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Preoperative and Postoperative, Three-dimensional Gait Analysis in Surgically Treated Patients With High-grade Spondylolisthesis

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Background: High-grade spondylolisthesis (HGS) (Myerding grade III-V) in adolescents can lead to a marked alteration of gait pattern and maybe the presenting symptom in these patients. This characteristic gait pattern in patients with HGS has been referred to as the "pelvic waddle." Modern 3-dimensional (3D) gait analysis serves an important tool to objectively analyze the different components of this characteristic gait preoperatively and postoperatively and is an objective measure of postoperative improvement. This study demonstrates the use of 3D gait analysis preoperatively and postoperatively in a cohort of 4 consecutive patients with HGS treated surgically at a single tertiary referral center and utilize this to objectively evaluate outcome of surgical treatment in these patients. This has not been reported previously in a cohort of patients.

Methods: This is a prospective analysis of patients with HGS who underwent surgical intervention for spondylolisthesis at a single institution. Patient demographics, clinical, and radiologic assessment were recorded, and all patients underwent 3D gait analysis before and after surgical intervention. Kinetic, kinematic, and spatial parameters were recorded preoperatively and postoperatively for all patients. This allowed the outcome of change in gait deviation index, before and after surgical treatment, to be evaluated.

Results: We were able to review complete records of 4 adolescent patients who underwent surgical treatment for HGS. Mean age at surgery was 13.5 years with a minimum follow-up of 2.5 years postoperatively (average 40 mo). Preoperative gait analysis revealed marked posterior pelvic tilt in 2 patients, reduced hip and knee extension in all 4 patients and external foot progression in 3 of the 4 patients. Along with an observed improvement in gait, there was an objective improvement in gait parameters postoperatively in all 4 patients. Gait deviation index score improved significantly from 78.9 to 101.3 (mean).

Conclusions: Preoperative gait abnormalities exist in HGS and can be objectively analyzed with gait analysis. Surgical intervention may successfully resolve these gait abnormalities and gait analysis is a useful tool to assess the outcome of surgery and quantify an otherwise intangible benefit of surgical intervention.

Level of Evidence: Level IV—case series.

Key Words: high-grade spondylolisthesis, gait analysis, gait deviation index

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In high-grade spondylolisthesis (HGS) (Myerding grades III and IV), Phalen and Dickson along with Newman described a characteristic gait pattern and attributed it to associated hamstring tightness in these patients.[1–3] This gait pattern has been referred to as the "pelvic waddle" and is characterized by a wide based stance, stiff lumbar spine increased lumbar lordosis, a retroverted pelvis and excessive knee flexion. This abnormal gait maybe the presenting symptom in adolescents with HGS.

Although hamstring tightness has been postulated as the driving mechanism for the abnormal gait in HGS clinically, its objective evaluation by utilization of 3-dimensional (3D) gait analysis has not routinely been done. Consequently objective improvement of gait following surgery, using modern 3D gait analysis in these patients has not been described. The authors are aware of only 2 studies in the literature reporting on gait analysis in surgically treated patients with HGS, of which, one was a case report. In the other study no preoperative gait analysis was undertaken.[4,5]

The use of gait analysis is widely used in the assessment and treatment of children with cerebral palsy and there are reports of gait analysis in children with adolescent scoliosis.[6–9] Likewise the use of gait analysis as an evaluation tool has been

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reported in adult spinal conditions such as cervical myelopathy[10,11] but the authors are not aware of any reports utilizing modern 3D gait analysis as an outcome tool in children with HGS.

We report our experience in the treatment of 4 consecutive adolescent females presenting to our department with the common features of an abnormal gait and a HGS and provide a detailed description and objective evaluation of the changes that occur in gait patterns following intervention. 3D gait analysis may offer an objective outcome measure in surgically treated patients with HGS and serves a useful tool to postulate causative mechanisms for the characteristic gait.

METHODS

This is a prospective, clinical case series review of 4 consecutive adolescent female patients with HGS who were treated surgically at single tertiary referral teaching institution in the period between 2013 and 2017. These patients represented the pilot group with no other comparative cohort. All 4 patients underwent gait analysis preoperatively and this was repeated postoperatively.

Preoperative clinical details, radiographic imaging and gait analysis measurements were recorded.

