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ORIGINAL CLINICAL ARTICLE

A comprehensive outcome comparison of surgical and Ponseti clubfoot treatments with reference to pediatric norms

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Abstract

Purpose Isolated congenital clubfoot can be treated either operatively (posteromedial release) or conservatively (Ponseti method). This study retrospectively compared mid-term outcomes after surgical and Ponseti treatments to a normal sample and used multiple evaluation techniques, such as detailed gait analysis and foot kinematics.

Methods Twenty-six children with clubfoot treated surgically and 22 children with clubfoot treated with the Ponseti technique were evaluated retrospectively and compared to 34 children with normal feet. Comprehensive evaluation included a full gait analysis with multi-segment and single-segment foot kinematics, pedobarograph, physical examination, validated outcome questionnaires, and radiographic measurements.

Results The Ponseti group had significantly better plantarflexion and dorsiflexion range of motion during gait and had greater push-off power. Residual varus was present in both treatment groups, but more so in the operative group. Gait analysis also showed that the operative group had residual in-toeing, which appeared well corrected in the Ponseti group. Pedobarograph results showed that the operative group had significantly increased varus and significantly decreased medial foot pressure. The physical examination demonstrated significantly greater stiffness in the operative group in dorsiflexion, plantarflexion, ankle inversion, and midfoot abduction and adduction. Surveys showed that the Ponseti group had significantly more normal pediatric outcome data collection instrument results, disease-specific indices, and Dimeglio scores. The radiographic results suggested greater equinus and cavus and increased foot internal rotation profile in the operative group compared with the Ponseti group.

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Conclusions Ponseti treatment provides superior outcome to posteromedial release surgery, but residual deformity still persists.

Keywords Clubfoot · Ponseti · Pediatrics · Foot · Kinematics · Gait analysis

Introduction

Clubfoot is the most common congenital deformity of the lower extremity [1]. Most orthopedic surgeons agree that initial treatment should be non-operative, but there is controversy over whether operative intervention is more beneficial than the continuation of non-operative treatment [1]. Surgical treatment can be placed into two groups: 'a la carte' and extensive posteromedial release (PMR) [2] in its many variants. Surgical treatment provides a high percentage of short-term, clinically satisfactory radiological results [3]; however, long-term follow-up results, based on examinations, questionnaires, radiographic analyses [4, 5], and kinematics [6], are disappointing. Currently, most physicians agree that extensive soft-tissue release surgeries (joint invasive) should be avoided and that a more conservative, joint-sparing approach should be considered first [5, 7–13].

The Ponseti technique, currently the most widely accepted treatment of clubfoot, consists of a series of long-leg casts, and, in most cases, a percutaneous tenotomy of the Achilles tendon, followed by 4 years of foot abduction orthosis use [14, 15]. The method is a safe and effective treatment for congenital isolated clubfoot, and it radically decreases the need for extensive corrective surgery. High success rates have been seen functionally [8, 9, 16, 17] through examinations and surveys, and through gait analysis [10].

Gait analysis with multi-segment foot kinematics is a new evaluation technique that, for the first time, allows for the quantification of dynamic, intrinsic foot motion and has recently been used to quantify foot deformity in a variety of diagnoses [18–20]. Previous studies have looked at various treatment options' effectiveness in children with clubfeet [2–5, 7–12, 16, 17, 21–25]; however, there has not been a comprehensive comparison between the Ponseti method and surgical intervention that has included instrumented gait analysis with single- and multi-segment foot kinematics and foot pressure studies. The purpose of this study was to complete a long-term follow-up (5–10 years) that comprehensively compared outcome in patients with a history of clubfoot treated either surgically or with the Ponseti technique to a normal sample. We hypothesized that the Ponseti group would have better outcomes than the surgically treated group, as examined by the five testing modules (gait study, pedobarograph, physical examination, outcome questionnaires, and radiographic measurement).

