Assessment of Clubfoot Treatment Using Movement Analysis

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Clubfoot is a congenital deformity of the foot that has traditionally been treated operatively. In recent years, a shift in ideology has shifted standard practice away from surgical management, to a nonoperative approach, gaining correction through gentle stretching and positioning or casting of the foot. Nonoperative treatment for clubfoot using the Ponseti casting protocol has become more prevalent in expanding areas of the world. Outcomes reported following clubfoot treatment, typically focus on both a clinical assessment and radiographic results. Recent work has shown Gait Analysis to be a useful and objective tool to assess functional outcome following both surgical and nonoperative approaches. The purpose of this paper is to describe the use of gait analysis in the assessment of outcome of clubfoot treatment.

1. Introduction

Clubfoot, also known as talipes equinovarus, is a congenital condition of the foot present in one in 1000 live births. The condition is unilateral in two-thirds of babies and bilateral in one-third, and is slightly more prevalent in males than females. The foot is held in an inverted and plantarflexed position at birth. The clubfoot deformity consists of forefoot adduction and supination, midfoot cavus, hindfoot varus and ankle equinus. The severity of the deformity is variable, ranging from a positional clubfoot which is passively correctable to a very severe deformity in which the foot is rigid and pathologic skin creases are present in the hindfoot and midfoot. The affected foot is slightly smaller than the contralateral normal foot in children with unilateral clubfeet. Clubfeet may be a manifestation of an underlying neurologic disease, such as spina bifida, or of a more generalized syndrome, such as diastrophic dysplasia or Larsen's syndrome. Idiopathic clubfeet are foot deformities that occur in otherwise normal newborns.

2. Non operative treatment protocols

2.1. Ponseti method

Treatment of babies with clubfoot has changed over the past 10 years, with nonoperative treatment becoming more prevalent and successful in expanding areas of the world. The most widely used method of nonoperative treatment is the Ponseti method. Weekly long leg casts are applied, beginning in the newborn period, and the foot progressively abducted and externally rotated with the fulcrum of rotation the head of the talus to achieve correction. When correction of the adduction and varus have been achieved, most often an Achilles tenotomy is performed subcutaneously to allow dorsiflexion of the ankle and therefore to complete the correction of the deformity and achieve a plantigrade and shoeable foot. The hallmarks of the Ponseti technique are the rotation of the foot about the head of the talus without direct manipulation of the calcaneus, the full correction into external rotation prior to tenotomy, and the need for long leg rather than short leg casts. Typically, correction may be achieved by the sixth cast. Following the period of casting, an abduction orthosis comprised of bilateral shoes attached to a bar in external rotation is used to maintain correction of the feet. Use of the bar is initially full time, followed by nightly wear for a variable period of time, ranging from 2 years to 4 years.

2.2. Physiotherapy method

An alternative nonoperative technique to achieve correction of the clubfoot is the French functional physiotherapy program (French PT method), credited to Henri Bensahel and championed by Alain Dimeglio. Daily physical therapy is performed to manipulate and mobilize the foot, followed by a specific taping technique to maintain correction between therapy sessions. While the Achilles tenotomy was not initially included in the protocol, more recent recommendations have been made for correction of residual equinus by gastrocnemius fascial lengthening or heel cord tenotomy as needed in select infants with resistant feet. The French technique requires a trained physical therapist and a committed...
family for success. This program is still in existence in our center as well as in areas of Europe.

3. Outcome assessment

The orthopedic literature is replete with reports of outcomes following treatment for clubfoot. Before the renewed popularity of nonoperative treatment, the results of surgical clubfoot release were published using radiographic alignment and the need for repeat surgical release as primary outcome parameters. Newer studies now report results of nonoperative treatment, with successful outcomes reported as those feet in which surgical release was not required.

There are two simple long-term goals in the treatment of children with clubfoot. First, the foot should be free of pain during activities of daily living. Second, the foot should allow the child to walk as close to normal as possible, to run with their peers, and to participate in the typical activities of childhood, adolescence, and finally of adulthood. While studies reporting radiographic measures may reflect the correction of the clubfoot deformity, they may have poor correlation with how the foot actually works in allowing normal function of the child. Similarly, while the goal of nonoperative treatment is to correct the deformity without the need for surgical release, it is the hope that the foot will function better without surgery that is the motivation for the pediatric orthopedic surgeon to strive for nonoperative correction.

