A Comparison of the Effects of Solid, Articulated, and Posterior Leaf-Spring Ankle-Foot Orthoses and Shoes Alone on Gait and Energy Expenditure in Children with Spastic Diplegic Cerebral Palsy

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Abstract

Fourteen children with spastic diplegic cerebral palsy were evaluated wearing three different ankle-foot orthoses and shoes alone. The ankle-foot orthoses included solid, articulated ankle, and posterior leaf-spring types. Evaluation measures included computerized gait analysis, Energy Efficiency Index data, and individual preference. Highly significant kinematic differences were found at the ankle with shoes alone approaching normative data and braces showing abnormal dorsiflexion. No significant differences were found in velocity, cadence, stride length, or in the Energy Efficiency Index. Eight children preferred articulated braces, six chose posterior leaf-spring, and none chose the solid brace.

Health survey information on payment for braces indicates 54% of children with cerebral palsy will use braces. Based on the incidence of cerebral palsy, 5400 new patients each year in the United States will be prescribed braces for ambulation. In addition to new cases, many children require replacement of their braces due to growth and change in their ability. The financial ramifications of this are staggering. Gait analysis has allowed clinicians to examine various interventions, among them orthotics. Equinus is an inherent condition of spastic diplegia and negatively impacts on gait over time by reducing swing phase clearance and prepositioning of the foot for stance. Braces have been credited with many beneficial results, including increased function and speed of walking, decreased metabolic expenditure, and energy consumption.

This study tested shoes alone against braced conditions on the same individual on the same day using computerized motion analysis. Results of shoes alone and braced conditions against barefoot norms previously established for our geographic area were compared. Heart rate and velocity under shoes alone and braced conditions also were measured to establish a measure of energy cost while walking.

This study objectified the process by which braces are selected for children with spastic diplegic cerebral palsy. Braces were chosen under the assumption that they improve the efficacy of gait, both its motion and energy costs.

Materials and Methods

Fourteen children (eight boys and six girls) were selected consecutively from the pediatric orthopedic practice at our institution. Inclusion criteria included 5° of passive dorsiflexion at the ankle while the knee was in extension and parental consent. Average age was 10.7 years (range: 6.9-16 years). All children had been diagnosed with spastic diplegia and demonstrated spasticity of the gastrocsoleus group. All children were independent ambulators; however, two used walkers.

Baseline measures included ankle joint dorsiflexion and plantar flexion, height and weight of individuals, and resting heart rate. Individuals were tested in the gait analysis laboratory in the
TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>Initial Contact</th>
<th>Mid-stance</th>
<th>Maximum Dorsiflexion Stance</th>
<th>Toe-off</th>
<th>Mid-Swing</th>
<th>Maximum Dorsiflexion Swing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hinged</td>
<td>11.68</td>
<td>5.16</td>
<td>7.04</td>
<td>19.35</td>
<td>10.65</td>
<td>7.32</td>
</tr>
<tr>
<td>Leaf</td>
<td>9.5</td>
<td>5.54</td>
<td>5.85</td>
<td>16.69</td>
<td>8.65</td>
<td>4.54</td>
</tr>
<tr>
<td>Shoe</td>
<td>7.54</td>
<td>4.77</td>
<td>6.38</td>
<td>7.68</td>
<td>6.99</td>
<td>4.69</td>
</tr>
<tr>
<td>Solid</td>
<td>10.91</td>
<td>3.46</td>
<td>3.13</td>
<td>19.55</td>
<td>9.6</td>
<td>4.21</td>
</tr>
</tbody>
</table>

*P<.05.

space of a single day. Orthotics were fabricated and fit prior to gait analysis to ensure a short break-in period for comfort, but no training effects were assumed.

The first brace was a solid ankle-foot orthosis, custom-made from a positive model taken by an orthotist. It was then fabricated from polypropylene, extending distally to the toe sulcus and proximally on the posterior part of the leg to approximately 2.5 cm distal to the neck of the fibula. The second brace included articulated (hinged) ankle joints that allowed the ankle to bend. The hinges (Tamarack style) were set bilaterally at the malleoli and padded for comfort. They also had a posterior plantar flexion stop. The final brace, termed a posterior leaf-spring design, was fabricated from the same positive mold of the foot. The plastic was cut back laterally behind the malleoli, allowing approximately 25° of dorsiflexion and plantar flexion at the ankle. The ankle-foot orthoses were made from 5/32-inch polypropylene, vacuum-formed using “drape forming,” trimmed at the toe sulcus, and positioned with Velcro straps over the anterior proximal shin area and dorsum of the ankle.