Methods

The study is an IRB-approved bi-institutional retrospective study. The inclusion criteria were diagnosis of isolated clubfoot treated from birth and minimum follow-up (post-treatment) of 5 years. The diagnosis of isolated clubfoot was made by the treating orthopedic surgeon based on the absence of other identified diagnoses. Participants in the operative group were recruited from a single site, while participants from the Ponseti treatment group were recruited from a second site. All children who were treated surgically at the first hospital and all children who were treated with the Ponseti technique at the second hospital, during the time period 1999–2003, and who fitted the criteria, were contacted. During this time frame, all children with clubfeet at the Ponseti site were treated with the Ponseti method; all children with clubfeet at the surgical site were treated initially with casting and then operatively to correct the feet. These two groups were age-matched but they could not be matched according to severity because pre-operative data were not available for the operative site. All children were subjected to an evaluation that included a gait study with multi- and single-segment marker sets, a pedobarograph, a physical examination, patient outcome surveys (completed with the help of the parents), and radiographic studies.

Subjects

Children were evaluated in two groups retrospectively. Group 1 included 26 children (19 male/7 female), with 43 involved feet, who were diagnosed with isolated clubfoot, treated operatively at a mean age of 10 months (2–33 months), and followed up at age 5–11 years (average 9.2 ± 1.3 years). Group 2 included 22 children (9 male/13 female), with 35 involved feet, who were diagnosed with clubfoot, treated with the Ponseti technique from birth, and followed up at age 5–10 years (average 6.3 ± 1.4 years). Due to data processing issues, multi-segment foot kinematic data were analyzed in only 23 of 35 involved feet in the Ponseti group.

Gait study

Kinematic data were collected using an eight-camera Motion Analysis system (Motion Analysis; Santa Rosa, CA). Foot motion was measured with a multi-segment foot marker set [26] and with a single-segment marker set. The results were compared to normative data collected from 34

children (aged 4–17 years). Normative data were collected from a convenience sample of subjects with no reported foot deformity, motor disorder, or pain, and no observable gait deviations. The multi-segment foot model allowed us to calculate the position and orientation of the hindfoot, medial forefoot, lateral forefoot, and the hallux. The medial longitudinal arch of the foot was characterized by the ratio of its height to its foot length (arch index). Kinetics were calculated using data from two AMTI force plates (Advanced Mechanical Technology; Watertown, MA).

Pedobarograph study

Dynamic foot pressure readings were collected using a pedobarograph (Tekscan; South Boston, MA). Heel pressure and medial and lateral column pressures were compared to published normative values [27].

Physical examination

Physical examination measurements evaluated lower extremity passive range of motion, flexibility, static rotational alignment, and manual muscle-testing strength. Range of motion measurement and manual muscle-testing techniques were performed as described in Norkin and White's "Measurement of joint motion: a guide to goniometry" [28] and Kendall et al.'s "Muscles: testing and function with posture and pain" [29]. Range of motion values were compared to laboratory normative values and references [30, 31]. A standing heel-raise test measured the distance that the heel rises from the floor in single-leg stance.

Outcome questionnaires

Outcome measures included the Pediatric Outcomes Data Collection Instrument (PODCI) [32, 33], the Activities Scale for Kids (ASK) [34], the clubfoot disease-specific instrument (DSI) [35], and the Dimeglio scale [36, 37]. A normal score for the PODCI and ASK tests is 100; a higher number represents a better outcome. The DSI scores range from 10 to 40 points and higher DSI scores are associated with better health-related quality of life; lower DSI scores are related to special healthcare needs [38]. The Dimeglio scale ranges from 0 to 20; a lower number represents a more favorable outcome.

Radiographic examination

Standing anteroposterior and lateral radiographs of the feet were made and included the following: anterior/posterior adductus, anterior/posterior talo first metatarsal angle, lateral talo first metatarsal angle, lateral talocalcaneal, lateral calcaneal pitch, lateral tibiocalcaneal, and axial tibiocalcaneal. These angles were measured and compared between the operative group, the Ponseti group, and published normative values [39].

