Improvement in Gait Parameters After Lengthening for the Treatment of Limb-Lengtth Discrepancy

BY ANIL BHAVE, P.T., DROR PALEY, M.D., F.R.C.S.(C), AND JOHN E. HERZENBERG, M.D., F.R.C.S.(C), BALTIMORE, MARYLAND

Investigation performed at the Maryland Center for Limb Lengthening and Reconstruction, Baltimore

A Abstract

Background: Patients who have limb-length discrepancy demonstrate an altered gait pattern or a limp. The purpose of this prospective study was to compare the objective gait parameters for the shorter lower limb with those for the longer lower limb before and after lengthening and to compare these data with those for a group of twenty subjects who had no limb-length discrepancy.

Methods: Eighteen patients had equalization of limb length to within one centimeter. We analyzed the stance time, the second peak of the vertical ground-reaction-force vector, and the rate of loading with use of two force-plates arranged in a series.

Results: The difference in the mean stance times between the shorter and longer limbs before lengthening was 12 percent, whereas that after lengthening was 2.4 percent; the difference between the values before and after lengthening was significant (p < 0.001). The difference in the stance times between the limbs of the patients who did not have limb-length discrepancy was 2 percent. Preoperatively, the mean second peak was 104 percent of body weight for the shorter limb compared with 116 percent for the longer limb; this difference was significant (p < 0.001). A tter lengthening, the mean second peak for the shorter limb increased to 113 percent of body weight. The difference in the means for the second peak before and after lengthening was significant (p < 0.001). With the numbers available, no significant difference was detected in the means for the second peak between the shorter and longer limbs after lengthening (p = 0.12).

Conclusions: This study shows that lengthening of the shorter limb of patients who have limb-length discrepancy can normalize symmetry of quantifiable stance parameters and eliminate a limp.

*Although none of the authors has received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article, benefits have been or will be received but are directed solely to a research fund, foundation, educational institution, or other nonprofit organization with which one or more of the authors is associated. No funds were received in support of this study.

†Maryland Center for Limb Lengthening and Reconstruction, The James Lawrence Kernan Hospital, 2200 Kernan Drive, Baltimore, Maryland 21207. The e-mail address for Mr. Bhave is abhave@mcllr.ummc.ab.umd.edu.

Copyright 1999 by The Journal of Bone and Joint Surgery, Incorporated
limbs. In contrast, a normal gait is symmetrical as shown by equal vertical ground-reaction-force vectors for both limbs. Many people who have a normal gait may have limb-length discrepancy of as much as eight millimeters. Such discrepancy usually is not considered to be of any functional importance as it is easily compensated for without a limp. Limb-length discrepancies of 1.2 to 2.5 centimeters have been shown to be associated with arthritis of the hip joint on the side with the longer limb. Using ground-reaction-force-vector analysis, Kaufman et al. found that limb-length discrepancy of more than two centimeters caused an asymmetry in gait between the longer and shorter limbs. Those authors quantified the asymmetry by comparing the stance time, the first and second vertical force peaks, and the rates of loading and unloading for both the shorter and the longer limbs. They found that the amount of asymmetry was greater than that observed in the normal population, that it tended to increase as the limb-length discrepancy increased, and that it varied among individuals depending on functional adaptation. Limb-length discrepancy of more than 5.5 percent leads to greater mechanical work by the longer limb and also to a greater vertical displacement of the center of gravity of the body.

It has been documented that, when using a shoe-lift, patients who have limb-length discrepancy have an improvement in stance time, resulting in a more symmetrical gait. However, to our knowledge, such a study has not been performed after operative correction of limb-length discrepancy. In the current prospective study, we analyzed objective gait parameters for the shorter limb and compared them with those for the longer limb before and after limb-lengthening in order to determine if operative correction produced symmetry of ground-reaction-force vectors, thereby normalizing gait. We also compared these findings with those of twenty subjects who had no limb-length discrepancy in order to determine if the correction resulted in gait parameters that fell within the normal range.

