Effects of gastrocnemius fascia lengthening on gait pattern in children with cerebral palsy using the Gait Profile Score

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1. Background

Cerebral palsy (CP) is a permanent but not immutable postural and movement disorder resulting from a non-progressive brain lesion due to hereditary factors or adverse events during pregnancy, childbirth or the neonatal period. CP is characterized by movement and postural disorders, which are often accompanied by impairments in sensory, cognitive, communication, perception and behavioral aspects (Rosenbaum et al., 2007). Excessive palntarflexion (equinus) and walking on the tiptoes are common abnormalities among patients with CP. The equinus gait is frequently

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caused by the contracture (i.e. shortening of the fibers) of the triceps surae: the inadequate opposition from the anterior tibial musculature results in the triceps surae dominance, which can lead to a static contracture over time as the children grow. Dynamic equinus is caused by spasticity and is common seen in young children and can be treated with braces, physical therapy, stretching, strengthening of the dorsiflexors and/or botulinum toxin injections; in time, progressively spasticity will eventually lead to a fixed equinus caused by a contracture and fixed shortening, which may require surgical correction. In particular, equinus foot is treated by surgical lengthening of the triceps surae, generally in children between the ages of 6 and 12 years (Gage, 2004). Most relevant functional consequences of equinus are impairment of body segment vertical alignment, loss of body progression during stance phase, reduction of step length and velocity and impairment of both static and dynamic balance (Benedetti, D'Apote, Faccioli, Costi, & Ferrari, 2011). Two different categories of surgical interventions are generally performed: the first category alters the length of both the gastrocnemius and soleus muscle-tendon unit and it includes *Z*-lengthening (Gaines & Ford, 1984), step lengthening or sliding lengthening (Hoke) (Green & McDermott, 1942; White, 1943), tenotomy (Grabe & Thompson, 1979) and subcutaneous lengthening (Banks & Green, 1958); the second category alters the length of the gastrocnemius muscle-tendon unit without altering soleus (Baker, 1956; Strayer, 1950; Vulpius & Stoffel, 1913; Yngve & Chambers, 1996). The gastrocnemius fascia lengthening surgery (modified Vulpius technique) consists of a chevronlike incision of the gastrocnemius aponeurosis followed by ankle dorsiflexion to neutral position and not beyond to avoid overlengthening (Etnyre, Chambers, Scarbourough, & Cain, 1993). Although both procedures typically improve ankle kinematics throughout the gait cycle (Rose, DeLuca, Davis, Ounpuu, & Gage, 1993; Yngve & Chambers, 1996), they both may also weaken the plantaflexor muscle, resulting in decreased ankle power during stance phase of gait. Etnyre et al. (1993) compared the effects of two different methods of corrective operation (muscle lengthening and tendon lengthening method) and operative results significantly improved ankle motion in subjects, although no differences were observed between surgical methods. Rose et al. (1993) demonstrated positive results in terms of static ankle Range of Motion, dynamic ankle motion during gait and ankle power generation from the modified version of the Baker lengthening in conjunction with other simultaneous orthopedic surgeries performed. Yngve and Chambers (1996) made an evaluation of ankle function in gait after Vulpius lengthenings of the gastrocnemius fascia and *Z*-lengthenings of the Achilles tendon in CP patients. Simultaneous hip or knee surgeries or both were performed in most instances. There were no significant differences between the two techniques of the ankle parameters 1 year after. Kay, Rethlefsen, Ryan, and Wren (2004) studied preoperative and postoperative gait analysis data in children who underwent gastrocnemius recession or tendo-Achilles lengthening as part of multilevel surgery and they found that both surgeries are effective in appropriately selected patients.

Three-dimensional (3D) gait analysis (GA) is a multifactorial and integrated evaluation that combines a set of measures (kinematics, kinetics and electromyography) providing a quantitative description of normal and pathological gait pattern (Carriero, Zavatsky, Stebbins, Theologis, & Shefelbine, 2009). GA is recognized by be a fundamental tool in clinics to evaluate the gait pattern in different pathological states, such as in CP (Gage, 2004). It provides, in fact, crucial information to quantify the degree of functional limitation due to the disease and its progression over time, to plan the rehabilitation process and to quantify the effects of a specific treatment (Bonnefoy-Mazure, Sagawa, Lascombes, De Coulon, & Armand, 2013; Kawamura et al., 2007; Speciali et al., 2013).

