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The Effect of Imposed Leg Length Difference on Pelvic Bone Symmetry

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This study was designed to examine the effect of varying degrees of imposed leg length difference on symmetry of the innominate bones in healthy college women with relatively equal leg lengths. Subjects' leg length was determined by clinical and roentgenographic procedures. Position of the innominate bones with and without lifts under one foot was measured with respect to the transverse plane using the Waterloo Spatial Motion and Recording Technique (WATSMART™; Northern Digital, Inc., Waterloo, Ontario, Canada), which allows very high spatial resolution. Our results show that posterior innominate bone rotation occurs on the side of the lengthened limb, and anterior rotation occurs on the shorter limb. The amount of pelvic obliquity increased in an approximately linear fashion as the leg length difference was increased from 2/8 to 7/8 inch. Some individual differences were evident. [Key words: leg length, pelvic obliquity, innominate bone rotation]

A difference in the length of the lower limbs (LLD) has been identified as a predisposing factor for acute and chronic injuries to the sacroiliac (SI) joint. Pitkin and Pheasant[33] ascribed pain arising from the SI joint to strain of the SI ligaments. They thought that in many cases the strain was a result of a LLD. Cibulka and Koldenhoff[5] argued that asymmetry of the innominate bones, which may result from a LLD, is a common component of low-back dysfunction. Such observations have been reported frequently by practitioners from a number of clinical disciplines.[1–4,6,8,11,12,13,16,19,21,22,25,26,27,32,35,37,39,41,45] Since an LLD of 5 mm or more has been estimated to be present in approximately half the adult population,[13–14,23,31,34] a better understanding of the relationship between LLD, innominate bone symmetry, and low-back pain is needed.

Pitkin and Pheasant[33] introduced the model that strain of the SI joint is predisposed by a LLD because the LLD is assumed to cause asymmetrical innominate bone rotation, placing the joints near the ends of their available motion. Despite the common clinical impression that a LLD results in SI strain and often leads to low-back pain, there remains surprising disagreement on the exact relationship between a LLD and the direction or extent of innominate bone rotation. For example, several authors have reported that a LLD results in a posterior rotation of the innominate bone on the side of the longer extremity.[10,21,25,33,39] Others have reported posterior rotation of the innominate bone on the side of the shorter limb.[5,40] DonTigny[11] has argued that only anterior innominate rotation is significantly associated with SI strain.

One complication in searching for a relationship between LLD and pelvic sagittal plane rotation is that other factors may contribute to innominate bone asymmetry, possibly independent of a LLD. Giles[20] and Subotnick[39] have pointed out that the mechanical affects of a LLD on the pelvis can be predicted only if there is normal anatomic structure and function of the SI joint. Studies of Solonen[38] and of Weisl[43,44] found extensive variability in the structure and presumably the arthrokinematics of this joint. Weisl[43] also reported articular surface degenerative changes and soft tissue or bony ankylosis in 30% of SI joints of anatomic specimens from subjects over the age of 30 years. Walter and Dickson[42] found no correlation between LLD, sacral angle, or the height of the iliac crests among children with an idiopathic scoliosis. Given such variability, prediction of the direction or extent of innominate bone rotation from a LLD would appear to be difficult at best, particularly in a clinical population where several factors may be operating at once. In light of this problem, we became interested in the extent to which a relationship could be established between these variables in a healthy population with apparently normal SI joints and equal leg lengths. Only two studies were found that investigated the effect of a LLD on pelvic asymmetry in normal subjects. Pitkin and Pheasant[33] studied 144 normal male college freshmen. They measured the inclination of the innominate bones in the sagittal plane under three conditions: standing with both feet on a

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level surface, followed successively by the right and the left foot on a 106-mm-thick board. They found consistent antagonistic movement of the two innominate bones, with anterior rotation on the short side and posterior rotation on the long side. The average total mobility was 11° of rotation (range, 3°–19°).[33] This report has several limitations, however. The authors did not report the reliability of their measurement instrument, nor did they screen the subjects to determine whether they had equal initial lower extremity length. They measured the effect of only one, rather extreme lift height. This leaves the question of whether the effect they found is a continuous, linear effect, or whether it occurs only at the lift height studied. Last, their finding of bilateral, asymmetrical innominate bone rotation in the sagittal plane has not been confirmed by other investigators.

