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By Benjamin M. Rogozinski, DPT, Jon R. Davids, MD, Roy B. Davis III, PhD, Gene G. Jameson, MA, and Dawn W. Blackhurst, DrPH

Investigation performed at Shriners Hospitals for Children, Greenville, South Carolina

Background: The floor-reaction ankle-foot orthosis is commonly prescribed for children with cerebral palsy who walk with excessive ankle dorsiflexion and excessive knee flexion during the stance phase of gait. The purposes of this study were to evaluate the efficacy of this orthosis objectively and to identify clinical parameters that may compromise its function.

Methods: All children with cerebral palsy who had comprehensive gait analyses in both barefoot and braced walking conditions during a single visit to our Motion Analysis Laboratory between January 2001 and August 2007 were identified. Kinematic study parameters included mean sagittal dynamic range of motion of the ankle in stance, peak ankle dorsiflexion in stance, peak knee extension in midstance, and mean foot progression angle in stance. The minimum sagittal knee moment in midstance was also examined in this study for subjects who walked without assistive devices. Range-of-motion and skeletal alignment data obtained from the physical examination record of each subject included knee flexion contracture, popliteal angle, hip flexion contracture, and thigh-foot angle.

Results: Twenty-seven children had quantitative gait analyses (barefoot and with the orthoses in the same visit). The mean sagittal plane dynamic range of motion of the ankle in stance was reduced from 23° ± 9° when walking barefoot to 10° ± 3° when the orthosis was worn ($p < 0.001$), and the mean peak knee extension in midstance improved from 29° ± 14° of flexion to 18° ± 14° of flexion ($p = 0.013$). Strong negative linear correlations were found between the magnitude of knee and hip flexion contractures on physical examination and the amount of peak knee extension in midstance ($r = -0.784$ and $r = -0.705$, respectively). A strong positive correlation was found between the mean minimum sagittal knee moment in midstance and the amount of peak knee extension in midstance ($r = 0.820$). Our investigation did not provide evidence of a correlation between peak knee extension in midstance and any of the following parameters in the orthosis: clinical examination measurements of the thigh-foot angle ($r = 0.120$), the popliteal angle ($r = -0.300$), or the mean foot progression angle in the stance phase of gait ($r = -0.188$).

Conclusions: The floor-reaction ankle-foot orthosis is effective in restricting sagittal plane ankle motion during the stance phase of gait in patients with cerebral palsy. As a result, improvements in knee extension and the sagittal plane knee extensor moment in stance phase are achieved. The best outcomes with this orthosis, as determined by peak knee extension in midstance, were seen in the subjects with knee and hip flexion contracture of ≤10°. Knee and hip flexion contractures of ≥15° were found to limit the efficacy of the orthosis in controlling knee extension in midstance. Such contractures should be considered as contraindications to the prescription of this orthosis or should be addressed (surgically or otherwise) prior to the application of a floor-reaction ankle-foot orthosis in these patients.

Level of Evidence: Therapeutic Level III. See Instructions to Authors for a complete description of levels of evidence.

Cerebral palsy is a common neurological disorder characterized by an injury to the immature brain that results in variable neuromuscular and cognitive impairments[1]. Cerebral palsy is not a single specific disease process, but rather a clinical condition with multiple possible etiologies. Neuromuscular impairments such as spasticity, diminished motor control, and impaired proprioception may compromise gait function. As such, children with cerebral palsy often use ankle-

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foot orthoses to facilitate and optimize their ability to walk. The selection of the proper orthotic design should be based on an understanding of the primary gait deviations of the patient[2]. The floor-reaction ankle-foot orthosis is one type of ankle-foot orthosis that is commonly prescribed for children with cerebral palsy. The floor-reaction ankle-foot orthosis is both a stance and swing phase control orthosis designed to provide increased resistance to both ankle dorsiflexion and plantar flexion[2]. The floor-reaction ankle-foot orthosis has trim lines that incorporate the malleoli and extend up and anterior to the proximal third of the shank segment to provide control of the foot and ankle and constrain ankle dorsiflexion during the second rocker component of gait (Fig. 1). The floor-reaction ankle-foot orthosis is thought to be effective by limiting ankle dorsiflexion and reducing knee flexion in stance by controlling the amount of tibial advancement over the foot during this second rocker (Fig. 2). This improved ankle and knee position is thought to reduce the elevated internal knee extensor moment in stance commonly associated with crouch gait, thereby reducing the activation of the quadriceps muscle required to stabilize the knee during stance[2]. At our institution, this brace design is used in the management of children with cerebral palsy who walk in a crouch pattern, characterized by excessive ankle dorsiflexion and excessive knee flexion during stance phase[2,3]. We utilize the floor-reaction ankle-foot orthosis in the slightly older and/or larger child in whom it is thought that a typical solid ankle-foot orthosis may not provide sufficient lower-limb support during second rocker. Although it is fabricated from the same plastic as a solid ankle-foot orthosis, the floor-reaction ankle-foot orthosis is more structurally rigid because of increased plastic thickness, more extreme anterior trim lines, and in some cases embedded carbon fiber composite reinforcement. It is standard practice for our orthotists to set the floor-reaction ankle-foot orthosis in a neutral position with respect to ankle angle (i.e., the tibia perpendicular to the plantar surface of the foot). In some cases, however, the braces are set in a slight amount of dorsiflexion to accommodate knee flexion contractures.