However, GA produces a wide quantity of kinematic and kinetic variables involving different joints and positions. As clinical decision-making is often based on the interpretation of GA data (Assi, Guanem, Lavaste, & Skalli, 2009), a single measure of gait pattern could often be helpful. A number of global indices have been proposed by literature for an overall measure of gait, such as the Gillette Gait Index (GGI, Schutte et al., 2000), the Hip Flexor Index (HFI, Schwartz, Novacheck, & Trost, 2000), Gait Deviation Index (GDI) (Schwartz & Rozumalski, 2008) and recently the Gait Profile Score (GPS) with Gait Variable Scores (GVS) (Baker et al., 2009). These indices revealed to be useful when used together with GA to provide a better overall understanding of gait in individuals with different conditions (Schwartz & Rozumalski, 2008).

The GA has a wide use for quantification of surgical treatment for correction of equinus foot in CP. A large number of studies have quantified the effects of surgery demonstrating a significant reduction of equines foot, with improvements in the biomechanical position of the ankle and knee as well as an increase or absence of change in muscle energy of the ankle following surgery, and thus an improvement in gait performance (Dreher et al., 2013; Filho, Yoshida, Carvalho, Stein, & Novo, 2008; Galli, Cimolin, Crivellini, & Albertini, 2005; Galli, Cimolin, Crivellini, & Albertini, 2009; Patikas et al., 2007; Seniorou, Thompson, & Theologis, 2006; Sung et al., 2013; Van Bemmel, Van der Bekerom, Verhart, Diederik, & Vergroesen, 2012; Wren et al., 2013). Generally these studies have been conducted using specific parameters obtained by GA (time/distance parameters, angles joint values in specific gait cycle instant, peaks of angles joint). Only few researches used global measures, and among these the GGI and GDI were computed (Bass, Holmes, Sampath, & Trinca, 2009; Cimolin, Galli, Virmercati, & Albertini, 2011; Gannotti, Gorton, Nahorniak, & Masso, 2010; Rutz et al., 2011; Sagawa et al., 2013; Thomason et al., 2011; Wren et al., 2013). As concerns the GPS, as it is a recent index, the experience is limited (Beynon, McGinley, Donson, & Baker, 2010; Firth et al., 2013; Rutz, Donath, Tirosh, Graham, & Baker, 2013; Thomason, Selber, & Graham, 2013).

Focusing the attention only to studies on CP, Rutz et al. (2013) used the Gross Motor Function Classification System and the GPS to quantify improvements in children submitted to single-event multilevel surgery; they found that children with more accentuated abnormality in the gait pattern had the most significant improvements in the GPS. Thomason et al. (2013) used different gait measures (GPS, GGI, GDI, Gross Motor Function Measure-66 and Functional Mobility Scale) on children with CP submitted to single-event multilevel surgery; improvements were displayed in gross motor function achieved in 12 and 24 months after surgery and they were maintained after five years. In a retrospective study involving 40 children with spastic diplegia and equinus gait submitted to multilevel surgery, Firth et al. (2013) analyzed improvements in a mean period of 7.5 years using the GPS and GVS on two postoperative evaluations. These studies evidenced that GPS seems to be a good measure to quantify the effects of surgical program; it is important to highlight that these analyses evaluated the effects of single-event multilevel surgery and they are not specific to isolated gastrocnemius lengthening technique for the correction of equinus foot deformity in CP.

Thus, the aim of the present study was to investigate the efficacy of the GPS and GVS to quantify the effects of gastrocnemius fascia lengthening for the correction of equinus foot deformity in children with CP.

