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Leg-Length Discrepancy, Functional Scoliosis, and Low Back Pain

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Abstract

» In the setting of leg-length discrepancy (LLD), functional scoliosis occurs when the lumbar spine compensates for pelvic obliquity to maintain shoulder balance.

» Long-standing LLD may result in degenerative changes of the lumbar spine, altered gait mechanics, and low back pain.

» Patients with LLD, low back pain, and functional scoliosis should undergo radiographic evaluation with the pelvis leveled using blocks placed under the shorter limb. When the LLD or symptoms are minimal, patients may benefit from a shoe lift. Patients with an LLD of >20 mm may be considered for operative intervention.

Much has been postulated and written about the influence of leg-length discrepancy (LLD) on the lumbar spine with regard to functional scoliosis. Functional scoliosis is defined as the compensatory changes in the lumbar spine that maintain shoulder balance in the setting of pelvic obliquity (Fig. 1). Numerous observational studies have revealed correlations between LLD, degenerative changes in the lumbar spine, and low back pain; however, the exact relationship between LLD and the lumbar spine has not yet been clearly elucidated.[1-4] In this review, we summarize the theories and evidence regarding the relationship between spinal biomechanics and low back pain in patients with LLD and offer a critical appraisal of the literature, treatment considerations, and directions for future research.

Spine Biomechanics and Degenerative Changes Associated with Static LLD

In the search for a better understanding of the etiology of low back pain and effective treatment strategies, early investigators attempted to explain the observed correlation between low back pain, scoliosis, and LLD[1-5]. The prevailing theory was that pelvic tilt and compensatory, or functional, scoliosis in the short term resulted in asymmetrical loading of the intervertebral discs and facet joints in the lumbar spine (Fig. 2). That abnormality in turn led to mechanical low back pain and sciatica secondary to foraminal stenosis resulting from disc bulging or herniation[6,7]. Furthermore, long-standing abnormal spinal biomechanics were thought to result in degenerative disc disease and permanent changes in the lumbar spine[4,8].

Studies investigating lumbar radiographic changes in the setting of LLD have sought to better elucidate these associations. Giles and Taylor conducted a study evaluating the vertebral asymmetrical structural differences in 100 patients ranging from 19 to 61 years of age[4], 50 of whom had low back pain and an LLD of >9 mm and 50 of whom had low back pain and an LLD of 0 to 3 mm. In addition to noting a high prevalence of functional scoliosis in

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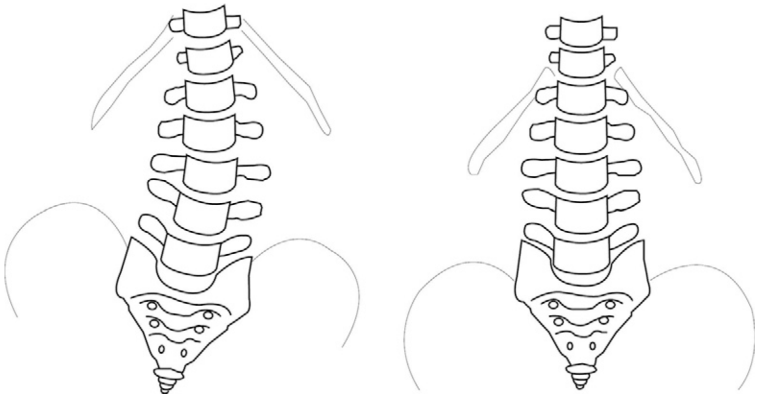

Fig. 1
In patients with functional scoliosis in the setting of pelvic obliquity, the lumbar spine compensates for leg-length discrepancy by bending toward the longer leg, thus maintaining upright shoulder balance (left). When the pelvis is leveled, the flexible lumbar spine resumes neutral alignment (right).

