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Does footprint and foot progression matter for ankle power generation in spastic hemiplegic cerebral palsy?

Spastik hemiplejik beyin felcinde ayak izi ve ayağı ilerletme açısı ayak bileği güç üretiminde rol oynuyor mu?

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Objectives: We investigated how foot pressure pattern and foot progression relate to power generation from the ankle joint in children with spastic hemiplegic cerebral palsy (CP).

Methods: The study included 35 children (13 girls, 22 boys; mean age of 8.8 years; range 4 to 19.8) with CP, all having independent ambulation. The children underwent three-dimensional gait analysis and a set of pedobarographic data were obtained. The pedobarographs were analyzed by dividing the foot into five segments.

Results: The mean power generation from the ankle was 7.6 watts/kg on the hemiplegic side, and 15.9 watts/kg on the uninvolved side (p=0.000). Based on the pedobarographic data, hemiplegic feet exhibited significantly less heel pressure/impulse (8.0 *vs*. 24.7; p=0.000), time to heel rise (32.1% of stance phase *vs*. 61.9%; p=0.000), and decreased pressure of the medial forefoot segment (40.8 *vs*. 52.2; p=0.009). The children were divided into two groups depending on the ankle power generated on the hemiplegic side (<8.0 watts/kg and ≥8.0 watts/kg). Those with an ankle power generation of ≥8.0 watts/kg had significantly longer step length (49 cm *vs*. 41 cm; p=0.001) and increased velocity (109 cm/sec *vs*. 89 cm/sec; p=0.000) in gait analysis, and in pedobarographic measurements, increased heel impulse (11.6 *vs*. 4.4; p=0.047), time to heel rise (46.6% *vs*. 17.1%; p=0.000), and less varus/valgus positioning (11.1° *vs*. -34.6°; p=0.013). In bivariate correlation analysis, ankle power generation on the hemiplegic side demonstrated a significant association with time to heel rise (r=0.574; p=0.000) and varus/valgus positioning (r=0.420; p=0.017), and almost a significant association with heel pressure (r=0.342; p=0.052).

Conclusion: Deviations in the pedobarographic data are reflected in the power generation of the ankle joint and can be of help in decision making of treatment in spastic hemiplegic CP. We speculate that efforts to normalize the heel segment pattern may result in decreased power generation differences.

Key words: Ankle joint/physiopathology; cerebral palsy/complications; child; foot deformities; gait/physiology; hemiplegia/physiopathology; pressure; weight-bearing.

Amaç: Bu çalışmada, spastik hemiplejik beyin felçli (BF) çocuklarda ayak basınç paterninin ve ayağı ilerletme açısının ayak bileği eklemi kaynaklı güç üretimiyle ilişkisi araştırıldı.

Çalışma planı: Çalışmaya bağımsız yürüyebilen BF'li 35 çocuk (13 kız, 22 erkek; ort. yaş 8.8; dağılım 4.0-19.8) alındı. Tüm hastalarda üçboyutlu yürüme analizi ve pedobarografik ölçümler yapıldı. Pedobarografi verileri ayağı beş segmente bölerek değerlendirildi.

Sonuçlar: Ayak bileği kaynaklı ortalama güç üretimi hemiplejik tarafta 7.6 watt/kg, tutulu olmayan tarafta 15.9 watt/kg bulundu (p=0.000). Pedobarografide hemiplejik tarafta anlamlı derecede daha düşük topuk basıncı/itme gücü (8.0 ve 24.7; p=0.000), topuk kaldırma zamanı (basma fazının %32.1'i ve %61.9'u; p=0.000) ve medial önayak segmenti basıncı (40.8 ve 52.2; p=0.009) elde edildi. Hastalar hemiplejik taraftaki ayak bileğinden üretilen güce göre iki gruba ayrıldı (<8.0 watt/kg ve ≥8.0 watt/kg). Güç üretiminin daha fazla olduğu grupta, yürüme analizinde adım uzunluğu (49 cm ve 41 cm; p=0.001) ve hızı (109 cm/sn ve 89 cm/s; p=0.000) anlamlı derecede fazla idi. Aynı grupta pedobarografik verilerden topuk basıncı (11.6 ve 4.4; p=0.047) ve topuk kaldırma zamanı (%46.6 ve %17.1; p=0.000) daha fazla, varus/valgus pozisyonu (11.1 ve -34.6; p=.013) daha az bulundu. İkili korelasyon analizinde, hemiplejik tarafta ayak bileği ekleminden üretilen gücün topuk kaldırma zamanı (r=0.574; p=0.000) ve varus/valgus pozisyonu (r=0.420; p=0.017) ile anlamlı ilişki gösterdiği, topuk basıncı ile ise anlamlı düzeye çok yakın ilişkide olduğu görüldü (r=0.342; p=0.052).