Bilateral three-dimensional temporal-spatial and kinematic data were collected using a Motion Analysis 3D 6 camera system (Motion Analysis Corp., Santa Rosa, Calif.) and processed using Eva 5.0 and Orthotrak software. Motion analysis markers were applied using the standard protocol; 25 retroreflective markers were placed over bony landmarks and motion was captured at 60 frames per second. Individuals walked at their self-selected speed. They walked a minimum of three trials for each condition. The three trials were averaged and analyzed for absolute differences from normal kinematics. Temporal-spatial data were collected using two standard AMTI force plates (Advanced Mechanical Technology Inc., Watertown, Mass.).

A linear relationship exists between oxygen uptake and heart rate throughout a wide range of walking speeds for children with cerebral palsy and normal children. The Energy Efficiency Index was collected during 6-minute walks under each of the braced and shoe conditions. The Energy Efficiency Index is calculated as heart rate minus resting heart rate, divided by walking speed (beats/min). Heart rate was measured every minute on a measured walkway, and velocity information was calculated in distance over time. A Hewlett-Packard 6-lead telemetry heart rate monitor (Andover, Mass) and recorder was used for data capture. No attempt was made to control gait velocity during Energy Efficiency Index trials. Individuals were instructed to walk at a self-selected pace and trials were randomized. Individuals were allowed to select their own footwear, and in all cases, a comfortable tennis-style shoe was chosen.

Ankle, knee, hip, and pelvic peak joint angles were evaluated at initial contact, mid-stance, pre-swing, mid-swing, and terminal swing under the shoes alone and braced conditions. During motion analysis, a minimum of three walks were averaged and normalized to the gait cycle. Comparisons of the conditions were made with reference to the normal kinematic data of our laboratory. Means were compared for temporal-spatial (time and distance) gait characteristics, which provided information about cadence and stride length. Shoes alone and each of the brace conditions were tested for each individual during consecutive 6-minute walks. The order of walks was randomized to statistically allow for fatigue and other possible confounding variables. This prospective randomized trial used a repeated measures (cross-over) design, wherein each individual was evaluated under all four conditions (shoes and three braces). Individuals were randomized according to a Latin square design to add balance to the order of presentation of the conditions.

Data were analyzed with repeated measure analysis of variance (ANOVA), with comparisons of the conditions adjusted for potential period and carry-over effects. Kinematic data were evaluated based on absolute differences from the mean of a normal reference cohort in: initial contact, toe-off, mid-stance, maximum dorsiflexion in stance, mid-swing, maximum dorsiflexion in swing, and the area between the kinematics curves. Velocity, cadence, stride length, and energy efficiency were analyzed on their original scales. Results in this report are declared significant at $P<.05$, and pair-wise contrasts of each brace with the shoe condition have not been adjusted for multiple comparisons.

RESULTS

Kinematics

At the ankle, highly significant differences were found at initial contact, maximum dorsiflexion in stance, mid-swing, maximum dorsiflexion in swing, and toe-off (Table 1). At initial contact, each brace type contrasted significantly with shoes alone, and the brace and shoe conditions differed from the normative data. A mean 7.54° absolute difference from normal was recorded for
the shoe conditions, while the leaf-spring, solid, and hinged braces varied in means of 9.5°, 10.91°, and 11.68°, respectively.

Maximum dorsiflexion in stance showed a significant difference for all brace and shoe types compared to normal data. However, only the solid brace contrasted significantly with the shoe condition. During mid-swing, each of the braced and shoe conditions again varied significantly from normal. The hinged brace contrasted highly with the shoe condition (P=.007), while the solid brace contrasted to a lesser degree (P=.049). The leaf-spring style did not vary significantly.

At maximum dorsiflexion in swing, highly significant differences were noted between the hinged brace and shoe conditions. The leaf-spring and solid brace styles were not significantly different from the shoe condition (P=.001 for hinged, P=.839 for leaf-spring, and P=.523 for solid). Each of the braced conditions and the shoe condition alone were significantly different from the normative data (P=.001).

The greatest differences measured in range of motion in the gait cycle were at toe-off. Each of the brace and shoe conditions contrasted significantly from the shoe condition and the normalized data (P<.001). Shoes alone averaged a difference of 7.68° from normal data, and braced conditions varied in contrast to normal from 16.69° to 19.55°.

At the knee, two statistically significant differences were observed (Table 2). The first was the maximum amount of knee flexion in swing, and the second was during knee flexion in mid-swing. Only the hinged brace differed significantly from shoes alone with maximum knee flexion in swing (9.28° versus 5.93°, respectively, with the brace achieving greater dorsiflexion than shoes alone). All three braces and the shoe conditions varied significantly from the normal population data. During mid-swing, a significant difference from normal in each of the braced and shoe conditions was noted. The hinged and solid brace styles differed from shoes alone, while the posterior leaf-spring style failed to do so. The mean knee range of motion during mid-swing for shoes alone was 7.29° of flexion, while the braces ranged from 9.32° to 10.95°, signifying an increase in flexion with each of the braces.

