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The added value of orthotic management in the context of multi-level surgery in children with cerebral palsy

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ABSTRACT

Background: Treatment of cerebral palsy includes an interdisciplinary concept and in more severe cases the well-established multi-level surgery (MLS). Different kinds of orthoses are typically part of postoperative treatment but there is a lack of knowledge about their additional benefit.
Research question: Do ankle foot orthoses lead to an additional, measurable improvement of gait after MLS?
Methods: 20 children with bilateral spastic cerebral palsy (9 retrospective, 11 in a postoperative clinical routine) were included. All had a preoperative gait analysis before MLS. Postoperatively, they were fitted with different ankle foot orthoses (AFO), depending on their individual needs. Dynamic ankle foot orthoses (DAFO), combined DAFO with additional dynamic, elastic shank adaptation (DESA) and ground reaction force AFOs (GRAFO) were used. Patients underwent a second gait analysis 1.5 (± 0.6) years postoperatively barefoot and with orthoses. Data analysis included testing for normal distribution (Shapiro-Wilk-Test) and further nonparametric statistical testing on basis of a Wilcoxon Single-Rank Test.
Results: The operation produced changes in the hip, knee and ankle joint, and the pelvis. Spatiotemporal parameters showed significant changes due to additional use of the orthoses. Further, additional kinematic changes occurred at the hip, knee and ankle joint as well as the foot. The Gillette Gait Index (GGI) improved significantly by supplementary orthoses, but not by surgery alone. The Gait Profile Score (GPS) and Gait Deviation Index (GDI) rather showed changes due to the surgery.
Significance: MLS significantly improves GPS and GDI more than a year after surgery, which can be interpreted as an improvement in gait pattern. In contrast, the GGI is improved by additional postoperative orthotic treatment, which implies that walking ability itself has improved, rather than the gait pattern. Orthoses show a positive additional effect on surgical results at different anatomical levels. Spatiotemporal parameters are positively influenced solely by additional orthotic support.

1. Introduction

The prevalence of cerebral palsy (CP) is reported in the literature to be in the range of 1.4–2.3 ‰ in western civilization [1]. Thus, it is thought to be the most common cause of motor disability in children. An interdisciplinary therapy concept for CP is required owing to the regularly associated impairments in postural and selective motor control as well as concomitant spasticity and muscular weakness. The therapeutic goal here is functional independence and the child's social and cultural participation. Since the primary brain damage is not curable, therapy is targeted to reduce impairments. In children under the age of 6, conservative therapy strategies dominate due to the predominantly dynamic nature of the condition. Therapeutic options consist in particular of physiotherapy and detonating medication, but a variety of technical orthopedic aids are also available. The latter represent an integral part of almost all patients and are tailored to the individual pattern of expression. As associated ankle and foot deformities are present in over 90% of children, which in turn are the result of associated impairments, orthoses are regularly implemented in the treatment concept [2].

Orthoses have been defined by the International Organization for Standardization as [3]:

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Externally applied device used to modify the structural and functional characteristics of the neuromuscular and skeletal systems (plural: orthoses)

Among the variety of designs, ankle foot orthoses (AFO) are generally the most common form of care in patients with neurological problems and, in particular, those with CP [4,5]. They are defined as [6]:

Orthoses that encompass the ankle joint and the whole or part of the foot

The primary aims of AFO use are to stabilize the foot as the base and to correct, or at least stabilize, deformities to avoid further deterioration. As a result, gait patterns should be measurably optimized. Among other improvements, studies showed an improvement of walking speed, stride length, cadence, oxygen consumption, and knee and hip kinematics [7–9]. Overall, however, the results are inconsistent, possibly due to the great variety of individual designs, with potentially different effects, making it difficult to describe these different orthotic devices accurately [4,5,10,11].

Regardless of the conservative treatment options, surgical interventions in children with CP are common from the age of 6 years. Spasticity is the most common pattern of tonus in affected individuals and leads to progressive contractures and bony deformities due to disproportional muscle growth and nonphysiological growth stimuli to the bone [12,13]. Contrary to the former practice of "birthday surgery", i.e., frequent and more or less isolated bony or soft tissue interventions, modern therapy concepts include multi-level surgery (MLS). By definition, these treatments involve more than four separate surgical procedures at the affected anatomical heights, at both lower extremities during one operation combined with a prolonged rehabilitation period [14]. The aim of this strategy is to address the multiple pathologies at the same time and to avoid multiple operations. Study results show promising short- and long-term results [15].

