Surgical Treatment of Calcaneal Deformity in a Select Group of Patients with Myelomeningocele

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Background: The surgical treatment of calcaneal deformity in patients with myelomeningocele has not been uniformly successful in correcting the deformity and preventing recurrence. The purpose of the present study was to examine the results of posterior transfer of the anterior tibial tendon with concurrent procedures in an attempt to balance the muscular forces on the foot and ankle and to obtain a plantigrade foot. We investigated whether surgery improved pressure distribution over the plantar surface of the foot and whether concurrent abnormal movements observed at the knee, hip, and pelvis influenced the surgical outcome.

Methods: Thirty-one feet in eighteen patients who were able to walk were included in the study. The mean age at the time of surgery was seven years and four months, and the mean duration of follow-up was forty-seven months. Eight patients were classified as having an L5-level myelomeningocele, and ten patients were classified as having a sacral level myelomeningocele. A tibialis anterior tendon transfer was performed in all patients, and accompanying osseous deformities were also corrected in twelve feet. Measurements on plain radiographs, the results of gait analyses, and dynamic foot pressures that were determined before surgery and at the time of the final follow-up were compared.

Results: No recurrence or worsening of the deformity was observed in any of the patients, and no other types of foot deformity developed after surgery. Postoperative kinematic studies showed a significant ($p < 0.0001$) increase in peak plantar flexion and a significant decrease in peak dorsiflexion force of the ankle in the stance phase of gait. Peak pressures under the forefoot and midfoot were increased after surgery, and the relative amount of weight-bearing on the heel as compared with the forefoot was shifted toward more equal weight-bearing. However, less improvement in foot-pressure distribution was observed in patients with increased pelvic rotation before surgery. Those patients also had decreased knee extension in stance phase and increased hip abduction and pelvic obliquity both before and after surgery in comparison with patients who had normal pelvic rotation.

Conclusions: Appropriately combined corrective surgical procedures for the treatment of calcaneal deformity in patients with myelomeningocele can effectively reduce the pressure placed on the calcaneus, increase pressures in the forefoot and midfoot, and prevent recurrence of the calcaneal deformity. However, in the presence of excessive pelvic movement in the coronal and transverse planes and decreased knee extension in stance phase, adequate improvement in pressure distribution over the plantar surface of the foot is not likely to occur after this type of foot surgery.

Level of Evidence: Therapeutic Level IV. See Instructions to Authors for a complete description of levels of evidence.

Foot deformities in children with myelomeningocele are frequently caused by muscle imbalance around the foot and by external forces acting on the foot by gravity or ground-reaction forces. A classical example of a deformity secondary to muscle imbalance is calcaneal deformity, which is caused by the active anterior leg muscles and inactive posterior muscles[1-17]. However, not all developmental calcaneal deformities can be explained solely on the basis of muscle imbalance or spasticity[10-13]. Although more commonly associated with L4-level involvement, calcaneal deformity is nearly as common in patients with L5 and sacral level involvement[2,4,5,7-9,11-16,18,19], and a high prevalence of calcaneal deformity has been reported in patients with high-level spina bifida without muscle spasticity[10,11]. Therefore, the concept that voluntary muscle imbalance

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is responsible for all foot deformities may no longer be accepted, which is consistent with findings that voluntary muscle imbalance cannot explain all of the deformity seen at the hip and the knee[20,21].

Calcaneal deformity is largely progressive and notoriously difficult to brace if left uncorrected. This deformity makes it difficult to walk in the community because of the development of foot ulcerations or a crouch gait. Many authors have stressed that early surgical correction of calcaneal deformity is necessary in order to prevent worsening of the deformity and the development of secondary osseous deformities[1-17]. Lengthening of the tibialis anterior tendon and Achilles tenodesis to the fibula have been proposed, although the clinical outcomes have not been particularly satisfactory[6,22]. Rodrigues and Dias reported that a simple tenotomy and tendon excision of all ankle dorsiflexors, the peroneus brevis, and the peroneus longus achieved a braceable foot[7]. However, almost half of the subjects in that study were children with thoracic and high-lumbar functional levels in whom anterior tibial function was weak and often was under reflex rather than voluntary control. Tenotomy combined with bracing would seem to be a simpler and preferred technique in this subset of patients.

The technique of posterior transfer of the anterior tibial tendon has been recommended for patients with myelomeningocele who have an unopposed ankle dorsiflexion-producing dynamic and a potentially fixed calcaneal deformity of the ankle. However, the results of earlier studies have been inconsistent, and this method has not been uniformly successful for correcting the deformity and preventing recurrence, with favorable outcomes having been reported for only one-third to one-half of the patients[1,4,8,14,16,17]. Review of the literature is difficult because patients are grouped differently according to different classification systems[5], and the neurological level of the lesions is different among studies. Furthermore, the definition of a "good" result has varied, and we are not aware of any previous reports describing other aspects of foot and ankle deformities associated with pes calcaneus.

The present retrospective study was carried out to examine the results of posterior transfer of the anterior tibial tendon with concurrent procedures in an attempt to balance the muscular forces on the foot and ankle in order to obtain a plantigrade foot. With use of dynamic foot-pressure measurements and instrumented gait analysis, we investigated whether surgery improved pressure distribution over the plantar surface of the foot and whether concurrent abnormal movements observed at the knee, hip, and pelvis influenced surgical outcomes.

Materials and Methods

Subjects

The present study was a retrospective review and was approved by our hospital's institutional review board. A total of thirty-one feet in eighteen selected patients with a minimum duration of follow-up of two years after surgery were included in the study; in all cases, the follow-up included gait analysis and pedobarographic evaluation. The study group included seven boys and eleven girls. The mean age at the time of the operation was seven years and four months (range, four years eleven months to fourteen years nine months), and the mean duration of follow-up was forty-seven months (range, thirty-four to sixty-five months). All children could walk independently without any assistance or orthosis before surgery. All children had bulky, hypertrophied heel pads and/or skin breakdown of the heel but no open ulceration at the time of surgery.