**M aterials and M ethods**

Eighteen patients (fourteen male and four female) who had limb-length discrepancy participated in this prospective study. All patients had limb-lengthening between June 1993 and November 1995. The mean age at the time of the operation was twenty-four years (range, six to eighteen months) after removal of the external fixator. The preoperative analysis showed that all patients held the foot in equinus to varying degrees as a compensatory mechanism. Because rehabilitation is more rapid after lengthening with use of a nail, the patients who were managed with the traditional Ilizarov method were those who were managed earlier postoperatively than those who were managed with the traditional Ilizarov method.

For comparison, we analyzed the gait of twenty normal subjects who had no history of musculoskeletal or neuromuscular impairment. These individuals had no clinical evidence of limb-length discrepancy (the pelvis was level with the subject standing), although radiographs were not made for this group. The age-range of these subjects was sixteen to thirty-two years (mean age, twenty-one years). We chose to use a comparison group instead of data from the literature because the type of platform that we used to measure ground-reaction-force vectors differed from those used in previous studies and because we used dual platforms whereas in previous studies' single platforms were used.

**I nstrumentation**

Two strain-gauge force-platforms (AMTI; Advanced Medical Technologies, Watertown, Massachusetts) were arranged end-to-end in the frontal plane and were offset in the sagittal plane in the middle of a walkway that was thirty feet (9.1 meters) long and 4.5 feet (1.4 meters) wide. Data were gathered from the force-plates at a frequency of 1000 hertz. An analog-to-digital converter connected to an IBM-compatible computer was used to collect amplified force data. The ground-reaction-force vectors were analyzed with use of A riel Dynamics
software (version 6.88; Ariel Life Systems, San Diego, California). This software allows the accurate measurement of vertical, mediolateral, and anteroposterior ground-reaction-force vectors; however, only the vertical ground-reaction-force vector was analyzed as this vector has been shown to correspond the most to gait deviation associated with limb-length discrepancy4,12.

Procedure

The force-plates were calibrated and set to zero before each trial. To begin the data collection, force-plate 1 was triggered with use of the patient’s body weight and data were collected for three seconds from both plates. The trigger also instructed the computer to recover the data that were recorded during a 0.6-second interval (20 percent of the three-second test interval) before the trigger. Patients were instructed to walk over the force-plates, making complete contact with each (Fig. 1). All trials were performed with the patients barefoot.

Force-plate 1 measured the ground-reaction-force vector of the left limb, and force-plate 2 measured the subsequent ground-reaction-force vector of the right limb. Each patient was allowed to walk over the force-plates several times to establish their natural gait. The patients were instructed to walk at their preferred rate. Five values of ground-reaction-force vectors were obtained for each limb.

Data Analysis

The stance time and the second peak of the vertical ground-reaction-force vector were measured for both limbs (Fig. 2). We also measured the rate of loading from the time of foot contact to the first peak of the vertical ground-reaction-force vector on both sides. The difference between the stance times of the two limbs was normalized and was expressed as a percent reduction for the shorter limb compared with the longer limb. The second peak of the ground-reaction-force vector was normalized to the patient’s body weight and was expressed as a percentage of body weight. The rate of

![Diagram showing the walkway with the dual force-plates arranged end-to-end in order to measure consecutive stance parameters. Plate 1 (channel c) was used as the trigger to begin data collection. Five measurements of the vertical ground-reaction-force vector were obtained for each limb of each patient.](image1)

**Fig. 1**

![Graph showing the normal vertical ground-reaction-force vector versus time. The rate of loading equals the peak ground-reaction-force vector (GRFV [1]) divided by the time to peak load.](image2)

**Fig. 2**
loading, measured as the peak load during initial stance divided by time, was expressed as the product of body weight per second. For example, if a person weighed 100 pounds (45.4 kilograms) and the value recorded at the first peak of the ground-reaction-force vector was 150 pounds (sixty-eight kilograms) in 0.5 second, the rate of loading would be three times the body weight per second.

