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Percutaneous Lengthening with an Intramuscular Needle of the Gastrocsoleus Complex Improves Critical Ankle Kinematic Values in Resistant Pediatric Equinus: A Pilot Study

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Abstract: Retrospective analytical study that aims to evaluate the kinematic and kinetic results obtained after percutaneous lengthening with an intramuscular needle (PLIN) of gastrocsoleus complex (GSC) zones I, II, and III, performed outside the operating room between 2018 and 2019, in pediatric patients with equinus gait resistant to non-operative treatment. Gait analysis was performed prior to treatment and 6 months post treatment in 48 ankles (30 patients), with a median patient age of 10.11 (2.85) years. Twelve patients had a diagnosis of idiopathic equinus, twelve spastic hemiplegia, and six spastic diplegia. Statistical analysis included pre–post comparison, correlation, and linear regression of critical kinematic and kinetic ankle values. Significant improvement was observed for the following parameters: ankle angle at initial contact, −4.57(10.31)/0.05(3.04)°; maximum ankle dorsiflexion in the stance phase (mADFStP), 3.70(7.56)/10.42(4.52)°; and maximum ankle dorsiflexion in the swing phase (mADFSwP), −6.54(8.41)/−0.35(6.17)°. In addition, an inversely proportional correlation with pre-intervention values was obtained for those parameters, with rho values of −0.864, −0.755, and −0.696, respectively ($p < 0.0005$). No significant changes in ankle kinetics were evidenced. Linear regression equations allowed for estimation of the post mADFStP, with a standard error (SE) = 1.82; $R^2 = 0.797$ ($p < 0.0005$), and the post mADFSwP, with an SE = 2.376; $R^2 = 0.829$ ($p < 0.0005$). To conclude, the addition of the GSC in patients with resistant equinus significantly improves ankle initial contact, mADFStP, and mADFSwP, with greater changes occurring with worse initial values. The regression formulas used to estimate post-procedure results will allow therapeutic indications to be adjusted.

Keywords: ankle; equinus; kinematics; kinetics; gait analysis; outpatient care; orthopedic procedures

1. Introduction

Equinus gait is the most common pediatric ambulation disorder in cerebral palsy (CP) [1], and among the population without neuromuscular disorders, idiopathic equinus is the most frequent diagnosis. Equinus deformity of the foot is mainly due to contracture of the gastrocsoleus complex (GSC), which reduces ankle dorsiflexion, an essential component of a normal gait. Equinus gait has a negative effect on prepositioning of the foot for initial contact, stability and adequate step length in stance, and foot clearance in swing [2], and also increases energy demands during walking.

Non-surgical management is the first treatment option. Non-operative therapies such as physiotherapy and orthoses and the application of botulinum neurotoxin A (BoNT-A) with serial casting have demonstrated effectiveness [3–8]. However, during growth, as fixed contractures progressively develop and the ankle deformity becomes rigid, surgery within the operating room is often the next step [9]. Several surgical methods for soft tissue release have been described, varying from intramuscular or aponeurotic lengthening to tenotomy and Z tendo-Achilles lengthening, either proximal or distal and percutaneous or open [10,11].

An alternate approach to resistant equinus management before deciding to perform surgery combines the benefits of botulinum toxin and casting with percutaneous lengthening with an intramuscular needle (PLIN) of the GSC. This procedure, which is performed outside the operating room, aims to section the superficial soft tissue responsible for restricting ankle dorsiflexion by performing oscillating movements with the bevel of the needle.

Percutaneous soft tissue lengthening with an intramuscular needle has been previously described in the treatment of other diseases, such as Dupyutren's contracture of the hand [12], tendinitis [13,14], epicondylitis [15], and congenital talipes equinovarus [16,17], as well as for muscle contractures at different locations [18–21]. However, we are not aware of any publication describing the application of this technique in pediatric patients with equinus ankle.

Treatment outcomes in ankle equinus are usually presented by measuring the passive range of motion, without a precise and dynamic method of evaluation. In addition, objective measurements of gait function in young children with equinus gait are not routinely used in studies, despite their advantages. Three-dimensional (3D) instrumented gait analysis helps to quantify the results and increases the precision, sensitivity, and reliability of assessments used to detect changes in gait.

Using 3D instrumented gait analysis, this study aimed to quantify the effect of adding PLIN of the myotendinous unit (MTU) on the GSC to BoNT-A and casting on the kinematics and kinetics of ankle function during the gait cycle in children with resistant equinus. Regarding kinetics and given that surgical lengthening of plantar flexors is related to a loss of joint power, it is important to investigate whether this technique renders the same biomechanical result.