In good clinical practice the previously mentioned conservative and operative therapy concepts need to be combined. In this way, patients receive orthoses postoperatively in order to prevent the deformities from recurring, to support their ability to walk, and to stabilize the gait pattern, which are accompanied by a positive effect on the metabolic cost and furthermore to initially stabilize the surgical outcome [16]. However, it is still not fully clear whether such additional care can provide a supplementary benefit to surgery, which already involves the correction of the pathological orthopedic condition. Thus, this study aimed to address the question of what additional effects on gait can be achieved by ankle foot orthoses during the postoperative treatment phase in CP patients.

We hypothesized that next to surgery, ankle foot orthoses lead to an additional, measurable improvement in gait, which can be determined by improvement in the kinematic, kinetic, and spatiotemporal parameters of gait analysis.

2. Methodology

Study subjects were recruited from a patient collective of the neuro-orthopedic department of the University Hospital Heidelberg and from the established CP register. Twenty children with spastic bilateral CP were included in the study. The data from 9 patients were retrospectively evaluated from the database and a further 11 were included in a routine postoperative gait analysis. All patients and their legal guardians were fully informed about the study and gave written informed consent for participation.

A positive vote by the ethics committee of the University of Heidelberg`s faculty of medicine was available (S-090/2016). A group of 30 normally developing children served as controls for comparison.

Inclusion criteria for this study were an age at baseline of 6–17 years, the presence of bilateral spastic CP at GMFCS level 1–3, and the feasibility of gait analysis with or without an additional walking aid (e.g., crutches or walker). Patients with knee contracture were excluded.

Preoperatively, the participants underwent conventional, instrumented 3D gait analysis. Gait analysis included a standardized clinical examination performed by a physiotherapist. For gait analysis, a 120-Hz 12-camera system (Vicon, Oxford, United Kingdom) and two force plates (Kistler, Winterthur, Switzerland) were used. Skin mounted markers were applied to the bony landmarks, according to PlugInGait (Vicon, Oxford, United Kingdom) on the basis of the classic lower limb measurement model established by Kadaba and Davis et al., while patients walked a defined distance at a self-selected speed [17]. For each gait analysis at least 8 strides were taken into account and joint kinematics were averaged across trials. Stride-to-stride consistency was checked by eye, outliers deleted and only those of homogenous patterns (min. 8 strides) were averaged. Both the instrumented 3D-gait analysis and the clinical exam were performed by the same physiotherapists on expert level with more than 10 years of experience. Measurements errors are to be expected well below 3° for most of the joint angles according to McGinley et al. [18]. On the basis of this analysis, the patient-specific surgical strategy was determined. All patients received MLS including the lower extremities. Postoperatively, they were fitted with different ankle foot orthoses (AFO) by an in-house team of certified orthotists with at least 5 years of experience. The design choice was adapted to the patients` individual needs and was carried out according to a defined clinical algorithm. The following concepts and groups of designs were used:

1. Dynamic ankle foot orthosis (DAFO): Also known as Nancy Hylton orthosis according to the first description from the year 1989 [19]. This orthosis is made of thin, flexible thermoplastic polypropylene surrounding the foot up to the ankle joint (Fig. 1a). With respect to Hylton`s explanations the special, custom-made footplate supports the dynamic arches of the foot and is intended to induce proprioceptive stimuli on a reflex-based level. This is intended to achieve a detonating effect.

2. Combined DAFO with additional dynamic, elastic shank adaptation (DESA): In addition to the aforementioned DAFO, patients received

Fig. 1. (a) DAFO, (b) DAFO with ToeOff, (c) DAFO with custom-made, lightweight AFO, (d) GRAFO with unilateral adjustable hinge joint, (e) DAFO with GRAFO with unilateral adjustable hinge joint.

Table 1
Surgeries. Abbreviations: (F)DO Femoral Derotation Osteotomy, DVO Derotation-Varisation Osteotomy, bilat bilateral, ATL Achilles Tendon Lengthening, Tib Tibialis, ant anterior, post posterior.

