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ScienceDirect

Neuromuscular Disorders 29 (2019) 427–436

www.elsevier.com/locate/nmd

Surgical outcomes of cavovarus foot deformity in children with Charcot-Marie-Tooth disease

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Received 25 March 2018; received in revised form 7 April 2019; accepted 24 April 2019

Abstract

Charcot-Marie-Tooth disease (CMT) causes disabling cavovarus foot deformity. Orthopaedic surgery is performed in severe cases; however few studies have investigated whether surgery improves health outcomes during childhood. This study investigated the impact of cavovarus surgery on validated physical, functional, parent/self-reported and biomechanical measures in 21 consecutive patients (mean age at surgery 12.5 years, SD 2.7) evaluated before and after surgery (mean duration 15.7 months, SD 5.9), and compared to natural history data from 206 children with CMT. Measures from the CMT Pediatric Scale evaluated foot alignment (Foot Posture Index), ankle flexibility (lunge test), strength (foot dorsiflexion/plantarflexion by hand-held dynamometry), function (balance, long jump, 6-minute walk test) and self-reported symptoms. Quality of life (Child Health Questionnaire) and gait (pressure loading) were also assessed. Foot Posture Index and lunge improved with surgery by 6.0 points (SD 3.2) and 6.1° (SD 7.3) respectively ($p < 0.01$), and differed to the natural course of the disease ($p < 0.005$). Self-reported daily trips/falls reduced from 60% to 13% ($p = 0.016$). Pressure improved beneath the rearfoot and midfoot ($p = 0.043$). Surgery had no effect on strength, function or quality of life, which generally mirrored the natural course. Cavovarus surgery improved foot alignment, ankle flexibility and self-reported trips/falls in children with CMT.

Keywords: Charcot-Marie-Tooth disease; Foot deformities; Child health; Clinical outcome assessment; Orthopaedic procedures.

1. Introduction

Charcot-Marie-Tooth disease (CMT) is a heterogeneous group of inherited peripheral neuropathies affecting 3–82 per 100,000 individuals of both sexes and all backgrounds [1]. CMT is characterised by demyelination and/or axonal degeneration of the peripheral nerves, with typical onset in the first two decades of life [2,3]. More than 90 causative genes have been identified so far, and CMT type 1A is the most common subtype [4]. Most patients exhibit a length-dependent progression of symptoms and impairments, with symptoms initially distal at the feet and hands, progressing proximally. The clinical phenotype is characterised by progressive muscle weakness, atrophy, sensory deficits and skeletal deformities. Foot deformities, such as cavovarus (highly-arched) and clawed toes, are observed in patients with CMT in 60–90% of cases [5–7]. The cavovarus foot deformity commonly features an excessively high medial longitudinal arch that does not flatten on weight bearing, varus (inverted) rearfoot and a plantarflexed (downward) position of the first metatarsal, adducted forefoot, claw toes and secondary contracture of the plantar fascia [8]. A flexible deformity usually develops during childhood, and is often bilateral, painful and becomes increasingly severe and rigid as the disease progresses [9]. Imbalance of foot and ankle musculature is thought to play a critical role in the development of cavovarus foot deformity [10,11], whereby the length-dependent nerve degeneration

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https://doi.org/10.1016/j.nmd.2019.04.004
0960-8966/

Table 1
Common surgical procedures for the correction of cavovarus foot deformity in CMT.

Types of procedures	Examples
Soft tissue procedures	• Plantar fascia release • Tendon lengthening (e.g., of the Achilles, tibialis posterior tendon) • Tendon transfers (e.g., Peroneus longus to peroneus brevis transfer, tibialis posterior tendon to peroneus brevis transfer)
Bony procedures	• Osteotomies (Removing a wedge of the bone to correct the altered bony anatomy e.g., of the metatarsal, calcaneal, tarsometatarsal and tarsal bones)
Joint stabilising procedures/fusions:	• Triple arthrodesis (Consists of fusion of the three joints in the foot, i.e., the talocalcaneal, talonavicular and calcaneocuboid joints. Generally reserved for those with extremely severe and fixed deformity or for salvage of failed correction attempts)

affects the intrinsic foot muscles, progressing to selected extrinsic lower leg muscles responsible for foot eversion and dorsiflexion (e.g., peroneus brevis muscles and tibialis anterior). Whilst the foot invertors and plantarflexors (e.g., tibialis posterior, triceps surae and peroneus longus muscle) remain relatively stronger and overpower the opposing evertors and dorsiflexors resulting in an adducted forefoot, inverted rearfoot and plantarflexed first metatarsal [10].

There are a multitude of physical, functional, psychosocial and biomechanical sequelae of the cavovarus foot deformity associated with CMT during childhood. These include ankle contracture, impaired balance and power, foot pain, unsteady ankles, frequent trips and falls, poor walking ability and decreased endurance [12–14]. Health-related quality of life is also commonly affected in children with CMT who have cavovarus foot deformity [15]. Furthermore, patients commonly exhibit abnormal plantar pressure loading during gait which are significantly related to callosities, foot pain and stress fractures [16].