2. Materials and Methods

This is a retrospective, observational, before-and-after intervention cohort study involving pediatric patients treated between 2018 and 2019 at a pediatric reference hospital. The intervention consisted of PLIN of the MTU on GSC zones I, II, and III in addition to BoNT-A and casting while under sedation and on an outpatient basis. Prior to initiation of the study, approval was obtained from our Institutional Review Board (no. R-0047-21).

The indication for treatment with PLIN was the presence of equinus gait during observational gait analysis, along with passive ankle dorsiflexion under physical examination of less than 0° with the knee extended and the foot in inversion, all of which would have followed insufficient improvement with BoNT-A and casting. Among all patients who had indication for treatment, those who had an instrumented 3D gait analysis completed before and approximately 6 months after the procedure that confirmed true equinus gait were included in the study. Patients with different sagittal gait patterns, such as jump gait or pseudo-equinus, as well transverse gait anomalies or dyskinesia as assessed by instrumented 3D gait analysis were excluded. The final study group consisted of 48 ankles from 30 patients, with a median (interquartile range) age of 10.11 (2.85), 73.3% of whom were male. The diagnosis was idiopathic equinus in 12 patients, spastic hemiplegia in 12, and spastic diplegia in 6. Among CP patients, 8 had a functional level GMFCS I and 10 a functional level GMFCS II.

PLIN is an outpatient technique carried out after the application of 3–4 U/kg of BoNT-A in the gastrocnemius and is performed outside the operating room in designated sedation facilities in the intensive care unit of our hospital (Figure 1A). Patients must present for the procedure following a 7 h fasting period and be accompanied by their family members. Under the monitoring of pediatric intensive care specialists and under sedation with fentanyl and propofol, patients undergo PLIN of the MTU on the GSC. After antiseptic measures, an assistant places the ankle in maximum dorsiflexion with the knee extended, and the tip of a 21-gauge × 25 mm intramuscular needle is inserted into the MTU of the GSC to section the superficial aponeurosis of the muscles with the bevel of the needle through oscillating movements (Figure 1B,C). This procedure is performed in zones I and II until 10–20° of ankle dorsiflexion is reached with the knee extended. If this desired range of motion is not achieved, zone III is approached following the same procedure. A fiberglass-reinforced, weight-bearing short leg cast is placed in ankle dorsiflexion for 2 weeks. Thereafter, use of a full-time ankle–foot orthosis is recommended for another 3 weeks to achieve complete healing of the partial thickness section performed in the GSC, and physiotherapy is then initiated. This period of orthotic use is important to avoid pain in the GSC, which may occur due to the potential for increased tissue disruption. Physical therapy treatment should be tailored to soft tissue response after surgery. The immobilization period requires action observation and motor imagery to enhance motor learning. During the next phase, gentle passive mobilization of the ankle joint and isometric contractions should be introduced after the casting period. Adapted load and strengthening exercise with low-intensity loads using isometric and concentric actions in open kinetic chains (elastic bands and active movements) is suitable. Gait and balance training will be initiated in this phase. Eccentric exercise and increased load intensity should be started 4 weeks after cast removal, and advanced gait, running, and jumping training will be part of the last stages of physiotherapy treatment.

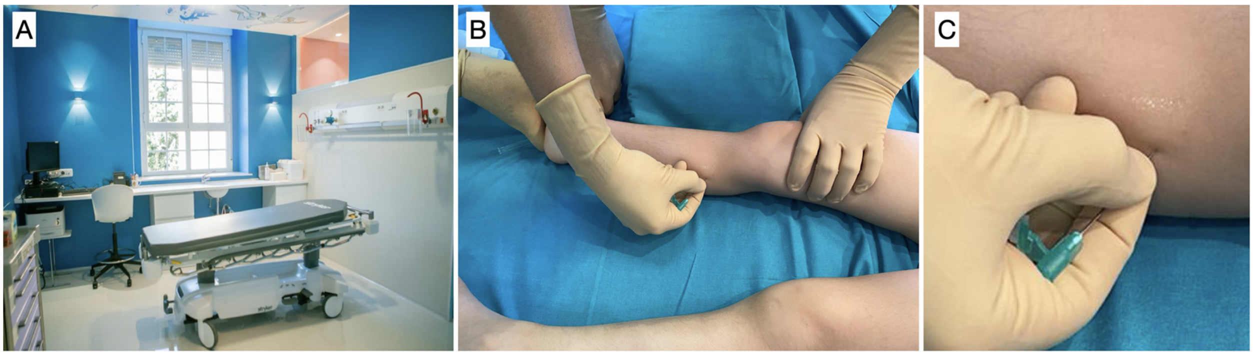


Figure 1. (**A**) Sedation room in the intensive care unit where procedures are performed. (**B**) Positioning with the knee extended and maximum ankle dorsiflexion. (**C**) PLIN of the GSC, achieved by introducing the tip of an intramuscular needle to section muscle aponeurosis with the bevel of the needle through oscillating movements.