Statistical methods

Post hoc power analysis was performed to determine if there was sufficient power to detect differences between the Ponseti and operative techniques using the key outcome variable (ankle power generation). Power generation was selected due to its relation to both flexibility, active movement, and strength, and powers' key role in function. Using sample sizes of $n = 35$ (Ponseti group) and $n = 43$ (operative group), type I error of 5%, mean 18.2 (standard deviation [SD] 5.8) Ponseti group, mean 13.5 (SD = 3.9) operative group, we obtained a power of 98.3%, which is sufficient to detect any minimum difference between these two groups. Normally distributed data were analyzed with analysis of variance (ANOVA) or independent samples t-test. Non-normally distributed data and categorical data were analyzed with non-parametric tests (Kruskal–Wallis or Mann–Whitney). X-ray results were compared to age-matched means/SDs from the literature [39] using a single-sample t-test (normally distributed data) or a sign test (non-normal data).

Results

Treatment

Children in the operatively treated group were initially casted serially (3–4 casts) and then they received traditional posterior medial releases [40]. Following surgery, the children were casted with pins for 4 weeks and then followed up with splinting. In the surgical group, 14/43 feet (33%) required repeat surgical intervention. Of the 14 feet requiring repeat surgery, 11 (79%) required major surgery. Minor surgeries were joint-sparing and included tendon lengthenings and tendon transfers. Major surgeries were joint-opening procedures or boney realignment procedures, such as arthrotomies and osteotomies.

The Ponseti group was treated with an average of 5.0 casts and for an average of 5 weeks. All Ponseti-treated patients used a foot abduction brace (FAB), as recommended by the protocol [41]. Eighteen of 22 subjects had percutaneous Achilles tenotomies after initial casting was complete, followed by an additional 3 weeks of casting. Five patients in the Ponseti group relapsed, requiring additional casting and, in some cases, surgery (two patients: tibialis anterior tendon transfer [TATT], one patient: tendon Achilles lengthening [TAL]). None of the

patients needed any orthosis other than the FAB used by all Ponseti children.

Gait study results

Dynamic range of motion during gait was reduced in both groups compared to normal reference values, but significantly more so in the operative group (Tables 1 and 2). This dynamic stiffness during gait was demonstrated in both single-segment and multi-segment kinematic results, including ankle dorsiflexion (DF), plantar flexion (PF), and varus/valgus range of motion ($p < 0.01$). Sagittal plane motion was restricted in both swing and stance phase.

Force production was reduced in both treatment groups, but significantly more so in the operative group when compared to normal values (Tables 1 and 2). The normal ankle push-off power generation was 24.9 ± 6.5 watts/kg, and the Ponseti group (18.2 ± 5.8 watts/kg) was significantly closer to that normal value than the operative group (13.5 ± 3.9 watts/kg; $p < 0.01$). The ankle plantarflexor moment during stance was reduced in both groups when compared to the normal value ($p < 0.01$).

Dynamic rotational alignment analysis revealed residual internal rotation in the operative group that was largely corrected in the Ponseti group (Tables 1 and 2). Significantly less external tibial torsion was present in the two treatment groups compared to normal values ($p < 0.01$). Significant residual internal foot rotation was present in children who underwent operative treatment ($p < 0.01$), while children who underwent Ponseti treatment were within the normal range. To partially compensate for the comparative internal rotation at their tibia and foot, children in the operative group maintained their hips in a significantly greater amount of external rotation compared to children in the normal and Ponseti groups ($p < 0.01$). Overall, there was no significant difference between the normal and Ponseti groups' foot progression angles, but the operative group was significantly less externally rotated ($p < 0.01$).

Though range and force generation were reduced, and residual internal rotation was present in the operative group, generally, good intrinsic foot position was noted in both treatment groups. This was demonstrated by the fact that the Ponseti and operative groups' hindfoot valgus mean position in stance, forefoot valgus/varus, and medial arch height were all not significantly different from the normal group.

Walking velocity was within the normal range for both treatment groups. No significant differences existed between the two treatments in the step length, but both treatment groups' step length was reduced compared to normal ($p < 0.01$). The operative group's step width was larger than normal ($p < 0.01$).