The function of the clubfoot, whether treated surgically or with either the Ponseti or French PT techniques, can be studied using gait analysis. Aronson and Puskarich, in 1990, are credited with first studying children with clubfoot in a gait lab. They described limited ankle range of motion and plantarflexion weakness in patients who had undergone surgical release, also known as post-eromedial release (PMR), as treatment for clubfoot. In 1997, our center studied our patients with clubfoot following what was felt to be successful clubfoot PMR surgery at an average 10 years follow-up using gait analysis. This study served as the impetus to develop a nonoperative treatment program at our hospital, which includes gait analysis as an outcome measure. The purpose of this paper is to describe the use of gait analysis in the assessment of outcome of clubfoot treatment.

3.1. Gait analysis

Gait analysis is the assessment of temporal parameters (including cadence, step length, step time and speed), three dimensional kinematics and kinetics and plantar pressures. Kinematics is the assessment of joint motion in the sagittal, coronal and transverse planes. Kinetic data, defined as the measurement of forces exerted by the body during gait, are obtained simultaneously as children walk across force plates (Advanced Mechanical Technology Inc., Watertown, Massachusetts, USA) embedded in the gait lane. Kinetic data can be obtained when a child strikes the force plate with a single foot during gait. Patients walk at a self-selected walking speed wearing a standard lower body marker set as defined by Davis et al. Since gait patterns change with maturation, gait data is collected across all age groups, for comparative purposes.

At this institution, patients presenting with idiopathic clubfoot are invited to participate in an IRB approved Clubfoot Research Study (originating in 1996). Gait outcomes are evaluated at ages 2 years, 5 years and 10 years, and at skeletal maturity. Kinematic measures at the hip, knee and ankle are made throughout the gait cycle using VICON analysis software (Oxford Metrics Group, Oxford, UK). When our patients return for evaluation at 5 years of age, kinetic data is also obtained. (Due to the short stride length and cooperation level of the typical 2-year-old child, we do not obtain kinetic data until the age of 5 years.) Kinetic variables include peak ankle moment during stance phase, maximum ankle power in late stance phase and maximum hip power generated at the transition from stance to swing phase.

Additional testing is conducted when the children are older. At 10 years of age and at skeletal maturity, a multi-segment foot model is applied where additional markers are placed on the hindfoot, forefoot and hallux to assess motion within the foot, as described by Tulchin et al. Maximum plantarflexion and dorsiflexion strength are also measured using a Biodex machine (Biodex Medical Systems, Shirley, New York, USA) in the older child.

Pedobarography is the analysis of foot pressures during gait and can be assessed across all age groups. The pedobarograph is a pressure plate embedded in the floor which contains high density sensors which measure pressure exerted during stance phase (Emed ST Platform System; Novel, Munich, Germany). For analysis, the foot is divided into regions and pressure, force, and time information can be reported for each of those regions. The center of pressure line can also be assessed using a pedobarograph. In a normal healthy foot, the line of progression normally begins in the heel at initial contact, moves through the midline of the midfoot, through to the second metatarsal region in the forefoot and terminates between the hallux and second toe. The magnitude of deviation of the center of pressure line in children with clubfoot can be evaluated especially in feet with residual deformity.

4. Clubfoot gait analysis studies

In 1997, the results following full surgical release in 23 children with unilateral idiopathic clubfeet using gait analysis and muscle strength testing at an average 10 years of follow-up after surgery, were reported. Ankle motion was found to be abnormal in 87% of children. Two patterns of kinematic abnormality were found. In 43% of the clubfeet, ankle dorsiflexion was limited as the foot remained in relative equinus. The other group, comprising 17% of the test population, had excessive dorsiflexion during stance phase, with limited plantarflexion at the transition from stance to swing phase. Swing phase foot drop (defined as the inability to dorsiflex the ankle during swing phase) was documented in 30% of operated feet. Ankle power generation was diminished by 23%, and gastrocnemius isokinetic muscle strength was diminished by an average of 27% compared to the contralateral leg.