Muscle strength was graded with use of the scale of the Medical Research Council[23]. According to the functional classification of motor paralysis based on voluntary control of a joint as described by Asher and Olson, the neurosegmental level was defined as the lowest level that innervates any functioning muscle that is capable of an antigravity (grade-3 or more) voluntary contraction[19,24,25]. Eight patients were classified as having an L5-level myelomeningocele (grade-3 ankle dorsiflexion), and ten patients were classified as having a sacral level myelomeningocele (grade-3 ankle plantar flexion). The criteria for assigning an L5-level classification included voluntary control of foot dorsiflexion and eversion by functioning tibialis anterior and peroneal muscles. The criteria for assigning a sacral level classification included voluntary control of foot plantar flexion by the triceps surae and tibialis posterior muscles.

No patient had limitation of motion at the knee or hip joint. All patients had normal muscle power of the quadriceps and iliopsoas. Gluteus maximus muscle strength was graded as trace in two patients, poor in nine, and fair in seven. Gluteus medius muscle strength was grade 3 in eight patients, grade 4 in nine, and grade 5 in one. Medial hamstrings muscle strength was grade 4 in five patients and grade 5 in thirteen, and lateral hamstrings muscle strength was grade 3 in nine patients and grade 4 in nine. The ankles in all subjects could not be passively plantar flexed >15° beyond the neutral position. Tibialis anterior muscle strength was grade 4 in twenty feet and grade 5 in eleven. With regard to the other muscles around the foot and ankle, extensor digitorum longus muscle strength was grade 3 in one foot, grade 4 in nineteen, and grade 5 in eleven; peroneus tertius muscle strength was grade 4 in seventeen feet and grade 5 in fourteen; peroneus brevis muscle strength was grade 3 in two feet, grade 4 in seventeen, and grade 5 in twelve; triceps surae muscle strength was grade 1 in one foot, grade 2 in twelve, and grade 3 in eighteen; tibialis posterior muscle strength was grade 3 in twelve feet, grade 4 in seventeen, and grade 5 in two; flexor digitorum longus muscle strength was grade 2 in twenty-one feet and grade 3 in ten; and peroneus longus muscle strength was grade 3 in one foot, grade 4 in nineteen, and grade 5 in eleven.

Surgical Technique

All operations were performed by a single surgeon (H.W.K.). First, the anterior tibial tendon was divided from its insertion underneath the medial cuneiform through a curvilinear medial incision on the foot. After making a serpentine-shaped second incision on the anterolateral aspect of the distal part of the leg and ankle, the surgeon performed an anterior capsulotomy of the ankle. Through this incision or a separate lateral incision around the fibula, additional intramuscular lengthening of the peroneus brevis and tenotomy of the peroneus tertius[1,3,7] were carried out in order to prevent any potential valgus deformity of the ankle in all but five feet. Tenotomies of the toe extensors were not performed in any of the feet. The anterior tibial tendon was delivered through the second incision at the junction of the middle and distal thirds of the tibia, and a window was created in the interosseous membrane. Through a third incision over the medial aspect of the Achilles tendon, the tendon was then passed posteriorly through the interosseous membrane. The most distal part of the Achilles tendon was split in half for a distance of 1.5 cm, and the tibialis anterior tendon was passed through this opening. A periosteal flap was raised in the calcaneus at the exact level of attachment of the Achilles tendon, and the anterior tibial tendon was attached to the bone with use of an anchoring screw with the ankle plantar flexed to 20°. The repair was then reinforced by tautly suturing the Achilles tendon to the anterior tibial tendon (Figs. 1-A and 1-B).

In an attempt to reinforce the anterior tibial muscle, an additional peroneus brevis tenodesis to the calcaneus and the Achilles tendon[1,3] was carried out in three feet in patients who had a severe fixed calcaneovalgus deformity, grade-4 tibialis anterior strength, and grade-5 peroneus brevis strength. We also corrected any accompanying osseous deformities around the foot and ankle. Ancillary procedures that were performed for this purpose included three supramalleolar varus tibial osteotomies and one distal medial tibial epiphysiodesis for the treatment of ankle valgus associated with lateral wedging of the distal tibial epiphysis; one supramalleolar tibial derotation osteotomy for the treatment of increased external tibial rotation; three calcaneal lengthenings (two of which were combined with a supramalleolar derotation osteotomy); three extra-articular arthrodeses of the subtalar joint; and one posteromedial displacement osteotomy of the calcaneus for the treatment of valgus deformity of the hindfoot.

Postoperatively, in order to prevent migration of the foot within the cast, a long-leg cast with the knee flexed 20° and the ankle plantar flexed 20° was worn for six weeks. When the index operation was combined with osseous procedures, the original cast was converted to a below-the-knee cast at four weeks after surgery and the latter was worn for an additional four weeks. After cast removal, a solid ankle-foot orthosis was prescribed to substitute for the weakened plantar flexors, to restrain tibial advancement during stance, and to maintain a more upright posture by preventing excessive ankle dorsiflexion during stance. The patient was managed with either of two types of orthoses: (1) a crouch-control ankle-foot orthosis with medial and lateral reinforcement strips at the ankle trim and with an adjustable pretibial Velcro dorsal foot closure or (2) a floor-reaction ankle-foot orthosis with circumferential extension of the orthosis over the dorsum of the ankle joint, with a few degrees of plantar flexion built into the foot component to transfer its reactive force to assist in knee extension and to enable the patient to stand upright with the ankle locked in a neutral alignment[3].

Measurement of Outcome: Radiographs, Gait Analysis, and Dynamic Foot Pressure

The radiographic results were analyzed by measuring the lateral talocalcaneal angle and calcaneal pitch angle with use of standardized weight-bearing foot and ankle radiographs[26,27] that were made before surgery and at the time of the follow-up. The anteroposterior talus-first metatarsal angle was measured only at the time of the latest follow-up because of the difficulty of measurement related to the foot position before surgery. These radiographic measurements in children are known to have excellent intraobserver and interobserver reliability[26].