All 4 patients presented to the spinal department with predominant symptoms of an abnormal gait associated with varying intensity of low back pain, that had resulted in notable restriction of exercise tolerance with resultant reduction in school attendance. No patient reported of any neurological or radicular symptoms. Clinical examination revealed a characteristically abnormal gait in all 4 patients characterized by hip and knee flexion in a crouched posture with external rotation of the feet. All 4 patients exhibited hamstring tightness. Two patients had a mild associated scoliosis without cosmetic concerns for the patients. No objective neurological deficit was noted in any patient.

Standing postero-anterior (PA) and lateral radiographs of the spine with computerized tomography (CT) and magnetic resonance imaging (MRI) scans of the lumbar spine were undertaken on all patients (Figs. 1A–E).

Gait Analysis

3D gait analysis was performed preoperatively and postoperatively using the Smart-DX system (BTS Bioengineering S.p.A, Milan, Italy). Standard kinematic and kinetic measurements were made in the frontal, transverse, and sagittal planes.

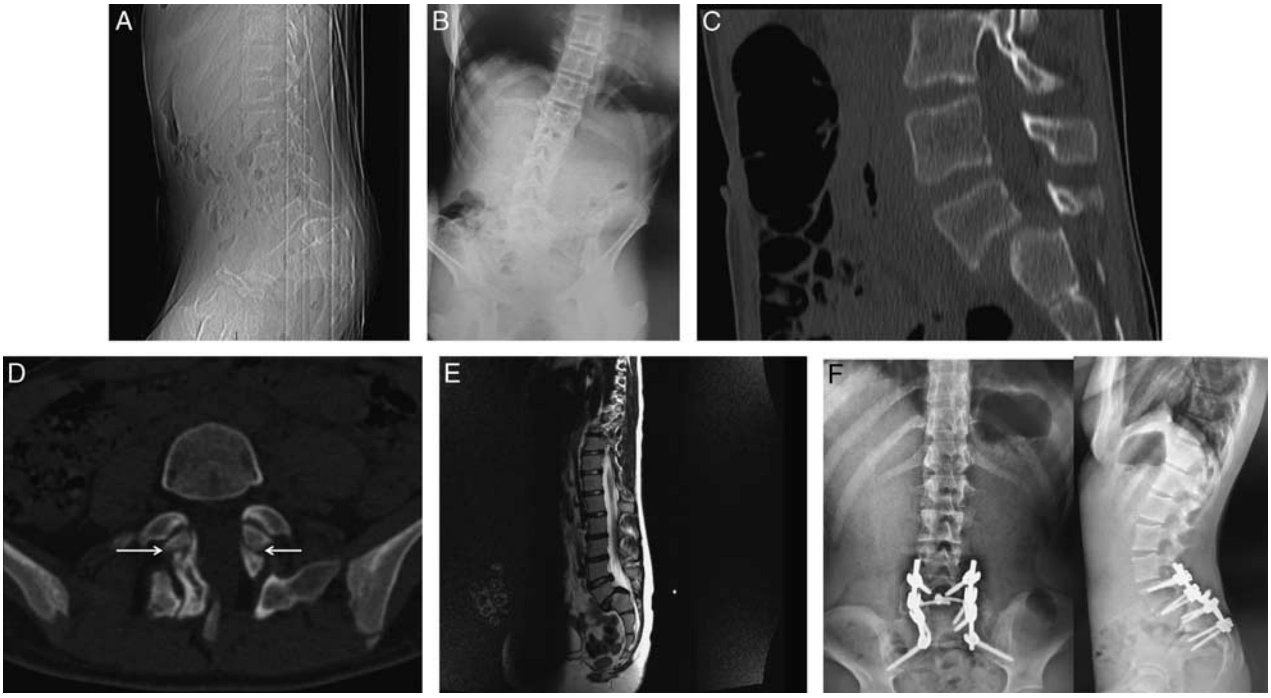

FIGURE 1. A, Preoperative lateral radiograph of the lumbosacral spine of case 4 aged 12 years at initial presentation showing a grade III spondylolisthesis of L5/S1. Note the vertical orientation of the sacrum indicative of the pelvic tilt. This is evident on the preoperative kinematics of gait analysis (Fig. 2A). B, Preoperative postero-anterior radiograph of case 4 at initial presentation. Mild scoliosis is seen. C, Lateral mid-sagittal CT scan image of case 4 preoperatively revealing a grade III spondylolisthesis. The vertical orientation of the sacrum is once again evident. D, Axial CT scan image at the level of L5/S1 in Case 4 showing the presence of bilateral pars defects associated with the spondylolisthesis in this patient (highlighted by solid arrows). This was noted in 2 of the 4 patients. The remaining 2 had an elongated pars. E, Preoperative mid-sagittal T2-weighted magnetic resonance imaging scan image of the spine in case 4 revealing narrowing of the spinal canal at the level of the spondylolisthesis. There were no neurological symptoms. F, Postoperative PA and lateral radiographs of the patient at 24 months postoperative follow-up showing good fusion with no loosening of metalwork. The grade of spondylolisthesis has improved from III to I.