2. Materials and methods

2.1. Participants

Nineteen children with CP (9 with hemiplegia and 10 with diplegia; 13 males and 6 females; mean age: 8 ± 3.4 years) enrolled at IRCCS San Raffaele, Tosinvest Sanità in Rome (Italy) for multidisciplinary rehabilitation were selected by clinicians based on the eligibility criteria. The subjects were evaluated before (mean: 3.1 ± 2.6 months) and approximately one year (mean: 13.1 ± 5.1 months) after gastrocnemius fascia lengthening. The diplegic participants were treated bilaterally while the hemiplegics were treated only at the plegic side, for a total of 29 sides. The inclusion criteria were: diagnosis of CP, recommendation before surgery of isolated gastrocnemius fascia lengthening to reduce gastrocnemius spasticity and no previous orthopedic surgery of the lower limbs. All patients had no other surgeries between preoperative and postoperative evaluations and were able to walk independently without the use of crutches, walkers or braces in both sessions. A control group composed of 10 healthy children (mean age: 9.9 ± 2.5 years) was recruited. The selection criteria for this group included no prior history of cardiovascular, neurological or musculoskeletal disorders. The control subjects exhibited normal ROM and muscle strength and had no apparent postural or motor deficits. All participants were volunteers and their parents/guardians signed a statement of informed consent authorizing their participation. This study received approval from the ethics committee of the Institute.

2.2. Intervention

The surgical procedure was the modified Vulpius technique, which involves percutaneous lengthening through partly cutting the myotendinous junction of the triceps surae. The surgery was conducted on both limbs in diplegic patients and on the plegic side in hemiplegic patients. Hospital stay ranged from three to five weeks, during which daily physical therapy, strength and gait training were provided. Passive physical therapy in the form of joint mobilization was initiated four to seven days after surgery. Standing therapy and gait training were initiated seven to ten days after surgery. Following discharge, the patients underwent physical therapy on an outpatient basis as required and were monitored at the orthopedic outpatient department at monthly intervals.

2.3. Experimental set-up

All patients were evaluated instrumentally using an optoelectronic system with passive markers (ELITE2002, BTS, Milan, Italy) with a sampling rate of 100 Hz, two force platforms (Kistler, CH) and 2 TV camera video system (BTS, Italy) synchronized with the system and the platforms for videorecording.

After the collection of anthropometric measures (height, weight, tibia length, distance between femoral condyles or diameter of the knee, distance between malleoli or diameter of the ankle, distance between the anterior iliac spines and thickness of the pelvis), passive markers were placed at points of reference directly on the skin, as described by Davis, Ounpuu, Tyburski, and Gage (1991), for the evaluation of the kinematics of each body segment. Markers were placed over C7, sacrum and bilaterally on the anterior iliac spines, greater trochanter, femoral epicondyle, femoral wand, tibial head, tibial wand, lateral malleolus, lateral aspect of the foot at the fifth metatarsal head and the heel (only for static offset measurements).

After placement of the markers, the participants completed two or more practice trials across the plate walkway to become familiarized with the experimental procedure. After familiarization, at least six trials were performed. The participants were instructed to walk barefoot at a self-selected pace along the walkway (10 m in length). Average values of three consistent trials from each side foot were analyzed.

2.4. Signal processing

Only kinematic data were considered in the signal processing. Although ground reaction forces are also acquired for this study, these are not included in the present analysis and are not discussed in this paper because the GPS is a summary measure related only to kinematic variables and not to kinetics (ground reaction forces, joint moment and power).

All kinematic graphs obtained during the gait analysis were normalized as the percentage of the gait cycle, producing sagittal kinematic plots of the pelvis, hip, knee and ankle for each cycle. The BTS ElitClinic software (version 3.4.109, BTS, Italy) was used, with the data exported to txt. files to compute the GPS.

From these data format we computed the Gait Profile Score (GPS) which summarizes the overall deviation of kinematic gait data relative to normative data (Baker et al., 2009). The GPS and MAP method was implemented as described by its authors (Baker et al., 2009) using our control data. GA data were then processed to obtain GPS and MAP according to the published method (Baker et al., 2009).