Following the discovery of these gait disturbances, a nonoperative program was initiated with the goal of achieving a more
normal gait following correction of the clubfoot deformity, without surgery. In 1996, we implemented the French PT program at our hospital, with great success. In 2005, we compared the gait outcomes of children who were treated with the French PT method to those children who underwent surgical correction by the age of 2 years. This study reported on 90 children with 127 idiopathic clubfeet. Fifty-seven feet had either no surgery or just a tendoachilles lengthening, 19 feet underwent a tendoachilles lengthening with a posterior ankle capsulotomy, and 51 feet had undergone a complete clubfoot release (including ankle, subtalar, and talonavicular capsulotomies and lengthening of the tendoachilles, flexor hallucis longus, flexor digitorum longus, and tibialis posterior tendons), usually as the result of unsuccessful correction after short leg casts.

Findings showed that at the age of 2 years, 31% of feet treated nonoperatively with the French PT method had limited stance phase dorsiflexion, compared to 18% of feet treated by complete surgical release ($p < 0.05$). Lack of ankle plantarflexion at push-off was statistically more prevalent in the surgical feet (29%) compared to the nonoperative feet (8%), $p = 0.005$. Surprisingly, an internal foot progression angle (indicating persistant intoeing gait) was most likely in the surgical foot, despite complete clubfoot release (45%) compared to those treated nonoperatively (31%) ($p = 0.005$). Normal gait was defined as normal ankle dorsiflexion during stance phase, normal ankle plantarflexion at push-off, the absence of a foot drop and absence of intoeing. Normal gait was present in few children in either group, but was more likely in the French PT nonoperative group (33%) compared to the full surgical release group (14%). The conclusion drawn from this study was that continued efforts to treat children with clubfoot nonoperatively were merited, as surgical release resulted in the fewest children with normal gait parameters.

Encouraged by the outcomes following the French PT method, increased enthusiasm arose to adopt a nonoperative casting technique that would elicit similar results. In 2001, the Ponseti method was adopted and study patients were invited to self-select the treatment protocol (French PT or Ponseti method) that best fit their needs and situation. Assessment of these two nonoperative methods was made in a comparison study evaluating the kinematic outcomes at the age of 2 years in 105 clubfoot patients with 154 treated feet (75 French PT and 79 Ponseti feet). Those children who did not have normal ankle motion in the French PT group demonstrated diminished ankle dorsiflexion during gait, with 15% having ankle equinus (defined as less than three degrees of dorsiflexion) during stance phase. The incidence of foot drop was 19% in the French PT feet. Excessive dorsiflexion during stance phase was seen in 48% of the Ponseti feet and only 12% in the PT feet ($p < 0.001$). Limited plantarflexion at the transition from stance to swing phase (defined as calcaneus gait), was seen in 10% of the Ponseti feet (Figure 2). Persistent internal rotation of the foot (documented as an internal foot progression angle) was present in 44% of the PT and 24% of the Ponseti feet, indicating this to be the most difficult aspect of the clubfoot deformity to correct. The decreased incidence of persistent intoeing in the Ponseti group was theorized to be due to the continued nightly prescription of the foot abduction bar still in use at the time of the gait analysis. Analysis of the different kinematic patterns of ankle motion led us to consider heel cord release in the PT feet to achieve better dorsiflexion, while the increased dorsiflexion in the Ponseti group may have differed from normal, did not seem to be problematic, at least in the short term.

In 2009, a review of the intermediate gait results (at 5 years old) was made, following patients initially treated nonoperatively. El Hawarayet al found that nearly 30% of feet had undergone surgery by the age of 2 years. The gait findings in these patients were not included in the 2008 publication. At the age of 5 years, we found that several of the children who had not required surgery by 2 years old had recurrence and required surgery by the age of 5 years (total of 51 surgical feet). This has been described in the Ponseti literature, as up to one-third of children may require anterior tibialis tendon transfer for residual or recurrent internal rotation and supination of the foot during follow-up. Nonetheless, the remaining nonoperative feet treated by the French PT ($n = 40$) and Ponseti ($n = 34$) programs were compared. Ankle equinus, which had been present in 15% of PT feet at 2 years of age, was decreased, now present in only 5% of the feet. This was likely due to the surgical treatment of residual equinus via limited posterior release with Achilles lengthening and ankle posterior capsulotomy. The excessive dorsiflexion seen in 48% of the Ponseti feet at 2 years of age was also decreased, persisting in only 24% at 5 years of age. Intoeing remained common in all groups, with an internal foot progression angle in 30% of French PT, 32% of Ponseti, and 51% of surgical feet. Yet again, the kinematic results were best in those children who were able to avoid surgery.