To our knowledge, only one article in the literature has evaluated the effectiveness of the floor-reaction ankle-foot orthosis in children with cerebral palsy[4]. That article includes a single case report of an eleven-year-old boy with cerebral palsy who underwent quantitative gait analyses while walking barefoot and wearing bilateral floor-reaction ankle-foot orthoses. The authors concluded that the floor-reaction ankle-foot orthosis improved the gait pattern (as demonstrated by improved stride length and gait velocity) primarily by preventing excessive ankle dorsiflexion, thus maintaining the location of the ground reaction force vector anterior to the knee joint center and creating an external knee extensor moment[4]. They identified five prerequisites for the appropriate application for the floor-reaction ankle-foot orthosis, including the absence of flexion contractures at the knee and hip of >10°. However, since that time, there has been limited objective, quantitative research examining the effects of the floor-reaction ankle-foot orthosis on walking in children with cerebral palsy.

Fig. 1
Photographs of the floor-reaction ankle-foot orthosis.

Contraindications to the use of the floor-reaction ankle-foot orthosis, such as knee and hip contractures, and transverse plane malalignments, such as excessive external tibial torsion, have been anecdotally reported[2]. The purposes of the current study were to evaluate objectively the efficacy of the floor-reaction ankle-foot orthosis in children with cerebral palsy and to identify clinical parameters that have the potential to compromise the function of the orthosis.

Materials and Methods

The study design was a retrospective, consecutive case series, which was reviewed and approved by our Institutional Research Review Committee. Twenty-seven patients with cerebral palsy between the ages of seven and sixteen years who had comprehensive gait analyses performed while walking both barefoot and with use of floor-reaction ankle-foot orthoses during a single visit to the Motion Analysis Laboratory in our institution between January 2001 and August 2007 were identified. This subject group represents all patients evaluated in our outpatient clinic who were prescribed a floor-reaction ankle-foot orthosis because of a crouch gait and subsequently were referred for (1) preoperative evaluation, (2) postoperative follow-up, or (3) assessment of the efficacy of the ankle-foot orthosis. It is important to note that these patients arrived in the Motion Analysis Laboratory with their orthoses. These patients were examined and tested in both walking conditions on the same day in one session. No subject was fitted with floor-reaction ankle-foot orthoses for the purpose of this study. The original records associated with the motion study for each child were reviewed to determine the age, sex, physical geographic classification of the cerebral palsy (hemiplegia, diplegia, triplegia, or quadriplegia), and functional level as