patients with an LLD of >9 mm, with the convexity of the curve located on the side of the shorter leg, the authors observed structural changes in vertebral morphology, including an increased prevalence of inferior end-plate asymmetry of the apical vertebra and wedging and increased height of the fifth lumbar vertebra, again on the side of the short leg (Fig. 3). Also noted were traction osteophytes, primarily in patients older than 40 years with LLD, suggestive of degenerative changes in the spine in response to long-standing functional scoliosis. Of the 50 patients with an LLD of >9 mm, 28% demonstrated end-plate asymmetry and 83% had traction osteophytes, compared with 2% and 25%, respectively, for the patients with little or no LLD. These findings led the authors to conclude that superimposed functional scoliosis is likely to result in accelerated disc degeneration. Murray et al., in a study of 225 patients presenting to a chiropractic clinic for the treatment of low back pain, evaluated standing anteroposterior and lateral lumbopelvic radiographs for indirect LLD on the basis of femoral head height and graded degenerative joint disease with use of the Kellgren-Lawrence criteria[9,10]. Patients with LLD had a significantly increased prevalence of degenerative joint disease at the L5/S1 spinal motion segment ($p < 0.0001$ for men, $p < 0.05$ for women) and at the L4/L5 segment ($p < 0.001$ for men, $p < 0.01$ for women) compared with corresponding male and female cohorts without LLD. When L5/S1 segment degeneration was evaluated as a function of age, men >50 years old with LLD had a significantly increased prevalence of degenerative changes compared with an age-matched cohort without LLD ($p < 0.01$).

Despite the observed radiographic changes in the lumbar spine, we are aware of only 1 study that has demonstrated an association between LLD, the resulting pelvic obliquity, and lumbar spine surgery. Radcliff et al. found an association between pelvic obliquity and degenerative scoliotic curve morphology in patients undergoing lumbar fusion for the treatment of degenerative scoliosis or degenerative spondylolisthesis[11]. Of 127 patients (mean age, 58.2 years) who presented with a single degenerative scoliotic curve, 91% demonstrated pelvic obliquity, and, in 71% of those patients, the curve pattern was consistent with a compensatory lumbar scoliosis. The authors concluded that there is a correlation, if not a cause-and-effect relationship, between pelvic obliquity and degenerative scoliosis resulting in lumbar spine surgery.

While other studies have not demonstrated similar morphological or degenerative changes in the lumbar spine in patients with LLD, they have supported the supposition that LLD and pelvic tilt have a lasting effect on lumbar biomechanics. Papaioannou et al. investigated functional scoliosis in 23 asymptomatic, skeletally mature patients who had had notable LLD (range, 12 to 52 mm) since childhood[12]. All patients demonstrated compensatory lumbar scoliosis, which corrected nearly completely when the pelvis was leveled using blocks placed under the shorter limb. Notably, patients maintained spinal asymmetry in lateral bending after neutralization of the LLD with a lift. The spinal asymmetry was decreased toward the previous convexity of the curve, or the shorter leg. While none of the patients complained of low back pain and no degenerative changes were seen on radiographs, these findings were suggestive of possible permanent structural changes in the lumbar spine resulting from long-standing LLD.

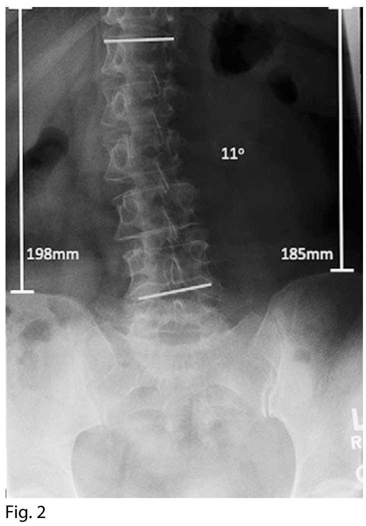

Fig. 2
Preoperative standing anteroposterior radiograph of the lumbar spine in a patient who was scheduled to undergo laminectomy for the treatment of multilevel spinal stenosis. The patient had a 13-mm indirect leg-length discrepancy and 11° of functional lumbar scoliosis. Notably, the 11° Cobb angle corrected fully when the patient was lying supine for magnetic resonance imaging.