Kinematic and kinetic analyses were performed with use of the VICON 370 Motion Analysis System (Oxford Metrics, Oxford, England) with six infrared cameras, and ground-reaction-force data were gathered with use of multiple force platforms (Advanced Mechanical Technology, Watertown, Massachusetts). All subjects were asked to walk barefoot at a self-selected speed along a 15-m walkway with the markers in place. The normal range for kinematic data was defined as two standard deviations from the mean. Force-plates under the path recorded ground-reaction forces during walking trials, and joint moments were expressed as internal moments to counter the ground-reaction force.

Kinematic and kinetic data from successful trials were averaged and used for statistical analysis.

The F-Scan high resolution pressure assessment system (Tekscan, South Boston, Massachusetts) was used to measure dynamic foot-pressure. The pressure was recorded at 50 Hz with a pressure-sensitive insole consisting of a 0.15-mm-thick sensor with an embedded gridwork of 960 pressure-sensing cells, evenly distributed at 0.5-cm intervals. Before use, a disposable insole was trimmed to fit into light and flexible shoes. Foot pressures in seven areas, including the hallux, the first metatarsal head, the second metatarsal head, the third and fourth metatarsal heads, the fifth metatarsal head, the midfoot, and the calcaneus, were recorded for five steps in the middle of a test walk, and the mean value at each location was calculated. The pressure-reading data were saved and processed with custom-made software. The pressure-time data for each individual area were plotted on a graph with use of a normalized pressure and time scale. The integrals of the pressure-time graphs show total pressure experienced by each area of the foot. Besides the absolute values of peak pressure exerted on each area of the foot, the relative vertical impulse, which is the percentage of impulse exerted on each area with respect to the total impulses of all areas, was calculated; therefore, the data were not affected by body weight, plantar surface area, the size of the foot, the thickness of the heel pad, or the contact time of the foot during walking[28-32] (Fig. 2). Another parameter that was examined was the anteroposterior index (calculated as the anteroposterior length of the path of the center of pressure divided by the anteroposterior length of the foot) for the evaluation of posteroanterior movement of the center of pressure[31,32].

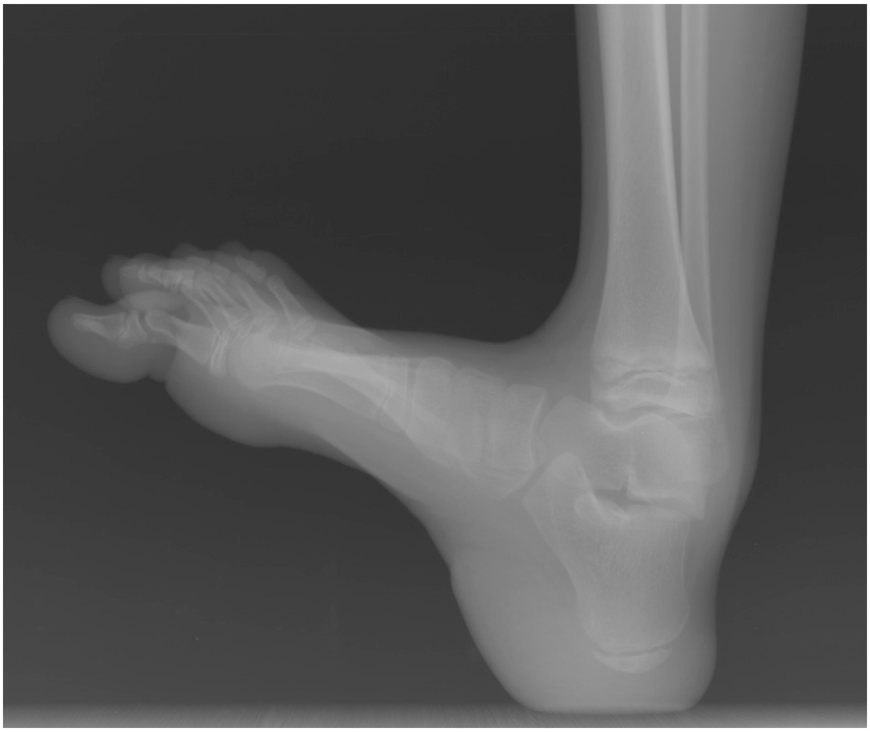

Fig. 1-A

Fig. 1-B

Figs. 1-A and 1-B Lateral radiographs of the foot and ankle of a girl who underwent anterior capsulotomy of the ankle, intramuscular lengthening of the peroneus brevis, tenotomy of the peroneus tertius, and posterior transfer of the anterior tibial tendon at the age of nine years. The calcaneal deformity resolved and a plantigrade foot was obtained after surgery. **Fig. 1-A** Preoperative radiograph. **Fig. 1-B** Radiograph made three years and six months postoperatively.

Statistical Analysis

In order to minimize measurement errors, two fellowship-trained pediatric orthopaedic surgeons (K.B.P. and S.Y.J.) performed all radiographic and pedobarographic measurements with use of the techniques described in the literature from which the normative data were generated[26,28,31]. All parameters were measured twice, and the measurements were averaged. To determine the influence of surgery, the measured values from radiographs, gait analyses, and dynamic pedobarographs obtained before surgery and at the time of the final follow-up were compared.