The direction of pelvic asymmetry in response to LLD reported by Pitkin and Pheasant[33] is supported by Giles.[20] He used radiographs to measure the angle of the L5–S1 facet relative to the horizontal. Subjects were measured with and without an imposed LLD created by lifts under one foot. He found that the facets lay parallel when leg length was equal but not in the presence of a LLD. There was always a smaller angle with the horizontal on the short leg side, indicating ipsilateral sacral flexion and innominate bone anterior rotation on the short side. Although this study supports the direction of the resulting pelvic asymmetry reported by Pitkin and Pheasant,[33] it does not identify whether the asymmetry is created by rotation of one or both innominate bones.

The purpose of our study, then, was to investigate the effect of an imposed leg length inequality on pelvic symmetry. The questions asked were spurred by the conflicting reports found in the literature that speak to the nature of the effect as well as the degree of leg length inequality required to produce a significant change in pelvic obliquity. Therefore, our experimental questions were as follows:

1. Does a leg length inequality result in asymmetric rotation of the right and left innominate bones of the pelvis (i.e., anterior rotation on one side, posterior rotation on the other side)?
2. If a leg length inequality leads to pelvic asymmetry, what is the direction of the asymmetry?
3. Are there individual differences in the nature of the asymmetry (i.e., which innominate rotates anterior)?
4. Assuming that a leg length inequality does result in pelvic obliquity, what magnitude of leg length difference is necessary to produce an effect?
5. Is the effect of leg length inequality on pelvic symmetry continuous or discontinuous beyond a critical magnitude of leg length difference?

■ Methods

Subject Selection Procedure. Ten female college students, 19–23 years of age, served as subjects. Volunteers were recruited by posting a notice describing the experimental procedures on university bulletin boards. The experimental protocol, including subject selection, was approved by the University's Institutional Review Board.

All volunteers were screened by one of the authors (GC) to determine that each person's legs were equal in length by clinical measure,[46] and that both innominate bones were equally tilted to the horizontal. Pelvic inclination was measured with an instrument developed by one of the authors (GC).[9] The instrument was a hand-held calipers on which was mounted an electronic level with digital readout (Swiss Precision Instruments, Inc., Hackensack, NJ). This pelvometer was used to determine the angle of inclination of each innominate bone with the horizontal. Readings were taken after placing the two ends of the calipers over the anterior and posterior superior iliac spines. Intertester reliability for three testors on 20 subjects averaged 0.95, using the ICC(3) statistic.[9] Validity was established by comparison to radiographic measures. Differences between the measures were 0°–2°. The correlation between the pelvometer and radiographic estimates was 0.97, using the ICC(3).[9]

Subjects also were screened for movement dysfunction of the pelvis or spine. This was done subjectively by observing and palpating these structures while the individual (1) alternately raised one knee at a time toward the abdomen and lowered it back to the floor, (2) bent forward at the waist and returned back to the upright position, and (3) twisted the trunk slowly from side to side. Volunteers who were found to have a leg length inequality of greater than 4 mm, a pelvic obliquity greater than 5° degrees, or noticeable asymmetry of movement were eliminated from participation in the study.

Clinical measures of leg length have limited validity.[46] Therefore, volunteers who were selected after this initial screening received a standing anteroposterior roentgenogram using the method of Friberg.[14] We adopted this method of measuring leg length because it is the most valid method for estimating the total, functional length of the lower extremity, including such factors as differences in articular cartilage thickness, and calcaneal varus or valgus. Subjects stood with their feet spread apart such that a plumb line dropped from either anterior superior iliac spine bisected the foot into medial and lateral halves. Each subject's leg lengths were measured to the nearest millimeter from the resulting roentgenograms according to the method of Friberg.[14] Subjects whose leg lengths differed by less than 4 mm were considered to have equal leg lengths for the purpose of this study. Of the 12 people selected after initial screening, 10 qualified for the study.

Equipment. Pelvic position and motion was measured during the experiment using the Waterloo Spatial Motion and Recording Technique (WATSMART™, Northern Digital, Inc., Waterloo, Ontario, Canada). The reliability and validity of this motion analysis system for measuring angular position and motion in different spatial locations recently was documented in our experimental environment.[36] Infrared light-emitting diodes (IREDs) were attached bilaterally to the following landmarks using double-sided adhesive tape: (1) posterior superior iliac spine (PSIS), (2) greater trochanter, (3) lateral condyle, (4) lateral malleolus, and (5) base of the fifth metatarsal. The IREDs were wired to a strober that was connected to the control unit of the system. The control unit controlled the sequence of firing of each IRED.