The values of these three parameters were recorded and averaged for the five trials of both limbs. In addition, for patients who had had tibial lengthening, we recorded the ability to perform a single heel-rise in order to assess the strength of the plantar flexors as described by Lunsford and Perry. We used a force-plate to document the vertical ground-reaction-force vector during the single-heel-rise test. The force-plate was calibrated to the patient's body weight, after which the patient stepped on the plate and performed the maximum number of single-stance heel-rises possible. We documented the maximum number of repetitions that the patient could perform and also recorded the peaks of the force-plate data. The data from ten of these trials were averaged for each patient and were expressed as a percentage of body weight.

The significance of the findings was evaluated with a paired t test for comparison of all paired variables before and after limb-lengthening. Regression analysis was used to compare the effect of limb-length discrepancy on the variables that were measured before lengthening. Comparison between the patients who had limb-lengthening and the twenty normal subjects was done with a standard t test. A p value of less than 0.05 was considered significant.

**Results**

All patients had equalization of the limbs to within one centimeter after the lengthening procedure. The mean increase in length was 4.7 centimeters (range, three to eleven centimeters). The difference in the mean stance times between the shorter and longer limbs was 12 percent (range, 4.9 to 19.8 percent) before lengthening, whereas the mean difference in the stance times between the two limbs of the normal subjects was 2 percent (range, 1.4 to 3.5 percent); this difference between the patients and the normal subjects was significant (p < 0.01).

After limb-lengthening, the mean difference in the stance times between the two limbs was 2.4 percent (range, 0.5 to 6.5 percent). The difference in the stance times before and after lengthening was significant (p < 0.001; Fig. 3). With the numbers available, we detected no significant difference between the variation in the stance times between the two limbs of each of the patients who had had lengthening and that between the two limbs of each of the normal subjects (p = 0.8). For five patients, the reduction in the stance time of the shorter limb after lengthening was greater than the mean difference between the stance times of the two limbs of each of the twenty subjects who did not have a limb-length discrepancy. Three of these patients had a stance-time asymmetry of 4 percent, and the other two had a stance-time asymmetry of 5 and 6.5 percent. The latter two patients walked with an imperceptible limp after lengthening.

We measured the second peak of the vertical ground-reaction-force vector, which corresponds to the capacity of the gastrocnemius-soleus muscle to stabilize the
ankle joint and to the body rolling forward over the supporting foot. For the shorter limb, the mean was 104 percent (range, 101 to 123 percent) of body weight, which was significantly less (p < 0.01) than the mean value for either limb of the twenty normal subjects (mean, 121 percent; range, 112 to 131 percent). For the longer limb, the mean was 116 percent (range, 110 to 125 percent) of body weight. After limb-lengthening, the second peak of the vertical ground-reaction-force vector for the shorter limb increased to a mean of 113 percent (range, 101 to 126 percent), which was a significant improvement compared with the value before lengthening (p < 0.001).

We also compared the second peak of the vertical ground-reaction-force vector of the longer limb with that of the shorter limb before and after lengthening. This difference was significant before lengthening (p < 0.001), but no significant difference could be detected after lengthening, with the numbers available for study (p = 0.12). After lengthening, all patients except one had an open lengthening of the Achilles tendon at the time of application of the Ilizarov frame for a concomitant lengthening of the femur and tibia and also had a stance-time asymmetry of 6.5 percent after lengthening. For the three patients who had had percutaneous lengthening of the Achilles tendon, the second peak of the vertical ground-reaction-force vector was within the normal range.

The ten patients who had had lengthening of the tibia (of the tibia only [eight patients] or of both the tibia and the femur [two patients]) also had assessment of the strength of the plantar flexors as described previously. Seven patients had strength that was grade 4 (of 5), meaning that they were able to perform more than twenty heel-rises, and two had grade-4 strength, meaning that they could perform ten repetitions. The remaining patient could not perform any heel-rises. Of the seven patients who had had normal strength preoperatively, six had complete recovery. The seventh patient had a decrease in strength, to grade 4. The three patients who initially had had less-than-normal strength had no change postoperatively. Thus, nine of the ten patients who had had normal strength preoperatively had an improvement in this parameter. The patient with no improvement had had an open lengthening of the Achilles tendon at the time of application of the Ilizarov frame for a concomitant lengthening of the femur and tibia and also had a stance-time asymmetry of 6.5 percent after lengthening. For the three patients who initially had had less-than-normal strength, there was no change postoperatively. Thus, nine of the ten patients who had had normal strength preoperatively had an improvement in this parameter.