Patient Number	Bony Femur/ Tibia	Bony Foot	Soft Tissue Hip	Soft Tissue Hamstrings/Knee	Soft Tissue Rectus Transfer	Soft Tissue Calf Muscle/ Achilles Tendon	Soft Tissue Tib. Ant/ Post Transfer
1		Evans bilat		bilat	bilat		
2		Chopart bilat		bilat	bilat	ATL left	Tib ant right
3	FDO bilat			bilat	bilat	bilat	Tib post bilat
4	FDO left	Chopart bilat		bilat	bilat	bilat	
5		Grice bilat		bilat	bilat	Strayer bilat	
6	DVO bilat	Chopart bilat		bilat	bilat		
7		Chopart bilat		bilat	bilat	Strayer bilat	
8	FDO bilat	Evans bilat	Adductors right	bilat	bilat	Strayer bilat	
9		Chopart bilat	Psoas bilat	bilat	bilat	Strayer bilat	Tib post bilat
10	FDO right; Tibia left					Baumann bilat	
11	DVO bilat	Arthrodesis bilat			bilat	Strayer bilat	
12	FDO bilat				tenotomy bilat		
13	DVO bilat			bilat		Baumann right	
14	DVO bilat			bilat		Strayer bilat	
15	FDO bilat					Strayer right, ATL left	
16	FDO bilat	Arthrodesis bilat					
17	DVO bilat					Strayer right	
18	DVO left					Baumann right, ATL left	Tib ant left
19	DO Tibia bilat		Adductors bilat	bilat		Baumann bilat	
20	DVO bilat	Arthrodesis bilat		Patella distalization bilat		ATL bilat	
Sum	**25 FDOs**	**22 Bony foot corrections**	**2 Psoas lengthenings**	**24 Hamstring lengthenings**	**20 Rectus transfers**	**29 Calf/Achilles lengthenings including 4 ATLs**	**6 Tib post/ant transfers**
	3 Tibia DOs		**3 Adductor lenghtenings**	**2 Patella distalisations**	**2 Rectus recession**		

a DESA with ventral attachment [ToeOff, Allard USA Inc., USA (Fig. 1b)] or individually custom-made, light-weight, flexible DESA (Fig. 1c). This off-the-shelf (ToeOFF) or custom-made orthosis consists of a carbon fiber foot plate, which is inserted into the footwear and connected via a spiral carbon fiber spring with a proximal shell at the shank and fixed via velcro or similar straps. Deformation of the carbon fiber lamella or spring enables motion. The DAFO needs to be adapted to the DESA, and an overall static and dynamic alignment is performed during the fitting process by using wedges under the DESA. In addition to the effects of an isolated DAFO, the carbon fiber adaptation results in a dynamic elastic behavior and additional support of the ankle and the extension of the knee throughout the stance phase. A beneficial effect on the plantar flexion-knee extension couple is expected as well. In clinical practice it was shown that it is beneficial to have a discrete dorsi-plantar stop with the flexible carbon fiber structures, as opposed to having a hinge.

3. Ground reaction force AFO (GRAFO): Custom-made carbon orthosis with semicircular ventral tibial shell and uni- or bilateral hinge joints at the ankle [20]. Adjustable dorsi-plantar stops are used to limit the range of motion (hinged AFO) and combined with springs for a slight support of toe lift (Fig. 1 d & e). Foot structure is incorporated and stabilized by a circular foot shell or by a DAFO. The primary effect is expected at the dorsal stop by producing a defined ankle moment and indirectly by a knee-extending moment via the plantar flexion-knee extension couple, as described previously [20]. Additionally, a higher stabilization in all three planes is achieved by a rather rigid structure. In particular the foot lever is stabilized in such orthoses, via circular containment of the foot.

With the exception of the off-the-shelf ToeOFF adapted to the DAFO, the orthoses were all custom-made. They were manufactured by experienced, certified orthotists in the technical orthopedics department of the Heidelberg University Hospital and subject to individual medical control of fit and adjustment.

On average patients underwent a second instrumented 3D gait analysis 1.5 (± 0.6) years postoperatively. Two conditions were measured: with and without orthosis.

Data from gait analysis enabled us to calculate the Gillette Gait Index (GGI), Gait Profile Score (GPS), and Gait Deviation Index (GDI), all established gait indexes [21–23]. GPS and GDI provide a general description of gait deviations based on the same 9 joint angle curves, namely pelvic tilt, obliquity, and rotation, hip flexion/extension, hip ab/adduction, and hip rotation, knee flexion/extension, ankle dorsi/plantarflexion as well as foot progression. The GGI is a convolution of 16 clinically important gait features, including spatiotemporal parameters, into a single number.

3. Statistical analysis

Gait data was analyzed from all limbs individually but for further analysis left and right limb of each subject was averaged. SPSS version 22 (International Business Machines Corporation Corp. [IBM], Amonk, New York, USA) was used for the statistical analysis. Initially, a descriptive data analysis was calculated with the values standard deviation (SD) and mean. This was followed by testing for normal distribution based on the Shapiro-Wilk test. A non-normal distribution was confirmed. Therefore, we decided to identify differences with non-parametric statistical tests. A Wilcoxon Single-Rank Test for related samples to compare the groups "normal collective", "pre-OP barefoot", "post-OP barefoot", and "post-op orthosis" was performed.

The significance level was set to $\alpha = 0.05$.