Clinically, our patients walked with or without gross lateral movement of the pelvis, hiking the legs forward to

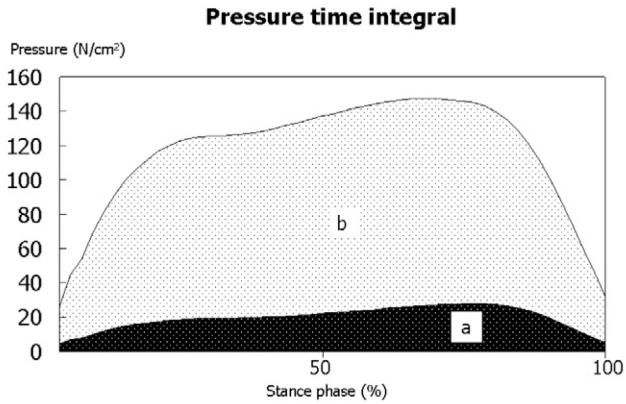

Fig. 2

Hypothetical example of a pressure-time curve for the foot. Relative vertical impulse was calculated at each region. The relative vertical impulse of a equals a/(a + b), where a + b is total impulse.

swing. In order to determine the effect of surgery in cases in which exaggerated pelvic motion was present preoperatively, the results were compared and analyzed by dividing the patients into two groups according to the kinematic findings. Group I included eighteen feet in patients in whom internal rotation of the pelvis during the single-limb stance phase was within the normal range before surgery, and Group II included thirteen feet in patients in whom there was increased pelvic rotation outside the two-standard-deviation range.

To determine the influence of surgery and to identify significant differences between the groups, the mixed model was used to allow for the repeated measurements from individual patients and to adjust for intra-person correlation to ensure validity of the results. In addition, in order to adjust for the effects of age, sex, and time to assessment, we performed a multivariate analysis. Plantar pressure data obtained for our patients were also compared with data from our normative database of fifty age-matched healthy volunteers. P values were adjusted for multiple comparisons with use of the Bonferroni method. The adjusted p value was the minimum value of $P_{unadj} \times k$ or 1, where P_{unadj} was the unadjusted value and k was the number of comparisons. The level of significance was set at $p < 0.05$.

Results

Clinical and Radiographic Outcomes

At the time of the latest follow-up examination, no recurrence or worsening of the calcaneal deformity was observed in any of the patients. No other types of foot deformity developed after surgery, and all of our patients and their families were satisfied with the appearance of the foot. However, a mild degree of ankle valgus with a lateral talar tilt of 5° was observed in two cases. The passive range of ankle dorsiflexion was decreased from 42.4° ± 13.4° before surgery to 24.6° ± 5.7° after surgery (p = 0.0017), whereas ankle plantar flexion was increased from −6.1° ± 14.5° before surgery to −36.6° ± 11.8° after surgery (p = 0.0004).

The lateral talocalcaneal angle increased from 39.8° ± 11.5° before surgery to 42.7° ± 7.6° at the time of the latest follow-up (p = 0.4781), and the calcaneal pitch angle decreased from 37.8° ± 11.2° to 21.2° ± 8.9° (p = 0.0425). The anteroposterior talus-first metatarsal angle at the time of the latest follow-up was 11.6° ± 5.7°. All of the above-mentioned angles were within the normal range at the time of the latest follow-up[26,27].

Gait Analysis

Cadence was decreased from 132.0 ± 15.2 steps per minute before surgery to 115.8 ± 16.4 steps per minute at the time of the

TABLE I Preoperative and Postoperative Kinematic Parameters During Stance Phase

Parameters	Preoperative* *(deg)*	Postoperative* *(deg)*	Normal* *(deg)*	P value†
Sagittal plane				
Peak ankle dorsiflexion‡	33.05 ± 6.80	27.37 ± 4.59	18.66 ± 3.58	0.0018
Peak ankle plantar flexion‡	9.16 ± 5.64	−0.71 ± 3.20	−4.66 ± 6.31	<0.0001
Knee flexon angle at peak knee extension	11.99 ± 7.74	10.20 ± 8.11	11.01 ± 4.46	0.4621
Peak hip extension	3.73 ± 8.88	6.49 ± 8.27	−5.12 ± 5.52	0.8095
Coronal plane				
Peak knee valgus	8.47 ± 3.73	7.33 ± 4.79	−4.08 ± 3.89	0.4073
Peak hip abduction	5.96 ± 8.38	5.03 ± 9.49	−2.77 ± 3.03	0.7466
Transverse plane				
Peak foot internal rotation	1.19 ± 16.93	−4.01 ± 12.36	−7.21 ± 6.36	0.6908
Peak knee external rotation	25.37 ± 10.48	22.65 ± 9.15	0.98 ± 6.83	0.6759
Peak hip internal rotation	11.58 ± 7.71	12.38 ± 7.91	1.61 ± 7.96	0.7510

*The values are given as the mean and the standard deviation. †The p values pertain to the comparison between the preoperative and postoperative values. The p value was the minimum value of $P_{unadj} \times k$ or 1, where P_{unadj} was the unadjusted value and k was the number of comparisons (k = 4 for parameters in sagittal plane, k = 2 for parameters in coronal plane, and k = 3 for parameters in transverse plane). ‡Ankle dorsiflexion was expressed as a positive value, and plantar flexion was expressed as a negative value.

TABLE II Peak Pressure Under Each Area of the Foot Before and After Surgery

	Peak Pressure* *(N/cm²)*			P Value†		
	Preoperative	Postoperative	Normal	Preoperative Compared with Postoperative	Preoperative Compared with Normal	Postoperative Compared with Normal
Hallux	1.62 ± 5.64	6.48 ± 8.40	21.84 ± 10.05	0.0485	<0.0001	<0.0001
First metatarsal head	3.00 ± 5.78	11.75 ± 8.86	9.91 ± 9.22	0.0011	<0.0001	<0.0001
Second metatarsal head	4.25 ± 6.67	12.94 ± 7.28	10.06 ± 5.12	0.0006	<0.0001	<0.0001
Third and fourth metatarsal heads	2.02 ± 5.32	7.65 ± 5.97	9.42 ± 3.60	0.0045	<0.0001	<0.0001
Fifth metatarsal head	1.09 ± 3.16	3.77 ± 4.04	7.65 ± 2.81	0.0319	<0.0001	<0.0001
Midfoot	0.77 ± 1.24	2.84 ± 4.00	3.61 ± 2.32	0.0460	<0.0001	<0.0001
Calcaneus	51.28 ± 20.25	41.04 ± 15.71	20.14 ± 4.24	0.0700	<0.0001	<0.0001

*The values are given as the mean and the standard deviation. †The p value was the minimum value of $P_{unadj} \times 7$ or 1, where P_{unadj} was the unadjusted value and 7 was the number of comparisons.

latest follow-up (p = 0.0029), whereas the step time was increased from 0.45 ± 0.06 second before surgery to 0.53 ± 0.08 second after surgery (p = 0.0019). With the numbers available, there were no differences between the preoperative and postoperative findings with regard to velocity, step length, or single-limb support (p = 0.3366, p = 0.7243, and p = 0.4591, respectively).