The GPS represents the root mean square (RMS) difference between particular gait trial and averaged data from people with no gait pathology. It has an advantage over the other indices as it is comprised of a number of gait variable scores (GVSs) representing an equivalent RMS difference for different kinematic variables. The GPS is based upon a number of gait variable scores (GVSs) each of which is the root mean square difference between a specific time normalized gait variable and the mean data from some reference population calculated across the gait cycle. Thus if $x_{i,t}$ is the value of gait variable i calculated at a specific point in the gait cycle t, and $\bar{x}_{ref}^{i,T}$ is the mean value of that variable at the same point in the gait cycle for the reference population then the ith gait variable score is given by:

$$\mathrm{GVS}_i = \frac{1}{T}\sum_{t=1}^{T}(x_{i,t} - \bar{x}_{i,T}^{ref})^2$$

where T is the number of instants into which the gait cycle has been divided. The GPS is then the RMS average of the GVS variables:

$$\mathrm{GPS} = \frac{1}{N}\sum_{i=1}^{N}\mathrm{GVS}_i^2$$

The overall GPS is based upon 15 clinically important kinematic variables (Pelvic Ant/Pst, Pelvic Up/Dn Obliquity and rotation of the left side and hip flexion, abduction, internal rotation, knee flexion, dorsiflexion and foot progression for left and right sides). In this analysis a GPS for each side was used based on all nine GVS for that side.

As the GPS represents the difference between the patient's data and the average from the reference dataset, the higher the GPS value is, the more compromised the gait pattern is.

2.5. Statistical analysis

Kolomogorov–Smirnov tests were used to verify if the parameters were normally distributed; as the data were not normally distributed statistical analysis was conducted using non-parametric tests.

For each participant, the median (quartile range) of each side was computed separately for the two evaluations (PRE and POST sessions). In the PRE session, data from the right and left sides were compared using the Mann–Whitney *U*-test to detect any significant differences between sides and considering the two groups the sides are independent of each other. After that the median (quartile range) of all parameters were calculated for the entire population in the PRE and POST session. The Wilcoxon test was used to compare the data from the PRE and POST evaluations, because we compared the same sample in repeated measurements (PRE and POST session). The percentage of GPS change between PRE and POST sessions was computed according to the following formula:

$$\frac{\mathrm{GPS_{POST}} - \mathrm{GPS_{PRE}}}{\mathrm{GPS_{PRE}}} \times 100$$

Spearman correlation coefficients were computed for the determination of the correlation between the degree of functional limitation (represented by the GPS value in the PRE session) and percentage of GPS changes. Statistical significance was set at $p < 0.05$.

3. Results

In the PRE evaluation, the GPS values of the right and left legs of diplegic children were compared and no statistically significant differences were found ($p = 0.25$). The data from both sides of these children were then pooled and then combined with the data of GPS related to the plegic side of children with hemiplegia. The coefficient of variation in the entire group with CP (diplegia and hemiplegia) was less than 25%, indicating satisfactory consistence in the data.

Significant reduction of GPS values close to 23.3% was found after the treatment (PRE: $13.38 \pm 5^{\circ}$; POST: $10.26 \pm 2.41^{\circ}$; $p < 0.05$), demonstrating improvements in gait pattern following gastrocnemius fascia lengthening. Moreover, the GVS results demonstrated statistically significant improvements in ankle dorsi-plantarflexion (PRE: $22.20 \pm 16.36^{\circ}$; POST: $11.50 \pm 6.57^{\circ}$; $p < 0.05$) and pelvic rotation (PRE: $9.53 \pm 3.87^{\circ}$; POST: $6.47 \pm 2.98^{\circ}$; $p < 0.05$) (Table 1).

Table 1
Mean and standard deviation (SD) of gait profile score (GPS) and GVSs (gait variation scores) in PRE and POST session for the considered CP group.

	PRE session	POST session	Variation (%)
GPS (°)	13.3 (5.00)	10.26 (2.41)*	23.31
GVS pelvic tilt (°)	4.77 (2.93)	5.70 (2.71)	19.56
GVS pelvic obliquity (°)	3.71 (1.74)	3.89 (1.65)	4.86
GVS pelvic rotation (°)	9.53 (3.87)	6.47 (2.98)*	32.06
GVS hip flex-extension (°)	10.41 (5.42)	10.45 (4.50)	0.35
GVS hip abd-adduction (°)	6.30 (3.01)	6.77 (3.63)	7.34
GVS hip rotation (°)	14.8 (8.89)	11.12 (6.90)	25.13
GVS knee flex-extension (°)	17.06 (6.34)	15.06 (4.05)	−11.73
GVS ankle planti-dorsiflexion (°)	22.2 (16.3)	11.50 (6.57)*	48.21
GVS foot progression (°)	9.52 (4.85)	9.36 (5.57)	−1.75

* $p < 0.05$, PRE compared to POST session.