As yet there is no disease modifying therapy to reverse or halt the progression of CMT during childhood. Symptomatic management of cavovarus deformity is often necessary to ameliorate symptoms, improve impairments and maintain function. These interventions include orthotic therapy to accommodate the deformity, improve pressure loading and reduce foot pain [13,17], physiotherapy such as stretching, mobilisation, splinting and serial casting to increase ankle flexibility [14,18] and progressive resistance exercise to improve or maintain muscle strength [19]. Surgical management of the cavovarus deformity is often indicated when symptomatic management has failed. Indications may include inability fitting orthoses and footwear due to severity of foot deformity and ankle contracture, recurrent musculoskeletal complications such as trips/falls and pain, significant gait impairment, day-to-day limitations such as walking difficulties and fatigue. The goals of surgery are to produce well-aligned, plantigrade and functional feet by correcting the bony deformity (via osteotomies) and rebalancing the deforming muscles (via soft tissue transfers). Surgical decisions are individualised and multifaceted. An overview of the common types of surgical procedures for cavovarus foot deformities is summarised in Table 1.

Whilst a variety of surgical procedures for cavovarus deformity have been described in the literature [20–24], very few studies have evaluated the impact of foot surgery on health outcomes in children with CMT. The evidence base on surgical management of cavovarus deformity in CMT includes case reports or case series that are limited by small sample size [21,24–27], mixed cohorts of paediatric and adult patients [20,21,23,27–30], heterogeneous cavovarus aetiology with a subset of CMT cases [21,26,31,32], primarily radiographic outcomes [21,30,32], or non-validated measures [26,31]. There is a need to longitudinally evaluate the impact of cavovarus foot surgery on paediatric patients with CMT using validated and multifaceted outcome measures. Therefore, the aim of this study was to investigate the effect of cavovarus foot surgery on validated physical, functional, parent/self-reported and biomechanical outcome measures in affected children and adolescents before and after surgery, and compared to the natural course of the disease.

2. Materials and methods

2.1. Study design and participants

This is a pre- and post-operative cohort study involving all patients enrolled in the Australasian Paediatric CMT Registry who were treated surgically for cavovarus foot deformity at The Children's Hospital at Westmead (Sydney, Australia) by a single surgeon (P.G.) from January 2006 to August 2017. Written informed consent was obtained from all participants' parents or guardians in accordance with the requirements of the Human Research Ethics Committee, and when appropriate, participant's assent was obtained. Additional eligibility criteria were: aged under 18 years; confirmed genetic diagnosis of CMT or a consistent clinical phenotype with genetic testing in a first- or second-degree relative and confirmatory phenotype/electrophysiology in the child. The indication for surgery was progressive and symptomatic flexible or fixed cavovarus foot deformity resulting in impairment of gait (4 patients), despite conservative management. Other indications included daily trips/falls (12 patients), ankle or foot pain (12 patients), ankle instability (13 patients), functional impairment resulting from pain and pressure areas within ankle-foot orthoses (AFOs) (6 patients). In the absence of any of these symptoms, flexible rearfoot deformity thought likely to become fixed (1 patient), and severe or progressive deformity thought likely to become symptomatic later in adult life (1 patient) were further indications. The selection process for each child was based on comprehensive evaluation of all components of

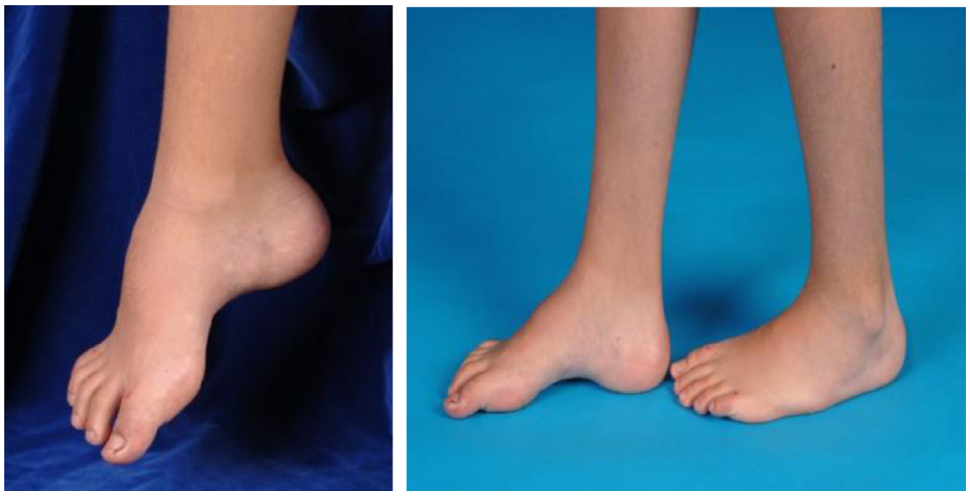

Fig. 1. Cavovarus foot deformity in a 14-year-old boy with CMT1A (Foot Posture Index score of −8 on the right foot and −7 on the left foot).

the deformity including site, direction and magnitude of the deformities, flexibility and muscle strength. Children were excluded from this study if they had undergone previous foot or ankle surgery, or were diagnosed with diabetes, infectious or inflammatory arthropathies, congenital defects, neurological or neuromuscular disorders other than CMT.

