Coronal Plane Knee Moments Improve After Correcting External Tibial Torsion in Patients With Cerebral Palsy

Michael Aiona MD, Kosta Calligeros MBBS, BSc,
Rosemary Pierce PT

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Abstract

Background External tibial torsion causes an abnormal axis of joint motion relative to the line of progression with resultant abnormal coronal plane knee moments and affects lever arm function of the foot in power generation at the ankle. However, it is unclear whether surgical correction of the tibial torsion corrects the moments and power.

Questions/purposes We evaluated whether surgical correction of external tibial torsion in patients with cerebral palsy would correct the abnormal coronal plane knee moments and improve ankle power generation.

Methods We studied 22 patients (26 limbs) with cerebral palsy (Gross Motor Function Classification System Level I or II) who underwent distal internal rotation osteotomies for correction of external tibial torsion as part of a multi-level surgical intervention. There were 10 males and 12 females with a mean age at surgery of 14 years (range, 6.8–20.9 years). All patients had pre- and postoperative standardized clinical evaluation and computerized three-dimensional gait analysis. Minimum followup was 9 months (average, 13 months; range, 9–19 months).

Results On physical examination, the mean ($\pm$ SD) transmalleolar axis improved from $43^\circ \pm 10^\circ$ preoperatively to $20^\circ \pm 7^\circ$ postoperatively. Mean knee rotation improved kinematically from $40^\circ \pm 9^\circ$ preoperatively to $21^\circ \pm 9^\circ$ postoperatively. Twenty-two of 26 limbs (88%) improved in one or both peaks of the abnormal coronal plane knee moments. Ankle power generation did not change from preoperative (1.6 ± 0.7 W/kg) to postoperative (1.6 W/kg).

Conclusions Correction of external tibial torsion in ambulatory patients with cerebral palsy improves the kinematic and kinetic deviations identified by gait analysis.

Levels of Evidence Level IV, therapeutic series. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

Though the vast majority of rotational deformities cause minimal to no functional problems, external tibial torsion can produce substantial abnormal pressure across the knee. The resultant gait abnormalities and pain may occur in patients with myelodysplasia [6, 8, 28] with potential long-term effects of arthritis [29]. Similar findings were described in those with no neuromuscular disorder [5, 14, 16]. Correction of the deformity results in improvements in symptoms and the abnormal knee forces [6, 14].

The motor deficits in patients with cerebral palsy (CP) differ considerably from those with myelodysplasia, specifically the presence of spasticity. Bony torsional deformities in CP arise from the complex interaction between the growing human skeleton and the abnormal forces applied by the spastic muscles acting across growth plates, joints, and connective tissue. Fabry et al. [9] demonstrated the anteversion in patients

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Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

M. Aiona (✉), K. Calligeros, R. Pierce
Medical Staff Department, Shriners Hospitals
for Children, Portland, 3101 SW Sam Jackson Park Road,
Portland, OR 97239, USA
e-mail: maiona@shrinernet.org

with CP did not undergo the normal remodeling with growth. Although this common internal femoral rotational deformity can adversely affect gait during childhood [2, 4, 21], correction by femoral osteotomies can be successful [1, 11, 17, 21, 23, 27].

A smaller subset of patients has excessive external tibial rotation, which produces abnormal torque at the knee when its axis of rotation is no longer in line with the forward line of progression. This abnormal force may result in pain and gait deviations, similar to those described in otherwise normal children and patients with myelodysplasia. The external rotation may reduce ankle push-off power as the lever arm is not in the line of progression [10, 12, 28]. As bracing does not influence tibial torsion [25], surgery is the only option to correct this bony abnormality.

We determined whether surgical correction of external tibial torsion in patients with CP would achieve similarly reported results in other patient populations by examining changes in (1) tibial torsion as measured by the transmalleolar axis, (2) coronal plane knee moment, (3) ankle push-off power, and (4) pain at the knee or foot by subjective evaluation through direct questioning.