Çıkarımlar: Pedobarografik verilerdeki farklılıklar ayak bileği ekleminin güç üretiminden kaynaklanmaktadır ve spastik hemiplejik BF'de tedaviye karar vermeye yardımcı olabilir. Topuk segment paternini normalleştirme girişimlerinin iki taraftaki güç üretimi arasındaki farklılıkları azaltacağını düşünüyoruz.

Anahtar sözcükler: Ayak bileği eklemi/fizyopatoloji; beyin felci/komplikasyon; çocuk; ayak deformitesi; yürüme/fizyoloji; hemipleji/fizyopatoloji; basınç; yük verme.

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In cerebral palsy (CP) foot deformity often develops over time and is one of the most common causes for treatment including orthotic and surgical intervention. The foot function influences the ankle, knee, and hip joints and therefore foot deformity and malfunction have an impact on the entire gait pattern. The deformity results in decreased stability in stance and shortened lever arm with decreased moment and decreased power generation from the triceps surae muscles.[1,2] To quantify and objectively describe gait, three-dimensional gait analysis (GA) often in combination with pedobarograph (PB) is used in children with CP. Three-dimensional gait analysis provides information on movement and forces acting over the different joints. For body propulsion, concentric muscle contraction from the ankle and hip joint can be calculated. In GA, different foot models has recently been developed and provide three-dimensional descriptions on foot positioning during the gait cycle.[1,2]

The PB, which measures the foot-floor contact pressure during walking, provides a quantitative functional assessment. An objective dynamic assessment of the foot while walking is obtained and the degree of deformity can be quantified.[3-7]

Even if GA and PB investigations are performed at the same time, they are most often assessed separately in children with CP. However, not all clinicians have access to GA and maybe the less expensive and, for the patient, easier PB assessment could provide useful information.

To our knowledge, there are few reports on comparison of data from GA and PB in children with CP. The purpose of this study was to investigate how foot pressure pattern and foot progression relate to power generation from the ankle joint in children with spastic hemiplegic CP.

Patients and Methods

Institutional Review Board approval was obtained from the Hospital's ethics committee.

The study population consisted of 35 children (13 girls, 22 boys, mean age of 8.8 years; range 4.0 to 19.8 years) with spastic hemiplegic CP.

The diagnosis of spastic hemiplegic CP is defined as unilateral neurological involvement registered on the physical examination with the typical upper and lower extremity positioning. Additionally, gait deviations found in the kinematics and kinetic data on GA defines the diagnosis. All children were fully independent community ambulators graded as Gross Motor Function Classification System level I.[8]