The Helen Hayes protocol for placement of reflective markers was followed for the kinematic study. Trajectories were captured by 8 3D infrared capture cameras, and this information was processed by the BTS Motion Analysis Lab system (BTS Bioengineering). Two Kistler force plates provided kinetic data during the stance phase. Three physiotherapists with more than 5 years of experience in instrumented 3D gait analysis performed the studies of all patients. These studies were performed without assistive devices.

The differences after treatment were evaluated, obtaining the average critical kinematic and kinetic values of the best 3 out of a total of 5 walks. Ankle position at initial contact, maximum ankle dorsiflexion in the stance phase (mADFStP) and maximum ankle dorsiflexion in the swing phase (mADFSwP) measured in degrees were the chosen values for the kinematic study. For kinetic evaluation, peak values of ankle generation power in W/Kg and plantar flexion moment in N·m/Kg were compared. The gait deviation index (GDI) was also considered, with normal values being those above 100.

SPSS version 23 software (IBM Inc., Chicago, IL, USA) was used for statistical analysis. Since the distributions of kinematic and kinetic variables were not normal according to the Shapiro–Wilk test, neither before nor after the procedure, and given that these were either highly (Pearson's rho > 0.90) or poorly (Pearson's rho < 0.10) correlated between each other in most cases, a nonparametric Wilcoxon signed rank test for repeated measures was applied to determine the statistical significance between variables before and after the procedure. An additional correlation analysis between the variables before and after the procedure was performed using Spearman's rho test with Bonferroni correction for multiple comparison. Finally, multiple linear regression analyses for each of the post-procedure variables with regard to all the pre-procedure variables were performed. All tests were two-tailed, and the significance level was set at $p < 0.05$.

3. Results

No clinical complications were observed in this group of patients. Analysis of the biomechanical evaluation yielded the following results.

3.1. Kinematic Results

For the entire group, a significant pre–post improvement was obtained in ankle position at initial contact, in the mADFStP, and in the mADFSwP, as displayed in Table 1 and Figure 2A.

Table 1. Pre- and post-intervention gait analysis values.

	Pre	Post	Statistics
GDI	90.87 (9.36)	92.10 (7.47)	Z = −0.600, p = −549
GDI interval	1.88 (1.17)	2.77 (2.91)	Z = −0.843, p = 0.399
Ankle position at initial contact +	−4.57 (10.31)	0.05 (3.04)	Z = −2.366, p = 0.018 +
Ankle position at initial contact interval	0.32 (0.57)	0.11 (0.51)	Z = −1.187, p = 0.235
mADFStP +	3.70 (7.56)	10.42 (4.52)	Z = −4.107, p < 0.0005 +
mADFStP interval	1.82 (1.79)	1.93 (1.91)	Z = −0.568, p = 0.570
mADFSwP +	−6.54 (8.41)	−0.35 (6.17)	Z = −4.010, p < 0.0005 +
mADFSwP interval	1.11 (0.69)	1.34 (1.46)	Z = −0.149, p = 0.881
Ankle generation power (W/Kg)	1.55 (0.58)	1.65 (0.61)	Z = −1.178, p = 0.239
Ankle generation power interval (W/Kg)	0.32 (0.77)	0.16 (0.43)	Z = −0.158, p = 0.874
Ankle plantar flexion moment (N·m/Kg)	0.93 (0.21)	0.90 (0.45)	Z = −0.310, p = 0.757
Ankle plantar flexion moment interval (N*m/Kg)	0.08 (0.22)	0.11 (0.42)	Z = −0.312, p = −755

+ Statistically significant; GDI, gait deviation index; mADFStP, maximum ankle dorsiflexion in the stance phase; mADFSwP, maximum ankle dorsiflexion in the swing phase.

When comparing differences in improvement according to several demographic and clinical variables, no statistically significant differences were obtained, although trends could be observed (Figure 2B); a tendency toward greater improvement in the maximum values on the right sides was observed, there seemed to be no improvement at initial contact in spastic diplegia, and a trend toward greater improvement of the mADFSwP in spastic diplegia with respect to hemiplegia was also seen.