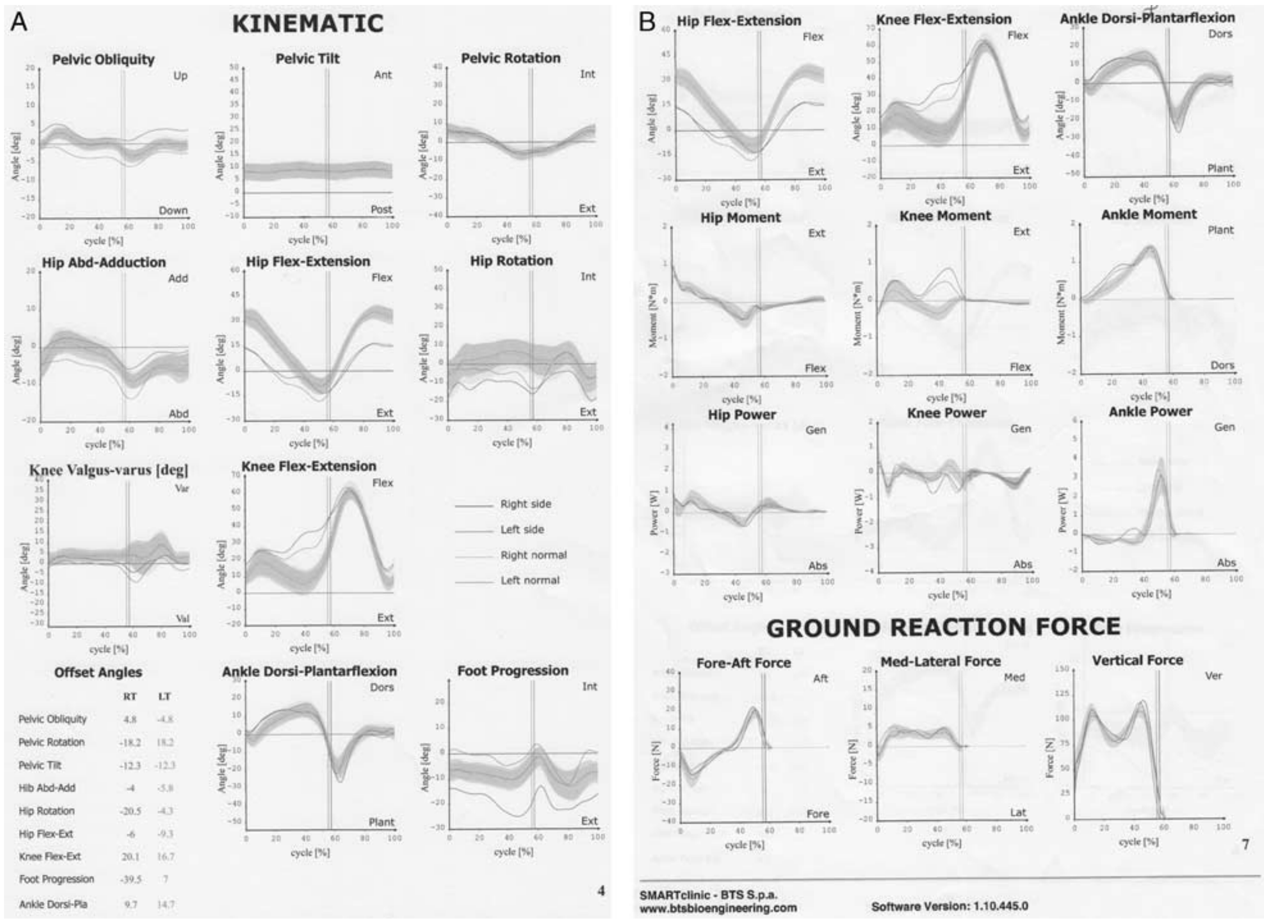

FIGURE 2. A, Preoperative gait analysis on case 4 showing the kinematic data. Marked posterior pelvic tilt along with persistent flexion of the knee in stance and swing phases of gait. There is external rotation of the right foot. B, Preoperative kinetics data on case 4: of note is the internal extensor moment at the knee caused by the persistent flexion at the knee.