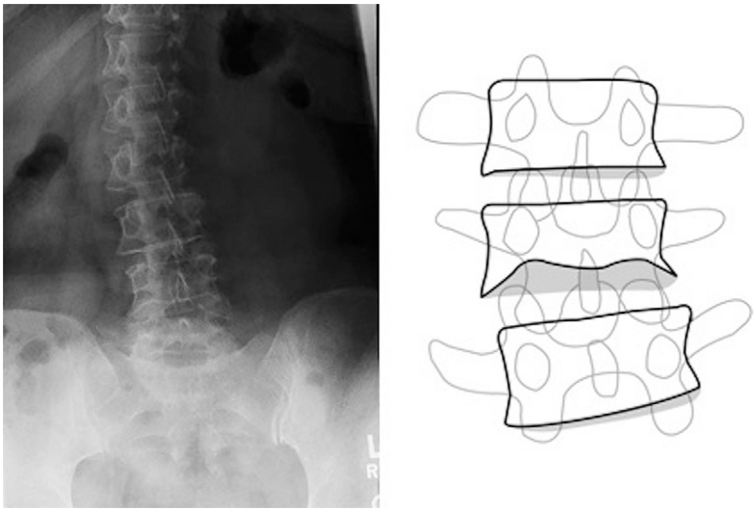

Fig. 3
Anteroposterior radiograph of the lumbar spine (left) of the same patient described in Figure 2, demonstrating the abnormal contour of the L4 vertebral end plate as originally described by Giles and Taylor[4]. The illustration on the right is provided to accentuate the changes in vertebral body morphology.

Gibson et al., in a study of patients with an LLD of ≥15 mm (range, 15 to 55 mm) secondary to a femoral shaft fracture sustained after skeletal maturity, found that functional scoliosis resolved nearly completely after correction of the LLD[5]. However, in that study, patients had a paradoxical increase in lateral bending toward the shorter leg, although the spine regained symmetry after correction of the LLD. This finding is contrary to that in the study by Papaioannou et al., which included only patients who had had LLD since childhood. These findings suggest that long-duration functional scoliosis may result in permanent, albeit poorly understood, biomechanical changes in the lumbar spine[12,13]. Notably, no degenerative changes in the spine were noted in the study by Gibson et al., although all patients were <31 years of age.

There is evidence to support LLD as a cause of persistent biomechanical changes in the lumbar spine, and those biomechanical abnormalities may result in permanent degenerative changes to the vertebral bodies. The duration of time that the spine is subjected to functional scoliosis also appears to affect the risk of degenerative changes, with older patients being more likely to demonstrate degenerative changes radiographically. However, to our knowledge, no study has demonstrated LLD as a causative factor in the development of lumbar degenerative scoliosis.

Spine Biomechanics During Gait in Patients with LLD

Whether LLD alters the biomechanics of the spine during gait is an important question, but little is known about this relationship. The majority of studies examining the impact of LLD have focused on energy expenditure, total work, and gait changes in the lower extremities without analysis of kinetic changes in the spine. Khamis and Carmeli, in a recent systematic review on this topic, found that an LLD of >10 mm can generate substantial changes in gait, with greater differences in leg length having greater impact[14]. Those authors also reported compensatory strategies involving both the shorter and longer limbs, with the magnitude of compensation proportional to the size of the LLD. Most investigators agree that pelvic obliquity is a common compensatory strategy during gait among patients with LLD[6,15-19].

Gurney et al., in a study examining the gait of 44 healthy men and women who were exposed to artificial LLD (in the form of shoe lifts), found that patients experienced greater oxygen consumption and perceived exertion when they walked with a 20-mm discrepancy as compared with no discrepancy[16]. Those exposed to a 30-mm difference additionally experienced an increase in heart rate, minute ventilation, and quadriceps fatigue. Song et al., in another study of gait changes, evaluated 35 neurologically normal children with LLD and found no correlation between the magnitude or percentage of LLD and any kinematic or kinetic variables, including pelvic obliquity[18]. In that study, the average obliquity in patients with LLD was no different than that seen in normal controls. However, the authors reported that an LLD constituting >5.5% of the length of the long extremity resulted in greater mechanical work and greater vertical displacement of the center of mass, although the observed compensatory mechanisms in response to those LLDs were related to the lower extremity and not the spine. Patients in both studies were observed to exhibit similar compensatory gait behaviors, such as steppage, circumduction, vaulting, and toe-walking gait in response to LLD[16,18].