The mean rate of loading of the shorter limb before lengthening was 5.7 times body weight per second (range, 3.8 to 8.0 times body weight per second). The mean rate of loading after lengthening of the shorter limb was 4.7 times body weight per second. The difference in the rates of loading of the shorter limb before and after lengthening was significant (p < 0.001). The mean rate of loading for the normal individuals was 3.9 times body weight per second (range, 3.0 to 5.1 times body weight per second); this value was significantly less than the value for the shorter limb before lengthening (p < 0.001), and it remained significantly less after lengthening (p < 0.01).

None of the eleven patients who had had lumbosacral pain preoperatively had such pain at the time of the follow-up evaluation.

Discussion

The long-term effects of limb-length discrepancy include arthritis of the hip on the side with the longer limb and low-back pain. This study demonstrates that the
shorter limb bears weight for less time than does the longer limb. The longer limb also bears a greater load than does the shorter limb. The cumulative effect of increased loads for a longer duration may be a reason for the development of early degenerative arthritis. Furthermore, when patients who have limb-length discrepancy compensate by lowering the pelvis on the shorter side while walking, the coverage of the femoral head by the acetabulum decreases on the side with the longer limb. This decreased area of weight-bearing in the hip joint, combined with the bearing of increased loads for a longer duration, may be the cause of early osteoarthriti- tis of the hip on the side with the longer limb.

Regression analysis showed a greater stance-time asymmetry, a decrease in the second peak of the vertical ground-reaction-force vector for the shorter limb, and an increase in the rate of loading of the shorter limb with an increase in limb-length discrepancy. Of the three variables that were studied, stance-time asymmetry between the shorter and longer limbs was closely associ- ated with the amount of limb-length discrepancy ($r^2 = 0.6$; Fig. 4).

Sixteen of the eighteen patients who had limb- length discrepancy benefited from lengthening as documented by normalization of the stance time and the second peak of the vertical ground-reaction-force vector. The lengthening did not normalize the stance time for the two remaining patients. This was thought to be due to weakness of the gastrocnemius-soleus muscle after lengthening of the Achilles tendon in one of these patients. This patient also had the largest amount of shortening (eleven centimeters) in the study. The second patient had a recurrence of an equinus contracture. This resulted in predominant loading of the forefoot during gait, leading to a shorter stance time on the lengthened side.

We paid particular attention to the results for the patients who had had tibial lengthening as weakness of the limb muscles often develops in these patients. We did not find evidence of such weakness, as docu- mented by the second peak of the ground-reaction- force vector, except in the patient who had had an open lengthening of the Achilles tendon. Percutaneous lengthening of the Achilles tendon may be preferable to open lengthening if it is done in conjunction with bone- lengthening. The percutaneous technique may be less likely to over-lengthen the tendon.

The rate of loading of the lengthened limb continued to be substantially higher than that of the limbs in the normal subjects. We are unable to explain this finding; however, it may be due to residual muscle weakness, which may or may not resolve with additional time and therapy.

In summary, this study documented measurable and significant stance-time asymmetry in the gait of patients who had moderate limb-length discrepancy. Limb-lengthening that was performed to equalize the limbs normalized this stance parameter. Back pain that was relieved by use of a shoe-lift also was relieved by correction of the limb-length discrepancy. Factors that should be considered critical for the normalization of gait after lengthening include correction of the limb-length discrepancy to within one centimeter, an adequate range of motion and strength of the lengthened limb, and an absence of pain in the lengthened limb. Without careful attention to these factors and compliance with rehabilita- tion during and after lengthening, the procedure does not guarantee an improvement in gait.

References