2.2. Data collection

Participants underwent standardised pre-operative (baseline) and post-operative evaluations. Baseline measures encompassed demographic, anthropometric and physical characteristics, including sex, age, height, weight, body mass index (BMI) percentile, CMT subtype and clinical symptoms. Health outcomes were obtained by one of two experienced clinical evaluators (J.B. or K.C.) using highly reliable and validated age-appropriate measures. Both evaluators had previously demonstrated acceptable intra- and inter-rater reliability for all measures. The primary outcome measure was change in foot alignment. Secondary outcomes included change in ankle flexibility, strength, function, parent/self-reported and biomechanical measures.

2.2.1. Physical, functional, parent/self-reported and biomechanical measures

Many of the outcome measures collected were from the lower limb items of the Charcot-Marie-Tooth Pediatric Scale (CMTPedS). The CMTPedS is a well-validated, responsive and psychometrically robust clinical outcome assessment for individuals with CMT aged 3–20 years [33,34]. It comprises the Foot Posture Index for foot alignment, lunge test for ankle dorsiflexion flexibility, self-reported symptoms, as well as 11 performance-based upper and lower limb functional items.

The Foot Posture Index is an observational clinical tool evaluating the multi-segmental and multi-planar aspects of foot alignment. It has demonstrated acceptable intra- and inter-rater reliability in both children and adults, and is deemed superior to visual inspections or other clinical measures in quantifying foot alignment. The Foot Posture Index allocates a score between −2 and +2 to each of six criteria related to foot posture. The aggregated score ranges from −12 (highly cavovarus) to +12 (highly planovalgus). An example is shown in Fig. 1. Flexibility of ankle dorsiflexion was assessed in weight bearing using the lunge test with a digital inclinometer. The lunge test has been shown to have excellent reliability in both children and adults. Five of the 11 performance-based items of the CMTPedS were collected. Maximal voluntary isometric strength of foot dorsiflexors and plantarflexors was quantified using hand-held dynamometry (Citec, CIT Technics, Groningen, Netherlands). Balance was evaluated barefoot using the Bruininks-Oseretsky Test of Motor Proficiency, 2nd Ed (BOT-2, Pearson Education, Upper Saddle River, New Jersey). Power was assessed by standing long jump. Endurance was evaluated by the 6-minute walk test, which is an accurate and meaningful measure of function in children. Performance-based items in the CMTPedS are converted to z-scores based on age- and sex-matched normative reference values from the 1000 Norms Project [35,36] to ensure variables are independent of growth and development. Each of the 11 individual item z-scores can also be converted to category scores ranging from 0 (unaffected) to 4 (severely affected) and summed to produce a CMTPedS total score ranging from 0 (unaffected) to 44 (severely affected).

Self-reported symptoms (foot pain, leg cramps, unsteady ankles, daily trips/falls) were also collected from the CMTPedS. Health-related quality of life was assessed with the parent-reported questionnaire, the Child Health Questionnaire [37]. The Child Health Questionnaire has been validated to assess pre- and post-intervention studies in children aged 2–18 years [38]. The Child Health Questionnaire contains two summary scores for the psychosocial and physical domains, whereby the scores range from 0 representing the worst score to 100 denoting the best score. Gait was measured by capturing barefoot plantar pressure loading using the EMED–X capacitance transducer matrix platform (Novel gmbh,

Munich, Germany) using our previously validated protocol [16]. Three successful trials were recorded from each foot, averaged, and divided into five regions of the foot (masks) to investigate the local pressure pattern: rearfoot, medial and lateral midfoot, medial and lateral forefoot (Fig. 2). Pressure-time integrals (kPa*s) were calculated using the Novel software (Scientific Medical, version 22) as the area under the pressure time graph, and is an expression of pressure experienced in the mask region over the entire duration of stance phase. These values were converted to z-scores based on age- and sex-matched normative reference values from the 1000 Norms Project [39] to enable comparison between different ages and sexes.

2.3. Statistical analyses

Data were analysed in SPSS v22 (IBM SPSS Statistics for Windows, Armonk, NY). Normality of data distribution was assessed using the Kolmogorov–Smirnov test and the appropriate parametric or non-parametric tests were subsequently employed. Data were analysed from one limb only for each participant (operated limb in unilateral cases and the dominant limb in bilateral cases) to satisfy the independence requirements for statistical analysis [40]. Paired-sample *t* tests were calculated to assess the significance of change between the pre-operative and the post-operative visit. One sample *t* tests were used to compare the participants' outcomes measures with the equivalent time-adjusted natural history data from 206 children with CMT [34]. Self-reported symptoms were reported as present (n,%), and change analysed using the McNemar's chi-square test. Changes in gait were assessed using the Wilcoxon signed-rank test.