Kakushima et al. evaluated the biomechanics of the spine in a study of healthy male volunteers in whom LLD was simulated with a 30-mm heel-raising orthotic device[20]. Significantly increased lateral bending motion was observed when heel-raising gait was compared with normal gait, with maximum lateral bending angles of 4.2° ± 1.4° (versus 3.0° ± 1.0°; $p < 0.001$) and 8.1° ± 2.8° (versus 6.1° ± 2.1°; $p < 0.0001$) in the thoracic and lumbar spine, respectively. The thoracic bending angle was greater on the raised side, whereas the lumbar bending angle was greater on the nonraised side, suggesting that spinal compensation to LLD involves both curves. Additionally, those authors reported significantly increased maximum lateral bending angular velocity of the thoracic ($p < 0.001$) and lumbar ($p < 0.01$) spine when heel-raised gait was compared with normal gait. Finally, they noted a significantly increased maximum shoulder girdle-pelvis rotation angle, defined as the angle between the shoulder girdle and pelvic lines in the axial plane, when heel-raised gait was compared with normal gait ($p < 0.001$). Changes in the lateral bending angles and shoulder girdle-pelvis bending angles were symmetrical during normal gait but were asymmetrical during heel-raised gait. From these data, the authors concluded that all of these changes in patients with LLD are likely to expose the spine to increased lateral bending stress, potentially increasing the risk of degenerative disease. However, no evidence was presented to support this claim, and other authors have questioned whether changes of such small magnitude translate into clinically meaningful differences[21].

In a similar study, Needham et al. evaluated the effect of 1, 2, and 3-cm heel lifts on the kinetics and kinematics of the pelvis and spine in 7 healthy male participants[22]. Although the authors found asymmetry in lumbar lateral bending similar to that reported by Kakushima et al., they doubted the clinical importance of the findings because the differences were <2° from baseline. Needham et al. also noted small differences in lumbar range of motion in the sagittal plane when the simulated 3-cm LLD condition was compared with baseline, but they found no such range-of-motion differences in the frontal or axial planes. The authors posited that compensatory mechanisms in the lower extremities may account for the lack of significant differences in spine flexion, extension, and rotation observed in their study.

Despite published data on simulated LLD, our understanding of spine biomechanics during gait in patients with actual LLD remains rudimentary. Although research has focused on the impact of LLD on lower-extremity biomechanics, compensatory gait patterns, and energy expenditure, data on the impact of LLD on spinal biomechanics remain limited to these simulation studies. From these early data, we may conclude that an LLD of ≥3 cm may induce changes in lateral bending and velocity during gait, although the magnitude of those changes appears small and of unclear clinical importance. More research is needed to better define changes in spine biomechanics in the setting of LLD.

Nonradiographic Evaluation of Functional Scoliosis

There has been increased interest in evaluating the relationship between spinal alignment and LLD through nonradiographic means. Rasterstereography—a 3-dimensional, optical imaging modality involving the use of body sensors and triangulation to create a surrogate for skeletal compensatory changes—has been shown to be an accurate means of assessing pelvic and spinal posture in patients with LLD[23]. Rasterstereography has been suggested as a radiation-free screening modality for scoliosis, and it has been used in several studies to evaluate spinal biomechanics in response to LLD.