The hardware used was Smart-DX (12 Infrared TVC Smart-DX 6000 cameras) with BTS FreeEMG 300 (16 Channels). It included 4 BTS P-6000 Force plates and 4 BTS Vixta video cameras. The software used included SMART Analyzer/Capture/Tracker/Viewer/Clinic 1.10.462.0; EMG-Analyzer 2.9.25.0 Digivec 1.0.4.0 and Sway 1.4.10.6.

Outcome Measures

Kinetic and kinematic data along with temporal and distance parameters were recorded in each patient preoperatively and repeated at 12 months postoperatively (Figs. 2, 3). The summative impact of these parameters on gait was assessed by calculation of the gait deviation index (GDI). GDI was documented at the preoperative visit and repeated at 1-year following surgery. The GDI is referenced to a normal developing population. It is a linearly constructed mathematical value with an accepted normal range between 100 and 125, obtained from 15 gait feature scores for a subject and the average of the same 15 gait feature scores for a control group of typically developing children.[12,13] A GDI of $\sim\geq 100$ indicates absence of gait pathology and each 10-point reduction represents 1 SD from normal.[12]

Surgery

All patients underwent surgery undertaken by the 2 senior authors. This was done using multimodal spinal neurophysiological monitoring consisting of motor-evoked potentials, somatosensory-evoked potentials and free running EMG. Particular emphasis was given to the neurophysiology of the L5 and the S1 nerve roots through the recording of continuous free running EMG. There was no alteration of neurophysiology potentials, from baseline data recorded at the start of the surgical procedure. No postoperative neurological deficit was noted in any patient. Surgery was done using a midline posterior approach. A laminectomy was performed at L5 and S1 to decompress the neural structures. L5 and S1 nerve roots were identified bilaterally and decompressed. Fluoroscopy guided pedicle screws were inserted in L4, L5, and sacrum. In 2 patients in addition, pelvic fixation was undertaken with S2 alar screws. The decision to instrument L4 was due to the severity of the slip in all 4 patients. Any reduction in the grade of the spondylolisthesis was obtained by gradual introduction of the rods into the screws with no significant emphasis on obtaining a complete reduction. Decortication of the exposed laminae of the instrumented levels was