3. Results

3.1. Participant characteristics

Table 2 presents the baseline demographic, anthropometric and clinical characteristics of the sample. Twenty-one consecutive children and adolescents (13 males, mean age at the time of surgery 12.5 years, SD 2.7, range 8–16 years) included in the study were surgically treated for cavovarus foot deformity at The Children's Hospital at Westmead (Sydney, Australia) by a single surgeon (P.G.) between January 2006 and August 2017. None were excluded. As part of the Inherited Neuropathies Consortium, we aim to systematically assess patients annually. The mean duration of follow-up was 15.7 months (SD 5.9, range 8–30 months). The majority of participants (57%) had a diagnosis of CMT1A. The mean CMTPedS total score of disease severity at baseline was 21 (SD 7, range 10–33: mild to severe).

Table 2
Baseline demographic, anthropometric and clinical characteristics of the cohort.

Characteristic	Participants
Age at surgery (yr), mean (SD), ($n=21$)	12.5 (2.7)
Child (6–11), n (%)	11 (52)
Adolescent (12–17), n (%)	10 (48)
Gender, *n* (%) ($n=21$)	
Male	13 (62)
Female	8 (38)
Body mass (kg), mean (SD), ($n=21$)	47 (13)
Height (m), mean (SD), ($n=21$)	1.54 (0.15)
BMI percentile, mean (SD), ($n=21$)	55 (40)
Charcot-Marie-Tooth subtype, *n* (%), ($n=21$)	
CMT1A	12 (57)
CMT1E	1 (5)
CMT2A	1 (5)
CMTX1	1 (5)
CMTX3	3 (14)
Genetically unclassified	3 (14)
CMTPedS score (0–44 score), mean (SD), ($n=17$)	21 (7)
Self-reported symptoms, n (%), ($n=18$)	
Foot pain	12 (55)
Leg cramps	5 (23)
Unsteady ankles	13 (60)
Daily trips and falls	12 (55)

CMTPedS, Charcot-Marie-Tooth disease Pediatric Scale.

3.2. Surgical procedures and post-operative protocol

Sixteen combinations of surgical procedures were performed (Table 3). The predominant procedures were first metatarsal osteotomy ($n=18$), plantar fascia release ($n=17$) and peroneus longus to brevis tendon transfer ($n=14$). Nineteen patients received simultaneous or staged bilateral surgery, and two received unilateral surgery. Of note, there was a change in surgical approach during the study based on research showing an improvement in claw toe deformity if the plantar fascia was preserved [41]. Therefore, all patients received a plantar fascia release unless there was significant clawing of the toes. Where the plantaris deformity predominantly arose from the first metatarsal, a dorsal closing wedge first metatarsal osteotomy was performed. If the plantaris deformity arose from a more global forefoot plantarflexion, dorsal closing wedge mid-tarsal osteotomy was performed. Fixed hindfoot varus was corrected with a lateral displacement calcaneal osteotomy, or a lateral closing wedge calcaneal osteotomy for more severe varus. The standard tendon transfer used was peroneus longus to peroneus brevis, sometimes combined with tibialis posterior lengthening if the latter was thought to be a strong contributor to the equinovarus. If there was foot drop, tibialis posterior transfer to the dorsum of the foot was used. In occasional cases of excessive flexible or dynamic supination, the tibialis anterior tendon, provided its strength was MRC grade 4 or higher, was transferred laterally. Any residual hindfoot equinus was addressed with either a percutaneous tendon-Achilles lengthening or a Strayer calf lengthening. Symptomatic toe deformities were not common and were managed with Jones transfer and interphalangeal joint fusion in the hallux and proximal interphalangeal joint fusion in a second toe.

The post-operative protocol included pain relief as required and elevation of the operated limb overnight for the first two