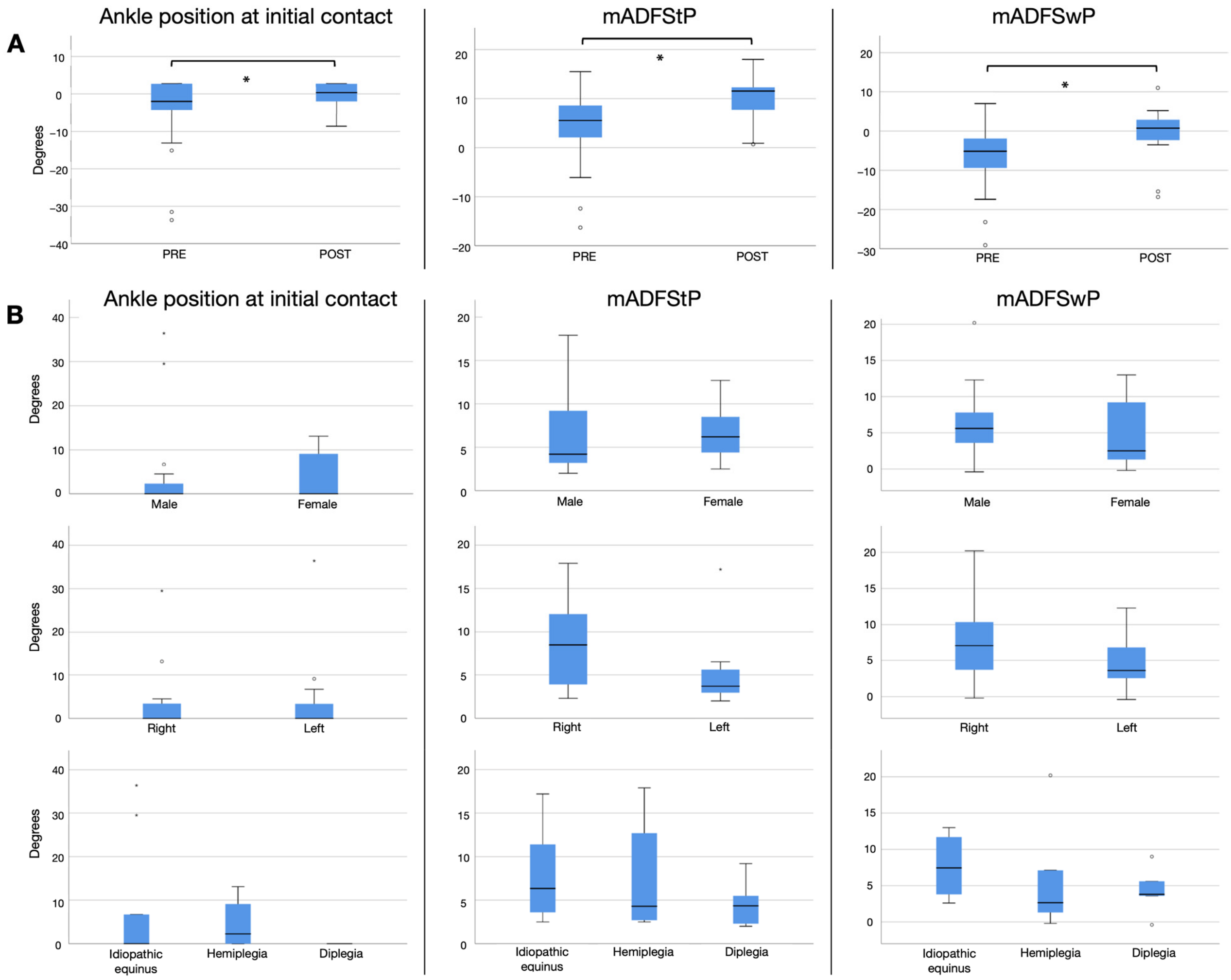


Figure 2. (**A**) Boxplots representing the pre- and post-intervention data regarding ankle position in initial contact, the mADFStP, and the mADFSwP, where statistically significant differences (*) can be found in the three critical kinematic values. Positive and negative values mean the degrees of ankle motion in dorsiflexion (+) or plantar flexion (−). (**B**) Representation of the improvements in critical kinematic parameters for the different demographic and clinical variables, which shows no statistically significant differences. Values are provided in degrees (deg). mADFStP, maximum ankle dorsiflexion in the stance phase; mADFSwP, maximum ankle dorsiflexion in the swing phase.

3.2. Kinetic Results

Overall, both for patients with unilateral or bilateral involvement, no significant changes in ankle kinetics were observed, neither in ankle generation power nor in ankle plantar flexion moment, as seen in Table 1 and Figure 3.