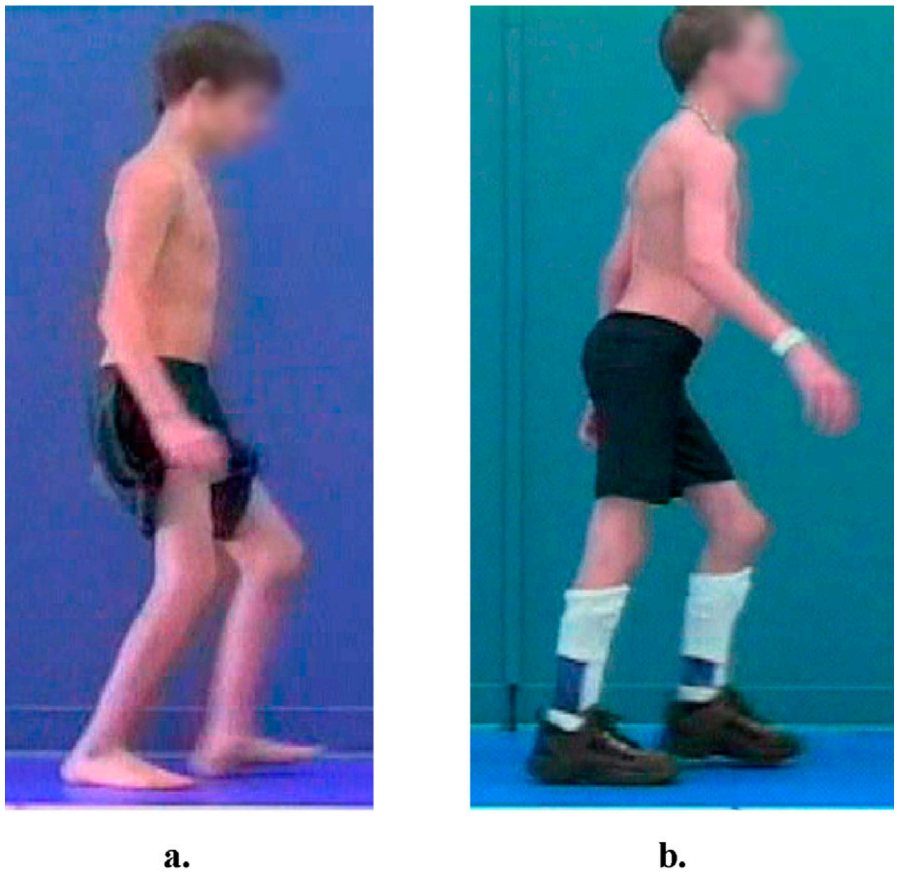

Fig. 2

A child with cerebral palsy walking barefoot and with floor-reaction ankle-foot orthoses. The excessive ankle dorsiflexion when the child walked barefoot (a) is reduced with the floor-reaction ankle-foot orthosis. As a result, knee extension in stance is improved and a correction of the crouch gait pattern can be appreciated (b).

determined by the Gross Motor Function Classification System[5] (Table I). The range-of-motion and skeletal alignment data obtained from the Motion Analysis Laboratory physical examination record for each child included knee flexion contracture (indicative of non-hamstring-related limitation of knee extension), the 90°/90° popliteal angle measure (indicative of hamstring-related limitation of knee extension), hip flexion contracture (due to all periarticular soft tissues), and thigh-foot angle (indicative of the skeletal alignment of the tibia and foot in the transverse plane) (see Appendix). All goniometric measurements were made with use of the Shriners Hospitals Motion Analysis Laboratory Network standard clinical examination protocol with measures recorded to the nearest 5° increment[6,7].

Bilateral three-dimensional kinematic and kinetic data were collected by using a twelve-camera motion measurement system (VICON 512; Oxford Metrics Group, Oxford, England) and two force platforms (Advanced Mechanical Technology, Watertown, Massachusetts). Subjects were instrumented with passive reflective markers consistent with the Newington model for gait analysis[8]. Subjects made several passes through the laboratory measurement volume walking at a self-selected speed in the barefoot and the braced condition. A standing subject calibration trial was collected prior to gait analysis in both barefoot and braced conditions. The purpose of this calibration trial was to establish the relationship between the external markers and the underlying anatomical references, e.g., the plantar surface of the foot and the long axis of the tibia. In this way, the same anatomical references were used in both barefoot and braced testing conditions, and measurement artifact associated with shoe and/or brace wear was minimized.

Gait kinematic parameters examined in this study included mean sagittal dynamic range of motion of the ankle in stance, peak ankle dorsiflexion in stance, peak knee extension in midstance, and mean foot progression angle in stance. The minimum sagittal knee moment in midstance was also examined in subjects who walked without assistive devices. Time-distance parameters including speed (meters per second), stride length (meters), and cadence (steps per minute) were also analyzed. An adequate kinematic outcome when walking with the floor-reaction ankle-foot orthosis was defined

TABLE I Changes Between the Barefoot and Brace Conditions

Variable	Barefoot*	Floor-Reaction Ankle-Foot Orthosis*	P Value
Speed *(m/s)*	0.72 ± 0.25	0.83 ± 0.19	0.070
Stride length *(m)*	0.84 ± 0.19	1.00 ± 0.17	0.002‡
Cadence *(steps/min)*	50.9 ± 12.6	49.8 ± 8.9	0.711
Sagittal ankle dynamic range of motion in stance	23° ± 9.1°	10° ± 3.3°	<0.001‡
Peak ankle dorsiflexion in stance	27° ± 8.1°	11° ± 6.0°	<0.001‡
Peak knee extension in stance	29° ± 14.3°	18° ± 14.4°	0.013‡
Minimum sagittal knee moment in midstance *(Nm/kg)*	0.2 ± 0.3	−0.1 ± 0.3	0.072

*The values are given as the mean and the standard deviation. †P values are from repeated-measures analysis of variance. ‡The difference was significant ($p < 0.05$).

as achieving peak knee flexion in midstance of ≤20°, on the basis of previous kinetic analyses of crouch gait pattern in children with cerebral palsy[9,10].