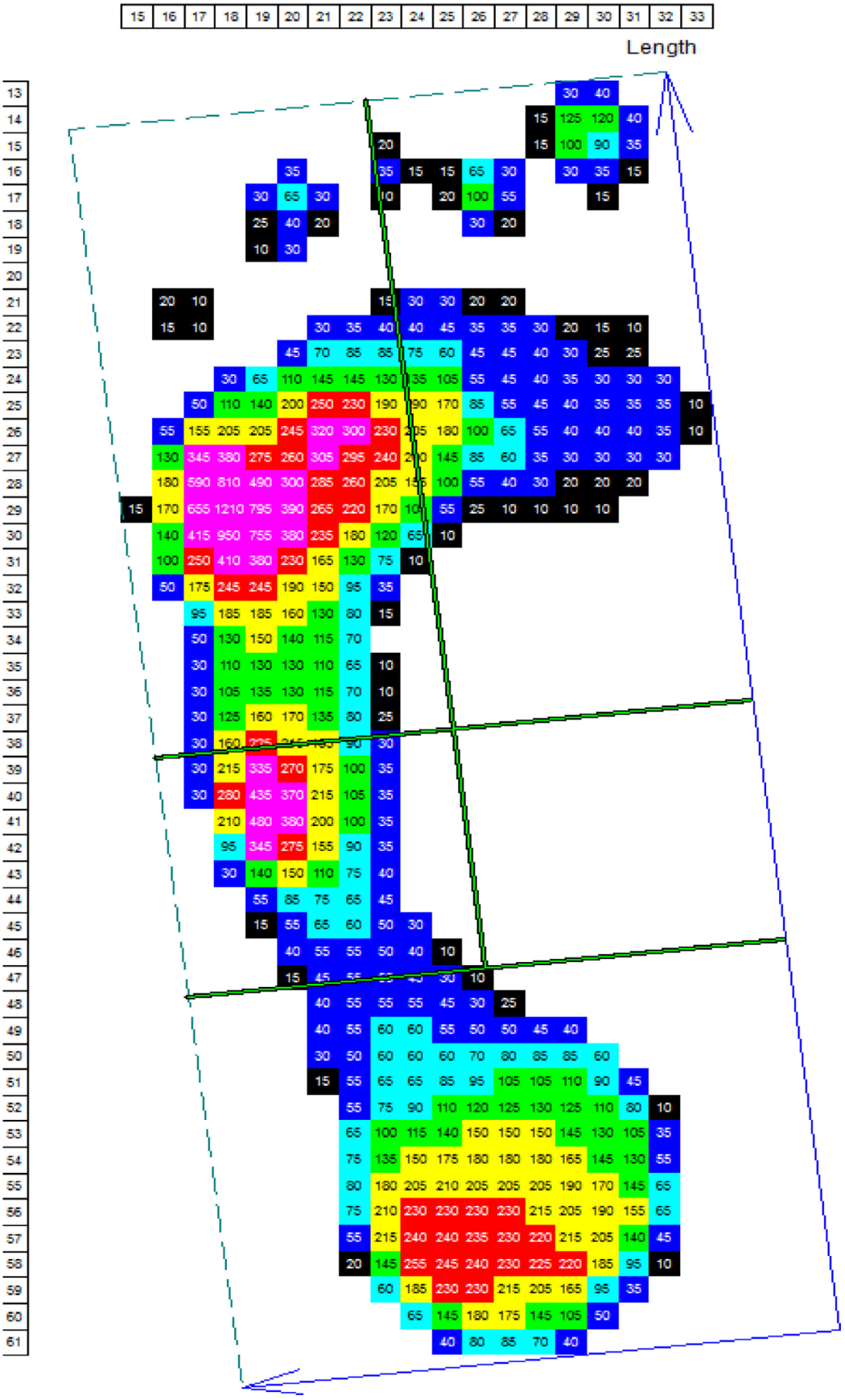

Fig. 2. The foot was divided into five regions to investigate local plantar pressure distribution: rearfoot, medial and lateral midfoot, medial and lateral forefoot.

Table 3
Surgical details for each participant in the study.

Age at surgery (yrs)	Gender	CMT type	Procedure
8	M	CMT1E	PFR, TPL, PLB, 1st MTO
8	M	CMT1A	PFR, PLB, 1st MTO
9	M	CMT1A	PFR, PLB, 1st MTO
9	M	CMT1A	PFR, PLB, 1st MTO
9	M	Genetically unclassified CMT1	TPL, PLB, TATT, LCWO
10	F	Genetically unclassified CMT2	PFR, TPT, 1st MTO
10	F	CMT1A	PFR, TAL, PLB, 1st MTO, LDCO
10	M	CMTX3	TAL, LDCO, MO
11	F	CMT1A	PFR, PLB, TATT, 1st MTO
11	F	CMT1A	PFR, TAL, TPBT, PLB, 1st MTO, LDCO
11	M	CMTX	PFR, TAL, PLB, 1st MTO, LDCO
12	F	CMT1A	PFR, 1st MTO
14	M	CMTX3	PFR, TPBT, LDCO
14	F	Genetically unclassified CMT2	PFR, TAL, PLB, 1st MTO, LDCO
14	F	CMT1A	TAL, TPT, 1st MTO, LDCO
14	M	CMT1A	PFR, TAL, SPLATT, TPT, 1st MTO, LCWO, 2nd toe PIPF
15	F	CMT1A	PLB, TATT, 1st MTO, LDCO
15	M	CMT2A	PFR, PLB, SL, 1st MTO
15	M	CMT1A	PFR, TAL, TPL, PLB, 1st MTO, Jones with IPF
16	M	CMT1A	PFR, PLB, 1st MTO
16	M	CMTX3	PFR, TAL, TPT, 1st MTO, LDCO

PFR = Plantar fascia release; 1st MTO = First metatarsal osteotomy; PLB = Peroneus longus to brevis transfer; TATT = Tibialis anterior tendon transfer; SL = Strayer calf lengthening; TAL = Tendon Achilles lengthening; LDCO = Lateral displacement calcaneal osteotomy; Jones with IPF = Jones transfer with interphalangeal joint fusion; TPL = Tibialis posterior lengthening; TPBT = Tibialis posterior to peroneus brevis transfer; TPT = Tibialis posterior tendon transfer; SPLATT = Split anterior tibialis tendon transfer; Second toe PIPF = Second toe proximal interphalangeal joint fusion; MO = Lateral closing wedge mid-tarsal osteotomy; LCWO = Lateral closing wedge calcaneal osteotomy.

weeks. Patients were to remain strictly non-weight bearing for a total of six weeks and mobilised in wheelchair.