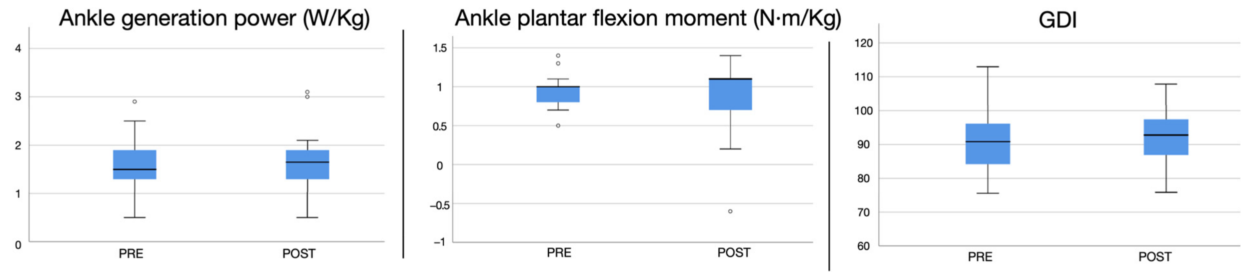
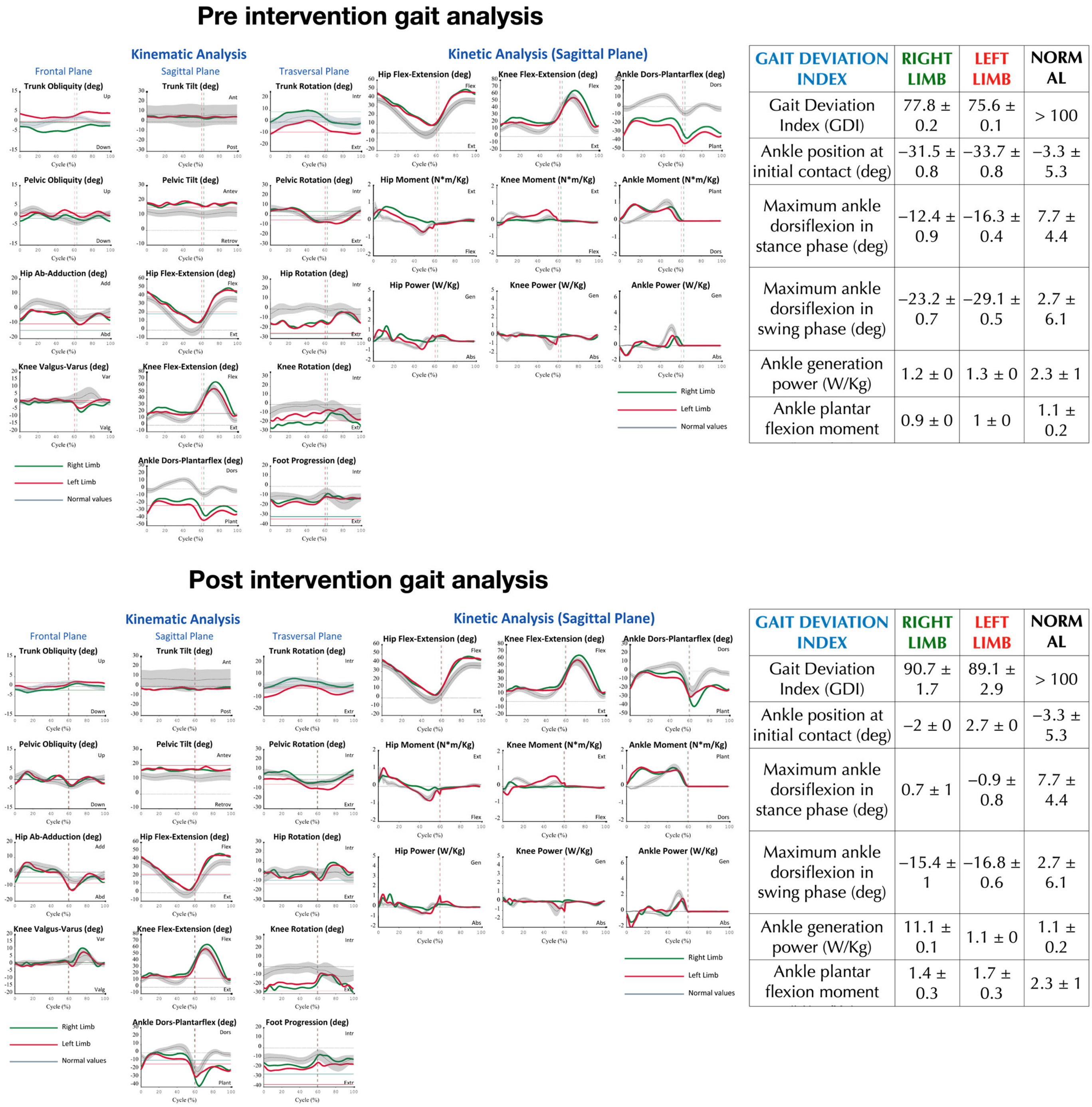


Figure 3. Boxplots representing pre- and post-intervention data regarding ankle kinetics and GDI, where no statistically significant differences can be seen.