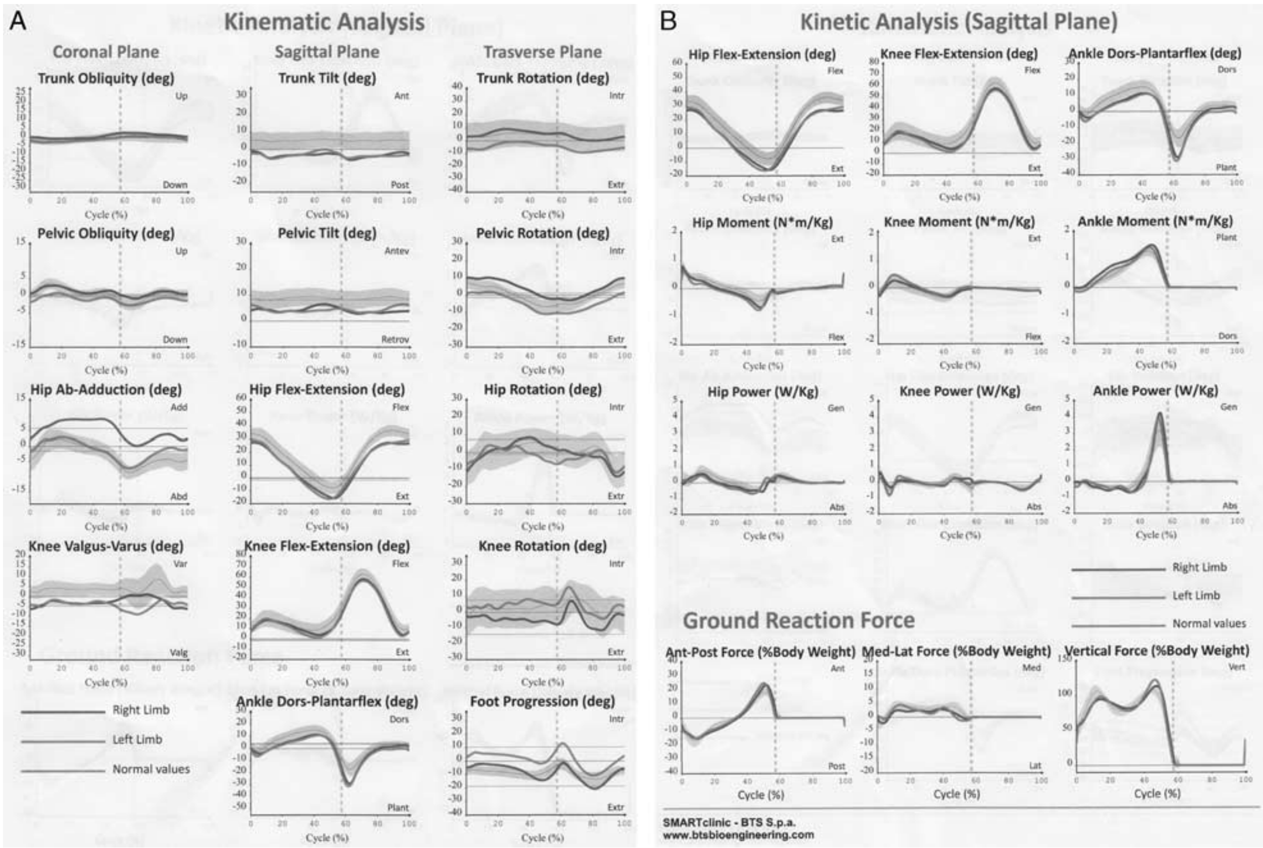

FIGURE 3. A, Postoperative kinematic data on case 4. The marked pelvic tilt seen preoperatively has improved significantly. Also the external rotation of the right foot has improved. Trunk kinematics is seen on this chart, which represents additional technology not available at initial examination. B, Postoperative kinetic data on case 4. The extensor knee moment seen in the preoperative analysis has normalized.

undertaken using a burr. The excised neural arch of L5 was milled and this bone graft was laid in the lateral gutters over the decorticated transverse processes. No external immobilization was used. Postoperatively, patients were prohibited from contact sports, gymnastics, swimming, and ballet for 12 months. Return to school was permitted at 4 weeks after surgery. Postoperative physiotherapy was not routinely needed with a notable improvement in back pain and gait pattern, observed in all patients by the 6-month stage after surgery. Radiographs of the spine were obtained usually at 3-month intervals to assess for integrity of instrumentation and fusion.

Ethics

The study was registered with the audit committee in our institution. As the gait analysis formed part of our normal investigative work up for these patients no ethical committee approval was required.

RESULTS

We had detailed analysis available in 4 female patients who were treated surgically for HGS at our institution between 2013 and 2017. They had an average follow up after surgery of 40 months (30 to 51 mo). Mean age at surgery was 13.5 years (range, 12 to 15). Patient characteristics are detailed in Table 1.

Standing preoperative radiographs of the spine confirmed the presence of grade IV spondylolisthesis at L5/S1 in 2 and grade III spondylolisthesis in the other 2 patients (Figs. 1A, C). The spondylolisthesis was associated with pars fractures in 2 patients and elongated pars without a fracture in 2 patients (Fig. 1D). In the 2 patients with pars fracture no activity related predisposing factors were noted. In specific these patients were not undertaking hyperextension activities such as gymnastics, ballet or significant contact sports that are normally associated with pars fractures. The radiographs at initial visit at our center represented the first radiologic investigation in these patients and no patient revealed any further progression of the spondylolisthesis from initial presentation to their surgical intervention. Two patients had an associated lumbar scoliosis measuring 30 degrees, which persisted after surgery without any cosmetic concerns or progression at last follow-up. MRI scans revealed the spondylolisthesis and this was associated with compression of the thecal sac at the level of the spondylolisthesis (Fig. 1E). In addition to the central stenosis, there was marked foraminal stenosis at L5/S1 in all patients. MRI scans ruled out any other pathology within the spine. Interestingly despite