As concerns the research of relationship between the preoperative GPS value and percentage of GPS change, a strong correlation ($r = 0.75$; $p < 0.05$) was found (Fig. 1).

4. Discussion

This study quantified the effect of gastrocnemius fascia lengthening on gait pattern in patients with CP using a summary measure recently proposed by literature, the GPS with GVS. We decided to use the GPS instead of the other summary indices proposed by the literature, such as Gillette Gait Index (Schutte et al., 2000), Hip Flexor Index (Schwartz et al., 2000) or Gait Deviation Index (Schwartz & Rozumalski, 2008) because of the nature of GPS, which provides both a summary measure (GPS) and the single values for each graph of gait analysis report (GVSs).

A number of authors report the efficacy of gastrocnemius fascia lengthening in children with CP using 3D gait analysis and in particular with specific indices (Adolfsen, Ounpuu, Bell, & DeLuca, 2007; Galli et al., 2005, 2009; Metaxiotis, Wolf, & Doederlein, 2004; Van Bemmel et al., 2012) and summary measures (Cimolin et al., 2011; Drongelen, Dreher, Heitzmann, & Wolf, 2013; Rutz et al., 2011; Thomason et al., 2013). Most of these paper analyzed the effects of surgery in CP are about gastrocnemius lengthening techniques in conjunction with other simultaneous orthopedic surgeries, which could have some influence on the results. The only papers which considered isolated gastrocnemius lengthening effects (Galli et al., 2005, 2009) demonstrated that significant improvements were found in terms of spatio-temporal parameters, kinematics and kinetics, mainly at distal joints. Although some decrease in muscle power was observed on physical examination, kinetic data showed an improvement in the power generation of the ankle over time. So, they demonstrated that gastrocnemius fascia lengthening is effective for correction of equinus foot deformity in particular at ankle and knee joint in children affected by CP and that it does not produce functional muscle weakness over time.

Some experiences on the use of GPS to quantify the degree of functional limitation in CP and in others pathologies and the effects of surgery in CP (Celletti et al., 2013; Firth et al., 2013; Rutz et al., 2013; Thomason et al., 2013), including astrocnemius fascia lengthening. However, also the analyses on the effects of surgery in CP are about gastrocnemius lengthening techniques in conjunction with other simultaneous orthopedic surgeries, which could have some influence on the results.

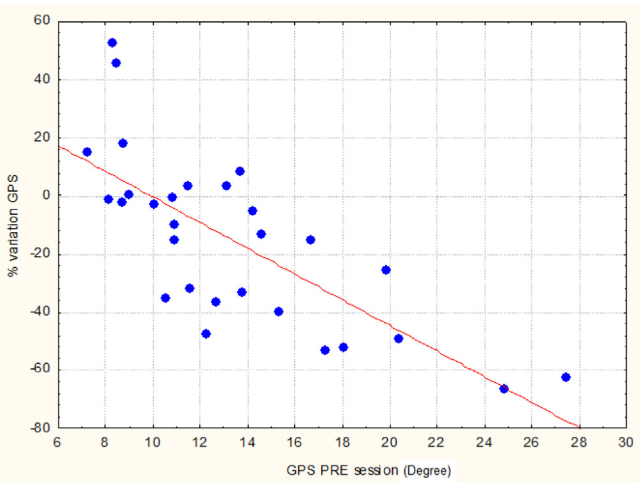

Fig. 1. Plot showing correlation between mean GPSs (°) in PRE evaluation and percentage of GPS variation after surgery ($r = 0.75$; $p < 0.05$).

To the best of our knowledge, no previous studies report the use of the GPS specifically to quantify the gait pattern in children with CP after isolated gastrocnemius fascia lengthening.