Patients and Methods

From 1997 to 2003, we surgically treated 44 patients with CP to correct external tibial torsion. For this study, we included patients with spastic CP, Gross Motor Function Classification System Level I or II [18], and preoperative and 1-year postoperative comprehensive motion analysis evaluation, including physical examination and three-dimensional (3D) gait analysis. We excluded 22 of the 44 patients: 11 had tibial osteotomy for correction of an internal rotation deformity, 10 were assisted ambulators (unable to obtain reliable force plate data), and one had additional coronal plane malalignment, which would affect moments across the knee. This left 22 patients with 26 treated limbs who underwent tibial osteotomy to correct external tibial torsion. There were 10 males and 12 females, 10 with hemiplegia and 12 with diplegia. The mean age at surgery was 14 years (range, 6.8–20.9 years). Preoperatively, eight patients reported pain in the knee and two pain in the foot. Bracing had been used preoperatively but only to help maintain ankle position for walking in the context of drop foot or dynamic equinus. The minimum followup was 9 months (average, 13 months; range, 9–19 months). This study was approved by our institutional review board. No patients were recalled specifically for this study; all data were obtained from medical records and gait records.

Our principal goal was to restore normal mechanical alignment and decrease the abnormal moments occurring at

the knee. The primary indication for surgical correction was at least 20° excessive external tibial rotation and was part of a single-event multilevel surgery to correct lower-extremity gait deviations. The contraindications for bony surgery were as in any long-bone surgery, including vascular concerns, soft tissue coverage, and healing concerns such as previous radiation. Patients had additional procedures performed, including both soft tissue (hamstring lengthenings [$n = 5$]) and bony procedures (femoral rotational osteotomies [$n = 12$]).

Trained gait laboratory staff measured the transmalleolar axis using a goniometer with the patient in the prone position with the knee flexed 90°. The midline of the thigh provided the stationary arm and the line connecting the medial and lateral malleolus provided the other arm of the angular measurement [13]. Standardization was achieved with the use of a standard instructional training video demonstrating the method.

Gait analysis involved the placement of 13 reflective markers on the extremities in accordance with the model described by Vicon™ Clinical Manager (Oxford Metrics Ltd, Oxford, UK). Specifically, markers were placed bilaterally over the dorsum of the foot between the second and third metatarsal heads, posterior aspect of the heel at the same level with the toe marker, lateral malleoli, distal-lateral aspect of the shank, lateral femoral epicondyle, distal-lateral aspect of the thigh, and anterior superior iliac spine, and one sacral marker was placed midway between the posterior superior iliac spines. In addition, markers were placed on the medial malleoli on static trials to estimate ankle joint centers, and a knee device was used on static trials to estimate knee joint centers. The subjects walked barefooted at a self-selected speed along a walkway, and 3D kinematic data were collected using a six-camera Vicon™ system (Oxford Metrics Inc). The sample frequency was 60 Hz. Ground reaction force was collected at 1080 Hz using two strain gauge force plates (Advanced Mechanical Technology, Inc, Watertown, MA, USA) [19].

Kinematic analysis was isolated to a tibial rotation graph, using the representative cycle of three trials. The two peak values of the internal coronal plane moment at the knee were compared preoperatively and postoperatively to provide a quantitative analysis. An internal varus moment would mean excessive valgus force on the knee, increasing the strain on the soft tissue on the medial side of the knee. The peak value of the ankle power generation (A2) during stance was compared preoperatively to postoperatively.

Although there are many techniques for performing tibial rotational osteotomy, the procedures in this series were all performed at the supramalleolar level with plate and screw fixation, not pins or cast alone [3, 7, 15, 20, 22]. The degree of correction varied as the goal was to achieve

a transmalleolar axis of 15° to 20°, with patients having varying degrees of deformity. Rotational reference pins were used in all cases to determine the intraoperative degree of correction. Avoiding the intact growth plate with the distal fixation determined the level of the osteotomy. A concomitant fibular osteotomy was performed in all cases.

Postoperative casting was at minimum below the knee, though above-knee casting was used in four of the 26 limbs when simultaneous procedures were performed. Weight-bearing transfers were allowed in the first 4 to 6 weeks, with progressive weightbearing determined by the patient's level of discomfort and signs of radiographic healing. Once weightbearing was allowed, the postoperative therapy was influenced by the associated soft tissue procedures. Patients underwent physical therapy initially to regain strength and return to independent gait function. The specific plan and frequency were based on the associated procedures along with the patient's response.