Pedobarograph results

The Ponseti outcomes were significantly more normal than the operative group for the coronal plane pressure index (varus/valgus alignment; $p < 0.01$), but the medial forefoot pressure and the lateral midfoot pressure of both groups were significantly different from normal (Table 3; $p < 0.01$). Residual varus foot pressure distribution remained in both groups, but the operative group was in significantly greater in varus (−36.8 ± 24.7) compared to the Ponseti group (−15.7 ± 18.9) and to a normal population (11.0 ± 23.6; $p < 0.01$). Medial forefoot pressure

Table 1 Kinematics in children with clubfeet: operative versus Ponseti treatment (parametric statistical comparison for normally distributed data: ANOVA)

	Normal Mean ± SD	Ponseti Mean ± SD	Operative Mean ± SD	*F* (*df*)	*p*-value
Multi-segment foot kinematics					
Arch height	0.26 ± 0.04	0.29 ± 0.05	0.27 ± 0.06	2.9 (2)	0.06
Single-segment foot kinematics					
Ankle DF/PF range (°)	28.3 ± 4.1	24.2 ± 2.8*[a,b]	19.4 ± 3.3*[a]	70.7 (2)	<0.0001
Ankle push-off power generation (watts/Kg)	24.9 ± 6.5	18.2 ± 5.8*[a,b]	13.5 ± 3.9*[a]	48.1 (2)	<0.0001
Ankle max. PF (°)	14.4 ± 4.5	11.8 ± 4.8*[b]	7.8 ± 6.5*[a]	16.6 (2)	<0.0001
Ankle peak moment stance (Nm/Kg)	2.2 ± 1.0	1.4 ± 0.7*[a]	1.4 ± 0.5*[a]	15.1 (2)	<0.0001
Foot progression stance mean (external +)	6.4 ± 4.5	4.1 ± 6.2	0.8 ± 6.7*[a]	10.5 (2)	<0.0001
Foot rotation compared to tibia (external +)	−7.8 ± 6.2	−4.5 ± 6.4*[b]	−13.6 ± 6.3*[a]	18.3 (2)	<0.0001
Tibial torsion stance mean (external +)	15.4 ± 7.4	8.5 ± 11.2*[a]	6.5 ± 9.4*[a]	11.0 (2)	<0.0001

*$p < 0.01$; [a]different from normal; [b]different from operative; varus (−)/valgus (+); internal (−)/external (+); adduction (−)/abduction (+); *DF* dorsiflexion; *PF* plantarflexion; *SD* standard deviation, F = ANOVA value; χ^2 = Chi-squared value for Kruskal–Wallis test; *df* degrees of freedom, *M* median, *IQR* interquartile range

Table 2 Kinematics in children with clubfeet: operative versus Ponseti treatment (non-parametric comparison for non-normally distributed data: Kruskal–Wallis test)

	Normal M (IQR)	Ponseti M (IQR)	Operative M (IQR)	χ^2 (*df*)	*p*-value
Multi-segment foot kinematics					
Hindfoot varus/valgus range (°)	8.2 (4.3)	6.3 (3.0)*[a]	4.9 (3.8)*[a]	30.0 (2)	<0.0001
Hindfoot valgus mean stance (°)	−0.8 (4.7)	0.7 (8.7)	−0.9 (7.8)	4.8 (2)	0.09
Forefoot varus/valgus mean stance (°)	−11.1 (6.0)	−11.3 (6.9)	−13.7 (10.6)	1.5 (2)	0.5
Single-segment foot kinematics					
Ankle max DF stance (°)	14.2 (3.0)	12.7 (3.8)	12.3 (4.6)	6.4 (2)	0.04
Ankle max DF swing (°)	5.7 (3.0)	3.2 (4.1)*[a]	4.4 (5.4)	17.4 (2)	0.0002
Hip rotation mean support (external +)	1.1 (6.4)	3.2 (9.5)*[b]	7.9 (12.0)*[a]	20.1 (2)	<0.0001
Temporal spatial data					
Forward velocity (cm/s)	127 (26)	120 (23)	122 (15)	9.1 (2)	0.01
Step length (cm)	60.4 (13.4)	46.7 (10.1)*[a]	51.4 (9.6)*[a]	40.1 (2)	<0.0001
Step width (cm)	9.6 (3.2)	8.8 (2.3)*[b]	11.2 (2.7)*[a]	19.3	<0.0001