Statistical Analysis

We initially assessed the correlation between left and right sides within the twenty-seven subjects. This analysis confirmed that there were strong linear correlations ($r > 0.7$) within subjects for six of the seven parameters examined. Thus, in order to account for this, repeated-measures analysis of variance was used to test for mean differences between ankle-foot orthosis and barefoot trials within subjects. All other analyses were performed with use of the subject as the unit of measurement with the average of right and left side within the subject. Outcomes were reported as the mean and standard deviation. Linear correlations between variables in bivariate analyses were assessed with use of the Pearson correlation coefficient (r value). Multiple linear regression analysis was used to assess possible predictive factors for peak knee extension in midstance; maximum R^2 improvement was used as the criterion for "best" model identification. P values were assessed at alpha = 0.05, and they were not adjusted for multiple hypothesis testing[11].

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Results

Twenty-seven children had quantitative gait analyses in both barefoot and braced walking conditions during a single laboratory visit, resulting in data on fifty-four total

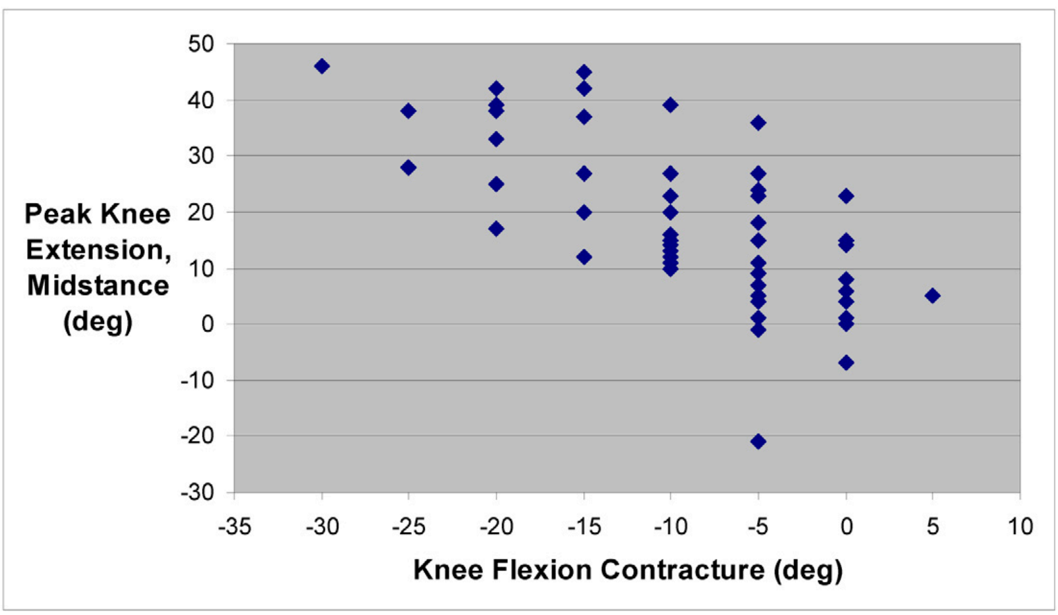

Fig. 3

Knee flexion contracture versus peak knee extension in midstance.