3.2.1. Complications and/or surgical revisions

No major complications occurred in anaesthesia, intra-operative and postoperative course, with the exception of one participant who developed signs of complex regional pain syndrome in the right lower limb, which had resolved at 12 months post-op following multimodal physiotherapy interventions. All osteotomies had united without complications and no deep infections, nerve damage or neuralgia were encountered. Superficial post-operative sensory symptoms, such as numbness in the operated extremities resolved spontaneously with time. One participant underwent a secondary surgery comprising of tibialis anterior tendon transfer and percutaneous tendon-Achilles lengthening 2.5 years following the principal corrective surgery due to dynamic supination whilst walking.

3.3. Evaluation of the health outcomes

Pre- and post-operative outcomes are presented in Table 4. Three participants are yet to return for follow-up. Foot alignment, measured by the Foot Posture Index, increased from a pre-operative mean of −7.4 (SD 2.6) to a postoperative mean of −1.5 (SD 3.3) representing a significant improvement in foot alignment ($p< 0.001$). This change was significantly different to the expected rate of progression of CMT from the longitudinal natural history data, which shows an expected worsening of −0.4 (SD 2.4) over a 16-month period ($p< 0.001$) [34]. Fig. 3 shows a large improvement in a 9-year old patient in this study. Ankle flexibility, measured by the lunge test, improved from a pre-operative mean of 16.7° (SD 7.1°) to a post-operative mean of 22.7° (SD 3.7°) ($p=0.003$). This change was also significantly larger than the expected rate of progression of 0.2° (SD 4.7°) ($p=0.003$). Strength, balance, long jump and the 6-minute walk test did not significantly differ pre- to post-operatively, and were consistent with the natural history of the disease ($p> 0.05$). Overall disability, measured by the CMTPedS total score, showed a non-significant worsening of 1.5 points (SD 4.5) at follow-up which mirrors the natural rate of disease progression ($p=0.525$).

Of the 15 children who completed self-reported symptom data, daily trips/falls significantly reduced from 9/15 (60%) to 2/15 (13%) ($p=0.016$), foot pain reduced from 9/15 (60%) to 7/15 (47%) ($p=1.000$), leg cramps increased from 3/15 (20%) to 6/15 (40%) ($p=0.375$), and unsteady ankles decreased from 10/15 (67%) to 9/15 (60%) ($p=1.000$). Of the 13 children assessed using the parent/proxy-reported Child Health Questionnaire, the physical and psychosocial domain summary scores did not significantly differ pre- to post-operatively ($p> 0.05$). The physical domain summary score reduced from 36.5 (SD 7.2) pre-operatively to 35.6 (SD 12.9) post-operatively ($p=0.840$). The psychosocial domain summary score decreased from 50.7 (SD 10.7) pre-operatively to 49.1 (SD 14.1) post-operatively ($p=0.375$). In a subset of five cases pre- and post-operative plantar pressure outcomes are shown in Table 5. The pressure-time integral z-score of the rearfoot region improved from −0.7 (SD 0.8) pre-operatively

Table 4
Pre-operative and post-operative cavovarus foot surgery outcomes in children with CMT, and in comparison to the 16 month natural history of the disease [34].

Outcome measures	Pre-op Mean (SD)	Post-op Mean (SD)	Difference Mean (SD)	Change (% from baseline)	Difference (P value)	Natural history Mean (SD)	Difference (P value)
Foot alignment							
Foot Posture Index, score ($n=18$)	−7.4 (2.6)	−1.5 (3.3)	6.0 (3.2)	82	<0.001*	−0.4 (2.4)	<0.001
Ankle flexibility							
Lunge test, degrees, ($n=18$)	16.7 (7.1)	22.7 (3.7)	6.1 (7.3)	37	0.008*	0.2 (4.7)	0.003
Strength							
Dorsiflexion, z-score ($n=15$)	−2.5 (0.8)	−2.9 (0.9)	−0.3 (1.0)	−12	0.186	−0.2 (0.8)	0.645
Plantarflexion, z-score ($n=15$)	−1.6 (1.4)	−1.9 (1.8)	−0.3 (1.7)	−19	0.495	−0.3 (1.0)	0.977
Function							
Balance, z-score ($n=15$)	−7.6 (4.4)	−8.4 (4.4)	−0.8 (2.5)	−11	0.230	−0.6 (1.9)	0.750
Long jump, z-score ($n=15$)	−4.0 (1.6)	−4.1 (1.6)	−0.1 (1.3)	−3	0.764	−0.3 (1.0)	0.564
6-min walk test, z-score ($n=15$)	−2.8 (1.8)	−2.7 (1.3)	0.1 (1.4)	4	0.346	−0.2 (1.6)	0.493
Overall disability							
CMTPedS, total score ($n=13$)	21.8 (7.3)	23.3 (9.4)	1.5 (4.5)	7	0.243	1.5 (3.2)	0.525

CMTPedS, Charcot-Marie-Tooth Disease Pediatric Scale.