From our results, the GPS revealed significant improvements in the overall gait pattern following gastrocnemius fascia lengthening surgery. Cimolin et al. (2011) reported similar results using the GDI on children with CP submitted to the same surgical procedure. These findings demonstrate that both measures could useful in the global evaluation of the gait pattern in this population. However, while the GDI quantifies the gait strategy and the surgical effects using a general and unique measure, on the contrary the GPS with its GVSs allowed defining the joints where the treatment had more effects. In the present study our data showed, in fact, that not only a global improvement of the gait strategy was present, as showed by the GPS value which decreased after surgery, but that the ankle and the pelvis benefited from the treatment. Interesting is to note that improvements were displayed not only at ankle joint, directly involved in the treatment, but also at distal level, like the pelvis on the transversal plane. The reduction of GVS related to pelvic rotation may be representative of the reduction of a copying response strategy at pelvis level we observed in PRE session. Before surgery, in fact, an abnormal pelvic rotation was displayed probably to compensate the uncorrected ankle position.

This study presents some limitations. The small sample size results, in fact, in limited strength of our findings; a larger group would have conferred stronger statistical findings. In addition the GPS methodology incorporates only kinematic patterns of the lower limb joints taking not in consideration spatio-temporal parameters and kinetics, which have been demonstrated to be fundamental to assess the gait pattern and the rehabilitative program outcomes in CP. Further studies should be conducted to assess the efficacy of GPS in detecting changes in gait due to other treatments commonly used to reduce spasticity, such as botulinum toxin injections, or to the use of orthoses, too.

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References

Adolfsen, S. E., Ounpuu, S., Bell, K. J., & DeLuca, P. A. (2007). Kinematic and kinetic outcomes after identical multilevel soft tissue surgery in children with cerebral palsy. *Journal of Pediatric Orthopaedics, 27*, 658–667.

Assi, A., Guanem, I., Lavaste, F., & Skalli, W. (2009). Gait analysis in children and uncertainty assessment for Davis protocol and Gillette Gait Index. *Gait & Posture, 30*, 22–26.

Baker, L. D. (1956). A rational approach to the surgical needs of the cerebral palsy patient. *The Journal of Bone & Joint Surgery, 38*, 313–323.

Baker, R., McGinley, J. L., Schwartz, M. H., Beynon, S., Rozumalski, A., Graham, H. K., et al. (2009). The gait profile score and movement analysis profile. *Gait & Posture, 30*, 265–269.

Banks, H. H., & Green, W. T. (1958). The correction of equinus deformity in cerebral palsy. *The Journal of Bone & Joint Surgery British, 40*, 1359–1379.

Bass, A., Holmes, G., Sampath, J., & Trinca, D. (2009). The impact of structured physiotherapy rehabilitation protocols on the outcome of single multi-level surgery in cerebral palsy as measured by the gait deviation index (GDI). *Gait & Posture, 30*(Supplement 2), 101.

Benedetti, M. G., D'Apote, G., Faccioli, S., Costi, S., & Ferrari, A. (2011). Equinus foot classification in cerebral palsy: An agreement study between clinical and gait analysis assessment. *European Journal of Physical and Rehabilitation Medicine, 47*, 213–221.

Beynon, S., McGinley, J. L., Donson, F., & Baker, R. (2010). Correlations of the gait profile score and the movement analysis profile relative to clinical judgments. *Gait & Posture, 32*, 129–132.

Bonnefoy-Mazure, A., Sagawa, Y., Jr., Lascombes, P., De Coulon, G., & Armand, S. (2013). Identification of gait patterns in individuals with cerebral palsy using multiple correspondence analysis. *Research in Developmental Disabilities, 34*, 2684–2693.

Carriero, A., Zavatsky, A., Stebbins, J., Theologis, T., & Shefelbine, S. J. (2009). Determination of gait patterns in children with spastic diplegic cerebral palsy using principal components. *Gait & Posture, 29*, 71–75.

Celletti, C., Galli, M., Cimolin, V., Tenore, N., Albertini, G., & Camerota, F. (2013). Use of the gait profile score for the evaluation of patients with joint hypermobility syndrome/Ehlers–Danlos syndrome hypermobility type. *Research in Developmental Disabilities, 34*, 4280–4285.

Cimolin, V., Galli, M., Virmercati, S., & Albertini, G. (2011). Use of the gait deviation índex for the assessment of gastrocnemius fascia lengthening in children with cerebral palsy. *Research in Developmental Disabilities, 32*, 377–381.