There were no significant differences between the preoperative and postoperative findings with regard to the kinematic and kinetic parameters for the pelvis, hip, and knee or the foot-progression angle. However, the postoperative kinematic study showed a significant increase in peak plantar flexion and a significant decrease in peak dorsiflexion of the ankle in the stance phase (Table I). The peak dorsiflexion in the swing phase decreased from 22.73° ± 7.85° preoperatively to 5.44° ± 5.45° postoperatively (p < 0.0001). The full range of motion of the ankle joint during the stance phase increased from 23.99° ± 8.18° preoperatively to 29.05° ± 4.77° postoperatively, and the range of motion during the swing phase increased from 9.49° ± 6.36° to 11.32° ± 6.76° (p < 0.0001). Kinetic analysis showed no significant changes in moments (0.26 ± 0.10 Nm/kg before surgery, compared with 0.33 ± 0.11 Nm/kg after surgery; p = 0.0919) or power generation at the ankle (0.35 ± 0.30 N/kg before surgery, compared with 0.30 ± 0.25 N/kg after surgery; p = 0.6783).

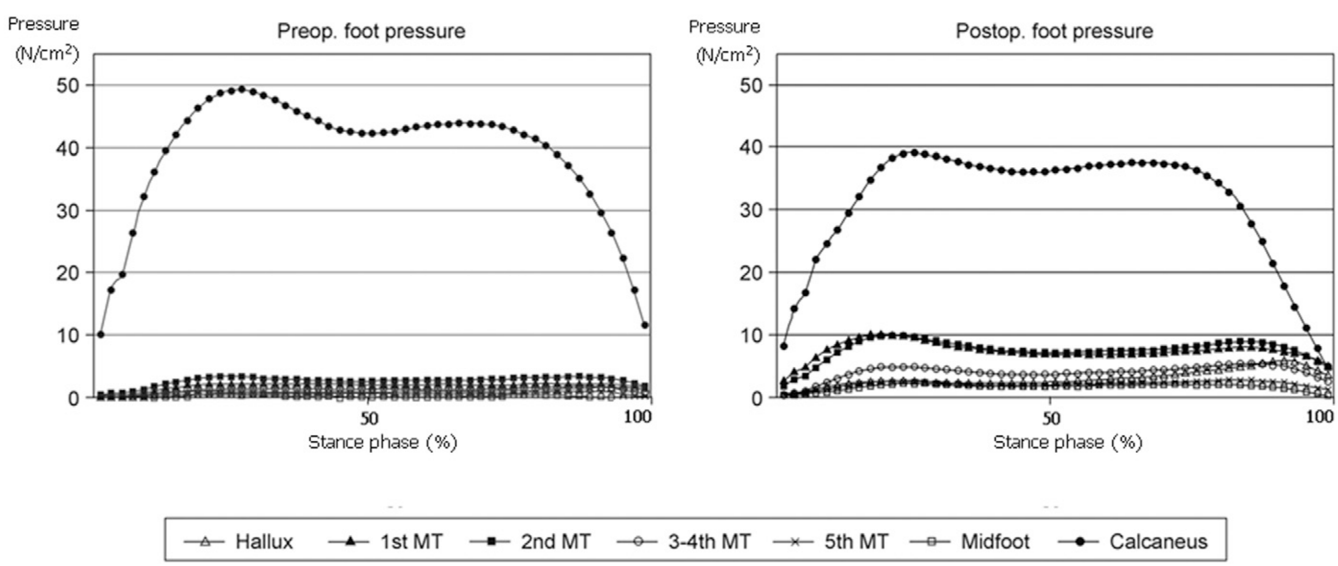

Fig. 3
Preoperative and postoperative pressure-time curves recorded simultaneously in seven measurement areas. MT = metatarsal.

TABLE III Relative Vertical Impulse Under Each Area of the Foot Before and After Surgery

	Relative Vertical Impulse* *(%)*			P Value†		
	Preoperative	Postoperative	Normal	Preoperative Compared with Postoperative	Preoperative Compared with Normal	Postoperative Compared with Normal
Hallux	2.1 ± 3.3	5.3 ± 6.1	21.3 ± 8.2	0.0174	0.0001	0.0001
First metatarsal head	4.2 ± 5.1	12.9 ± 8.5	9.7 ± 4.8	0.0002	0.0007	0.3809
Second metatarsal head	5.8 ± 6.0	13.2 ± 7.5	9.9 ± 3.1	0.0002	0.0082	0.1144
Third and fourth metatarsal heads	2.8 ± 4.2	6.9 ± 4.7	11.2 ± 2.4	0.0014	0.0001	0.0059
Fifth metatarsal head	1.4 ± 2.1	3.6 ± 3.3	10.3 ± 3.2	0.0084	0.0001	0.0001
Midfoot	0.5 ± 0.6	2.8 ± 5.4	4.3 ± 3.8	0.0214	0.0002	0.8319
Calcaneus	83.3 ± 17.6	54.0 ± 19.8	33.3 ± 11.3	0.0001	0.0001	0.0014

*The values are given as the mean and the standard deviation. †The p value was the minimum value of $P_{unadj} \times 7$, or 1, where P_{unadj} was the unadjusted value and 7 was the number of comparisons.

Dynamic Foot-Pressure Measurement

Peak pressures under the forefoot (the hallux and the metatarsal heads) and the midfoot were significantly increased after surgery. Pressures under the hallux, the third through fifth metatarsal heads, and the midfoot were lower than normal, whereas pressures under the first and second metatarsal heads and the calcaneus were higher than normal (Table II) (Fig. 3).