Table 5
Pre- and post-operative plantar pressure outcomes ($n=5$).

Plantar pressure regions	Pre-op Median (IQR)	Post-op Median (IQR)	Difference (P value)	Effect size (Cohen's d)
Whole foot, z-score	0.5 (5.7)	0.9 (4.1)	0.893	0
Rearfoot, z-score	−0.7 (0.8)	−0.3 (3.2)	0.043	0.6
Medial midfoot, z-score	−0.6 (0.2)	−0.7 (0.6)	1.000	0
Lateral midfoot, z-score	7.2 (29.5)	0.7 (16.4)	0.043	0.6
Medial forefoot, z-score	−1.3 (1.9)	−1.3 (1.9)	0.686	0.1
Lateral forefoot, z-score	2.1 (1.9)	−0.2 (3.0)	0.080	0.6

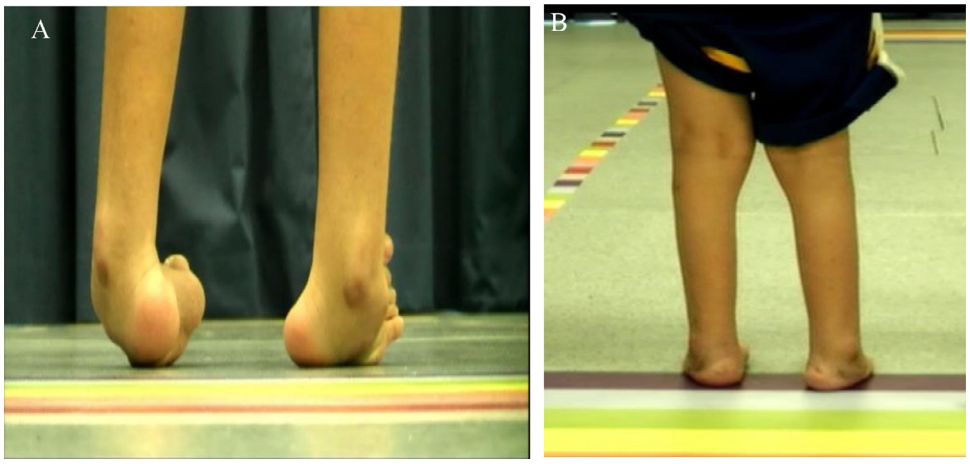

Fig. 3. Preoperative (A) and postoperative (B) images of cavovarus correction with surgery in a 9 year-old child with CMT (genetically unclassified CMT1). (A) Foot Posture Index score of −11 on the right foot and −12 on the left foot. (B) Foot Posture Index score of −4 on the right foot and −1 on the left foot.

to −0.3 (SD 3.2) post-operatively ($p=0.043$), and the lateral midfoot region improved from 7.2 (SD 29.5) pre-operatively to 0.7 (SD 16.4) post-operatively ($p=0.043$).

4. Discussion

The main findings of this study were that cavovarus foot surgery in children with CMT significantly improves foot alignment, ankle dorsiflexion flexibility, and frequency of trips and falls. Strength, function and quality of life did not significantly improve with surgery, and generally mirrored the natural course of the disease. Preliminary data suggests an improvement in plantar pressure loading beneath the rearfoot and midfoot following cavovarus foot surgery.

Direct comparison with the literature is challenging due to the variety and combinations of procedures, heterogeneity of patient cohorts, lack of uniformity in evaluation methods and disparities in length of follow-up periods. Although there are no published surgical studies specifically evaluating changes in foot alignment in childhood CMT, our findings

are consistent with the adult-focussed and mixed cohort literature [28,29]. Among these, Leeuwesteijn and colleagues retrospectively evaluated a mixed adolescent and adult series [29] of homogeneous cavovarus aetiology due to CMT and reported that first metatarsal dorsiflexion osteotomy combined with tendon transfers (i.e., peroneus longus to brevis, tibialis posterior tendon transfers) achieved a plantigrade foot that was maintained at follow-up (mean 56.9 months; range 13–153 months). However, foot alignment was based on a non-validated method of visual observation of the rearfoot. In our study, we used a well-validated multi-segment method (Foot Posture Index) to show significant changes in foot alignment following surgery in children with CMT.

Our findings of increased ankle dorsiflexion flexibility following surgery concur with the adult-focused literature [21,23]. Although we exceeded the minimal clinically worthwhile effect of 5° defined by Rose et al. [14], the amount of change was not as large as Vlachou and colleagues [21]. They evaluated the surgical outcomes of 19 adolescents and adults with mild to moderate cavovarus foot deformity, and showed an increase of 10° in ankle dorsiflexion range following surgery. Apart from inconsistency arising from variation in procedures, another possibility for such difference might be attributed to the likely worse contracture that they presented at the later stage of disease compared to our younger and milder cohort.