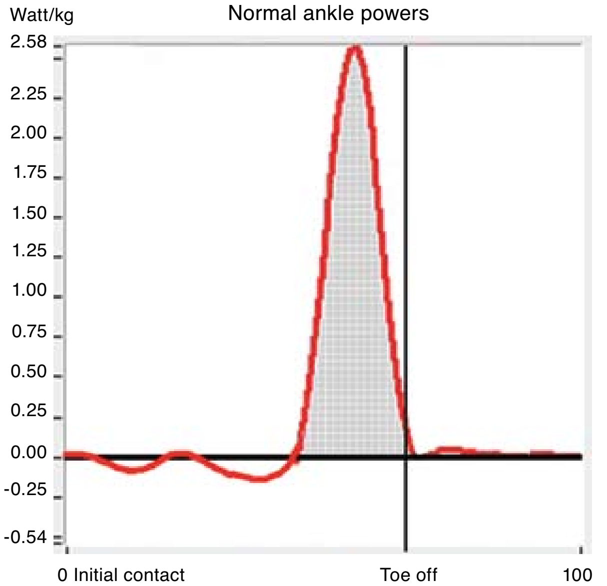
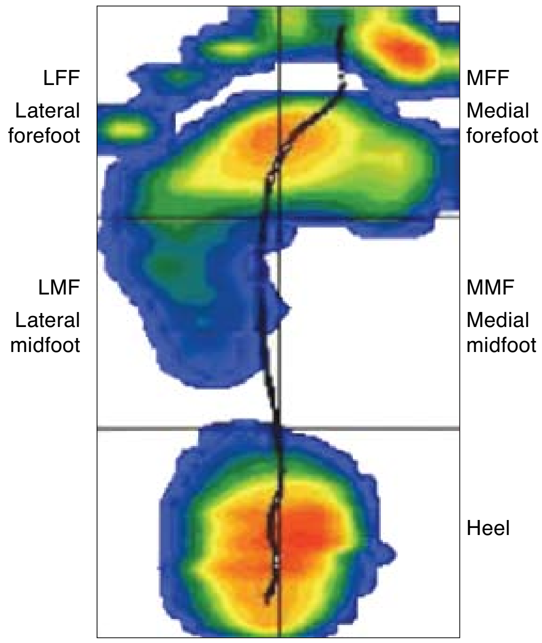


Fig. 1. Power generation / Work from the ankle joint. In three-dimensional gait analysis, the grey area represents the ankle power generation from the triceps surae muscles at late stance phase.



$$\text{Varus/valgus foot position} = \frac{(\text{MMF+MFF}) - (\text{LMF+LFF})}{(\text{MMF+MFF+LMF+LFF})}$$

Fig. 2. The pedobarograph with the five created segments and definition of varus/valgus positioning.