The relative vertical impulse of the calcaneus decreased significantly, from 83.3% ± 17.6% before surgery to 54.0% ± 19.8% after surgery (p = 0.0001). The relative vertical impulses of each of the remaining regions increased significantly after surgery, and those of the first and second metatarsal heads and the midfoot were comparable with normal values (Table III). The anteroposterior index for the path of the center of pressure increased significantly, from 0.10 ± 0.06 before surgery to 0.46 ± 0.14 after surgery (p < 0.0001).

Postoperative Changes According to Differences in Pelvic Motion Before Surgery (Fig. 4)

With regard to neurosegmental levels, Group I included eight feet in patients with an L5-level myelomeningocele and ten feet in patients with a sacral level myelomeningocele whereas Group II included seven feet in patients with an L5-level myelomeningocele and six feet in patients with a sacral level myelomeningocele. The passive range of ankle dorsiflexion was not different between Groups I and II either preoperatively (43.7° ± 14.5° compared with 41.1° ± 11.2°; p = 0.2781) or postoperatively (26.1° ± 8.7° compared with 23.2° ± 4.7°; p = 0.0998). The passive range of ankle plantar flexion also was not different between Groups I and II either preoperatively (−5.9° ± 12.2° compared with −6.3° ± 16.9°; p = 0.0860) or postoperatively (−35.9° ± 10.3° compared with −37.2° ± 13.4°; p = 0.0619).

There were no differences between Groups I and II with regard to the lateral talocalcaneal angle either preoperatively (42.5° ± 12.3° compared with 35.2° ± 6.8°; p = 0.2299) or postoperatively (42.8° ± 5.5° compared with 42.6° ± 12.4°; p = 0.8686). The calcaneal pitch angle also was not different between Groups I and II either preoperatively (39.5° ± 15.0° compared with 35.4° ± 14.9°; p = 0.2350) or postoperatively (20.1° ± 8.3° compared with 22.3° ± 7.7°; p = 0.7550). The anteroposterior talus-first metatarsal angle at the time of the latest follow-up was 11.9° ± 6.1° in Group I and 11.5° ± 8.3° in Group II (p = 0.3271).

The foot-progression angle in both groups was within the normal range before and after surgery. Although peak anterior tilt of the pelvis exceeded the normal range in both groups before and after surgery, there was no significant difference between the groups. However, the angles of pelvic obliquity and internal rotation were found to be greater in Group II than in Group I before and after surgery. In the hip joint, the peak abduction angle during single-limb stance phase was greater in Group II than in Group I before and after surgery. Sagittal plane kinematics showed that a nearly normal range of knee motion was maintained in Group I after surgery. In contrast, peak extension of the knee joint was significantly lower in Group II than in Group I before surgery (p = 0.0227) and after surgery (p = 0.0215). The peak extension moment in the knee was greater in Group II before surgery; however, there was no difference between the groups after surgery. There were no differences between the groups with regard to the kinematic and kinetic parameters at the ankle joint before or after surgery. The significant postoperative change in Group I was peak plantar flexion of the ankle (p < 0.0001). In Group II, sagittal plane ankle motion (including peak dorsiflexion [p = 0.0132] and peak plantar flexion [p = 0.0274]) and peak hip abduction moment (p = 0.0415) were significantly changed after surgery (see Appendix).

There were no differences between the groups with regard to the peak pressure exerted on each area of the foot before or after surgery (see Appendix). Although there were no differences in the preoperative relative vertical impulse of each area of the foot between the groups, postoperative relative vertical