TABLE 1. Patient Demographics

	Age (y)	Sex	Meyerding Grade	Preoperative and Postoperative (Parenthesis) Slip Angle	Surgical Procedure	Follow-up (mo) Postoperative
Case 1	14	F	IV	35 (28)	Posterior instrumented fusion L4 to S1 with decompression	51
Case 2	12	F	IV	31 (28)	Posterior instrumented fusion L4 to S1 with decompression	48
Case 3	15	F	III	37 (26)	Posterior instrumented fusion L4 to pelvis with decompression	30
Case 4	12	F	III	39 (29)	Posterior instrumented fusion L4 to pelvis with decompression	33

the presence of marked central stenosis on the MRI scan, no patient had any sphincter dysfunction prior to surgery. Likewise radicular symptoms did not feature in the initial symptomatology, with the abnormal gait and the back pain being the main concern for all patients.

At final follow-up no patient had any progression of the slip from the immediate postoperative radiograph (Fig. 1F). In all patients, surgery achieved an improvement of their slip by at least 2 grades. All 4 patients had observed improvement of their gait pattern postoperatively and this was confirmed objectively with gait analysis. In addition there was a notable improvement in exercise tolerance with all 4 patients reporting a reduction in the intensity of their back pain at final follow-up.

Preoperative Gait Analysis

All 4 patients had abnormalities of gait and the abnormality of gait was the main presenting feature in all of them.

Preoperative gait analysis, revealed a posterior tilt of the pelvis in half of the group with one of these patients having a very significant tilt in her pelvis. The pelvis tilt was accompanied by a tendency to an excessive hip flexion at initial contact, and a reduction of the expected hip extension in the preswing phase in all 4 patients (Fig. 2A). Within the knee, there was increased flexion at initial contact with reduction of knee extension in the stance phase. These features would reflect on the crouch posture adopted by these patients during stance and swing phases of the gait cycle. The abnormalities in hip and knee kinematics were accompanied by an external foot progression angle in 3 of the 4 patients. The second rocker was reduced in all 4 patients as would also be expected from the crouched posture prevalent in these patients.

The mean stride length preoperatively was 1.09 m and the mean gait velocity was 1.1 m/s.

Preoperative kinetics revealed an internal extensor moment in the knee in all patients (Fig. 2B), which normalised postoperatively (Fig. 3B). This co-related to the increased flexion of the knee at initial contact. The combined features of these gait abnormalities reflected on the lower preoperative GDI in all 4 patients with the mean preoperative GDI score being 78.9 (range, 70.64 to 92.32) (Table 2).

Postoperative Gait Analysis

Postoperative gait analysis revealed a significant improvement in all of the observed parameters in all planes (Figs. 3A, B). This was reflected in a visual improvement of the gait with improved stride length and mean velocity. In the sagittal plane there was a reduction of posterior pelvic tilt and a reduction of hip and knee flexion at initial contact (Fig. 3A). There was increased extension of hip in the preswing phase and increased knee extension in the stance phase. Foot progression was noted to improve with reduced external rotation of the foot in the transverse plane. (Fig. 3A). The mean stride length postoperatively, increased to 1.26 from 1.09 m preoperatively. The mean gait velocity postoperatively increased marginally to 1.2 m/s. This improvement in the spatial parameters may represent surrogate measures of the resolution of the crouch posture and the hamstring tightness.

GDI scores showed significant improvement after surgical correction. The mean postoperative GDI score was 101.3 (range, 84.8 to 114.4) (Table 2).

No further gait analysis was undertaken as the patients continued to be significantly improved with regards to their gait and symptoms at their final follow-up.

DISCUSSION

Phalen and Dickson reported on 2 patients with an abnormal gait pattern associated with HGS.[2] They attributed the abnormal gait to tightness of the hamstring muscles in these patients. However, they emphasised that tight hamstring muscles were not normally a feature of spondylolisthesis but instead caused by compression of the cauda equina that is thought to happen during the adolescent growth spurt.

Harnach et al[14] reported on a single case of a grade II spondylolisthesis in a 10-year-old girl who presented to their institution with an abnormal gait and limitation of lumbar flexion associated with "hamstring spasticity." The patient was initially treated with an anterior fusion at the lumbosacral junction. Despite a sound radiologic fusion

TABLE 2. Preoperative and Postoperative Gait Deviation Index (GDI) Scores

	GDI (Preop)	GDI (Postop)
Case 1	70.64	84.80
Case 2	77.32	98.65
Case 3	92.32	114.44
Case 4	75.12	107.37
Average	78.9	101.3

The GDI is referenced to a normal developing population (GDI scores between 100 and 125 indicate normal gait pattern).
GDI indicates gait deviation index.

the patient continued to have an abnormal gait and limitation of hip and knee extension and a restricted straight leg raise. Neurological examination, however, was normal. The patient then underwent a lumbar decompression and a laminectomy of L5, which resulted in resolution of symptoms. The authors postulated that symptoms were caused by compression of the lower lumbar and upper sacral roots although could not explain the paucity of any neurological signs in their patient.