Betsch et al. evaluated spinal compensation during progressively induced LLDs of 5, 10, and 15 mm in 115 healthy patients[24]. They noted that rasterstereography was useful for accurately measuring pelvic tilt and torsion in these subjects; however, the observed increases in pelvic tilt and torsion were not proportional to the amount of artificial LLD, suggesting that a high degree of compensation occurs through the lower extremities and possibly through torsion in the sacroiliac joints. Furthermore, no change in spinal alignment was detected in association with these relatively small induced LLDs. In a follow-up study that was performed to determine the amount of rasterstereography-detectable LLD that was sufficient to affect the spine, Betsch et al. found that a platform height of >20 mm caused notable coronal deviation of the spine to compensate for pelvic tilt[25]. While the authors noted a trend toward decreased thoracic kyphosis with increasing pelvic tilt, they did not observe a significant change in the sagittal plane, which was supported by similar findings from Kwon et al.[26]. These acute changes in lumbar compensation for induced LLD-related pelvic obliquity appear to be unaffected by the patient's age, despite the known age-related degenerative changes often seen in the elderly, such as decreased muscle tone, hip and facet osteoarthritis, and degenerative disc disease[27]. Interestingly, the finding of detectable changes in the lumbar spine with an LLD of >20 mm corresponds with the threshold at which these patients are typically considered for operative correction of LLD. Consequently, rasterstereography may serve as a useful screening adjunct to indicate further evaluation of LLD via standing hip-to-ankle radiographs.

LLD and Low Back Pain

The association between LLD and low back pain has been particularly controversial. Friberg, in a study of 653 Finnish military recruits with chronic low back pain and 359 asymptomatic controls, reported an LLD of >5 mm in 75% of the low back pain group, compared with 44% of the control group ($p < 0.001$)[6]. He further noted that symptomatic patients were 5.32 times more likely than asymptomatic patients to have an LLD of >15 mm. In further support of this positive association, the author reported that, among symptomatic patients treated conservatively with a shoe lift and followed for at least 6 months, 91% reported either decreased or resolved symptoms. Active patients who spent substantial time standing and those with spondylolysis and spondylolisthesis experienced a particularly positive response.

Biomechanically, Friberg surmised that functional scoliosis that occurs in response to LLD compresses the concave side of the disc, causing the disc to bulge posterolaterally toward the nerve root on the side of the longer leg. This hypothesis was supported by his finding that the majority of patients experienced symptoms on the longer side[6]. According to this theory, the posterior elements further rotate toward the curve concavity due to concomitant axial rotation, and the resulting physiological lumbar sway during gait causes asymmetrical bending and torsional loads that further damage the disc. In another study assessing the correlation between LLD and low back pain, Friberg analyzed 288 individuals with chronic low back pain who were patients in a Finnish military hospital[28]. The author found that the magnitude of LLD was significantly higher (10.6 versus 5.1 mm; $p < 0.001$) in the patients with chronic low back pain compared with asymptomatic controls.

After Friberg's work, several authors described positive results in association with the operative treatment of low back pain in patients with LLD. Rossvoll et al., for example, studied the effect of shortening osteotomy in 22 patients with LLD (average, 32 mm)[29]. After a mean duration of follow-up of 5 years, the authors reported a mean corrected LLD of 4.3 mm, with significant reduction in low back pain ($p = 0.02$). Similarly, Tjernström and Rehnberg performed lengthening in patients with an average LLD of 6 cm and reported a reduction in low back symptoms and improved ability to work, walk, and perform recreational activities postoperatively[30].

However, others have reported conflicting results when assessing the association between LLD and low back pain. Hoikka et al., in a study evaluating standing lumbar radiographs of 100 patients with chronic low back pain, found that LLD correlated poorly with lumbar scoliosis[31]. Although the average LLD in that population was small (mean, 5 mm), the findings nevertheless countered the prevailing belief that LLD always generates a corresponding lumbar scoliosis. In questioning the association between LLD and low back pain, the authors asserted that even a positive correlation between these 2 variables would not prove causation. Similarly, in a study of military recruits, Hellsing found no correlation between back pain or pain-provoking tests and LLD in patients with LLDs ranging from 5 to >35 mm[32]. Many other studies have demonstrated equivocal results regarding the relationship between low back pain and LLD[2,5,33-38]. In a more recent literature review, Knutson evaluated the data on a total of 573 patients with LLDs ranging from 0 to 20 mm (mean LLD, 5.2 mm) and found no difference in LLD between symptomatic patients and asymptomatic patients[39]. Other studies have demonstrated that pelvic asymmetry, which is thought to potentiate the effect of LLD, has no impact on low back pain, further weakening this association[40-42]. When considering these findings together, Knutson concluded that an LLD of <20 mm does not result in back pain, regardless of prolonged or repetitive loading[39].