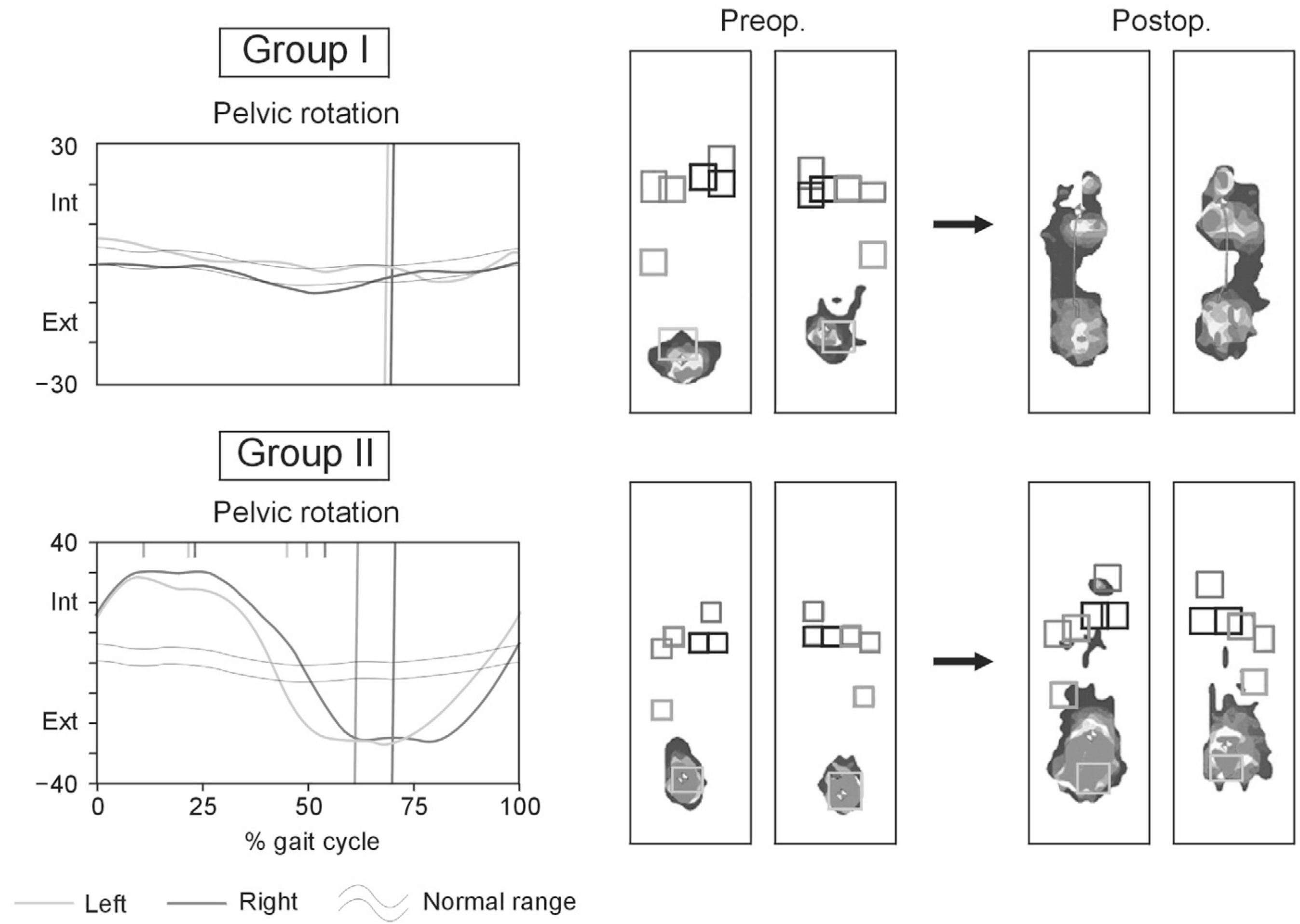

Fig. 4

Preoperative kinematics of the pelvis and changes of dynamic foot-pressure after surgery in Groups I and II. Less improvement of foot-pressure distribution was observed in patients with increased pelvic rotation before surgery.

impulses of the second through fifth metatarsal heads were significantly higher in Group I than in Group II ($p = 0.0067$ for the second metatarsal head, $p = 0.0001$ for the third and fourth metatarsal heads, and $p = 0.0070$ for the fifth metatarsal head) and the relative vertical impulse of the calcaneus was significantly lower in Group I than in Group II ($p = 0.0001$) (see Appendix). The relative vertical impulse of the calcaneus decreased significantly in Group I (from 80.9% ± 19.8% preoperatively to 44.8% ± 11.1% postoperatively; $p = 0.0001$) but not in Group II (from 89.7% ± 11.6% preoperatively to 74.7% ± 15.2% postoperatively; $p = 0.1311$) (see Appendix). The anteroposterior index was not different between Groups I and II preoperatively (0.11 ± 0.07 compared with 0.09 ± 0.05; $p = 0.4130$); however, the index was significantly higher in Group I than in Group II at the time of the latest follow-up (0.51 ± 0.09 compared with 0.36 ± 0.16; $p = 0.0214$).

Discussion

Our results demonstrate that pressures in the forefoot and midfoot were increased and calcaneal pressure was decreased after surgery. The amount of weight-bearing on the heel relative to the forefoot, as assessed on the basis of relative vertical impulse, was shifted toward more equal weight-bearing after surgery. These findings were correlated with increased plantar flexion and decreased dorsiflexion of the ankle in the stance phase. In addition, much less dorsiflexion in the terminal swing and early stance phases after surgery may be beneficial for weight acceptance or first ankle rocker motion, which is normally controlled by eccentric contraction of the ankle dorsiflexor muscles.

Dynamic foot-pressure measurements are objective measures of a patient's ability to support and efficiently transfer body mass during walking. Accordingly, it is important to assess whether surgery can result in the improvement of foot-pressure distribution and walking ability. Considering the fact that skin breakdown at the heel can be due to excessive pressure, it is important to calculate the absolute plantar pressure. However, absolute pressures exerted on each area of the foot before and after surgery do not necessarily represent redistribution of the plantar pressures. The key foot-pressure parameter examined in the present study was relative vertical impulse, which reflects the proportion of the force that is experienced by a particular part of the foot with respect to the pressure-time integral and denotes the pressure in a particular area of the foot during weight-bearing.

In our series, there were no differences between the groups with regard to the preoperative peak pressure and relative vertical impulse or the radiographic measurements, indicating that the plantar pressure distribution was not different between the groups before surgery and that the feet in both groups were similarly deformed. However, despite comparable postoperative radiographic results between the groups, sufficient postoperative reduction in the pressure exerted on the calcaneus was not likely to occur when excessive pelvic movement in the coronal and transverse planes was present preoperatively. In addition, this subset of patients was characterized by decreased knee extension in stance phase. Furthermore, more efficient forward movement of the center of pressure after surgery was achieved in Group I as compared with Group II. Increased pelvic motion in both the transverse and coronal planes and increased coronal plane hip motion are related to hip abductor weakness, although abnormal sagittal plane motion at the ankle and/or knee joint contributes to abnormal pelvic and hip motion as well[31,33-36]. Although the quadriceps functioned normally in all of our patients, the patients in Group II had decreased knee extension in the stance phase of the gait cycle before and after surgery.

In the presence of triceps surae weakness, the heel does not rise normally and the whole foot instead is lifted off the floor. Compensation for this plantar flexor weakness is provided by the hip abductors. Balance and posture in the mediolateral direction are controlled primarily by the position of the foot relative to the plane of progression of the body's center of gravity, which is assisted by isometrically contracting the hip abductors[33-36]. Less-than-normal muscle power of the gluteus medius is insufficient for stabilization of the pelvis during single-limb support, thus necessitating lateral movement of the pelvis over the stance limb in order to reduce the hip abduction moment[36]. Fraser and Hoffman found that hip abductor power of grade 3 or greater was a good predictor of a functional tibialis anterior tendon transfer[15]. That finding is in agreement with our finding that more patients in Group I than in Group II had gluteus medius muscle strength of grade 4 or higher; gluteus medius muscle power was grade 3 in three lower limbs, grade 4 in thirteen, and grade 5 in two in Group I; grade 3 in eight and grade 4 in five in Group II. However, the neurosegmental level involved was not a determinant of a successful surgical outcome in the present study. Clinical grading of the muscle strength and assignment of the neurosegmental level are subjective in nature[37], and the reliability and validity of any classification system should be established.