*$p < 0.01$; [a]different from normal; [b]different from operative; varus (−)/valgus (+); internal (−)/external (+); adduction (−)/abduction (+); *DF* dorsiflexion; *PF* plantarflexion; *SD* standard deviation, F = ANOVA value; χ^2 = Chi-squared value for Kruskal–Wallis test; *df* degrees of freedom, *M* median, *IQR* interquartile range

Table 3 Pedobarograph in children with clubfeet: operative versus Ponseti treatment

Foot pressure	Normal	Ponseti	Operative		
Parametric comparison	Mean ± SD	Mean ± SD	Mean ± SD	F (*df*)	*p*-value
Coronal plane pressure index (varus −/valgus +)	11.0 ± 23.6	−15.7 ± 18.9*[a,b]	−36.8 ± 24.7*[a]	50.6 (2)	<0.0001
Heel impulse	37.3 ± 9.6	42.2 ± 16.0*[b]	32.2 ± 14.4	5.4 (2)	0.006
Medial forefoot pressure	33.5 ± 9.2	39.8 ± 11.9*[a,b]	19.1 ± 8.8*[a]	45.5 (2)	<0.0001
Non-parametric comparison	M (IQR)	M (IQR)	M (IQR)	χ^2	*p*-value
Lateral midfoot pressure	5.3 (5.6)	23.7 (11.2)*[a]	25.0 (13.8)*[a]	66.5 (2)	<0.0001

*$p < 0.01$; [a]different from normal; [b]different from operative; F = ANOVA value; χ^2 = Chi-squared value for Kruskal–Wallis test; *M* median, *IQR* interquartile range

analysis showed slight overcorrection in the Ponseti group (39.8 ± 11.9) and significant undercorrection in the operative group (19.1 ± 8.8) compared to normal (33.5 ± 9.2; $p < 0.01$). Lateral midfoot pressures were significantly higher than the normal value for both treatment groups due to residual varus ($p < 0.01$). Heel impulse was well corrected in the operative group (32.2 ± 14.4) when compared to the normal value (37.3 ± 9.6), while the Ponseti group had a slightly higher impulse (42.2 ± 16.0).

Physical examination results

The Ponseti group demonstrated more motion than the operative group for all of the measured passive range of motion tests, including dorsiflexion, plantarflexion, total arc plantarflexion/dorsiflexion, forefoot inversion, forefoot eversion, midfoot abduction, and midfoot adduction (Table 4; $p < 0.01$). There was no significant difference in dorsiflexion between the normal group and the Ponseti group, but the operative group demonstrated a significant reduction in dorsiflexion ($p < 0.01$). Plantarflexion was significantly reduced from normal (56.2 ± 6.1) in both groups ($p < 0.01$), but much more so in the operative group (28.0 ± 10) compared to the Ponseti group (51.3 ± 10.3; $p < 0.01$).

Rotational measurements demonstrated significantly more residual internal rotation in the operative group compared to the Ponseti group in tibial torsion and the thigh–foot angle (hindfoot rotation; $p < 0.01$). Significantly greater plantarflexor weakness was demonstrated in the operative group, as shown by the single-leg stance heel-raise height measurement ($p < 0.01$).