Meyers et al[5] reported on one case of HGS again presenting with an abnormal gait that was analysed using 3D gait analysis. Preoperative gait analysis in their patient revealed posterior pelvic tilt with marked restriction of hip motion and abnormal kinematics of the knee as well with persistent flexion of the knee from initial contact through to the stance phase. This patient underwent a decompression and in situ fusion. Postoperative gait analysis of this patient at 10 months postoperatively revealed normalization of gait parameters in their patient. The authors postulated that the abnormal gait in their patient was due to hamstring tightness imposed by mechanical instability from the spondylolisthesis rather than neurological compression, as the patient had no detectable changes on neuro-monitoring preoperatively and they did not find any notable compression of the cauda equina intraoperatively. Their study is limited by the fact that it comprised of one patient only.

All 4 patients in our study revealed abnormalities in their gait analysis. Tight hamstrings would explain the abnormal hip and knee kinematics in all patients in our study. A posterior pelvic tilt may also be explained on the basis of hamstring tightness but this was present in only 2 of the 4 patients (Fig. 2). We analyzed the impact of the slip angle on pelvic tilt working on the assumption that the pelvic tilt maybe related to the lumbosacral kyphosis secondary to the spondylolisthesis. However, the preoperative slip angles as defined by Boxall et al[15] in the 2 patients with posterior pelvic tilt were 35, 39 degrees compared to the 2 patients with no pelvic tilt where the slip angles were 31 and 37 degrees. Hamstring tightness alone may not explain the pelvic tilt in these patients as all 4 patients in our study had hamstring tightness yet not all revealed pelvic tilt. It is possible that the pelvic tilt may be a compensation to the kyphosis at the lumbosacral junction imposed by the severity of the spondylolisthesis. The pelvic tilt improved in all patients in our study after surgery.

The other notable feature on the gait analysis was the external foot progression noted in 3 of the 4 patients. We believe that this could be secondary to the crouch posture in these patients. In the crouch posture, external foot progression is ergonomically more efficient in gait. This normalized in all patients postsurgery.

In all 4 of our patients, the presenting symptom was an abnormal gait and hence the use of gait analysis in the evaluation of these patients. Gait analysis provides useful objective data that can be used to assess functional impairment. However, it is also valuable to understand overall impairment caused by gait pathology. Schwartz et al[12] proposed the use of GDI as a measure of overall gait pathology. The GDI is defined as a scaled distance between the 15 gait feature scores for a subject and the average of the same 15 gait feature scores for a control group of typically developing children. The use of GDI as a measure of gait pathology is well validated.[16,17] Litrenta and colleagues reported on 1439 patients with 13 different diagnoses who underwent baseline gait analysis. Seventy-one of these patients had no underlying orthopaedic diagnosis.[16] The authors suggested quantifying gait impairment as mild, moderate or severe based on GDI values. A GDI value of > 80 was considered mild, and <70 as severe impairment. In addition to emphasizing on individual kinematic abnormalities we felt it necessary to utilize the GDI to focus on the severity of overall gait impairment in our patients. In our study 3 of the 4 patients would be designated as having moderate gait impairment (GDI between 70 and 80) on the basis of their GDI scores. In the remaining patient, gait impairment transitioned from the moderate threshold to mild impairment.