Davis, R. B., Ounpuu, S., Tyburski, D. J., & Gage, J. R. (1991). A gait analysis data collection and reduction technique. *Human Movement Science, 10*(5), 575–587.

Dreher, T., Brunner, R., Vegvari, D., Heitzmann, D., Gantz, S., Maier, M. W., et al. (2013). The effects of muscle-tendon surgery on dynamic electromyographic patterns and muscle tone in children with cerebral palsy. *Gait & Posture, 38*, 215–220.

Drongelen, S. V., Dreher, T., Heitzmann, D. W. W., & Wolf, S. I. (2013). Gait patterns in twins with cerebral palsy: Similarities and development over time after multilevel surgery. *Research in Developmental Disabilities, 34*, 1595–1601.

Etnyre, B., Chambers, C., Scarbourough, N., & Cain, T. (1993). Preoperative and postoperative assessment of surgical intervention for equinus gait in children with cerebral palsy. *Journal of Pediatric Orthopaedics, 13*, 24–31.

Filho, M. C. M., Yoshida, R., Carvalho, W. S., Stein, H. E., & Novo, N. F. (2008). Are the recommendations from three-dimensional gait analysis associated with better postoperative outcomes in patients with cerebral palsy? *Gait & Posture, 28*, 316–322.

Firth, G. B., Passmore, E., Sangeux, M., Thomason, P., Rodda, J., Donath, S., et al. (2013). Multilevel surgery for equines gait in children with spastic diplegic cerebral palsy: Medium-term follow-up with gait analysis. *The Journal of Bone and Joint Surgery America, 95*(10), 931–938.

Gage, J. R. (2004). In J. R. Gage (Ed.), *The treatment of gait problems in cerebral palsy*. London: Cambridge University Press.

Gaines, R. W., & Ford, T. B. (1984). A systematic approach to the amount of Achilles tendon lengthening in cerebral palsy. *Journal of Pediatric Orthopaedics, 4*, 448–451.

Galli, M., Cimolin, V., Crivellini, M., & Albertini, G. (2005). Gait analysis before and after gastrocnemius fascia lengthening in children with cerebral palsy. *Journal of Applied Biomaterials and Biomechanics, 3*, 98–105.

Galli, M., Cimolin, V., Crivellini, M., & Albertini, G. (2009). Long-term evaluation of isolated gastrocnemius fascia lengthening in children with cerebral palsy using gait analysis. *Journal of Paediatric Orthopedics, 18*, 228–233.

Gannotti, M. E., Gorton, G. E., Nahorniak, M. T., & Masso, P. D. (2010). Walking abilities of young adults with cerebral palsy: Changes after multilevel surgery and adolescence. *Gait & Posture, 32*, 46–52.

Grabe, R. P., & Thompson, P. (1979). Lengthening of the Achilles tendon in cerebral paresis. *South African Medical Journal, 56*, 993–996.

Green, W. T., & McDermott, L. F. (1942). Operative treatment of cerebral palsy of spastic type. *Journal of the American Medical Association, 118*, 434–440.

Kawamura, C. M., Filho, M. C. M., Barreto, M. M., Asa, S. K. P., Juliano, Y., & Novo, N. F. (2007). Comparison between visual and three-dimensional gait analysis in patients with spastic diplegic cerebral palsy. *Gait & Posture, 25*, 18–24.

Kay, R. M., Rethlefsen, S. A., Ryan, J. A., & Wren, T. A. (2004). Outcome of gastrocnemius recession and tendo-achilles lengthening in ambulatory children with cerebral palsy. *Journal of Pediatric Orthopaedics B, 16*, 92–98.

Metaxiotis, D., Wolf, S., & Doederlein, L. (2004). Conversion of biarticular to monoarticular muscles as a component of multilevel surgery in spastic diplegia. *The Journal of Bone and Joint Surgery British, 86*, 102–109.

Patikas, D., Wolf, S. I., Schuster, W., Armbrust, P., Dreher, T., & Döderlein, L. (2007). Electromyographic patterns in children with cerebral palsy: Do they change after surgery? *Gait & Posture, 26*, 362–371.