4. Results

The age of the patient population (n = 20; 5 females) at the preoperative exam was 10.4 ± 3.3 years with body height of 135.9 ± 18.5 cm and body mass of 33.5 ± 14.0 kg. The reference group (n = 30; 16 females) was a convenience sample from our data base matched in age (10.0 ± 2.8 years) having a slightly larger body height (141.4 ± 16.1 cm) and body mass (36.7 ± 12.4 kg). The follow-up examination was conducted on average 1.5 (± 0.6) years later with body height of 143.9 ± 17.4 cm body mass of 39.6 ± 15.2 kg, postoperatively.

The group of 20 patients received on average in their legs 70% derotations, 55% foot bony corrections, 60% hamstring lengthenings,

Table 2
Statistical evaluation of the collected measurement parameters including gait scores.

	Parameter	pre	post-barefoot	post-orthosis	norm	P pre-post barefoot	P post orthosis - barefoot
Indexes	GDI	62.6 ± 8.2	69 ± 7.2	71.5 ± 8.0	100 ± 9.6	**0.015**	0.167
	GPS	14.1 ± 3.5	11.7 ± 2.3	11 ± 2.0	4.7 ± 1.3	**0.011**	0.263
	GGI	408 ± 168	335 ± 157	243 ± 147	15 ± 6	0.135	**0.001**
Parameters of the GGI	Stance duration [%]	67.7 ± 6.3	70.6 ± 7.0	67.2 ± 5.9	60.0 ± 1.2	0.126	**0.006**
	Velocity [m/s]	0.69 ± 0.26	0.63 ± 0.35	0.81 ± 0.32	1.30 ± 0.16	0.456	**< 0.001**
	Cadence [steps/min]	105 ± 24	105 ± 39	101 ± 30	131 ± 13	0.296	0.370
	Mean pelvic tilt [°]	11.8 ± 8.6	19.4 ± 8.1	18.7 ± 7.6	12.5 ± 4.2	**0.012**	0.204
	Range of pelvic tilt [°]	8.4 ± 3.2	7.6 ± 3.4	7.5 ± 3.5	2.9 ± 0.7	0.167	0.433
	Mean pelvic rotation [°]	0.2 ± 0.5	0.3 ± 0.7	−0.1 ± 0.5	0.0 ± 0.4	0.575	0.117
	Minimum hip flexion [°]	2.4 ± 8.7	6.8 ± 8.6	2.3 ± 8.4	−9.4 ± 5.8	**0.025**	**0.001**
	Range of hip flexion [°]	38.3 ± 7.9	37.1 ± 8.3	42.5 ± 7.4	46.0 ± 4.6	0.601	**< 0.001**
	Max. hip abd. swing phase [°]	5.2 ± 2.9	4.3 ± 2	4.7 ± 2.3	5.9 ± 1.9	0.351	0.117
	Mean hip rot. stance phase [°]	10.8 ± 8.9	3.4 ± 8.3	1.9 ± 9.1	6.1 ± 8.5	**0.017**	0.455
	Knee flexion at init. contact [°]	35.8 ± 13	21 ± 10	17.8 ± 12.8	7.3 ± 3.5	**0.001**	**0.023**
	Time of peak knee flexion [%]	82.8 ± 3.9	81.5 ± 3.9	78.7 ± 4.6	71.9 ± 1.3	0.164	**0.002**
	Range of knee flexion [°]	31.9 ± 11.4	43.5 ± 12.4	46.5 ± 11.3	53.7 ± 5.5	**0.006**	0.185
	Maximum dorsiflexion in stance phase [°]	5.8 ± 7.0	12.8 ± 6	14.8 ± 6.1	13.5 ± 2.5	**0.004**	0.108
	Maximum dorsiflexion in swing phase [°]	−3.9 ± 9.0	4.8 ± 5.2	7.9 ± 5.2	2.6 ± 2.4	**0.001**	**0.033**
	Mean foot progr. angle [°]	2.2 ± 19.1	−1.9 ± 7.4	0.2 ± 7.6	−8.2 ± 3.8	0.263	**0.048**

55% rectus transfers, 73% calf muscle or Achilles tendon lengthenings, and 15% Tib. anterior/posterior transfers, respectively. The individual surgeries are listed in Table 1.

The orthotic distribution according to the three groups was 2x DAFO, 6x DAFO combined with a shank adaptation, and 12x ground reaction force AFO.

The surgical procedure produced changes in the hip, knee and ankle joint, and the pelvis (compare Table 2). Significant changes included an improvement in mean hip rotation in the stance phase, in knee flexion at initial contact, in range of motion of the knee, and in maximum dorsiflexion both in stance and swing phase but an aggravation of pelvic tilt and minimum hip flexion. The spatiotemporal parameters velocity and stance duration showed significant improvements due to additional use of the orthoses. The minimum hip flexion and range of motion of the hip joint displayed further significant improvements due to orthoses as well as knee flexion at initial contact, and time of peak knee flexion. Maximum dorsiflexion in swing phase showed a slight overcorrection in orthosis condition and the mean foot progression angle lead to a neutral foot orientation instead of a slight external position seen in normal gait.