More recent literature reflects the tenuous nature of this association. In a randomized study of patients with chronic low back pain and LLDs of ≤10 mm, Defrin et al. found that patients treated with shoe inserts experienced significant reductions in pain intensity ($p < 0.001$) and disability ($p < 0.05$), although the mean duration of follow-up was only 10 ± 2 weeks (range, 5 to12 weeks)[43]. Similarly, Golightly et al., in a study of 12 patients with low back pain and chronic LLD, found that the use of shoe lifts was associated with significant improvement in terms of general pain ($p = 0.0006$), pain with standing ($p = 0.002$), and disability ($p = 0.001$)[44]. In addition to correcting leg length, foot orthoses can alter foot posture, causing changes in kinematics in both the pelvis and lower extremity as well as in pelvic and lower extremity muscle firing[45]. Nevertheless, the results from other recent studies have countered these conclusions, demonstrating our lack of understanding about the impact of LLD on low back pain. For example, Morgenroth et al. studied LLD and low back pain in patients who had undergone transfemoral amputation (a population known to have a high prevalence of low back pain) and found no significant differences in static (standing) LLD or dynamic LLD during single or double-leg support throughout phases of the gait cycle between those with low back pain and asymptomatic patients[46].

Much effort has been devoted to understanding the association between low back pain and LLD, but many of the existing studies are small and there have been few randomized controlled trials. Given the equivocal nature of the results at this point, we conclude that the correlation between low back pain and LLD is weak at best. It is likely that a certain magnitude of LLD plays a role in low back pain, although it is unclear at this time what degree of LLD is required to cause symptoms. Furthermore, given changes in multiple parameters that tend to occur with LLD (e.g., sacral or pelvic tilt and lumbar scoliosis), it is likely that confounders are at play. Therefore, the true drivers of low back pain in these patients have yet to be fully elucidated.

Overview and Treatment Recommendations

There is a compelling body of literature investigating the relationship between LLD and functional scoliosis and its consequences, although there is also a notable dearth of definitive conclusions. Several studies have demonstrated an association between degenerative changes in the lumbar spine, alterations in spinal biomechanics, low back pain, and LLD, but they have failed to show causation, resulting in limited evidence to guide treatment.

While children typically do not complain of low back pain in the setting of LLD, the available evidence suggests that long-standing LLD may cause permanent changes in lumbar spine biomechanics, predisposing these patients to future low back pain and degenerative scoliosis[2,5]. Determining the precise correlations between LLD and its effect on the lumbar spine is further complicated by musculoskeletal compensation for LLD in the form of ankle equinus on the side of the short limb or knee flexion in the long limb, which may lead to altered ankle, foot, and knee biomechanics. Although long-standing lower-extremity compensatory mechanisms may protect the lumbar spine, they may also lead to a separate set of management considerations for the orthopaedic surgeon, including fixed flexion contractures, altered gait, and early arthritis[10,17].

Children and young adult patients with low back pain and an LLD of >20 mm in whom pelvic obliquity and scoliosis can be corrected with a shoe lift are thought to be good candidates for surgical correction of LLD[6]. While a shoe lift may be trialed in symptomatic patients with an LLD of <20 mm, there are limitations to this approach, including patient compliance and the inability to correct associated malalignment of the lower extremity. Consequently, in certain cases, patients with an LLD of <20 mm may be considered for surgical correction.

Effective shortening of the long leg may be achieved by means of epiphysiodesis in children and by means of femoral shortening osteotomy in adults. However, these surgical options have limitations, including loss of height and inability to correct associated malalignment of the lower extremity. After a trial with a shoe lift, lengthening of the short limb via distraction osteogenesis may be used to equalize the leg lengths and to level the pelvis. When possible, a motorized internal-lengthening nail should be used to avoid the challenges of external fixation. In growing children, the predicted LLD at maturity should be calculated before surgical lengthening is performed[47]. In adults with fixed pelvic obliquity, the surgeon may choose to lengthen the limb less than the full extent of the LLD, depending on the patient's comfort when the short limb is placed on blocks.