3.3. GDI

Similarly, no statistically significant differences beyond the minimum clinically relevant difference [22] were observed before and after in the outcome measure based on the GDI (Table 1 and Figure 2C), although overall values tended to improve after treatment.

An example of the kinematic and kinetic analysis graphs and the values obtained pre- and post-intervention can be seen in Figure 4.



GAIT DEVIATION INDEX	RIGHT LIMB	LEFT LIMB	NORMAL
Gait Deviation Index (GDI)	77.8 ± 0.2	75.6 ± 0.1	> 100
Ankle position at initial contact (deg)	−31.5 ± 0.8	−33.7 ± 0.8	−3.3 ± 5.3
Maximum ankle dorsiflexion in stance phase (deg)	−12.4 ± 0.9	−16.3 ± 0.4	7.7 ± 4.4
Maximum ankle dorsiflexion in swing phase (deg)	−23.2 ± 0.7	−29.1 ± 0.5	2.7 ± 6.1
Ankle generation power (W/Kg)	1.2 ± 0	1.3 ± 0	2.3 ± 1
Ankle plantar flexion moment	0.9 ± 0	1 ± 0	1.1 ± 0.2

GAIT DEVIATION INDEX	RIGHT LIMB	LEFT LIMB	NORMAL
Gait Deviation Index (GDI)	90.7 ± 1.7	89.1 ± 2.9	> 100
Ankle position at initial contact (deg)	−2 ± 0	2.7 ± 0	−3.3 ± 5.3
Maximum ankle dorsiflexion in stance phase (deg)	0.7 ± 1	−0.9 ± 0.8	7.7 ± 4.4
Maximum ankle dorsiflexion in swing phase (deg)	−15.4 ± 1	−16.8 ± 0.6	2.7 ± 6.1
Ankle generation power (W/Kg)	11.1 ± 0.1	1.1 ± 0	1.1 ± 0.2
Ankle plantar flexion moment	1.4 ± 0.3	1.7 ± 0.3	2.3 ± 1

Figure 4. Example of the kinematic and kinetic analysis graphs and the values obtained pre- and post-intervention for a patient included in the study.

3.4. Correlation Analysis

The improvement in ankle position at initial contact, the mADFStP, and the mADFSwP correlated significantly and inversely with pre-procedure values (rho = −0.864, −0.755, and

−0.696, respectively; $p < 0.0005$), as represented in Table 2. This means that the worse these initially were, the more they improved. Additionally, the improvement in the mADFSwP had an inversely proportional correlation with the pre-treatment mADFStP and vice versa. In contrast, improvement in the mADFSwP also correlated inversely with the previous ankle position at initial contact and previous ankle generation power.

Table 2. Correlation between the improvement in the three parameters (post–pre) and their values before the intervention (pre).

Spearman's Rho	GDI Interval, Pre	Ankle Position at Initial Contact, Pre	Ankle Position at Initial Contact Interval, Pre	mADFStP, Pre	mADFSwP, Pre	Ankle Generation Power, Pre
Ankle position at initial contact, post–pre	−0.606 (p = 0.004) +	−0.864 (p < 0.0005) +	0.967 (p < 0.0005) +			
mADFStP, post–pre		−0.488 (p = 0.025) +		−0.755 (p < 0.0005) +	−0.523 (p = 0.015) +	−0.651 (p < 0.0005) +
mADFSwP, post–pre				−0.488 (p = 0.025) +	−0.696 (p < 0.0005) +	

+ Statistically significant; GDI, gait deviation index; mADFStP, maximum ankle dorsiflexion in the stance phase; mADFSwP, maximum ankle dorsiflexion in the swing phase.

3.5. Regression Analysis

Of all the linear regression analyses performed for the post-procedure variables, only two were statistically significant. The regression equation in Figure 5A enabled us to estimate the post-procedure mADFStP, considering the pre-procedure mADFStP and its interval, as well as the prior ankle generation power, with a standard error (SE) = 1.82 and R^2 = 0.797, $p < 0.0005$ (Figure 5A). In addition, the regression analysis described by the equation in Figure 5B allowed for estimation of the post-procedure mADFSwP considering the side, the previous mADFSwP, the pre-procedure initial contact interval, and the prior ankle generation power interval, with SE = 2.376 and R^2 = 0.829, $p < 0.0005$ (Figure 5B).