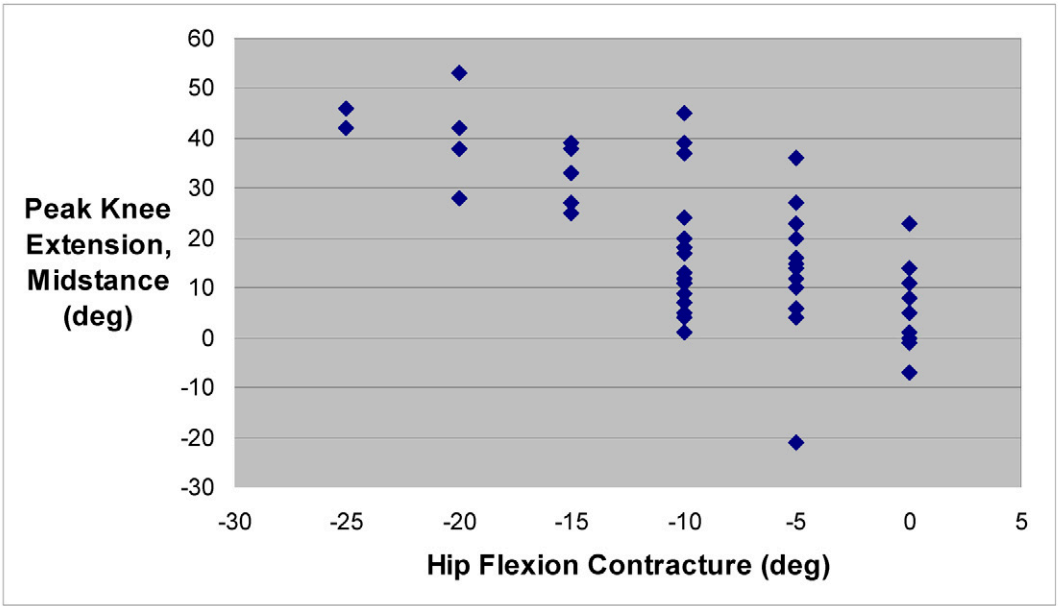

Fig. 4
Hip flexion contracture versus peak knee extension in midstance.

limbs. There were nineteen boys and eight girls in the study group with a mean age (and standard deviation) of 12.4 ± 2.4 years. With respect to physical geographic classification of cerebral palsy, twenty-four subjects were classified as diplegic; one subject, as triplegic; and two subjects, as quadriplegic. Of the twenty-seven subjects, fourteen were classified as level II, according to the Gross Motor Function Classification System, and thirteen were classified as level III, resulting in twenty-six trials (48%) performed with some form of assistive device. More complete details on the demographic data, clinical examination measures, and surgical history of the cohort can be found in the Appendix.

Changes between the barefoot and brace testing conditions for each variable are presented in Table I, and tables with complete subject-specific kinematic and kinetic data are available in the Appendix. Improvements were noted with respect to walking speed and stride length when the floor-reaction ankle-foot orthosis was worn, with the difference in stride length reaching significance ($p < 0.002$). At the ankle, peak dorsiflexion in stance was reduced from 27° ± 8° to 11° ± 6° ($p < 0.001$) when the floor-reaction ankle-foot orthosis was worn. The mean sagittal plane dynamic range of motion of the ankle in stance improved from 23° ± 9° when walking barefoot to 10° ± 3° with the floor-reaction ankle-foot orthosis ($p < 0.001$). The mean peak knee extension in midstance improved from 29° ± 14° of flexion when walking barefoot to 18° ± 14° of flexion when the floor-reaction ankle-foot orthosis was worn ($p = 0.013$). Although fourteen subjects were able to walk independently, sagittal plane knee kinetics were obtained from only nine subjects (eighteen extremities) because of the inability to collect adequate force platform data from five subjects associated with poor or reduced stride length and/or foot swing-phase clearance issues. The mean minimum sagittal knee moment in midstance improved from an internal knee extensor moment of 0.2 ± 0.3 Nm/kg to an internal knee flexor moment of −0.1 ± 0.3 Nm/kg ($p = 0.072$).

A strong negative correlation was found between the magnitude of knee flexion contracture on physical examination and the amount of peak knee extension in midstance ($r = -0.784$) (Fig. 3). The thirty-eight extremities that had a knee flexion contracture of ≤10° on physical examination had a mean peak knee extension in midstance of 12° ± 11° in the floor-reaction ankle-foot orthosis. Twenty-nine (76%) of the thirty-eight extremities achieved adequate knee extension in midstance (defined as knee flexion of ≤20°) with the floor-reaction ankle-foot orthosis. The sixteen extremities that had knee flexion contractures of ≥15° on physical examination had a mean peak knee extension in midstance of 34° ± 11° of flexion in the floor-reaction ankle-foot orthosis. Only three of these sixteen extremities achieved adequate knee extension in midstance (flexion of ≤20°) with the floor-reaction ankle-foot orthosis.

A strong negative correlation was also found between the magnitude of hip flexion contracture on the physical examination and the amount of peak knee extension in midstance ($r = -0.705$) (Fig. 4). The forty-two extremities that had a hip flexion contracture of ≤10° on physical examination had a mean peak knee extension in midstance of 13° ± 12° in the floor-reaction ankle-foot orthosis. Thirty-three (79%) of the forty-two trials achieved adequate midstance knee extension (flexion of ≤20°) with the floor-reaction ankle-foot orthosis. The twelve extremities that had a hip flexion contracture of ≥15° on physical examination had a mean peak knee extension in midstance of 37° ± 9° of flexion in the floor-reaction ankle-foot orthosis. None of these extremities achieved adequate

TABLE II Multiple Linear Regression Analysis with Use of the Maximum R^2 Improvement Method for Choosing the Best Model