When evaluating a patient with LLD and scoliosis radiographically, a true functional scoliosis will correct completely or partially when the pelvis is leveled with blocks placed under the short leg (Fig. 4). In this setting, and especially with younger patients, an orthopaedic surgeon with expertise in limb lengthening should evaluate the patient prior to addressing the spinal deformity. It should be noted that in some cases, patients with pelvic obliquity secondary to scoliosis may accommodate their coronal imbalance through the hip, knee, or ankle. When standing hip-to-ankle radiographs are made, it is crucial for the patient to stand with the hips and knees extended and the ankle in a neutral position in order to avoid the possibility of incorrectly classifying a fixed coronal imbalance as a functional deformity. In cases of fixed pelvic obliquity in which the lumbar scoliosis persists despite leveling the pelvis, the patient is not interested in addressing the LLD, or the LLD is negligible, the surgical plan for the spine—when indicated—should accommodate the LLD and maintain level shoulder balance. Therefore, in order to maintain overall coronal balance when there is fixed pelvic obliquity, the spine should not be aligned perpendicularly to the pelvis in a fusion to the sacrum. In cases in which the lowest instrumented vertebra is located above the pelvis in the setting of LLD (e.g., in a patient with adolescent

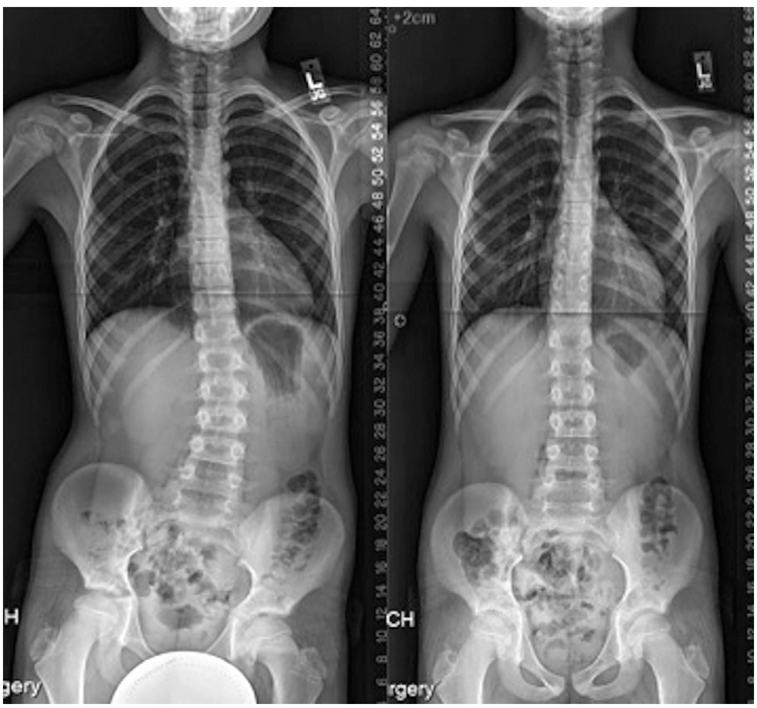

Fig. 4

Anteroposterior standing full-length radiographs of the spine in a patient with a 20-mm LLD and functional scoliosis who was referred to an orthopaedic spine surgeon. The existing lumbar curve (left) corrected completely after the placement of a 20-mm block under the left leg (right), and the patient was subsequently referred to a limb-lengthening specialist.

idiopathic scoliosis undergoing selective thoracic fusion), the flexible lumbar segment will accommodate the pelvic obliquity. The preoperative plan for spinal fusion is unaffected by whether the LLD is addressed before or after spinal fusion, or not addressed at all, although functional scoliosis would be expected to persist if the LLD is not corrected.

In patients with LLD and scoliosis, collaboration between surgeons specializing in the spine, limb lengthening, and complex deformities can help avoid unnecessary or incorrect surgery, resulting in improved outcomes. Given the prevalence of LLD in the general population and the increasing incidence of spine fusion over the past several decades, more meaningful research is needed to improve our understanding of how LLD affects the spine, especially with regard to its effect on the relative risk for future lumbar spine surgery.

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