Infrared light emitted from each IRED was captured by two infrared-sensitive charge-coupled device cameras. The cameras were mounted on a steel bar at the top of a wall, 12 feet opposite to the measurement volume, where the subjects stood. The cameras were tilted downward and angled inward toward the subject at 60°. This position allowed a clear view of each IRED by each camera. Each camera samples the centroid position of infrared light falling on its photoelectric plate. The x-y coordinate of the light centroid is digitized on-line and the coordinates of the two cameras for each sample are stored on disk. The x-y coordinates from the two cameras can then be used to estimate the three-dimensional coordinates of each IRED in space (see Scholz, 1989, for details). The IRED positions were sampled at 100 Hz.

Plexiglas rectangular plates measuring 15 × 6 × 1/8 inches were used to impose a leg length inequality. The maximum number of plates used under one foot was seven (7/8 inch).

Procedure. Subjects stood with their backs facing the cameras (Figure 1). They focused on a mark located at eye height on the wall directly in front of them. Since a LLD > 3 mm was found on radiographic examination of 3 of 10 subjects, we compensated for this difference by placing a 1/8-inch lift under their shorter leg. Thus, their baseline (i.e., no-lift condition below) had a lift to equalize their leg lengths. Each trial began with a subject standing with the appropriate number of lifts for that trial under one foot. The subject was instructed to stand as relaxed as possible. In examining the mechanical effect of LLD we anticipated that various compensatory mechanisms might come into play: namely, weight shift to one side, flexion of one knee, and asymmetrical stance.[29,30] Each of these compensatory responses may interact, leaving undetermined the effect of LLD alone on pelvic position. Therefore, we chose to perform this initial study while limiting tendencies to stand and bear weight asymmetrically, or to flex the knees. Subjects were instructed before each trial to keep their knees straight without hyperextending them and not to lean their trunk to one side or the other.

After providing a few seconds to accommodate to the lift, data collection was triggered by the computer. Recording proceeded for 3 seconds. Only the middle 2 seconds of data were used for this analysis. The order of presentation of each lift side (right or left) by lift size (2/8, 3/8, 4/8, 5/8, 6/8, or 7/8 inch) combination was randomized across trials. Six trials were recorded for each lift size by lift side condition. Trials were run in blocks of seven each, with the first trial of each block being a control trial, with no lift under either foot (no-lift condition).

Experimental Variables. The independent variables of this study were the side of the lift and the size of the lift. We had no a priori reason to expect a difference in response to the side on which the lift was placed. Given that this was an exploratory study and that asymmetries of upper and lower extremity use are known to exist, however, we chose not to collapse our analysis across the lift side.

The dependent variable in this study was the difference in pelvic tilt between the two innominates (i.e., pelvic asymmetry). Pelvic tilt was defined as the sagittal plane angle formed between the transverse plane and an imaginary line connecting the PSIS to the greater trochanter.

The anatomic coordinates obtained from the infrared system are relative coordinates, depending on the relative position of the cameras in space, their calibration, and the precision with which the IREDS were placed on the subject. As a result, it is possible for both innominate bones actually to be tilted to the horizontal by the same amount and for the two reconstructed angles of tilt to differ slightly in magnitude. Therefore, for each trial on which a LLD was imposed, the reconstructed angle of tilt of each innominate (e.g., RH and LH) was subtracted from the mean tilt angle calculated over all no-lift trials (RH_0 and LH_0). This procedure yielded the relative tilt of each innominate ($LT = LH_0 - LH$ and $RT = RH_0 - RH$) resulting from the imposition of a lift. Negative values indicate posterior tilt and vice versa (Table 1). The difference between the relative tilt of the two innominate bones (LT - RT) served as the dependent vari-

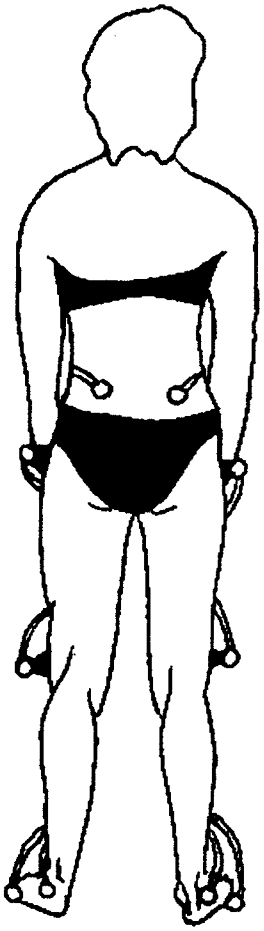

Figure 1. Placement of the infrared diodes (IREDs) on the subject, viewed from the plane of the cameras. Leg IREDs were mounted on dense foam with oblique surfaces so the IREDs faced backward and were clearly viewed by both cameras.