	P Value	R^2*	Conclusion
Barefoot variables			
One-variable model		0.6153	Best model
Knee flexion contracture	<0.001†		
Two-variable model		0.6212	Hip adds no additional information
Knee flexion contracture	0.0097†		
Hip flexion contracture	0.5475		
Three-variable model		0.6216	Knee × hip adds no additional information
Knee flexion contracture	0.0847		
Hip flexion contracture	0.6453		
Knee × hip interaction	0.8839		
Floor-reaction ankle-foot orthosis variables			
One-variable model		0.3578	Best model
Knee flexion contracture	0.001†		
Two-variable model		0.3592	Knee × hip adds no additional information
Knee flexion contracture	0.124		
Knee × hip interaction	0.819		
Three-variable model		0.3624	Hip adds no additional information
Knee flexion contracture	0.156		
Hip flexion contracture	0.739		
Knee × hip interaction	0.726		

*R^2 is the amount of variation explained in peak knee extension by the predictive variable. †The difference was significant.

knee extension in midstance (flexion of ≤20°) with the floor-reaction ankle-foot orthosis.

A strongly positive correlation was found between the mean minimum sagittal knee moment in midstance and the amount of peak knee extension in midstance (r = 0.820). Of the eighteen extremities with kinetic data, twelve achieved adequate midstance knee extension (flexion of ≤20°) with the floor-reaction ankle-foot orthosis. The mean peak knee extension in midstance for this group was 7° ± 11°. This group achieved a mean minimum internal knee flexor moment in midstance of −0.2 ± 0.2 Nm/kg. The mean knee flexion contracture for this group was 6° ± 5°. Six extremities had peak knee extension in midstance of >20° of flexion. The mean peak knee extension in midstance for this group was 32° ± 6° of flexion. This group demonstrated a mean minimum internal knee extensor moment in midstance of 0.2 ± 0.3 Nm/kg. The mean knee flexion contracture for this group was 16° ± 6°.

The data did not demonstrate evidence of linear relationships between the physical examination measure of the thigh-foot angle (mean external thigh-foot angle, 11° ± 12°; r = 0.120) or the mean foot progression angle in stance during gait (mean external foot progression angle, 10° ± 16°; r = −0.188) and the peak knee extension in midstance with the floor-reaction ankle-foot orthosis. Similarly, the physical examination measure of the popliteal angle (mean, −45° ± 13°) failed to demonstrate evidence of a correlation with peak knee extension in midstance with the floor-reaction ankle-foot orthosis (r = −0.300). The factors that demonstrated the greatest evidence of a linear relationship with peak knee extension (knee and hip flexion contractures) were then examined in multiple linear regression analysis with use of the maximum R^2 improvement method for choosing the best model. Knee flexion contracture was the only significant predictor of peak knee extension in midstance in both the barefoot and braced walking conditions (Table II).

The twenty-seven subjects were also divided into two groups on the basis of the magnitude of their knee and hip contractures as documented on physical examination. The first group had sixteen subjects in which both extremities had knee and hip flexion contractures of ≤10°. This group had a mean peak knee extension in midstance of 23° ± 15° in the barefoot condition. This significantly improved to 10° ± 9° when the floor-reaction ankle-foot orthosis was worn (p = 0.008). In this group, twenty-seven (84%) of the thirty-two extremities achieved peak knee extension in midstance of ≤20°. Eight of the thirty-two extremities achieved values that were within one standard deviation of our established laboratory reference norms with respect to peak knee extension in midstance (≤5°) and peak ankle dorsiflexion in stance (≤14°) when the floor-reaction ankle-foot orthosis was worn. All eight of these extremities had knee flexion contractures of ≤5° and hip contractures of ≤10°. A second group of eleven subjects had at least one limb with knee and hip flexion contractures of ≥15°. This group had a mean peak knee extension in midstance of 37° ± 9°

of flexion when walking barefoot. This improved slightly to 30° ± 12° when the floor-reaction ankle-foot orthosis was worn ($p = 0.153$). In this group, only six of the twenty-two extremities achieved ≤20° of peak knee extension in midstance. However, because only one limb was required to have knee and hip flexion contractures of ≥15° to be included in this second group, three of the six limbs that achieved peak knee extension in midstance of ≤20° had knee and hip flexion contractures of ≤10°.

Discussion

The primary goal of the current investigation was to evaluate quantitatively the efficacy of the floor-reaction ankle-foot orthosis in children with cerebral palsy. Compared with the barefoot condition, the results when the children wore the floor-reaction ankle-foot orthosis showed significant improvements in sagittal ankle and knee kinematics and stride-temporal parameters. Time-distance parameters improved with the floor-reaction ankle-foot orthosis, demonstrating an increase in both walking speed and stride length, a finding similar to prior investigations of other ankle-foot orthosis designs[12-15]. The floor-reaction ankle-foot orthosis was effective in providing a more neutral position for the ankle and limiting the amount of sagittal plane dynamic motion at the ankle in stance during gait. Constrained ankle dorsiflexion in the second rocker phase of gait controls tibial advancement over the foot and yields significant improvement in knee extension during midstance with an associated improvement in the sagittal plane knee extensor moment when the floor-reaction ankle-foot orthosis is worn.