**Temporal-Spatial**

The three braces were compared to the shoe condition with respect to velocity, cadence, and stride length, and analyzed using a one-way ANOVA. Velocity data showed no significant differences among the three different braces. There was a trend toward slower velocity in solid ankle-foot orthoses, but it did not reach statistical significance (Table 3). Similarly, cadence did not demonstrate significant differences between the three types of braces and the shoe condition (Table 3).

Stride length was not significant, but there was a trend toward shorter stride length in the solid brace as demonstrated by the mean values (Table 3).

**Brace Preference**

Eight children chose hinged braces and six chose the posterior leaf-spring style. No child chose the solid style.

**Energy Efficiency Index**

No significant differences were found. Means ranged from 0.728-0.787.

**DISCUSSION**

Earlier studies on the use of ankle-foot orthoses in children with cerebral palsy have varied in their conclusions. Radtka et al.7 conducted a study comparing two brace designs to a barefoot condition. They found that both braces increased stride length, decreased cadence, and reduced excessive ankle-plantar flexion compared with no orthoses, but there was no statistical difference between the two braces.7

Carlson et al.8 compared the effects of a solid ankle-foot orthosis, a supramalleolar orthosis, and a no-brace, shoes only condition on the gait of 11 children with spastic diplegia. They found solid ankle-foot orthoses reduced ankle range of motion, increased the dorsiflexion angle at foot strike, increased plantar flexion moment in push-off, decreased ankle power absorbed during the loading response, and decreased ankle power at push off. Supramalleolar orthoses did not restrict the ankle excursion or alter the power or moment values at the ankle. They concluded that while solid ankle-foot orthoses offered some advantage, supramalleolar orthoses had very little effect.

Oeffinger et al.9 compared the gait of
normal children in barefoot and shoe conditions. They found a decrease in plantar flexion kinematics during heel strike, terminal double limb support, and terminal swing at the ankle. They also found a significant increase in stride length with cadence decreasing from the barefoot to shoe condition. Thus, the velocity remained relatively constant.

Buckon et al. compared solid, hinged, and posterior leaf-spring ankle-foot orthoses in gait in children with spastic diplegia and hemiplegia. Those with diplegia had no significant effects at the knee, but peak dorsiflexion in stance increased in each of the braced conditions compared to barefoot. Ankle power generation was decreased in all ankle-foot orthoses trials compared with barefoot. Stride length increased in the solid and posterior leaf-spring styles. Velocity was greater in barefoot and posterior leaf-spring braces than in the hinged brace. All braces improved the energy cost of walking using oxygen consumption data for analysis, with no significant difference between the brace styles compared to barefoot walking.\footnote{10}

Abel et al.\footnote{11} measured the effect of fixed ankle-foot orthoses on gait in children with spastic diplegia. They concluded that ankle-foot orthoses improved velocity, reduced an abnormal power burst in early stance, and increased late stance ankle moments compared to no braces or shoes in these children. Benefits were elimination of premature motion and improved progression of foot contact during stance.

Retherfelson et al.\footnote{12} compared 21 individuals with spastic diplegic cerebral palsy using fixed (solid) and articulated ankle-foot orthoses and shoes alone. They found greater dorsiflexion at initial contact under the braced conditions than with shoes alone. Dorsiflexion at terminal stance was greatest in articulated ankle-foot orthoses, and plantar flexion power was preserved in preswing in articulated ankle-foot orthoses as well.\footnote{12}

Our study compared three different ankle-foot orthoses and shoes alone, and found that shoes alone produced kinematics that were closest to normal for our laboratory. Dorsiflexion averages of 7.54° above normal at initial contact were reported for the shoes alone condition. Each brace differed significantly from shoes alone, which also contrasted with normal. In other words, the braces held the foot in abnormal dorsiflexion at initial contact, stance, and swing, while the shoes did to a lesser degree. All braces and shoes produced significantly more peak dorsiflexion in stance than normal, although only the solid brace contrasted with the shoe condition.

Excessive dorsiflexion was found at toe-off for the braced conditions, which ranged from 16°-19°. By contrast, the braces alone condition averaged 7.68°, which was significantly different from the braced conditions. Likewise, all braces held the foot in excessive dorsiflexion in swing compared to shoes alone. Each of these differences was significant. The maximum value of dorsiflexion achieved in swing was increased 4.21° to 7.32° above normal. The hinged brace contrasted significantly from the shoe alone condition. None of the braces were significantly different from each other or shoes in terms of velocity, cadence, stride length, or energy efficiency data. This differs from data collected from numerous authors who support the use of ankle-foot orthoses for various populations.