Table 1. Mean Degree of Pelvic Tilt Resulting from Imposed Leg Length Differences

Side of Lift	Hip	2/8 in.	3/8 in.	4/8 in.	5/8 in.	6/8 in.	7/8 in.
Left	Left	-0.61	-0.89	-0.97	-0.99	-1.11	-1.45
	Right	1.01	1.51	1.87	2.17	2.97	2.83
Right	Left	1.05	1.52	2.18	2.46	2.72	3.25
	Right	-1.06	-1.38	-1.62	-2.21	-2.11	-2.48

Negative values indicate posterior tilt relative to no lift trials.

able because we were interested in the degree of asymmetry created by the imposed leg length inequality. Tilting of both innominates in the same direction (e.g., anterior) by the same amount would result in no difference in relative tilt (LT - RT = 0; i.e., no asymmetry). For each subject, the mean absolute value of pelvic asymmetry (i.e., |LT - RT|) was calculated over the six trials in each experimental condition and used for the statistical analysis.

Statistical Analysis. A lift side (2) by lift size (6) repeated measures analysis of variance (ANOVA) was performed on the dependent variable. We hypothesized that a significant effect would be found for lift size, with the degree of pelvic asymmetry increasing as lift size increased. No effect for lift side or interactions between lift side and lift size were expected. Tukey post-hoc comparison tests were done to determine where significant differences occurred.

Results

Table 1 presents the mean value of pelvic tilt across subjects for each hip. A lift placed under the left foot resulted in posterior tilting of the left innominate and anterior tilting of the right innominate. Placing a lift under the right foot led to the opposite effect. Thus, the transient imposition of a lift under one foot leads to pelvic obliquity. Moreover, the degree of pelvic obliquity increases linearly with the size of the lift (Table 1). The repeated measures ANOVA revealed significant effects for both lift side ($F_{1,9} = 6.684$, $P < 0.029$) and lift size ($F_{5,45} = 14.721$, $P < 0.001$). The single degree of freedom polynomial contrast for the linear trend of lift size also was significant ($F_{1,9} = 22.474$, $P < 0.001$). Placing a lift under the right foot resulted in greater obliquity than placing it under the left foot for all lift sizes. The interaction effect was nonsignificant ($P = 0.674$).

Although overall the effect of imposing a leg length discrepancy has clear effects on pelvic symmetry, even when imposed differences were as small as 2/8 inch, individual differences in response were clearly present, particularly for the effect of lift size. The most striking individual difference was found for subject S7. Her pelvic tilt data are presented in Table 2. In comparison to the remaining nine subjects (all of whom showed patterns of change similar to those depicted in Table 1), the left innominate of this subject consistently tilted in the direction opposite to that of other subjects, regardless of the side of the lift. Moreover, the pattern of change with increasing lift size was not consistent.

Discussion

Our study confirms and extends the findings of Pitkin and Pheasant.[33] That is, an imposed LLD causes pelvic obliquity, with posterior rotation of the innominate over the longer leg and simultaneous anterior rotation over the shorter leg. In addition, our results show that the effect is roughly linear in response to imposed differences between 1/8 and 7/8 inch.

One subject showed consistent motion of the left innominate in the direction opposite from all the others. We speculate that her left SI joint may have an anomalous formation with reversed orientation of the wedges of the articular surfaces.[38,43] This subject serves to remind us that individual differences exist that change the effects of a LLD on pelvic obliquity.

It is important to emphasize the scope of our study. Our subjects were young, healthy women with ideally functioning SI joints and relatively equal leg length. We tested the effect of imposed LLD under the artificial conditions of not permitting them to bend their knees or to shift their weight. We therefore investigated only the effect of imposed LLD on pelvic obliquity, but did not investigate the compensatory patterns of stance that might result from LLD. We anticipate that stereotypical patterns are naturally assumed from imposed or natural LLD, and that these patterns may themselves be important factors determining the ultimate effects of a LLD. This is suggested by Klein et al's finding that correction of a LLD with heel lifts resulted in restoration of equal leg length in children within 6 months.[28] That this occurred only among children with the lifts may reflect a change in the children's stance pattern, resulting in stimulation of bone growth in the limb that was originally shorter.[28]