Despite a previous report suggesting that one grade of strength on the MRC scale is typically lost following tendon transfer procedures [42], evidence using instrumented evaluation is lacking. We found no detrimental impact, relative to the natural course of the disease, of cavovarus foot surgery on dorsiflexion or plantarflexion strength in children with CMT. This is the first study to evaluate instrumented strength testing pre- and post-operatively in this clinical population, and our findings agrees with evidence from prospective surgical studies in other paediatric populations, such as clubfoot deformity [43,44]. The pathophysiology of clubfoot resembles that of the cavovarus foot deformity in that there is peroneal weakness causing muscle imbalance around the ankle. Gray et al. conducted a 12-month pre- and post-operative cohort study evaluating 20 children with clubfoot who underwent comparable tendon transfer procedures to our cohort. They also quantified muscle strength using hand-held dynamometry and found that dorsiflexion and plantarflexion strength remained similar at 3, 6 and 12 months after surgery [44]. Deterioration of strength reported in previous studies might be attributable to MRC manual muscle testing lacking responsiveness.

The functional outcomes of balance, long jump and the 6-minute walk test did not differ significantly between the pre- and post-operative measures, and were generally consistent with the natural course of CMT during childhood. This was unsurprising given functional performance is dependent on a complex interplay of various factors within the neuromuscular system. Correcting foot and ankle architecture alone may not be sufficient to significantly influence function. As such, adjunct interventions, such as exercise, specifically addressing functional deficits may be more appropriate to optimise these outcomes in this population.

Self-reported frequency of trips and falls significantly reduced post-operatively. Although no corresponding change in parent-reported quality of life was detected. While this may suggest that improvement in quality of life requires more than correction of the cavovarus foot deformity, it is possible that the parents' perception of their child's quality of life may have differed from that of the child. Alternatively, the generic quality of life instrument used in this study (Child Health Questionnaire) might lack sensitivity to change in CMT. A self-reported, disease-specific, paediatric measure is required in future trials to detect the influence of interventions on patient's quality of life.

Cavovarus foot surgery is thought to be beneficial because it redistributes abnormal pressure loading across the plantar surface of the foot during gait. In a subset of patients we found a significant reduction in loading beneath the lateral midfoot and confirms a previous study on adults with cavovarus foot deformity [45]. We also found significant post-operative increases in rearfoot loading, consistent with previous studies using pedobarography following cavovarus foot surgery in children with CMT [46,47]. During normal gait approximately two thirds of body weight are borne by the rearfoot region [48]. Enhanced heel loading in our cohort is likely to be a consequence of improved ankle flexibility and foot alignment, however larger studies are necessary to confirm these improvements.

The study has some limitations. First, despite the use of standardised, reliable and well-validated outcome measures, absence of blinding of the clinical evaluators (owing to postoperative scars) produced a potential bias. Second, although this study represents the most comprehensive series of surgical outcomes in children with CMT to date, the small sample size renders the study vulnerable to type II statistical errors. Third, even though all participants had a homogenous clinical phenotype, there was a range of CMT genetic subtypes. The majority of our sample had CMT1A, and the small numbers for the rarer genetic subtypes precluded a conclusive determination of their potentially disparate surgical outcomes, thereby limiting the generalisation of these conclusions to the other CMT subtypes. Future studies with large sample sizes and greater genotypic diversities are needed. Fourth, given the slowly progressive nature of CMT, further investigations should consider a longer follow-up duration to track long-term changes in health outcomes, and capture potential recurrence of deformity or the need for surgical revision in these patients into adulthood. Fifth, our study cohort was surgically treated for cavovarus foot deformity during adolescence. Since it is a mandatory requirement to transition paediatric patients to adult services at 16 years of age, longer-term data was often not possible to gather. Finally, our study might have been underpowered to detect a significant reduction in foot pain frequency post-operatively. Also, radiographic evaluations may further assist in clinical decision making and assessment of outcome. Future studies using self-reported

pain severity measures and radiographic data on a large sample of participants are required to fully understand the impact of surgery on patient outcomes.

In conclusion, this study represents a comprehensive evaluation of the physical, functional, parent/self-reported and biomechanical outcomes of cavovarus foot surgery in children with CMT. Our findings show that a combination of bony and soft tissue surgery improves foot alignment, ankle flexibility, self-reported trips/falls, and plantar pressure loading in this population. However, surgery had no effect on strength, function or quality of life, which generally mirrored the natural course of the disease.

Acknowledgements

The authors wish to thank the staff and patients of The Children's Hospital at Westmead (Peripheral Neuropathy Management Clinic and Paediatric Gait Analysis Service of New South wales) for their support and ongoing contributions to the data registry that made this study possible.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nmd.2019.04.004.

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