The accepted treatment for HGS is surgical.[18–20] However, controversy exists as to the type of surgery. In situ posterior fusion with decompression, reduction of spondylolisthesis with posterior fusion and decompression and circumferential anterior and posterior fusions have been described.[21–24] In situ fusions have been postulated to have higher pseudarthrosis rates and there have been reports of cauda equina syndrome after in situ fusions.[25,26] Proponents of reduction of spondylolisthesis report of better fusion rates and a better sagittal balance postoperatively.[27] However, reduction of spondylolisthesis has been associated with neurological deficits.[28]

Neurological complications either transient or long-term have been reported with surgical treatment of HGS.[15,25,26,29] The reported incidence of neurological complications with instrumented reduction of HGS varies from 8% to 30%.[29]

The preferred technique in our institution is to do a single midline posterior approach with decompression of neural elements, pedicle screw instrumentation and gentle partial reduction of the translation under neuro-monitoring. Although no patient in this study presented with neurological symptoms, preoperative MRI scans revealed severe stenosis at the level of the spondylolisthesis. There were no abnormalities in the neuro-monitoring undertaken intraoperatively but the severity of compression on the scans dictated the need for decompression in all 4 patients in the study. There were no postoperative neurological deficits in our study. All patients reported of symptomatic improvement and this was corroborated by the improvement seen on the postoperative gait analysis. The authors believe that in patients with HGS, the surgical technique described here may offer a safe way of improving symptoms, correct gait abnormalities and achieve satisfactory alignment of the spine. The authors, however, accept that this represents a small cohort of patients with a limited follow-up, despite the results being very encouraging.

The success of surgical treatment in patients with a spinal pathology is commonly assessed radiologically and through patient-reported outcome measures (PROMs) such as the Oswestry Disability Index. Radiologic assessment has the limitation of not being able to assess functional improvement while PROMs, especially in the pediatric population, maybe at risk of being promulgated by parents rather than the patients themselves. Gait analysis on the other hand may provide an impartial, objective assessment of treatment. Gait analysis is widely used in the assessment and treatment of children with cerebral palsy.[8,9] Its use in assessment of spinal disorders is less prevalent. Haddas et al[10] used gait analysis in 20 patients with adult degenerative scoliosis and 20 patients with cervical spondylomyelopathy and compared this with 15 healthy adult volunteers. Significant gait abnormalities including, reduced step length and cadence and longer stance time and step width were noted in affected individuals compared with healthy volunteers. The authors concluded that gait analysis offered an objective measure of functional gait in these conditions. However, gait analysis in the evaluation of paediatric spinal conditions seems to be limited.

Literature has focused mainly on fusion rates and restoration of sagittal balance as positive outcomes, from intervention in patients with HGS. However, gait abnormalities are common in these patients and yet the authors are not aware of any studies focusing on objective evaluation of gait in these patients or the use of gait analysis to document positive outcome in the surgical treatment of these patients. Meyers et al[5] published a case report of a patient with HGS with preoperative and postoperative gait analysis on their patient with an in situ fusion and decompression. Shelokov et al[4] undertook postoperative gait analysis only, on 7 patients, retrospectively who had undergone arthrodesis for spondylolisthesis in their adolescence to assess for any residual gait abnormalities in these patients. However, none of these patients had had a preoperative gait analysis. The authors believe that this study is the first of its kind with a detailed analysis of preoperative and postoperative gait patterns in a specific cohort of patients and wish to highlight the usefulness of gait analysis in the objective assessment of treatment in this group of patients.

Clinical symptoms were improved in all patients treated in our cohort but we specifically wanted to measure the outcome with respect to gait. We are able to show that significant improvement in gait parameters, that reached a minimum clinically important difference (10 point improvement in GDI) was achieved with surgical intervention.

We are aware of the small sample size and medium term follow-up in this study with the absence of a comparative cohort treated alternatively, but this has served as a suitable pilot cohort for future studies. All patients were followed up until they completed their skeletal growth with no patient showing progression of their slip after surgery.

Another limitation of the study is the absence of EMG analysis of the individual muscle groups in the gait analysis, which may have allowed us to focus treatment on specific muscles. However the observed improvement in gait clinically and on analysis postoperatively, emphasizes that the pathology lies within the spine in these patients with the muscle response especially within the hamstrings being secondary to the spinal pathology.

Studying gait patterns in surgically treated patients has allowed critical analysis of objective parameters and serves as an outcome measure of kinematic assessment. We have used a standardized and reproducible tool that can form the basis for future and more longer-term outcome studies with this rare condition.

CONCLUSIONS

In HGS preoperative gait abnormalities exist in the coronal, sagittal, and transverse planes that can be improved after surgical intervention. 3D gait analysis serves as a useful tool in assessing these abnormalities preoperatively and an objective outcome measure postoperatively. The authors propose that the surgical technique of gentle and partial reduction of the spondylolisthesis offers an effective way of obtaining resolution of symptoms and normalizing gait parameters.

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