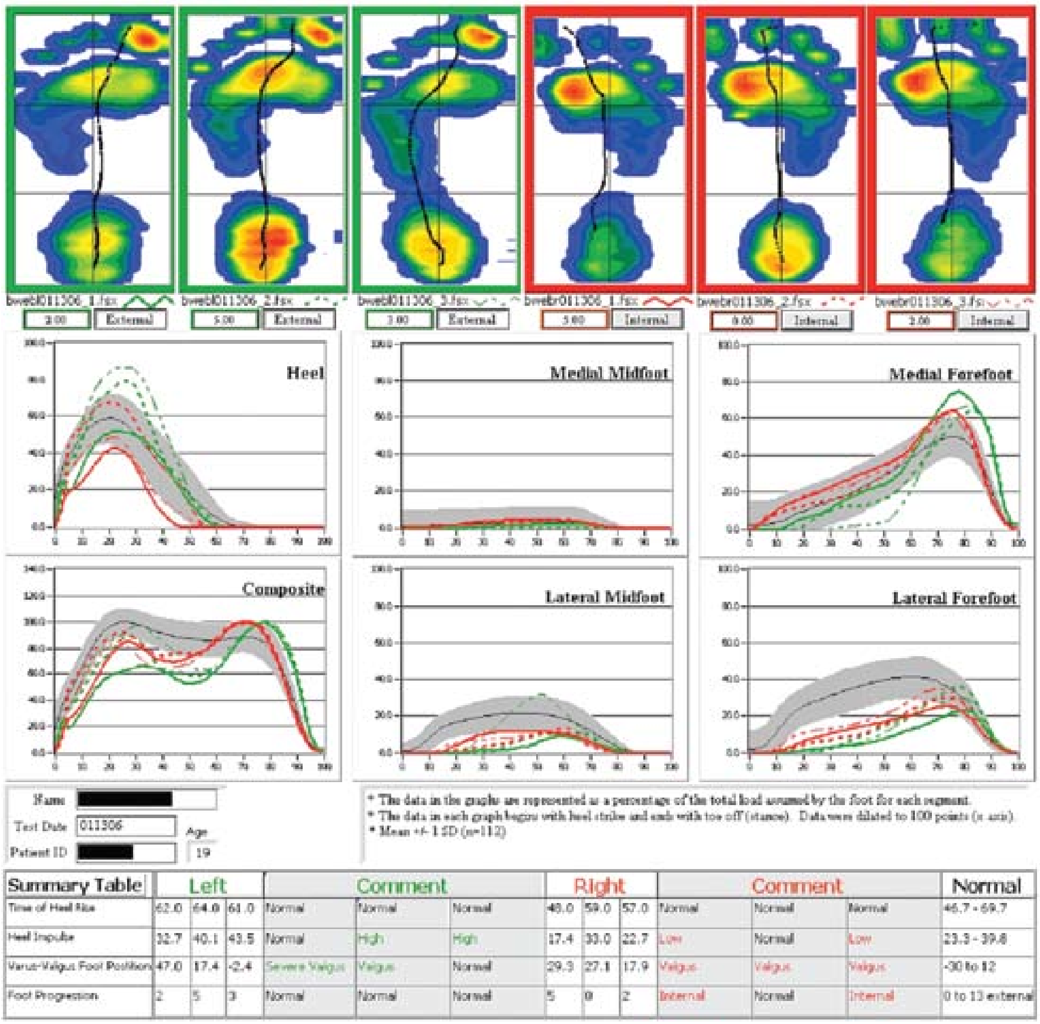


Fig. 3. Right and left pedobarograph with line of trajectory. Three trials for each foot, graphs for each foot segment and summation of data.

The medical records were reviewed and data were obtained regarding gender, age, and side of involvement.

Three-dimensional gait analysis

The indication for GA was variable, but most commonly was for the decision making before surgical intervention. Gait analysis was performed with a motion analysis video capture system and all the data were reduced using Orthotrak (Santa Rosa, California). The patients walked at a self-selected speed and the Orthotrak marker system was routinely used to collect kinematic data on the hemiplegic and uninvolved side. Kinetic data were collected using two force plates (Advanced Mechanical Technology Inc. AMTI, Watertow, MA). Generally, three trials from each foot were collected and kinetic and kinematic data were collected from the same trials. Ground reaction force vectors were collected together with kinematic data. The velocity of gait and the cadence were also recorded. Power generation is the product of angular velocity derived from the kinematic data and joint moments. The ankle power generation at late stance, which represents gastro-soleus concentric muscle contraction, was calculated as the positive area under the curve on the ankle graphs (Fig. 1).

Pedobarograph

To collect and analyze the data for PB, a Tekscan High-Resolution Pressure Assessment System (Tekscan, Inc., South Boston, MA, U.S.A) was used. The measurement method started with obtaining a visual record by making a video using a hand-held video camera with the child walking barefoot on a standard walkway. A physical measurement was then made of the child's foot length and width. The child was

Table 1. Comparison between hemiplegic and uninvolved sides

		Hemiplegic side	Uninvolved	Normal	*p*
Three-dimensional gait analysis	Ankle power generation (watt/kg)	7.6	15.9	–	0.000
	Step length (cm)	45.0	46.0	47-60	0.333
	Velocity (cm/sec)	98.0	98.0	104-141	0.983
Pedobarograph	Time of heel rise (% stance phase)	32.1	61.9	46.7-69.7	0.000
	Impulse				
	Heel	8.0	24.7	23.3-39.8	0.000
	Medial midfoot	10.4	8.1	–	0.322
	Lateral midfoot	33.4	24.0		0.066
	Medial forefoot	40.8	52.2		0.009
	Lateral forefoot	27.4	32.4		0.123
	Varus / valgus position index	-11.8	4.0	-15 to +15	0.131
	Foot progression (°)	-1.3	4.3	0 to 10 external	0.084

then instructed to walk at a self-selected speed on a pressure-sensitive floor mat (61x65 cm). No assistive devises were used. The foot pedobarograph was then rotated to a zero foot progression angle, recording the degree of rotation required. A rectangular mask with a length and width equal to the measured length and width of the child's foot was placed over the pedobarograph. The foot print was placed in the mask so that it corresponded to the visual appearance of the foot. This means that if the child was a high toe-walker with most weight appearing to be on the medial side of the foot, the foot print would be positioned on the anterior medial aspect of the mask.