A potential criticism of the present study is that the results may be skewed by the absence of data from patients with a myelomeningocele at L4 or higher. However, we think that those patients should have less improved foot-pressure distribution after surgery because the higher the lesion, the more severely the kinematic patterns at the pelvis, hip, and knee are affected. Another limitation of the present study is that the children were a select group of patients with an L5 or sacral level myelomeningocele. It has been assumed that children with L5 and sacral levels of function are more easily integrated into regular activities of daily living; however, the long-term prognosis may not be good[24]. Brinker et al.[18] reported that one-third of the children with a sacral level myelomeningocele, who initially could walk in the community, had progressive loss of ankle plantar flexor power. We think that any corrective surgery should be done at earlier ages in order to obtain a more balanced plantigrade foot. However, additional long-term study is warranted to answer the question of success of the procedure and to search for any correlation between improvements in the foot-pressure distribution and changes in the function of the foot.

Fernández-Feliberti et al. reported better outcomes following the tibialis anterior tendon transfer in children who were younger than five years of age and in whom the neural deficit was not higher than the fourth or fifth lumbar level[17]. However, most authors have reported better results in patients who were older than four or five years of age and in whom the neurosegmental level was at L5 or S1 without evidence of spasticity of the muscle, although only one-third to one-half of the patients managed with transfer had a favorable outcome[1,4,8,14,16,17]. This restriction comes mostly from the fact that whether or not the anterior tibial muscle is under voluntary control cannot be determined at younger ages. Bliss and Menelaus[1] noted persistent calcaneal deformity or secondary equinus deformity in twenty-five of forty-six feet and reported that only ten feet did not require subsequent surgery after the tibialis anterior tendon transfer. Most subjects in their series had an L4 neurosegmental level, and unrecognized spasticity in the transferred muscles was prognostic of a poor outcome.

It has been our experience that detachment of the tibialis anterior tendon, anterior capsulotomy of the ankle, and lengthening or tenotomy of the peroneus brevis and tertius substantially reduces the dorsiflexion deformity of the ankle, enabling the foot to achieve sufficient plantar flexion to allow the transfer to be sutured under adequate tension. However, our experience does not suggest that the above-mentioned procedures alone result in satisfactory outcomes. Even if all dorsiflexors were transferred, they would not replace the paralyzed triceps surae[22,38]. The transferred tendon will function as a tenodesis, and the goal of the surgery is to remove deforming forces rather than to replace the weakened plantar flexors. We carried out ancillary procedures to correct any "lever-arm disease" of the foot and ankle. This is important in general to meet the prerequisite of a tendon transfer that any abnormal osseous architecture should be corrected prior to tendon transfer.

Although ankle and subtalar valgus may develop primarily in patients with myelomeningocele[6,22,39,40], those deformities have been known to be the most common secondary deformity after tibialis anterior tendon transfer, reportedly occurring in 15% to 74% of cases[1,15-17]. Even after simultaneous anterolateral release of the ankle and/or transfer of toe extensors and peroneal muscles, Bliss and Menelaus[1] reported persistent calcaneal deformity, and many of them were associated with a valgus deformity at the ankle or subtalar joint. We think that the above-mentioned unsatisfactory results may be in part due to the failure of correction of an associated osseous deformity at the time of the tendon transfer. Many of our patients were not followed until skeletal maturity; however, postoperatively, only two patients had mild ankle valgus (which had already existed before surgery), and both patients had a dysplastic distal tibial epiphysis.

Although two earlier studies on the anterior tibial tendon transfer with or without Achilles tenodesis to the tibia demonstrated varying results with regard to the prevention of excessive dorsiflexion of the ankle during stance, the patients had a more upright posture with the use of an orthosis (a solid pretibial ankle-foot orthosis fixed at neutral[9] or a posterior shell ankle-foot orthosis fixed at 5° of equinus[14]). It can be argued that we did not examine the effects of any specific orthosis on the treatment outcomes. However, our patients wore different types of braces, as described earlier, and, in fact, each orthosis was found to be different in terms of each patient's overall comfort. Six children refused to wear an orthosis because of inconvenience, which may be related to previous findings that improvements of sagittal plane ankle motion associated with the use of a solid ankle-foot orthosis in patients with low lumbar and sacral level myelomeningocele were also associated with excessive transverse plane rotation of the knee[41,42]. Specifically, the ankle-foot orthosis in patients with a sacral level myelomeningocele was more detrimental to knee stability than barefoot walking[43]. In reality, tibialis anterior tendon transfer alone cannot sufficiently supplement the function of the weakened triceps surae and may not prevent the recurrence of calcaneus deformity. We believe that continued bracing is essential not only to protect the transferred tendons but also to promote optimum foot balance. However, which type of orthosis can best change abnormal gait patterns, especially those seen in Group II, remains to be investigated.

In summary, the current study demonstrates that posterior transfer of the anterior tibial tendon with additional procedures to obtain a balanced plantigrade foot effectively reduces the pressure exerted on the calcaneus, increases the pressure on the forefoot and midfoot, and prevents recurrence of the calcaneal deformity. Computerized gait analysis is valuable for the evaluation of these patients prior to surgery because, in the presence of excessive pelvic movement in the coronal and transverse planes and decreased knee extension in stance phase sufficient improvement of pressure distribution over the plantar surface of the foot is not likely to occur after surgery. Our findings concur with the fact that loss of two or more determinants of normal gait, such as pelvic rotation, pelvic obliquity, and knee flexion in stance, makes compensation difficult[44].

Appendix

eA A table showing stance phase gait parameters, a table and a figure showing foot pressure measurements, and a table showing the relative vertical impulse data are available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD/DVD (call our subscription department, at 781-449-9780, to order the CD or DVD). ■

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