The second goal of the investigation was to identify clinical examination parameters that have the potential to compromise the efficacy of the floor-reaction ankle-foot orthosis. It is widely presumed that knee and hip flexion contractures are contraindications for the use of the floor-reaction ankle-foot orthosis[2,4]. Our results substantiate these clinical assumptions with evidence of strong negative linear correlations between the magnitudes of knee and hip flexion contractures as measured on the physical examination and the amount of peak knee extension achieved during midstance when walking with the floor-reaction ankle-foot orthosis. The data demonstrate that extremities with knee and hip flexion contractures of ≤10° had significantly better peak knee extension in midstance with the floor-reaction ankle-foot orthosis than the extremities with knee and hip flexion contractures of ≥15°. In addition, approximately 84% of the group with knee and hip flexion contractures of ≤10° demonstrated peak knee extension in midstance of ≤20°. The kinetic analysis suggests that this degree of midstance knee extension is required to effectively "offload" the knee, as indicated by the presence of an internal knee flexor moment when the floor-reaction ankle-foot orthosis is worn. Previous kinetic analyses of subjects walking in crouch gait have shown increased internal knee extension moments throughout stance phase[10]. It is believed that this persistently elevated extensor moment may lead to patellofemoral overload because of the increased effort required of the knee extensors to stabilize the knee during the single support phase of gait[9,10]. These results indicate that the floor-reaction ankle-foot orthosis is effective in improving knee extension and reducing the internal knee extensor moment in midstance. As a result, less effort is required of the knee extensors to stabilize the knee, leading to a more efficient and sustainable gait pattern with less potential for excessive patellofemoral overload.

It is a common clinical assumption that proper lower-limb segmental alignment in the transverse plane (i.e., the foot is not excessively rotated, either externally or internally, relative to the knee flexion-extension axis) is required for the internal plantar flexor moment to most effectively facilitate knee extension in single support[2,16]. Transverse plane skeletal malalignments, such as excessive external tibial torsion, and foot segmental malalignments, such as equinoplanovalgus deformities, may contribute to an increased external foot progression angle. This external foot position can move the line of action of the ground reaction force lateral to the knee joint center and also can reduce the moment arm of the ground reaction force about the knee flexion-extension axis, resulting in lever arm deficiency[1]. Recent studies utilizing dynamic computer models of the musculoskeletal system have demonstrated that increased external tibial torsion impedes the capacity of the soleus to extend the knee during stance, which supports the hypothesis of lever arm dysfunction as an important contributor to crouch gait[17,18]. The clinical decision-making response has been to address transverse plane skeletal deformities surgically to reestablish normal skeletal alignment prior to the application of the orthosis[16]. However, our investigation did not provide evidence of a linear relationship between the clinical examination measure of the thigh-foot angle (a composite measure of tibial torsion and foot segmental alignment) or the foot progression angle in the stance phase of gait (influenced by tibial torsion, foot segmental alignment, or hip and pelvic rotation) and the magnitude of peak knee extension in midstance achieved in either the barefoot or the floor-reaction ankle-foot orthosis condition. These results suggest that aggressive surgical correction of transverse plane skeletal deformities to address mild to moderate external thigh-foot or foot-progression angles may not be necessary in children with cerebral palsy who use a floor-reaction ankle-foot orthosis. However, one limitation of the study is that none of the subjects had a thigh-foot angle of >30°, or a tibial torsion measurement of >50°, and only three had foot progression angles in stance of >35°. We therefore cannot speak to the possible effects that more extreme malrotations may have on knee extension. It is evident from our analysis, however, that sagittal plane limitations of motion, particularly knee and hip flexion contractures, are the more important predictors of efficacy of the floor-reaction ankle-foot orthosis. Further investigation correlating musculoskeletal modeling and actual clinical outcomes is clearly warranted.