The Gillette Gait Index improved significantly using supplementary orthotic support, but not solely by surgery. In contrast, the values of the Gait Profile Score and the Gait Deviation Index changed only by surgery at significance level. Orthoses led to no additional significant alteration.

5. Discussion

Aim of this study was to clarify in how far orthotics in the management post multi-level surgery of patients with CP may lead to additional improvements both in gait pattern and in walking ability, namely in the gait indices GGI, GDI, and GPS and spatiotemporal parameters.

According to our data, GDI ($p = 0.015$) and GPS ($p = 0.011$) improved significantly as compared to the pre- to postoperative barefoot measurement. The significant improvement in GGI, however, was observed for the postoperative supplementary use of orthoses ($p = 0.001$), but not for surgery alone ($p = 0.135$).

When assessing changes in gait characteristics, it is important to note that the findings are not related only to changing individual parameters, but also to the relationship between individual variables [22]. On the basis of this rationale, Schutte et al. developed the GGI (formerly known as 'normalcy index'), which convolutes 16 variables of the gait cycle to single a number. In contrast to the GDI and GPS, this score includes the spatiotemporal parameters stance duration, walking speed, and cadence. Additional orthotic support improved the first two variables on significance level ($p = 0.006$, $p < 0.001$). Surgical interventions alone did not result in any significant change in these parameters ($p = 0.126$, $p = 0.456$). This represents a relevant difference between the gait indexes and explains the discrepancies [24]. The fact that gait indexes can be positively influenced by MLS [14,25] and orthoses [11,26] has already been reported. In a 2015 publication, Danino et al. examined whether the three indexes can depict the effect of a targeted intervention, namely, the use of an AFO [24]. Although single parameters showed change at the significance level, the authors claimed that the three gait indexes were not sensitive enough overall. However, the data in this study show that when selecting the indexes, their underlying gait features must be taken into account. GDI and GPS are based on the same parameters and correlate closely [27]. The GDI was described as a good outcome parameter for MLS, which could illustrate the overall deviation from normal gait [12]. The changes in GPS were significantly higher than the reported, minimally clinically important differences (MCID) of 1.6° [27]. Here, our results differ slightly from those of Skaaret et al., who found a statistically significant but not clinically meaningful (0,7°) improvement from additional AFOs in a postoperative control one year after surgery [26]. In contrast, we see the strength of the GGI in measuring general walking ability, expressed in spatiotemporal parameters. In many previous publications, it was these parameters in particular that were positively influenced by orthoses [7–9]. We consider it positive that orthoses can exert this effect even under postoperative conditions so that they can additionally support the altered anatomical conditions. We agree with the results of Skaaret et al., despite substantial deviations in the percentage composition of performed bony and soft tissue interventions as well as the included orthotic designs [26]. Here, however, our results differ from a previous report of adult subjects with CP [28].

In the past, there has been repeated reference to the lack of scientific evidence when using AFOs [4,5]. In contrast to previous publications that showed a considerable inconsistency, which was explained by imprecise and differing orthotic descriptions and different interventions [5,10,29] the current study used some more clinically standardized orthotic management. The current setting followed in principle a design introduced by Nancy Hilton and addressing the orthotic height on an AFO by the patient's functional deficit regarding effective functional forefoot lever and sagittal plane knee stability. That AFOs of different characteristics can positively influence stance duration and walking speed has been repeatedly described in the literature [30–32]. In our cohort, the benefit achieved by using orthoses is close to 0.2 m/s, a value which is in line with de Wit et al. and considered clinically

relevant [33]. However, our results do not show improvements that are as marked as stated in the literature. A plausible explanation for this may be the smaller subgroups resulting out of the mixture of different heights of orthoses in our study subjects even do all orthosis investigated are following one principle: Stabilization of the foot lever, control of ankle motion and effective assist for an adequate knee extension, which is a limitation of this study, due to small subgroups.

The results of past studies on cadence were heterogeneous. Some studies showed unchanged values [24,31], and some highlighted a positive or negative change at significance level [26,32,34].

Our results show a significant increase in maximum dorsiflexion of the ankle during stance and swing phase of gait due to MLS. This significant improvement achieved by surgery is the result of soft tissue interventions (e.g., Achilles tendon lengthening) [35]. The fact that orthoses can also have this effect has been reported, too [31,36]. In the postoperative course, however, we only see an additional benefit in the swing phase of gait.