Outcome surveys

Outcome scores and clubfoot-specific scales demonstrated significant limitations in the operative group compared to the Ponseti group (Table 5; $p < 0.05$). The PODCI (normal

Table 4 Physical examination in children with clubfeet: operative versus Ponseti treatment

Result	Normal	Ponseti	Operative		
Parametric analysis	Mean ± SD	Mean ± SD	Mean ± SD	*F* or *t*	*p*-value
PF PROM (°)	56.2 ± 6.1	51.3 ± 10.3*[a,b]	28.0 ± 10.7*[a]	172	<0.0001
DF/PF passive range (total arc motion (°)	68.8 ± 5.3	61.0 ± 12.6*[a,b]	27.5 ± 9.2*[a]	214	<0.0001
Forefoot inversion (°) PROM	36.8 ± 4.5	41.6 ± 9.3*[b]	29.3 ± 16.3	4.2	0.0001
Midfoot adduction (°) PROM	20	24.6 ± 8.6*[b]	8.5 ± 5.8	9.4	<0.0001
Standing single heel-raise height (cm)	N/A	7.8 ± 1.6*[b]	5.7 ± 2.3	4.9	<0.0001
Non-parametric analysis	M (IQR)	M (IQR)	M (IQR)	χ^2 or *z*	*p*-value
DF with knee extended PROM (°)	8 (9)	10 (10)*[b]	2 (11)*[a]	37.0	0.0001
Calcaneal inversion/eversion PROM (°)	N/A	40 (15)*[b]	16 (12)	6.2	<0.0001
Forefoot eversion (°) PROM	20 (5)	20 (10)	16 (13)	2.2	0.03
Midfoot abduction (°) PROM	10	15 (15)*[b]	5 (2)	4.4	<0.0001
Tibial torsion (external +) (°) resting	15	20 (10)*[b]	12 (15)	3.0	0.003
Thigh–foot angle (external +) (°)	9 (8)	15 (10)*[a,b]	4 (21)*[a]	22.6	0.0001
Forefoot adduction at rest (°)	N/A	5 (10)*[b]	8 (10)	2.5	0.01

*$p < 0.01$; [a]different from normal; [b]different from operative; *N/A* not available, *DF* dorsiflexion, *PF* plantarflexion, *PROM* passive range of motion; *F* or *t* = ANOVA or independent sample *t*-test values; χ^2 or *z* = Chi-square value for Kruskal–Wallis test or *z*-value from Mann–Whitney test

Table 5 Surveys in children with clubfeet: operative versus Ponseti treatment

Result Outcomes survey	Normal	Ponseti M (IQR)	Operative M (IQR)	*z*	*p*-value
PODCI upper extremity and physical functioning	100	100 (8)	100 (8)	−0.20	0.84
PODCI transfer and basic mobility	100	100 (0)	100 (0)	0.31	0.75
PODCI sports and physical functioning	100	99 (6)	95 (11)	1.8	0.08
PODCI pain/comfort	100	100 (0)*[a]	100 (20)	2.5	0.01
PODCI happiness	100	100 (5)	100 (10)	1.3	0.19
PODCI global functioning	100	99 (5)*[a]	97 (8)	2.6	0.008
ASK survey	100	98 (6)	93 (8)	1.8	0.07
Disease-specific survey	10	12 (3)*[a]	16 (6)	−5.9	<0.001
Dimeglio score	0	4 (3)*[a]	15 (7)	−7.6	<0.001

*$p < 0.05$; [a]different from operative, *M* median, *IQR* interquartile range, *z* = *z*-value for Mann–Whitney test

score is 100) results showed sports and physical function to be mildly limited in the operative group (though not statistically significantly so). The happiness, upper extremity, and basic mobility sections were not statistically different in the two groups. In terms of pain and global functioning, the Ponseti group rates were significantly higher than the operative group ($p < 0.05$). The ASK survey (normal score is 100) did not reveal any significant differences, although the Ponseti group had higher scores than the operative group. The disease-specific survey (the lower the score the better the outcome) indicated that the Ponseti group scores were significantly closer to normal than the operative group ($p < 0.01$). Lastly, the Dimeglio score (again, the lower score indicates a more normal result) was significantly lower in the Ponseti group than the operative group ($p < 0.01$).