Rose, S. A., DeLuca, P. A., Davis, R. B., III, Ounpuu, S., & Gage, J. R. (1993). Kinematic and kinetic evaluation of the ankle after lengthening of the gastrocnemius fascia in children with cerebral palsy. *Journal of Pediatric Orthopaedics, 13*, 727–732.

Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., Bax, M., Damiano, D., et al. (2007). A report: The definition and classification of cerebral palsy. *Developmental Medicine & Child Neurology: Supplement, 109*, 8–14.

Rutz, E., Baker, R., Tirosh, O., Romkes, J., Haase, C., & Brunner, R. (2011). Tibialis anterior tendon shortening in combination with Achilles tendon lengthening in spastic equinus in cerebral palsy. *Gait & Posture, 33*, 152–157.

Rutz, E., Donath, S., Tirosh, O., Graham, H. K., & Baker, R. (2013). Explaining the variability improvements in gait quality as a result of single event multi-level surgery in cerebral palsy. *Gait & Posture, 38*, 455–460.

Sagawa, Y., Jr., Watelaina, E., De Coulone, G., Kaeline, A., Gorce, P., & Armande, S. (2013). Are clinical measurements linked to the gait deviation index in cerebral palsy patients? *Gait & Posture, 38*, 276–280.

Schutte, L. M., Narayanan, U., Stout, J. L., Selber, P., Gage, J. R., & Schwartz, M. H. (2000). An index for quantifying deviations from normal gait. *Gait & Posture, 11*, 25–31.

Schwartz, M. H., & Rozumalski, A. (2008). The gait deviation index: A new comprehensive index of gait pathology. *Gait & Posture, 28*, 351–357.

Schwartz, M. H., Novacheck, T. F., & Trost, J. (2000). A tool for quantifying hip flexor function during gait. *Gait & Posture, 12*, 122–127.

Seniorou, M., Thompson, N., & Theologis, T. (2006). Recovery of muscle strength following multi-level orthopaedic surgery in diplegic cerebral palsy. *Gait & Posture, 24*(2), 93–95.

Speciali, D. S., Oliveira, E. M., Santos, N. M., Pereira, F. V., Fracini, A. C., Fukuda, T. Y., et al. (2013). Use of the gait deviation index and spatiotemporal variables for the assessment of dual task interference paradigm. *Journal of Bodywork & Movement Therapies, 17*, 19–27.

Strayer, L. M. (1950). Recession of the gastrocnemius. *The Journal of Bone & Joint Surgery, 32-A*, 6716.

Sung, K. H., Chung, C. Y., Lee, K. M., Akhamedov, B., Lee, S. Y., Choi, I. H., et al. (2013). Long term outcome of single event multilevel surgery in spastic diplegia with flexed knee gait. *Gait & Posture, 37*, 536–541.

Thomason, P., Selber, P., & Graham, H. K. (2013). Single event multilevel surgery in children with bilateral spastic cerebral palsy: A 5 year prospective cohort study. *Gait & Posture, 37*, 23–28.

Van Bemmel, A. F., Van der Bekerom, M. P. J., Verhart, J., Diederik, A., & Vergroesen, A. (2012). Preliminary results of 97 percutaneous gastrocnemius muscular lengthening operations in neurologically healthy children with an equinus contracture. *Foot and Ankle Surgery, 18*, 160–163.

Vulpius, O., & Stoffel, A. (1913). *Tenotomie der end schnen der mm. Gastrocnemius et soleus mittels rutschenlassens hach vulpius: Orthopadische Operationslehre*. Stuttgart: Ferdinand Enkee.

White, J. W. (1943). Torsion of the Achilles tendon. *Archives of Surgery, 46*, 784–787.

Wren, T. A. L., Otsuka, N. Y., Bowen, R. E., Scaduto, A. A., Chan, L. S., Dennis, S. W., et al. (2013). Outcomes of lower extremity orthopedic surgery in ambulatory children with cerebral palsy with and without gait analysis: Results of a randomized controlled trial. *Gait & Posture, 38*, 236–241.

Yngve, D. A., & Chambers, C. (1996). Vulpius and Z-lengthening. *Journal of Pediatric Orthopaedics, 16*, 759–764.