All kinematic parameters of the knee showed a trend towards the normal controls. A significant influence on the total range of motion of the knee joint could only be addressed surgically, however: surgery rectified the structural causes. Feger et al. described this aspect in their comparison of surgical interventions in the context of an MLS compared to nonsurgical strategies [37]. However, knee flexion at initial contact and the timing of maximum knee flexion could significantly be improved by additional orthotic supply. These results differ slightly from those of Skaaret et al., who demonstrated a significant change in knee kinematics only surgically in the overall view of their collective [26]. Hayek et al. described a decrease in knee flexion at an initial contact of 8.5° in hemiplegic patients, without being able to detect this in diplegic patients [31]. However, the authors examined solid AFOs. A positive effect could also be shown using hinged AFOs, but the values differ from ours in a relevant magnitude [30]. Lam et al. described a decrease in knee flexion at initial contact wearing DAFOs [36]. Our heterogeneous patient group did not show this effect in the same way. Lee et al. published data demonstrating improved timing of maximum knee flexion after rectus femoris transfer [25]. In contrast, our patient group demonstrates this effect only under postoperative conditions. Surgical interventions typically aim for an optimization of structural deficits, whereas orthoses are external devices for the compensation of structural deficits [16]. The results of our research emphasize that these are complementary care strategies. Structural deficits resolved by surgical interventions sometimes require additional external support in order to result in a technically measurable kinematic change. We see here an improvement in walking ability and a basis to develop the gait favorably. Our interpretation is that persistent musculoskeletal deficits and selective motor control limitations do not allow the full exploitation of postoperative gains. We assume that the effect of orthoses is even more pronounced with increasing fatigue. However, this effect has not yet been investigated and further research work is necessary here.

Our data show a significant improvement of both maximum hip extension and joint range of motion of the hip in flexion/extension in gait when comparing the condition with and without AFO. In contrast, Buckon et al. found no significant influence on the pelvis, hip, and knee joint when comparing three different orthotic designs (SAFO, HAFO, and PLS) [38]. Also, Romkes and Brunner compared barefoot, DAFO, and HAFO conditions in patients with unilateral CP and found increased maximum hip flexion and hip flexion at initial contact when comparing to their reference subjects but did not detect any change due to the orthosis [39]. Unfortunately, the only study that is comparable in design did not give kinematic values concerning the hip and pelvis, so no specific comparison is possible here [26].

Kinematic parameters of the knee and hip as well as spatiotemporal parameters show a positive influence due to the additional use of orthoses even 1.5 years postoperatively. The study of these additional effects has received little attention in the literature so far. In our view, the results indicate adequate care.

5.1. Limitations

The study population was relatively small at n = 20. It was heterogeneous both in terms of surgical interventions and orthotic design. MLS was individually performed based on clinical findings and results of the pre-operative gait analysis. Likewise, the prescription of orthoses was based on the clinical judgment of a clinician with respect to internal strategies. Thus, a bias cannot be excluded. The data we collected are purely exploratory in character. Further investigations with larger and more homogeneous collectives are required.

The mean age of our study population at first gait analysis was 10.4 (± 3.3) years with a rather broad age span (6–17 years). It is not possible to exclude an influence of natural growth within the average of 1.5 (± 0.6) years until the second measurement.

The data analysis included statistical calculations on gait indexes. The explanatory power of these indexes is limited. Shortcomings of the GGI include arbitrary selection, imbalance, and incomplete nature of the 16 parameters included. The univariate parameters, the uncertainty of the scaling of the components, the non-normality of the index, and the lack of physical significance of multivariate components comprise further limitations. Furthermore, there is a strong dependence on the underlying dataset [23]. In addition, the technique for calculating the GDI requires a preliminary analysis of a large dataset of all likely gait deviations [21]. Finally, the GPS lacks normal distribution [27].

6. Conclusion

MLS significantly improves GPS and GDI more than a year after surgery, which can be interpreted as an improvement in gait pattern. In contrast, the GGI is improved exclusively by supplementary postoperative orthotic treatment, which implies that walking ability itself has improved, rather than the gait pattern. Orthoses show a positive additional effect on surgical results at different anatomical levels (ankle, knee, and hip). However, the improvement of some spatiotemporal parameters such as walking speed and stance phase duration in the postoperative situation is only made possible by the additive use of orthoses, but not by the operation alone.

Conflict of interest statement

All authors have no conflicts of interest.