Radiological results

Radiological measurements demonstrated the presence of residual deformity with measures of AP adductus, lateral talocalcaneal, and lateral tibiocalcaneal angles different from normal in both treatment groups and AP talo first metatarsal angle significantly different from normal in the operative group only (Table 6; all $p < 0.01$). Radiological results for the operative group showed significantly increased AP foot adductus and AP talo first metatarsal angle compared to those of the Ponseti group ($p < 0.01$). This increased foot internal rotation profile was consistent with the dynamic, residual internal rotation of the operative group. There was a significant difference in the lateral talo first metatarsal angle, with the operative group demonstrating greater cavus ($p < 0.01$).

Table 6 Radiographs

Measurement (°)	Norm (6 years old)	Ponseti	Norm (9 years old)	Operative
Parametric analysis	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Lateral talocalcaneal	43 ± 4	33.1 ± 6.5*	39 ± 4	30.7 ± 9.4*
Lateral calcaneal pitch	20!	15.8 ± 5.2	14!	12.6 ± 8.7
Non-parametric analysis	Mean ± SD	Median (IQR)	Mean ± SD	Median (IQR)
Lateral talus first metatarsal	2 ± 6	−4 (7)#	5 ± 6	7 (13)
Lateral tibiocalcaneal	65 ± 4	78 (7)*	68 ± 3	73 (16)*
AP talo first metatarsal	3 ± 3	2 (10)#	6 ± 8	11 (17)*
AP adductus	−2 ± 3	13.5 (8)#*	3 ± 5	32 (5)*

# $p < 0.01$ operative versus Ponseti; *$p < 0.01$ compared to normal; *AP* anterior posterior; ! = lateral calcaneal pitch calculated from lateral talocalcaneal and lateral talo-horizontal angle, so SD is not available, unable to complete statistical testing. Parametric analysis: independent sample *t*-test and single-sample *t*-test. Non-parametric analysis: Mann–Whitney test and sign test

Discussion

Zionts et al. [42] demonstrated that the percentage of clubfeet treated in the US with surgical release decreased from just over 70% in 1996 to just over 10% in 2006, suggesting a trend toward less invasive techniques. Our study is important because, although the use of the Ponseti technique has dramatically increased over the past decade, no studies as comprehensive as ours have been performed comparing the outcomes of surgical release to the Ponseti method. Studies have been conducted comparing the Ponseti method to the French method [43–45], which demonstrated that the Ponseti method had superior outcomes. Zwick et al. [9] compared the Ponseti method to the results of PMR surgery, but the outcome measures only included Laaveg and Ponseti's Functional Rating System, the PODCI, and radiographic measurement. The study also had a short-term follow-up of 3.5 years, compared to our study's mid-term follow-up mean of 6.3 years. Halanski et al. [46] compared the results of the Ponseti method to surgery, but they solely examined the need for repeated surgery. Also, boot and bar wear compliance in the Ponseti group of Halanski et al.'s paper was poor.

This study seeks to present a comprehensive comparison of the outcomes of operatively treated clubfeet to Ponseti-treated clubfeet. Multiple testing procedures were performed to assess areas of residual deformity for each treatment and to guide future treatment methods. In the past, a few studies have used gait analysis to evaluate clubfoot treatment effectiveness [6, 7, 10, 11, 22]; however, these studies have been limited to the use of single-segment foot kinematics. Our study is the first to fully analyze the Ponseti and operative treatments of clubfoot with the use of multi-segment foot kinematics. Multi-segment foot kinematics allow for the quantification of dynamic foot deformities, which were previously impossible to analyze in such detail. These analyses are of key importance when looking at clubfoot because the central location of the deformity is the foot itself.

As in previous studies [3, 5, 17], our study found that residual stiffness and deformity translated into functional limitations and pain in the operative group. In both pain and global functioning in the PODCI survey, the operative group had a significantly lower score (poorer outcome) than the Ponseti group. Significantly higher scores on the Dimeglio and clubfoot disease-specific instrument surveys for the operative group again demonstrated the superior functional outcome in the Ponseti group.