The pedobarographs were analyzed by dividing the foot into five segments starting with the heel segment (posterior third), the midfoot (middle third), and forefoot (anterior third). The midfoot and forefoot was divided into symmetrical medial and lateral segments yielding medial midfoot (MMF), medial forefoot (MFF), lateral midfoot (LMF), and lateral forefoot (LFF). The pressure/time integral was normalized with the body weight and foot size, and the impulse, total pressure during one step, of each segment was calculated. By adding the two medial segments of the foot and subtracting the two lateral segments, the result was divided into the whole forefoot and midfoot impulse to create an index. This index defines a measure of varus/valgus foot positioning, defined as the relative medial-lateral difference of combined mid and forefoot impulse (Fig. 2).

Three footprints from each foot were collected and the pressure distribution was also calculated and plotted on graphs for each segment (Fig. 3).

To better assess the difference in function and degree of involvement, we classified the patients according to the Winter classification.[9] The criteria used for Winter classification are based on sagittal plane kinematics from the gait analysis. In group 1 and 2 there is only involvement in the ankle joint, and in group 3 additional involvement in the knee, and in group 4 also of the hip joint.

Statistical analysis

Comparisons between the hemiplegic and uninvolved sides and between the two groups were made with the independent samples t-test and paired t-test using SPSS version 12.0 (SPSS, 2004, Chicago, Illinois). Bivariate correlations between GA and PB variables were sought. A P value of ≤0.05 was considered significant.

The Gait Laboratory's database of 54 normal subjects (108 feet) consisting of children and young adults were used as reference.

Results

First we compared all the patients regarding differences between the hemiplegic and uninvolved side (Table 1). From the GA, power generation from the ankle was collected together with step length and velocity. From the PB, the impulse from the different foot segments were collected together with time to heel rise and foot progression. The varus/valgus foot positioning was also calculated. The mean power generation from the ankle was 7.6 watt/kg on the hemiplegic side, and 15.9 watt/kg on the uninvolved side (p=0.000). The pedobarograph data re-

Table 2. The two groups of patients regarding power, number, age, and classification according to the Winter criteria

Group	n	Mean age and range	Power generation (Hemiplegic side)	Winter classification			
				1	2	3	4
1	17	8.1 (4.3-15.7)	0.0-7.0 W	7	3	1	6
2	18	9.4 (4.0-19.8)	8.0-20.3 W	11	4	3	–

vealed significantly less heel pressure/impulse on the hemiplegic side (8.0 *vs*. 24.7; (p=0.000). Time to heel rise differed as well, being 32.1% of stance phase in hemiplegic feet compared to 61.9% of stance phase in normal feet (p=0.000). The MFF segment on the hemiplegic side had less pressure, compared to the uninvolved side (40.8 *vs*. 52.2; p=0.009).

Secondly, the children were divided into two groups depending on their ability to generate power from the ankle joint on the hemiplegic side during gait (Table 2). Group 1 consisted of those with a fairly low power generation which was set to be less than 8.0 watt/kg, and group 2 included those with ≥8.0 watt/kg. The groups were comparable in number and age. They were also classified according to the Winter criteria as previously described.

The results from the second analysis revealed that group 2 had significantly longer step length (49 cm vs. 41 cm) and velocity (109 cm/sec vs. 89 cm/sec). In the pedobarograph data, heel impulse was 4.4 in group 1 compared to 11.6 in group 2 (p=0.047). Time to heel rise was 17.1% in group 1 and 46.6% in group 2 (p=0.000). Finally, varus/valgus positioning was -34.6 in group 1 (reference -15 to +15) and 11.1 in group 2 (p=0.013) (Table 3).

In bivariate correlation analysis, ankle power generation on the hemiplegic side demonstrated a significant association with time to heel rise (r=0.574; p=0.000) and varus/valgus positioning (r=0.420; p=0.017), and almost a significant association with heel pressure/impulse (r=0.342; p=0.052).