Postoperative monitoring was generally every 3 months, including self-assessment of pain by the patient. Radiographs were obtained until healing was seen and the patient could weightbear without pain. Modifications to the therapy plan were based on the patients' progress at these assessments.

Data were analyzed for normality using the Shapiro-Wilk statistical test. We used the paired t-test to determine whether the pre- and postoperative values for the parametric variables of transmalleolar axis, second peak varus moment, and ankle power generation differed. For the nonparametric data (preoperative tibial rotation and first peak varus moment), the Wilcoxon signed-rank test was applied to determine whether the changes after surgical correction were of statistical significance. Statistical analysis was performed using SPSS® v19.0.0 (SPSS, Inc, Chicago, IL, USA).

Results

The mean ($\pm$ SD) preoperative transmalleolar axis on physical examination measured $43^\circ \pm 10^\circ$, greater than 20° more than the normative value of 20° . Mean postoperative measurements averaged $20^\circ \pm 7^\circ$, indicating surgical correction

was achieved as measured by physical examination ($p < 0.001$) (Table 1). Kinematic changes in mean knee rotation mirrored the physical examination changes, on average 18° ($p < 0.001$), from $40^\circ \pm 9^\circ$ to $21^\circ \pm 9^\circ$ (Fig. 1).

Coronal knee valgus moments have two peaks occurring at the end of loading and at the end of single support with published normal values of 0.20 Nm/kg and 0.27 Nm/kg, respectively. Preoperatively, the average first and second peak moment values of the subjects studied were -0.24 ± 0.2 Nm/kg and -0.25 ± 0.16 Nm/kg, respectively; the negative moments indicate varus moments associated with medial knee thrust (Table 1). Postoperatively, the abnormal moments were reduced ($p < 0.001$) to -0.1 ± 0.17 Nm/kg and -0.1 ± 0.11 Nm/kg, respectively, although neither set of average values was within the normal range. In 23 of the 26 limbs, the knee valgus moment improved (88%) in one or both peak moments (Fig. 2).

Average push-off power did not change ($p > 0.1$) from preoperatively (1.6 ± 0.7 W/kg) to postoperatively (1.6 ± 0.7 W/kg) (Fig. 3).

Preoperatively, eight patients reported pain in the knee and two in the foot. Knee pain improved in all patients, although continued pain in the foot was present in two patients secondary to intrinsic foot deformity (Table 2).

Fig. 1 The knee rotation improved after osteotomy. R = right; Pre = preoperative; Post = postoperative; DFR = distal femoral rotational osteotomy; TRO = tibial rotational osteotomy; Norm = normal; Ext = external; Int = internal.

Table 1. Changes in physical examination (transmalleolar axis) and kinematics (knee rotation, coronal knee moment, and ankle power)

Time of evaluation	Transmalleolar axis (°)	Knee rotation (°)	First coronal knee moment (Nm/kg)	Second coronal knee moment (Nm/kg)	Ankle power (W/kg)
Preoperative	43 ± 10	40 ± 9	-0.24 ± 0.2	-0.25 ± 0.16	1.6 ± 0.7
Postoperative	20 ± 7	21 ± 9	-0.1 ± 0.17	-0.1 ± 0.11	1.6 ± 0.7
p value	< 0.001	< 0.001	< 0.001	< 0.001	> 0.1

Values are expressed as mean $\pm$ SD.

Fig. 2 The coronal knee plane moment improved after osteotomy with valgus moment present postoperatively. L = left; Pre = preoperative; Post = postoperative; DFR = distal femoral rotational osteotomy; TRO = tibial rotational osteotomy; Norm = normal; Valg = valgus; Var = varus.

All osteotomies healed with full weightbearing allowed at 6 weeks. No loss of fixation or osteotomy position was noted. One patient had posterior tibialis nerve dysesthesias that resolved in time with no sequelae. Two patients had pain over the prominence of the hardware.