Sagittal plane

The technical outcome is assessed by the kinematic, kinetic, and pedobarograph review based on gait analysis. Dorsiflexion was significantly decreased in the operative group, but it was within normal limits in the Ponseti group. Previously published studies report diminished push-off power in the sagittal plane, and we found similar results [6, 10, 13, 22, 23]. Push-off power was limited by 45.8% in the operative group and by 26.9% in the Ponseti group. This power reduction can be traced to two sources: reduced range of motion and reduced muscle strength [10]. Multiple studies have also found gastrocsoleus weakness and a reduction in power generation in children with clubfoot [6, 13, 23]. Our study is consistent with the plantarflexion weakness in children with clubfoot, with greater weakness appearing in the operative treatment group, as seen in the standing heel-raise test.

Coronal plane

Previous studies report residual varus following clubfoot treatment [24, 47]. This study demonstrated that both treatments resulted in residual varus as well, with the operative group having a significantly greater varus.

Similarly, Widhe and Berggren [24] reported a significant shift in the pressure from the center to the lateral side of the foot in children with clubfoot who had been treated conservatively. Furthermore, in a 2009 study, Sinclair et al. [47] reported that, compared to an unaffected foot, a surgically treated clubfoot had a reduced peak pressure over the medial hindfoot and forefoot. Sinclair et al. also reported an increase in pressure over the lateral midfoot, thereby, resulting in a varus position. In this study, both the Ponseti and operative groups demonstrated residual increase in lateral midfoot pressure, but the Ponseti group seemed to correct medial forefoot pressure well, while the operative group continued with a reduced pressure.

Transverse plane

The most common trait reported in studies that analyzed clubfoot treatment is residual in-toeing [10, 11, 23]. Foot progression angles from the kinematic study demonstrated in-toeing in the operative group, while the foot progression angle in the Ponseti group was within normal limits. This study demonstrates through kinematics that residual in-toeing in the operative group is present due to internal rotation of the foot and reduced external tibial torsion compared to the normal group. The radiographic results show only small variation between the two treatment groups, with the largest deviation from normative data present in the residual forefoot adductus, correlating well with kinematics and pedobarograph.

Surgical outcome

One method of reviewing the success of treatment is to analyze the rate of repeat surgery required for relapse. The operative group required a higher rate of surgical intervention and a higher percentage of major surgeries for relapse management when compared to the Ponseti group. In the surgical group, 14/43 feet (33%) required repeat surgical intervention. Of the 14 feet requiring repeat surgery, 11 (79%) required major surgery. Two of the 14 (14%) repeat surgeries for the surgical group also required a third surgical intervention. Of the Ponseti group, 3/35 (9%) required surgical intervention for relapse treatment, all of which were minor surgeries (two TATT, one TAL). Not only did the operative group require significantly more repeat surgeries, but most of the repeat surgeries in the operative group were major surgeries, compared to no major surgeries required in the Ponseti group.

Limitations

Limitations of our study include the length of follow-up and the difference in time to follow-up in the two subject groups. Because the subjects in this study were in middle childhood, this study should be considered as a mid-term outcome study, since feet may continue to change with age. Therefore, additional follow-up is required in order to observe further changes in presentation in the teenage years and into adulthood. The average subject age in the Ponseti group was 6.3 years, compared to the average age in the operative group of 9.2 years (though the age range was similar), which could introduce bias into our results, especially in the area of the frequency of recurrence of surgical intervention.

Conclusion

Over the past 10 years, there has been a rapid shift toward the conservative management of clubfeet [42], which is supported by this study. In conclusion, this study demonstrates, through its use of multiple dynamic assessments and outcome instruments compared to major surgical intervention, that Ponseti treatment results in better function and more normal foot motion and position for children with congenital isolated clubfoot. The Ponseti-treated group required fewer repeat surgical interventions, walked with a better quality of gait, showed better static alignment and foot mobility, and had better global functioning. It is important to note that residual deformity persists in both series, although deformity is much less severe in the Ponseti group, which showed very good functional results.

Conflict of interest No conflicts of interest or sources of funding exist to disclose.

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