analogue scale, numeric rating scale, and pain severity subscale of the brief pain inventory in patients with low back pain: a systematic review. *J Pain* 2019; 20: 245-263.
- [14] Ishibashi Y, Adachi N, Koga H, Kondo E, Kuroda R, Mae T and Uchio Y. Japanese Orthopaedic Association (JOA) clinical practice guidelines on the management of anterior cruciate ligament injury - Secondary publication. *J Orthop Sci* 2020; 25: 6-45.
- [15] Gwak GT, Hwang UJ, Jung SH, Kim HA, Kim JH and Kwon OY. Comparison of MRI cross-sectional area and functions of core muscles among asymptomatic individuals with and without lumbar intervertebral disc degeneration. *BMC Musculoskelet Disord* 2019; 20: 576.
- [16] Lakes EH and Allen KD. Quadrupedal rodent gait compensations in a low dose monoiodoacetate model of osteoarthritis. *Gait Posture* 2018; 63: 73-79.
- [17] Vårbakken K, Lorås H, Nilsson KG, Engdal M and Stensdotter AK. Relative difference among 27 functional measures in patients with knee osteoarthritis: an exploratory cross-sectional case-control study. *BMC Musculoskelet Disord* 2019; 20: 462.

3-D gait analysis in postoperative rehabilitation

- [18] Lakes EH and Allen KD. Gait analysis methods for rodent models of arthritic disorders: reviews and recommendations. *Osteoarthritis Cartilage* 2016; 24: 1837-1849.
- [19] Rasmussen HM, Pedersen NW, Overgaard S, Hansen LK, Dunkhase-Heinl U, Petkov Y, Engell V and Holsgaard-Larsen A. Gait analysis for individually tailored interdisciplinary interventions in children with cerebral palsy: a randomized controlled trial. *Dev Med Child Neurol* 2019; 61: 1189-1195.
- [20] Imagama S, Ando K, Kobayashi K, Machino M, Tanaka S, Morozumi M, Kanbara S, Ito S, Inoue T, Seki T, Ishizuka S, Nakashima H, Ishiguro N and Hasegawa Y. Multivariate analysis of factors related to the absence of musculoskeletal degenerative disease in middle-aged and older people. *Geriatr Gerontol Int* 2019; 19: 1141-1146.
- [21] Buckley E, Mazzà C and McNeill A. A systematic review of the gait characteristics associated with Cerebellar Ataxia. *Gait Posture* 2018; 60: 154-163.
- [22] Naili JE, Esbjörnsson AC, Iversen MD, Schwartz MH, Hedström M, Häger CK and Broström EW. The impact of symptomatic knee osteoarthritis on overall gait pattern deviations and its association with performance-based measures and patient-reported outcomes. *Knee* 2017; 24: 536-546.
- [23] Mañago MM, Cameron M and Schenkman M. Association of the Dynamic Gait Index to fall history and muscle function in people with multiple sclerosis. *Disabil Rehabil* 2020; 42: 3707-3712.
- [24] Cimolin V, Condoluci C, Costici PF and Galli M. A proposal for a kinetic summary measure: the Gait Kinetic Index. *Comput Methods Biomech Biomed Engin* 2019; 22: 94-99.
- [25] Matsunaga N, Ito T, Noritake K, Sugiura H, Kamiya Y, Ito Y, Mizusawa J and Sugiura H. Correlation between the Gait Deviation Index and skeletal muscle mass in children with spastic cerebral palsy. *J Phys Ther Sci* 2018; 30: 1176-1179.
- [26] Kobsar D, Charlton JM and Hunt MA. Individuals with knee osteoarthritis present increased gait pattern deviations as measured by a knee-specific gait deviation index. *Gait Posture* 2019; 72: 82-88.
- [27] Cahill-Rowley K and Rose J. Toddler temporal-spatial deviation index: assessment of pediatric gait. *Gait Posture* 2016; 49: 226-231.
- [28] Mar D, Lieberman I and Haddas R. The Gait Deviation Index as an indicator of gait abnormality among degenerative spinal pathologies. *Eur Spine J* 2020; 29: 2591-2599.
- [29] Haddas R, Lieberman IH and Block A. The relationship between fear-avoidance and objective biomechanical measures of function in patients with adult degenerative scoliosis. *Spine (Phila Pa 1976)* 2018; 43: 647-653.