In summary, this study illustrates the benefits of the use of floor-reaction ankle-foot orthoses in children with spastic cerebral palsy who exhibit excessive ankle dorsiflexion and associated knee flexion during stance phase. Compared with the barefoot condition, children wearing a floor-reaction ankle-foot orthosis showed significant improvements in sagittal ankle kinematics, sagittal knee kinematics, and stride length. The floor-reaction ankle-foot orthosis was effective in restricting sagittal plane ankle motion during stance phase. As a result, improvements in knee extension and the sagittal plane knee extensor moment in stance phase were achieved. Our investigation did not provide evidence of a correlation between the clinical examination measure of thigh-foot angle or the foot progression angle in the stance phase of gait and the magnitude of peak knee extension in midstance achieved in either the barefoot or the braced condition. The best outcomes with the floor-reaction ankle-foot orthosis, as determined by peak knee extension in midstance, were seen in the subjects with knee and hip flexion contractures of ≤10°. Knee and hip flexion contractures of ≥15° were found to limit the efficacy of the floor-reaction ankle-foot orthosis in controlling knee extension in midstance. Such contractures should be considered as contraindications to the prescription of this orthosis or should be addressed (surgically or otherwise) prior to the application of a floor-reaction ankle-foot orthosis.

Appendix

eA Tables showing the details of the gait analysis in all study subjects are available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD/DVD (call our subscription department, at 781-449-9780, to order the CD or DVD). ■

Benjamin M. Rogozinski, DPT
Jon R. Davids, MD
Roy B. Davis III, PhD
Gene G. Jameson, MA
Shriners Hospitals for Children,
950 West Faris Road, Greenville, SC 29605.
E-mail address for J.R. Davids: jdavids@shrinenet.org

Dawn W. Blackhurst, DrPH
Quality Management Department,
Greenville Hospital System, University Medical Center,
701 Grove Road, Greenville, SC 29605

References

1. Gage JR. Gait analysis in cerebral palsy. London: Mac Keith Press; 1991.

2. Davids JR, Rowan F, Davis RB. Indications for orthoses to improve gait in children with cerebral palsy. J Am Acad Orthop Surg. 2007;15:178-88.

3. Sutherland DH, Davids JR. Common gait abnormalities of the knee in cerebral palsy. Clin Orthop Relat Res. 1993;288:139-47.

4. Harrington ED, Lin RS, Gage R. Use of the anterior floor reaction orthosis in patients with cerebral palsy. Ortho Prosthet. 1984;37:34-42.

5. Palisano R, Rosenbaum P, Walter S, Russell D, Wood E, Galuppi B. Development and reliability of a system to classify gross motor function in children with cerebral palsy. Dev Med Child Neurol. 1997;39:214-23.

6. Hislop H, Montgomery J. Daniels and Worthingham's muscle testing: techniques of manual examination. 7th ed. Philadelphia: WB Saunders; 2002. p 464.

7. Staheli LT. Rotational problems in children. Instr Course Lect. 1994;43:199-209.

8. Davis RB 3rd, Õunpuu S, Tyburski D, Gage JR. A gait analysis data collection and reduction technique. Hum Mov Sci. 1991;10:575-87.

9. Gage J. The clinical use of kinetics for evaluation of pathologic gait in cerebral palsy. Instr Course Lect. 1995;44:507-15.

10. Lin CJ, Guo LY, Su FC, Chou YL, Cherng RJ. Common abnormal kinetic patterns of the knee in gait in spastic diplegia of cerebral palsy. Gait Posture. 2000;11:224-32.

11. Feise RJ. Do multiple outcome measures require p-value adjustment? BMC Med Res Methodol. 2002;2:8.

12. Abel MF, Juhl GA, Vaughan CL, Damiano DL. Gait assessment of fixed ankle-foot orthoses in children with spastic diplegia. Arch Phys Med Rehabil. 1998;79:126-33.

13. Buckon CE, Thomas SS, Jakobson-Huston S, Moor M, Sussman M, Aiona M. Comparison of three ankle-foot orthosis configurations for children with spastic diplegia. Dev Med Child Neurol. 2004;46:590-8.

14. Radtka SA, Skinner SR, Johanson ME. A comparison of gait with solid and hinged ankle-foot orthoses in children with spastic diplegic cerebral palsy. Gait Posture. 2005;21:303-10.

15. Rethlefsen S, Kay R, Dennis S, Forstein M, Tolo V. The effects of fixed and articulated ankle-foot orthoses on gait patterns in subjects with cerebral palsy. J Pediatr Orthop. 1999;19:470-4.

16. Davids JR, Ounpuu S, DeLuca PA, Davis RB 3rd. Optimization of walking ability of children with cerebral palsy. Instr Course Lect. 2004;53:511-22.

17. Hicks J, Arnold A, Anderson F, Schwartz M, Delp S. The effect of excessive tibial torsion on the capacity of muscles to extend the hip and knee during single-limb stance. Gait Posture. 2007;26:546-52.

18. Schwartz M, Lakin G. The effect of tibial torsion on the dynamic function of the soleus during gait. Gait Posture. 2003;17:113-8.