At the age of 5 years, the step lengths of the children were sufficiently long to be able to collect kinetic data from the force plates. Ankle power generation was found to be significantly diminished in all three groups (surgical releases, French PT, and

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**Figure 2** Example of a surgical patient walking with an internal foot progression angle compared to normal controls. Int FPA = internal foot progression angle; Nil Average = normal 2-year-old control group.

**Figure 3** Representative sagittal plane ankle kinematics from two patients compared to control data. Incr Dorfex: patient with increased dorsiflexion in stance phase and lack of plantarflexion at toe off. Equinus/DF: patient walking in equinus with a foot drop in swing phase. Control data from 15 normal 2-year-olds. DF = dorsiflexion; PF = plantarflexion.
compensatory abnormalities more proximally in the lower extremity. Theologis et al described dynamic foot motion during gait in 20 children. They found similar results as we did, with residual internal rotation of the foot, compensatory external rotation of the hip, and diminished ankle plantarflexor power generation. They were able to quantify segmental foot motion, and found increased midfoot dorsiflexion, thought to be compensatory to diminished hindfoot motion. Further study of segmental motion is important to orthopedic surgeons as they attempt to preserve as close to normal motion as possible in these children following clubfoot treatment.

Our study of pedobarography in nonoperatively treated clubfeet found deviations from normal as well, including diminished medial hindfoot pressure with a shift of peak pressures to the lateral mid and forefoot, similar to the study by Sinclair et al and by Hee et al. Liu et al described challenges in the measurement of dynamic plantar pressure in young children, particularly in relation to intoeing and outtoeing. We found that the application of standard algorithms used to identify specific regions of the foot (e.g., medial and lateral hindfoot) was difficult in those feet that had severe residual deformity. Computer assignment of the hindfoot region, e.g., in a child with residual equinus leads to error as the midfoot is incorrectly labeled as the hindfoot due to lack of heel contact. Such inaccuracies necessitate manually assigning the regions of the foot, which may be prone to error. Further development of technology which can “recognize” deformity may be useful in further studies of plantar pressure in clubfoot and other pediatric foot deformities.

Following the description of gait deviations in clubfoot, some clinicians are now using this data to assist in making clinical decisions in children with residual or recurrent clubfoot deformities. Residual intoeing is very prevalent in patients with clubfoot; its causes range from: supination due to tibialis anterior muscle over-activity, to internal tibial torsion, to midfoot adductus. As the treatment of intoeing from these causes is different, i.e., tendon transfer versus osteotomy, gait analysis with kinematics, plantar pressure analysis, and electromyography, can be clinically useful.

Through gait analysis, researchers have been able to quantify the motion of the lower extremity in patients with clubfoot, the forces during gait, and plantar pressures, but the question remains if this is a true measure of function. Does better ankle motion and greater power generation allow a child with clubfoot to participate as fully as possible in school activities and athletics with their peers? Validated assessment tools exist that can measure a child’s ability to perform gross motor tasks. Gross motor scales can give a global assessment of the patient’s ability to perform tasks, such as jumping, kicking a ball, and balancing on one foot. The child’s ability to perform these tasks is then normalized to age, and compared to normative data. It will be important to compare the data obtained from gait analysis with that of the Gross Motor Scale to see if limitations identified during gait, correlate to their global function.

6. Conclusions

In conclusion, gait analysis serves as an outcome tool used to evaluate the function of the foot following both operative and nonoperative clubfoot treatment. It is a valid measure of joint movement, joint powers and plantar pressures that can also be used to ascertain changes following surgical intervention (e.g., tendon transfer and limited clubfoot release). Gait deviations, such as limited ankle motion and power generation persist in some children with clubfoot, even after what is deemed to be successful nonoperative treatment. Gait analysis data however most closely approximates that of normal children in those feet initially treated with modern nonoperative treatment. Further work is underway to...
assess these feet at maturity, and to correlate gait characteristics with function in the community.

References