The statistical significance of our results justifies a discussion of whether the amount of pelvic obliquity seen is of clinical significance. One could argue that the pelvic obliquity found in this study is too small to

Table 2. Mean Degree of Pelvic Tilt Resulting from Imposed Leg Length Differences for Subject 7

Side of Lift	Hip	2/8 in.	3/8 in.	4/8 in.	5/8 in.	6/8 in.	7/8 in.
Left	Left	0.96	0.77	1.71	2.19	0.86	1.24
	Right	1.09	1.73	2.03	2.39	3.28	3.26
Right	Left	-1.49	-1.55	-1.42	-1.64	-1.98	-2.62
	Right	-0.89	-1.08	-0.05	-1.14	-1.37	-1.55

be meaningful clinically. Pitkin and Pheasant found innominate bone rotation of 3°–19°, although the reliability and validity of their method is unknown.[33] This appears consistent with maximal linear displacements at the SI joints of 5–6 mm.[7,44] We found between 2° and 6° of obliquity, which represents a significant percent of available motion at the joint. Whether a given degree of obliquity is likely to give rise to clinical problems is probably a function of whether it results in connective tissue strain. It is reasonable to assume that the amount of obliquity found in this study places the joint at or near the end of its available motion in subjects with below-average SI joint excursion. This positioning can be expected to limit movement strategies or patterns during activities that involve movement of the pelvis. Weisl[43] has shown that several SI ligaments are under constant loading in normal standing. Any amount of pelvic obliquity would therefore result in asymmetrical loading of these ligaments, which may predispose them to chronic strain.

The leg length difference imposed in this study was only transient. This may be seen to raise further doubts about the clinical significance of the findings. Although a more prolonged period of imposed LLD would be more meaningful, it likely would be viewed as unethical because of the potential negative consequences. A more adequate answer to the question of clinical significance probably will require more dynamic studies of the effect of imposed LLDs on the function of normal subjects, and eventually on subjects with pathologic conditions. That is, it will be important to determine the effect that imposed LLDs have on patterns of movement and the resulting joint mechanics during activities such as walking, lifting, stair climbing, or the like. Such experiments currently are being planned.

The effect of imposed LLD was shown to be immediately reversible under conditions of a lift under the opposite foot or removing the lift. This implies that whenever we stand on uneven surfaces, transient pelvic obliquity tends to occur unless we compensate for the difference by positioning of the lower limb joints. We would anticipate that clinical complaints may arise in this condition only when the same position is habitually assumed for long periods. An example might be if a worker had to stand in the same position on an uneven surface when at his or her work station.

This study did not investigate whether the same pelvic obliquity occurs in subjects with functional or anatomic LLD. That it does is suggested by most of the clinical opinion cited in the review of literature. Moreover, a natural LLD appears to cause a habitual postural asymmetry, whether by direct effect or through compensatory postures. The persistence of this effect was supported by Klein et al,[28] who found that naturally occurring LLD caused pelvic obliquity and compensatory scoliosis that persisted in both standing and sitting. Logic suggests that a LLD imposes a constant asymmetry of loading on the SI joint surfaces that might predispose the person to degenerative changes of the joint. The latter effect is clearly suggested by studies that showed earlier, and more extensive, degenerative changes in the SI joint on the side of the short limb.[18] Degenerative changes also were found in the lumbar vertebrae at the apex of the lumbar scoliosis secondary to LLD of 9 mm or more.[17] If chronic LLD is a cause of pelvic obliquity it also may predispose one to acute injury of the low back. Correlational studies have shown that among subjects with low-back pain, there is a higher than normal incidence of LLD. Conversely, in samples of the general population, a greater percentage of those with a LLD have low-back pain.[13,16,22,24,32,34] Despite the implication that there might be a causal relation between LLD and low-back pain, studies have not been found that demonstrate this relationship. Indeed, not all studies have found a correlation between LLD and low-back pain.[47] If, however, LLD does prove in the end to be a cause of low-back pain, pelvic obliquity may prove to be an important variable.

■ Summary

We have shown that in young women with relatively equal leg lengths an imposed LLD between 2/8 and 7/8 inch causes progressive pelvic obliquity, with the innominate on the side of the longer limb moving toward posterior rotation, and the contralateral innominate bone moving more anteriorly. Future studies are needed to determine the dynamic effect of this manipulation on function and the presence and significance of this response in subjects with natural or acquired LLD.

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