According to Harris et al.,\footnote{13} the Energy Efficiency Index correlated highly with normalized velocity in gait and had a highly negative correlation with the Gross Motor Function Measure. They postulated that those children who were less efficient performed fewer tasks on the Gross Motor Function Measure, while velocity appeared to be the gait parameter most closely tied with efficiency.

Mossberg et al.\footnote{14} studied the energy demands on children with spastic diplegic cerebral palsy while using bilateral ankle-foot orthoses. They monitored heart rate during a 5-minute walk with and without braces. Average heart rate and velocity for the last 3 minutes were analyzed. Of the 18 children studied, 13 had decreases in the heart rate to speed of ambulation ratio, 4 had lower energy costs out of orthoses, and 1 had no change. The average heart rate to velocity ratio in this population was 3.4 times higher than that reported as normal for their age group by other authors. The authors also noted that children with spastic diplegia typically walk at half the speed of healthy children. They concluded the results of the study strongly supported the use of ankle-foot orthoses for reducing the energy demands of gait in a child with spastic diplegic cerebral palsy. They also theorized that patients who derive marginal benefits in terms of energy cost reduction may demonstrate poor compliance in brace wear.\footnote{14}

Butler et al.\footnote{15} found the heart rate to walking velocity ratio was 0.4 beats/m in 72 able-bodied children. Adler and Bleck\footnote{16} found that the cost of ambulation in energy for children with spastic diplegia was 2.5 times that of healthy children. The energy efficiency of the children in our study did not vary between brace types. It is interesting to note, however, that our results were almost double the average energy expenditure in the normal pediatric population as reported by Butler et al.\footnote{15}

Although we found differences in kinematics, all braces appeared to produce an abnormal amount of dorsiflexion across the gait cycle. Shoes alone provided a more normalized pattern. Functionally, no differences were found among the conditions in walking speed or efficiency. We believe that although our data may give support to using shoes alone for children with at least 5° of passive dorsiflexion at the ankle, there may be situations in which bracing is warranted. Bracing may provide clearance and prevent falls in a child who cannot maintain adequate clearance in swing or preposition for heel strike. Bracing appeared to increase overall dorsiflexion values and may be
useful in putting the gastroc/soleus group on prolonged stretch. In that case, a hinged or posterior leaf-spring style should be considered. Kinematics in those two styles were closer to normal and shoes alone than the solid ankle-foot orthosis, and children preferred the former two styles to the solid brace. This also may improve compliance of wear in the braced population. Further studies are warranted. Although it was not a condition of inclusion, all individuals were at least 9 months out from any orthopedic intervention. This may have led to a more stable, strengthened population, which reflected in their ability to go without bracing. Conversely, walking without braces after surgery may have actively strengthened the gastroc/soleus complex, leading to more confident ambulators.

REFERENCES

EDITORIAL DISCUSSION
ORTHOPEDICS: Should all patients with 5° dorsiflexion be excluded from bracing?
Smiley et al: We do not believe all children with 5° of passive dorsiflexion should be excluded from bracing, and in fact there were several children whose sagittal plane curves were pathologic with plantar flexion noted in swing phase, but the averaged tended to exclude them. Children still need to be considered for bracing on an individual basis, but the shoes alone tended to act as an orthosis. The normalized data was a barefoot trial taken from our laboratory data, and not barefoot data from the individuals. That would have given us more information to use. However, it is evident from our study that the majority of children looked “better” when they were wearing their shoes, and those curves also were different from the barefoot “normal” conditions.

ORTHOPEDICS: Is the ease of quality of dorsiflexion (strong passive resistance) a significant factor?
Smiley et al: In theory, the quality of dorsiflexion may be very important. We did not indicate those children who had active dorsiflexion, those who had only patterned firing of groups of muscles, and those who had only passive motion available. Children with active dorsiflexion would be expected to perform clinically better than those who do not. The problem is that many children have a mix of the above, and some of our population had previous surgeries as well, which can change the overall length-tension relationship of the muscles and the quality of the muscle contraction. Each of these questions poses further questions to be investigated, and perhaps other researchers will join us in answering them.

As a final comment, several colleagues have noted increased dorsiflexion at initial contact beyond what is expected, especially in the fixed ankle-foot orthosis. Two factors were identified to account for this. Our orthotist routinely builds in 1°-2° of dorsiflexion in his ankle-foot orthoses to assist with clearance. In addition, we did not adjust our ankle-foot orthoses trials for heel height of the shoe. Some researchers are adjusting their laboratory measures for shoe heel heights. This often is 1/4-3/8 inches on a standard tennis shoe and may actually offset the true ankle angle by several degrees. This leads back to previous studies that have attempted to control ankle angle by prescribing a shoe and cutting out the ankle. All of these factors contribute to increasing the difficulty of attaining measures that are not only accurate, but also clinically relevant.