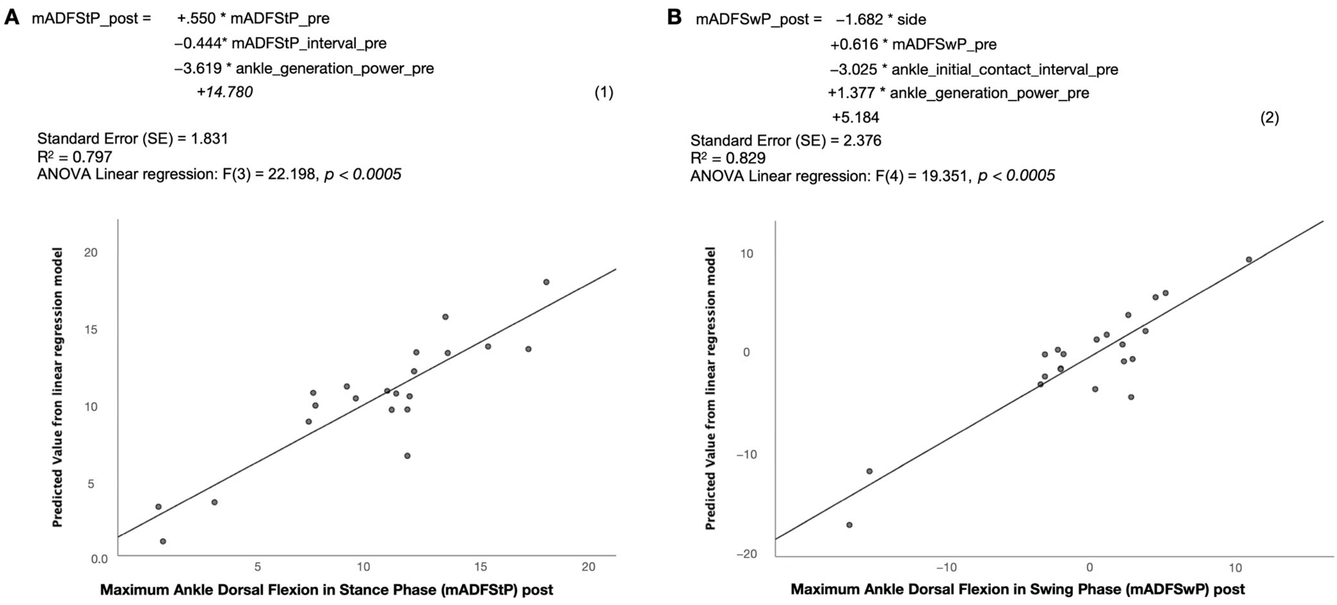


Figure 5. (**A**) Scatter plot showing a strongly positive linear relationship (R^2 = 0.797) between maximum ankle dorsiflexion in the stance phase (mADFStP) post intervention and the previous mADFStP and its interval, as well as prior ankle generation power. (**B**) Scatter plot showing a strongly positive linear relationship (R^2 = 0.829) between post-procedure maximum ankle dorsiflexion in the swing phase (mADFSwP) and the side, the previous mADFSwP, the previous initial contact interval, and the prior ankle generation power interval. mADFSwP, maximum ankle dorsiflexion in the swing phase.

4. Discussion

This pilot study evaluates quantitative biomechanical results on gait analysis to determine the effect of the PLIN procedure applied to the MTU on the GSC in addition to BoNT-A and casting for the treatment of resistant equinus, evidencing improvements in critical ankle kinematic values with no deterioration in kinetic parameters.

This simple and safe approach adds minimal morbidity to patients, as it addresses mechanical soft tissue shortening that occurs in both idiopathic and spastic equinus. Movement of the intramuscular needle in a windshield wiper-like pattern is used to cut the most superficial aponeurotic tissues in zones I and II of the GCS, as well as the posterior tendinous fibers located in zone III, which contribute to the lack of ankle dorsiflexion. This can be added to management of the neurological component of the equinus deformity with the application of BoNT-A. For improvement in the mechanical component of the equinus, the use of a cast in the desired position maintains elongation of the MTU. The results of the combination of these three aspects of management have not been previously reported.