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References

[1] K.B. Nelson, Cerebral palsy, in: A. Hofman, R. Mayeus (Eds.), Investigating Neurological Disease Epidemiology for Clinical Neurology, Cambridge University Press, New York, 2001, pp. 280–289.
[2] P. Kedem, D.M. Scher, Foot deformities in children with cerebral palsy, Curr. Opin. Pediatr. 27 (2015) 67–74.
[3] Prosthetics and Orthotics – Vocabulary – Part 1: General Terms for External Limb Prostheses and External Orthoses, International Organization for Standardization, Geneva, Switzerland, 1989.
[4] E.M. Figueiredo, G.B. Ferreira, R.C.M. Moreira, R.N. Kirkwood, L. Fetters, Efficacy of ankle-foot orthoses on gait of children with cerebral palsy: systematic review of literature, Pediatr. Phys. Ther. 20 (2008) 207–223.
[5] A. Healy, S. Farmer, A. Pandyan, N. Chockalingam, A systematic review of randomised controlled trials assessing effectiveness of prosthetic and orthotic interventions, PLoS One 13 (2018) e0192094.
[6] Prosthetics and Orthotics. Terminology. Glossary of General Terms Relating to External Limb Prostheses and External Orthoses, British Standard, 1990.
[7] C.E. Buckon, S.S. Thomas, S. Jakobson-Huston, M. Sussman, M. Aiona, Comparison of three ankle-foot orthosis configurations for children with spastic hemiplegia, Dev. Med. Child Neurol. 43 (2001) 371–378.
[8] K. Desloovere, C. Huenaerts, G. Molenaers, M. Eyssen, P. De Cock, Effects of ankle foot orthoses on the gait of cerebral palsy children, Gait Posture 10 (89) (1999).
[9] H. White, J. Jenkins, W.P. Neace, C. Tylkowski, J. Walker, Clinically prescribed orthoses demonstrate an increase in velocity of gait in children with cerebral palsy:

a retrospective study, Dev. Med. Child Neurol. 44 (2002) 227–232.
[10] N. Eddison, M. Mulholland, N. Chockalingam, Do research papers provide enough information on design and material used in ankle foot orthoses for children with cerebral palsy? A systematic review, J. Child. Orthop. 11 (2017) 263–271.
[11] A. Aboutorabi, M. Arazpour, M. Ahmadi Bani, H. Saeedi, J.S. Head, Efficacy of ankle foot orthoses types on walking in children with cerebral palsy: a systematic review, Ann. Phys. Rehabil. Med. 60 (2017) 393–402.
[12] M. Švehlík, G. Steinwender, T. Kraus, V. Saraph, T. Lehmann, W.E. Linhart, E.B. Zwick, The influence of age at single-event multilevel surgery on outcome in children with cerebral palsy who walk with flexed knee gait, Dev. Med. Child Neurol. 53 (2011) 730–735.
[13] I. Ziv, N. Blackburn, M. Rang, J. Koreska, Muscle growth in normal and spastic mice, Dev. Med. Child Neurol. 26 (1984) 94–99.
[14] T. Dreher, P. Thomason, M. Švehlík, L. Döderlein, S.I. Wolf, C. Putz, O. Uehlein, K. Chia, G. Steinwender, M. Sangeux, H.K. Graham, Long-term development of gait after multilevel surgery in children with cerebral palsy: a multicentre cohort study, Dev. Med. Child Neurol. 60 (2018) 88–93.
[15] J.L. McGinley, F. Dobson, R. Ganeshalingam, B.J. Shore, E. Rutz, H.K. Graham, Single-event multilevel surgery for children with cerebral palsy: a systematic review, Dev. Med. Child Neurol. 54 (2012) 117–128.
[16] A. Fuchs, L. Döderlein, Orthotics and cerebral palsy. Established treatments and trends in orthopaedic devices for patients with cerebral palsy, Orthopade 33 (2004) 1173–1182.
[17] R.B. Davis, S. Ounpuu, D. Tyburski, J.R. Gage, A gait analysis data collection and reduction technique, Hum. Movement Sci. 10 (1991) 575–587.
[18] J.L. McGinley, R. Baker, R. Wolfe, M.E. Morris, The reliability of three-dimensional kinematic gait measurements: a systematic review, Gait Posture 29 (2009) 360–369.
[19] N.M. Hylton, Postural and functional impact of dynamic afo's and fo's in a pediatric population, J. Prosthet. Orthot. 2 (1989) 40–53.
[20] S.I. Wolf, M. Alimusaj, O. Rettig, L. Döderlein, Dynamic assist by carbon fiber spring afos for patients with myelomeningocele], Gait Posture 28 (2008) 175–177.
[21] R. Baker, J.L. McGinley, M.H. Schwartz, S. Beynon, A. Rozumalski, H.K. Graham, O. Tirosh, The gait profile score and movement analysis profile, Gait Posture 30 (2009) 265–269.
[22] L.M. Schutte, U. Narayanan, J.L. Stout, P. Selber, J.R. Gage, M.H. Schwartz, An index for quantifying deviations from normal gait, Gait Posture 11 (2000) 25–31.
[23] M.H. Schwartz, A. Rozumalski, The gait deviation index: a new comprehensive index of gait pathology, Gait Posture 28 (2008) 351–357.
[24] B. Danino, S. Erel, M. Kfir, S. Khamis, R. Batt, Y. Hemo, S. Wientroub, S. Hayek, Are gait indices sensitive enough to reflect the effect of ankle foot orthosis on gait impairment in cerebral palsy diplegic patients? Pediatr. Orthop. 36 (3) (2016) 294–298.
[25] S.Y. Lee, S.S. Kwon, C.Y. Chung, K.M. Lee, Y. Choi, T.G. Kim, W.C. Shin, I.H. Choi, T.J. Cho, W.J. Yoo, M.S. Park, Rectus femoris transfer in cerebral palsy patients with stiff knee gait, Gait Posture 40 (2014) 76–81.
[26] I. Skaaret, H. Steen, T. Terjesen, I. Holm, Impact of ankle-foot orthoses on gait 1 year after lower limb surgery in children with bilateral cerebral palsy, Prosthet. Orthot. Int. (2018) Epub ahead of print.
[27] M.L. McMulkin, B.A. MacWilliams, Application of the gillette gait index, gait deviation index and gait profile score to multiple clinical pediatric populations, Gait Posture 41 (2015) 608–612.
[28] C. Putz, L. Döderlein, E.M. Mertens, S.I. Wolf, S. Gantz, F. Braatz, T. Dreher, Multilevel surgery in adults with cerebral palsy, Bone Joint J. (2016) 282–288 98-B.
[29] E. Ridgewell, F. Dobson, T. Bach, R. Baker, A systematic review to determine best practice reporting guidelines for afo interventions in studies involving children with cerebral palsy, Prosthet. Orthot. Int. 34 (2010) 129–145.
[30] B.R. Balaban, E. Yasar, U. Dal, K. Yazicioglu, H. Mohur, T.A. Kalyon, The effect of hinged ankle-foot orthosis on gait and energy expenditure in spastic hemiplegic cerebral palsy, Disabil. Rehabil. 29 (2007) 139–144.
[31] S. Hayek, Y. Hemo, S. Chamis, R. Bat, E. Segev, S. Wientroub, Z. Yzhar, The effect of community-prescribed ankle–foot orthoses on gait parameters in children with spastic cerebral palsy, J. Child. Orthop. 1 (2007) 325–332.
[32] T.A. Wren, J.W. Dryden, N.M. Mueske, S.W. Dennis, B.S. Healy, S.A. Rethlefsen, Comparison of 2 orthotic approaches in children with cerebral palsy, Pediatr. Phys. Ther. 27 (2015) 218–226.
[33] D.C. de Wit, J. Buurke, J.M. Nijlant, M.J. IJzerman, H.J. Hermens, The effect of an ankle-foot orthosis on walking ability in chronic stroke patients: a randomized controlled trial, Clin. Rehabil. 18 (2004) 550–557.
[34] K.C. Jagadamma, F.J. Coutts, T.H. Mercer, J. Herman, J. Yirrell, L. Forbes, M.L. van der Linden, Optimising the effects of rigid ankle foot orthoses on the gait of children with cerebral palsy (cp)–an exploratory trial, Disabil. Rehabil. Assist. Technol. 10 (2015) 445–451.
[35] M.C.M. Klotz, S.I. Wolf, D. Heitzmann, B. Krautwurst, F. Braatz, T. Dreher, Reduction in primary genu recurvatum gait after aponeurotic calf muscle lengthening during multilevel surgery, Res. Dev. Disabil. 34 (2013) 3773–3780.
[36] W.K. Lam, J.C.Y. Leong, Y.H. Li, Y. Hu, W.W. Lu, Biomechanical and electromyographic evaluation of ankle foot orthosis and dynamic ankle foot orthosis in spastic cerebral palsy, Gait Posture 22 (2005) 189–197.
[37] M.A. Feger, C.D. Lunsford, L.D. Sauer, W. Novicoff, M.F. Abel, Comparative effects of multilevel muscle tendon surgery, osteotomies, and dorsal rhizotomy on functional and gait outcome measures for children with cerebral palsy, PM R 7 (2015) 485–493.
[38] C.E. Buckon, S.S. Thomas, S. Jakobson-Huston, M. Moor, M. Sussman, M. Aiona, Comparison of three ankle-foot orthosis configurations for children with spastic diplegia, Dev. Med. Child Neurol. 46 (2004) 590–598.
[39] J. Romkes, R. Brunner, Comparison of a dynamic and a hinged ankle-foot orthosis by gait analysis in patients with hemiplegic cerebral palsy, Gait Posture 15 (2002) 18–24.