Discussion

In the management of foot deformities in children with CP, pedobarograph measurements have proved reliable and useful to assess surgical outcome after treatment for valgus deformity as well as other foot deformities. The functional and quantitative assessment is reliable, fairly inexpensive, and accessible. The investigation and analysis are quick and the data analysis and interpretation straightforward. The pedobarograph describe foot deformity and the analysis is ideal as an outcome tool in many ways.[10-14]

Power generation from concentric muscle contraction together with momentum determines the propulsive forces of the body. The power generation calculation is made from three-dimensional GA and often used in children with CP. Power generation is also partly a good outcome variable since it describes a summation of functions. The moment the foot is

Table 3. Comparison of two groups of hemiplegic patients with ankle power generation <8 watt/kg and ≥8 watt/kg

		Group 1 (<8.0 watt/kg) (n=17)	Group 2 (≥8.0 watt/kg) (n=18)	*p*
Three-dimensional gait analysis	Ankle power generation (watt/kg)	4.1	10.9	0.000
	Step length (cm)	41.0	49.0	0.001
	Velocity (cm/sec)	89.0	109.0	0.000
Pedobarograph	Time of heel rise (% stance phase)	17.1	46.6	0.000
	Impulse			
	Heel	4.4	11.6	0.047
	Medial midfoot	8.0	12.7	0.233
	Lateral midfoot	41.1	26.2	0.120
	Medial forefoot	35.2	46.1	0.142
	Lateral forefoot	31.7	23.4	0.109
	Varus / valgus position index	-34.6	11.1	0.013
	Foot progression (°)	-7.9	5.0	0.067

able to provide its positioning and stability plays a role. The motor control and balance that direct the velocity of joint movements are also of importance. Additionally, the degree of spasticity and balance contributes to the composed momentum and power generation.[2,15-17]

Our results show, not surprisingly, the differences between the hemiplegic and uninvolved side in power generation and PB results. Interestingly, the PB with the assessment of time to heel rise and heel impulse as well as varus/valgus positioning shows significant differences between the groups with high and low ankle power generation. Additionally, significant correlations between these variables were found.

From the results of this study we speculate that, by directing treatment towards normalizing heel segment pattern with the use of PB, one can expect power generation differences to decrease. Normalizing PB pattern in the heel segment includes treatment to increase step length. In relatively high functioning children with CP with a fair velocity, a good length of a step is reflected by good extension in the knee joint in late swing phase. A normal or close to normal step length results often with heel strike. Heel strikes at initial contact probably results in spasticity of the ankle joint in the individual with CP. If early spasticity can be avoided in stance phase, there are better possibilities for good power generation from the ankle joint in later stance phase. Ankle equinus and varus/valgus positioning expressing foot deformity must also be considered and our assumption is that treatment results in better function. Presumably a more normal looking foot works better than a deformed.

Another consideration is coping responses that the patient may have developed, which are often difficult to identify. An example would be the well-known fact that patients with hemiplegic CP have a tendency to retract the affected side's pelvis. This probably has to do with increased inward rotation that is present in the hip joint. By retracting the pelvis, the knee, and ankle joint, the foot is directed in a more forward direction than otherwise. The uninvolved side is better controlled and the individual can easily compensate for the rotation on this side, by externally rotating the hip to a certain degree. This phenomenon, also defined as hip involvement in the sagittal plane, not only seems to be present in the Winter classification group 4, but also in the other groups. This could be one explanation why the foot progression angle did not reveal a greater difference comparing the hemiplegic and uninvolved side. Another coping response in patients with spastic hemiplegic CP seems to be the shift of power generation from the ankle joint on both sides to the hip joint. This could influence the correlations with the pedobarograph results.[18]

This was a retrospective study with a small number of patients. The indication for the assessments with GA and PB were different and previous treatments including surgical were not accounted for. However, in spastic hemiplegic CP patients, a unique chance to compare the hemiplegic and uninvolved sides is possible. Probably one should be aware of the possibly not totally normal "non-involved side" and also be considering coping responses to be present on both sides, as to manage the primary movement impairment the static brain injury causes.

Conclusion

Deviations in the pedobarograph data are reflected in the power generation of the ankle joint and can be of help in decision making of treatment in spastic hemiplegic CP. We believe that reliable and useful information can be gained from both the three-dimensional GA and PB in children with CP. To some extent, the two different investigations provide similar or at least related information on foot deformity and function. The pedobarograph, being an easier and less expensive assessment tool, can be used monitoring foot deformity and follow progress over time.

Conflict of interest statement

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