Discussion

External tibial torsion causes an abnormal axis of joint motion relative to the line of progression with resultant abnormal coronal plane knee moments and affects lever arm function of the foot in power generation at the ankle. We therefore evaluated whether surgical correction of external tibial torsion in patients with CP would correct the abnormal coronal plane knee moments and improve ankle power generation.

One major study limitation is the correction of this deformity was part of a multilevel intervention for multiple gait deviations. Changes in the kinetic measures of coronal plane knee moments and ankle push-off power are influenced by other factors, including anatomic knee alignment and foot alignment. We did not routinely obtain standing radiographs of the limb to determine mechanical axis deviations, which may have contributed to moment changes. As the tibial osteotomies were distal in origin, the proximal alignment should not have changed with this procedure. The ideal study would have to examine the effect of correction of tibial torsion alone on ankle power and knee kinematics. However, it is clear external rotation does influence coronal plane knee moments. External rotation below the knee can have some contribution from a deformed foot, usually excessive midfoot abduction and heel valgus, commonly seen in our study population. Another limitation to this study is assessing the contribution of the foot configuration to this outcome variable as

Fig. 3 The ankle power did not increase after correction of tibial rotation. R = right; Pre = preoperative; Post = postoperative; DFR = distal femoral rotational osteotomy; TRO = tibial rotational osteotomy; Norm = normal; Gen = generation; Abs = absorption.

the gait analysis was performed in the barefoot condition. Clearly, correction of the foot deformity would improve the external rotation deformity in some of the cases. However, correction of the foot was not performed in many of these patients as the vast majority walked in an ankle foot orthosis (AFO) and the foot was still braceable. Although some patients had pedobarography, we did not investigate its correlation to the knee moments or the effect of the AFO.

Our study demonstrated children with CP who have external tibial rotation can reliably achieve surgical correction as measured by physical examination and kinematic measures. The procedure when performed with internal fixation is reliable, with minimal complications. Improvements in ankle push-off power, though described in other populations, were not seen in this population. Changes in medial knee thrust as demonstrated on gait analysis may be responsible for improvements in knee pain.

Stefko et al. [26] conducted a retrospective review of 10 ambulatory patients with CP with tibial torsion who underwent 13 distal tibial rotational osteotomies of which six were for excessive external rotation. They compared preoperative and postoperative 3D gait analysis, analyzing tibial rotation, foot progression angle, gait velocity, and moments about the ankle. They reported improvements in mean tibial rotation. They did not examine the forces across the knee and only six patients had any kinetic data. The patient number was insufficient to show moment changes at the ankle. Our study improves on that study by increasing the number of patients, which allowed more thorough evaluation of the kinetic changes at the knee. Other differences include the amount of correction, which was approximately 10° greater in our study, use of plate fixation for stability, and kinetic data demonstrating improvements at the knee.