In the therapeutic ladder of equinus gait in children, the PLIN procedure explained here constitutes an additional alternative prior to surgery. Multiple visits to the operating room often cause anxiety for both patients and their families and increase costs; therefore, the search for safe and cost-saving therapeutic alternatives is justified [23]. Since PLIN is performed outside the operating room, the emotional stress on the patient and their families is reduced; furthermore, this procedure presumably reduces costs and avoids increases in surgical waiting lists.

The potential benefits of this technique following the failure of conservative treatments, as well as those demonstrated with surgical lengthening of the calf muscles, are explained by the fact that spasticity is only partially behind contractures in CP [9] and plays no role whatsoever in typically developing children who present idiopathic toe walking. The most consistent mechanical change observed in the muscles of CP patients is extracellular matrix hypertrophy leading to increased muscle stiffness [24,25].

The kinematic values studied along the gait cycle in the present investigation are functionally correlated during walking and are related to tripping and falling and gait efficiency [26]. For instance, improvement in ankle dorsiflexion in the swing phase and at initial contact allows less toe dragging and a more stable gait.

The absence of deterioration in kinetic values, both in terms of ankle generation power and plantar flexor moment, is a positive finding and one that differs from the results obtained with traditional soft tissue surgery. Scalpel use for GSC lengthening acts in a wider tissue area, increasing the risk of weakening in the plantar flexors, which may lead to a crouched gait [11,27–30]. Our kinetic results could be attributed to the narrower section of the needle, which is less aggressive to soft tissues and is less likely to induce excessive elongation. This technique allows safer, more effective targeting of the surgical dose, that is, the dose that provides the right amount of muscle lengthening for each patient [9].

Calf lengthening procedures are typically performed in zone I and zone II to avoid loss of plantar flexion power in the ankle and over-lengthening, commonly related to the lengthening of zone III [31,32]. However, we performed this technique more distally when the patient did not reach 20° of ankle dorsiflexion after having acted in more proximal zones, mostly in hemiplegic patients.

Our finding that a higher degree of improvement was obtained in patients with worse pre-intervention values is important when establishing indications for the procedure, since it would be conceivable to expect a small effect from this less aggressive procedure in more severe deformities. The results, however, are better than expected and thus provide evidence for the use of this procedure, even in more severe cases. In addition, the regression analysis performed allows the therapeutic indications of this procedure to be adjusted by predicting the results based on the preceding values.

The use of gait analysis has been shown to delay the first orthopedic surgical procedure, increase the time interval to BoNT-A treatment, and reduce the frequency of surgical procedures in CP children [33]. Knowing that the use of BoNT-A and casting may be ineffective over time, adding PLIN may delay visits to the operating room, diminishing the risk of equinus recurrence related to growth and buying time for better patient cooperation. Therefore, due to the safety of the PLIN procedure, it can be administered simultaneously alongside other non-operative treatments. The procedure may also allow for the application of a lower dose of BoNT-A to the muscles, which may be relevant for cost saving and lower the possible long-term tissue damage reported in relation to its application [34–37].

As this is a pilot study, limitations include the small sample size, short follow-up period, and the heterogeneity of the etiology. Despite this, statistically significant differences have been identified. In most of the patients treated in our center during this period, treatment included interventions on other levels (e.g., hamstrings, psoas, and rectus anterior, among others); therefore, these patients were excluded from the current study so as to avoid this confounding factor. The need to perform further research with a larger sample to stratify the results according to the etiology of the equinus is recognized. The concept of equinus resistant to conservative treatments has been applied to idiopathic and spastic causes based on the shared treatment strategy for both etiologies. Despite the differences in etiologies, kinematic improvement was evidenced in all of them, with no differences found when comparing the kinematic and kinetic results according to etiology. Lastly, the follow-up period is limited to the immediate results, and no data have been recorded on the duration of improvement. Compared to the effects of BoNT-A, for which the peak is 4–6 weeks, PLIN is likely to have a longer lasting effect. Nevertheless, due to the growing condition of children, equinus deformity may increase, especially after puberty, and the procedure may need to be repeated.

5. Conclusions

In conclusion, the addition of PLIN of the MTU on the GSC as a therapeutic alternative in patients with resistant equinus prior to more aggressive surgical procedures significantly improves ankle position at initial contact, the mADFStP, and the mADFSwP, with greater changes occurring in cases with worse pre-procedure values. This outpatient and out-of-operating room procedure is easy to perform, safe, cost-effective, and is a resource-saving procedure that adds minimal morbidity to patients. PLIN of the MTU on the GSC is highly recommended as part of the gradual management of equinus gait in pediatric patients. The use of regression formulas to evaluate post-procedure outcomes will allow for the adjustment of therapeutic indications.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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