Table 2. Pre- and postoperative clinical characteristics of the patients

Patient	Surgery	Age (years)	Pain	Followup (months)	Pre transmalleolar axis (°)	Post transmalleolar axis (°)	Pre mean tibial rotation (°)	Post mean tibial rotation (°)
1	L-TRO	6.7	No pain	13.0	25	15	-26	-11
2	L-DFR, L-TRO	16.6	Hip pain-none post	13.0	40	20	-35	-15
3	B-HSL, R-DFR, R-TRO	14.2	No pain	19.0	30	10	-41	-3
4	B-HSL, B-HST, R-TRO	9.7	Foot pain- none post	17.0	35	20	-50	-26
5	B-DFR, B-TRO	13.4	B knee/ankle pain-none post	12.0	35	25	-37	-19
		13.4		12.0	30	20	-33	-14
6	L-STF, L-TAL, R-TRO	12.7	L foot pain-fusion with improvement	14.0	50	15	-40	-19
7	R-DFR, R-TRO	15.4	Knee pain-none post	12.0	40	20	-49	-19
8	R-DFR, R-TRO, R-HSL	17.7	Knee pain-none post	17.0	35	10	-47	-28
9	R-TRO	12.1	No pain	12.0	50	20	-51	-51
10	B-HSL, B-TRO, B-VUL	9.4	No pain	12.0	35	20	-42	-27
		9.4		12.0	30	15	-23	-15
11	R-ADL, R-DFR, R-TRO	12.3	No pain	12.0	40	20	-41	-19
12	B-TRO, B-CNL	16.3	B foot/thigh pain-none post	12.0	50	25	-22	-14
		16.3		12.0	55	35	-39	-28
13	L-PTL, L-VUL, R-TRO	12.1	Foot/knee pain-incisional post	10.0	50	35	-45	-24
14	L-HSL, L-ITO, L-ADL, L-TRO	21	No pain	10.0	50	20	-26	-18
15	R-DFR, R-TRO	14.6	No pain	15.0	45	20	-48	-18
16	R-DFR, R-TRO	18.8	No pain	12.0	40	10	-45	-13
17	L-DFR, L-TRO	19.8		9.0	55	20	-41	-23
18	B-TRO	12	B knee pain-one slight post	13.0	65	15	-52	-19
		12		13.0	65	20	-49	-24
19	L-DFR, L-TRO	17.5	Knee pain-slight post	12.0	40	25	-36	-25
20	R-DFR, R-TRO	18.6	Knee pain-none post	11.0	40	25	-50	-22
21	R-DFR, R-TRO	18.3	No pain	12.0	45	10	-41	-41
22	R-TRO	10	No pain	17.0	45	25	-42	-24
Average		14.2		12.9	43	20	-40	-21

Pre = preoperative; Post = postoperative; TRO = tibial rotational osteotomy; HSL = hamstrings lengthening; DFR = distal femoral rotational osteotomy; VUL = vulpius lengthening; ADL = adductor lengthening; CNL = calcaneal neck lengthening; PTL = posterior tibialis lengthening; ITO = intertrochanteric osteotomy; STF = subtalar fusion; HST = hamstrings transfer; R = right; L = left; B = bilateral.

External tibial torsion has been associated with abnormal forces applied across the knee in other populations. MacWilliams et al. [14], using 3D gait analysis, demonstrated improvement of the abnormal knee moments in nonneuromuscular patients with external tibial torsion after surgical correction. Our study demonstrated similar findings with improvements in coronal plane knee moments after surgical correction.

Hicks et al. [10] modeled the external tibial torsion to determine its biomechanical effects on gait. It affected soleus function but also changed the biomechanical function at the hip. They suggested external rotation of 30° leads to reduced function in the soleus, which contributed to poor knee extension and power generation. MacWilliams et al. [14] verified clinical improvements in ankle push-off power with correction of external tibial torsion in a population of

nonneuromuscular patients. In our study, ankle push-off power was not improved. As this patient population does not have normal muscle strength, it may be mere changes in lever arm are not sufficient to compensate for the abnormal power generation, as children with normal muscle strength are able to take greater advantage of a more aligned extremity. The foot deformity present may contribute to the moment generation at the ankle and may account for this lack of change in our population.

Senaran et al. [24] reported on anterior knee pain and mostly focused on patella femoral disease in a group of patients with CP. Of the 27 patients, only one had a tibial rotational osteotomy as part of the surgical management. Of the 13 patients with patella femoral subluxation, none were thought to be related to rotational malalignment, although the authors recommended gait analysis to assess rotational gait alignment. We observed subjective improvement in knee symptoms in all eight patients. It is not possible to discern what part of the kinematic improvements were responsible for this as crouch and patella alta may have contributed to the patient's symptoms. Delgado et al. [5] reported on a small series of normal children with this entity who underwent tibial osteotomies focusing on improving patella-femoral knee pain and knee joint axis rotation. The study did not employ 3D gait analysis but did report improvement in rotational profile on physical examination and all nine patients were reported to have improved functionally.

In conclusion, gait abnormalities including torsional deformities are present in many patients with CP. Sagittal plane deviations predominate, but transverse plane deformities can affect gait efficiency. We found improved varus knee moments and pain profiles in patients with CP after correcting external tibial torsion as part of a multilevel treatment plan. This procedure when performed with internal fixation is reliable, with minimal complications.

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