Tibialis Posterior Tendon Transfer Corrects the Foot Drop Component of Cavovarus Foot Deformity in Charcot-Marie-Tooth Disease

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Background: The foot drop component of cavovarus foot deformity in patients with Charcot-Marie-Tooth disease is commonly treated by tendon transfer to provide substitute foot dorsiflexion or by tenodesis to prevent the foot from dropping. Our goals were to use three-dimensional foot analysis to evaluate the outcome of tibialis posterior tendon transfer to the dorsum of the foot and to investigate whether the transfer works as an active substitution or as a tenodesis.

Methods: We prospectively studied fourteen patients with Charcot-Marie-Tooth disease and cavovarus foot deformity in whom twenty-three feet were treated with tibialis posterior tendon transfer to correct the foot drop component as part of a foot deformity correction procedure. Five patients underwent unilateral treatment and nine underwent bilateral treatment; only one foot was analyzed in each of the latter patients. Standardized clinical examinations and three-dimensional gait analysis with a special foot model (Heidelberg Foot Measurement Method) were performed before and at a mean of 28.8 months after surgery.

Results: The three-dimensional gait analysis revealed significant increases in tibiotalar and foot-tibia dorsiflexion during the swing phase after surgery. These increases were accompanied by a significant reduction in maximum plantar flexion at the stance-swing transition but without a reduction in active range of motion. Passive ankle dorsiflexion measured in knee flexion and extension increased significantly without any relevant decrease in passive plantar flexion. The AOFAS (American Orthopaedic Foot & Ankle Society) score improved significantly.

Conclusions: Tibialis posterior tendon transfer was effective at correcting the foot drop component of cavovarus foot deformity in patients with Charcot-Marie-Tooth disease, with the transfer apparently working as an active substitution. Although passive plantar flexion was not limited after surgery, active plantar flexion at push-off was significantly reduced and it is unknown whether this reduction was the result of a tenodesis effect or calf muscle weakness.

Level of Evidence: Therapeutic Level IV. See Instructions for Authors for a complete description of levels of evidence.
A cavovarus foot deformity may limit quality of life, reducing the ability to perform daily activities, and it may be associated with a high level of disability. Charcot-Marie-Tooth disease represents one of the most common neurogenic causes of bilateral cavovarus foot deformity. This progressive disease is caused by malfunction of the myelin sheath leading to muscle atrophy and muscle imbalance.

An abnormal gait, painful callus formation, and ankle instability may develop as part of the characteristic cavovarus foot deformity. One important etiologic factor is weakness of the tibialis anterior muscle, which presents clinically as foot drop. In combination with an abnormally strong pull by the peroneus brevis weakness, tibialis anterior weakness is a major underlying cause of cavovarus foot deformity.

As a result of foot drop, gait impairment can occur during the swing and stance phases of the gait cycle. Ferrarin et al. defined three gait patterns in young patients with Charcot-Marie-Tooth disease according to the results of a clustering analysis: pseudonormal, foot drop only, and foot drop with a push-off deficit.

Various procedures have been described to correct the foot drop component during a surgical intervention to correct the foot deformity. Some authors recommend transfer of the tibialis posterior tendon to the dorsum of the foot and report satisfactory results. However, previous studies have lacked an objective evaluation of ankle function after this transfer. Tendons are transferred to create an active substitution for a weak muscle or a tenodesis effect to dynamically fix a joint in a favorable position. An active substitution should be preferred for patients who are potentially able to relearn active function, such as patients with Charcot-Marie-Tooth disease. The tibialis posterior normally generates an internal plantar flexing moment and is coactivated with other plantar flexors (calf muscles and long toe flexors); however, it is not known whether it can adapt to a different activation pattern and act as an active dorsiflexor after being transferred to the dorsum of the foot in patients with Charcot-Marie-Tooth disease. These effects have not yet been investigated and compared with each other.

A major limitation of the use of conventional gait analysis models in evaluating foot deformities is their representation of the foot as a single rigid lever. The cavovarus foot also involves forefoot equinus (cavus), and changes in the arch as a result of cavus correction have a major impact on sagittal ankle function.

### TABLE I Outcomes for the Fourteen Involved Feet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline*</th>
<th>Follow-up*</th>
<th>P Value†</th>
<th>Normal*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clinical examination</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>AOFAS hindfoot score</td>
<td>55 ± 11</td>
<td>76 ± 10‡</td>
<td>&lt;0.001</td>
<td>100</td>
</tr>
<tr>
<td>Passive ankle dorsiflexion at 90° knee flexion (deg)</td>
<td>0 ± 11</td>
<td>15 ± 6‡</td>
<td>&lt;0.001</td>
<td>15-25</td>
</tr>
<tr>
<td>Passive ankle dorsiflexion in knee extension (deg)</td>
<td>−4 ± 11</td>
<td>9 ± 5‡</td>
<td>&lt;0.001</td>
<td>10-15</td>
</tr>
<tr>
<td>Passive ankle planter flexion (deg)</td>
<td>45 ± 5</td>
<td>36 ± 8‡</td>
<td>0.031</td>
<td>30-50</td>
</tr>
<tr>
<td>Range of passive ankle dorsiflexion and planter flexion in knee extension (deg)</td>
<td>41 ± 12</td>
<td>45 ± 9‡</td>
<td>0.340</td>
<td>40-65</td>
</tr>
<tr>
<td><strong>HFMM three-dimensional gait and foot analysis (deg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Swing phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. tibiotalar dorsiflexion</td>
<td>0.0 ± 5.5</td>
<td>6.3 ± 2.1‡</td>
<td>&lt;0.001</td>
<td>7.4 ± 2.2</td>
</tr>
<tr>
<td>Max. tibiotalar plantar flexion</td>
<td>−3.9 ± 4.5</td>
<td>2.8 ± 2.5‡</td>
<td>&lt;0.001</td>
<td>−12.8 ± 5.6</td>
</tr>
<tr>
<td>Range of tibiotalar dorsiflexion and plantar flexion</td>
<td>3.8 ± 2.3</td>
<td>3.6 ± 2.0</td>
<td>0.726</td>
<td>19.3 ± 5.1</td>
</tr>
<tr>
<td>Max. foot-tibia dorsiflexion</td>
<td>−15.9 ± 11.7</td>
<td>−1.8 ± 4.9‡</td>
<td>&lt;0.001</td>
<td>−3.0 ± 2.9</td>
</tr>
<tr>
<td>Max. foot-tibia planter flexion</td>
<td>−20.5 ± 10.4</td>
<td>−5.4 ± 5.3‡</td>
<td>&lt;0.001</td>
<td>−29.0 ± 6.6</td>
</tr>
<tr>
<td>Range of foot-tibia dorsiflexion and plantar flexion</td>
<td>4.6 ± 2.8</td>
<td>3.6 ± 2.0</td>
<td>0.305</td>
<td>25.9 ± 6.2</td>
</tr>
<tr>
<td>Stance phase</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. tibiotalar dorsiflexion</td>
<td>9.6 ± 5.6</td>
<td>12.4 ± 2.3†</td>
<td>0.093</td>
<td>10.1 ± 2.8</td>
</tr>
<tr>
<td>Max. tibiotalar plantar flexion</td>
<td>−11.8 ± 5.8</td>
<td>−5.5 ± 3.5†</td>
<td>0.002</td>
<td>−10.4 ± 4.8</td>
</tr>
<tr>
<td>Range of tibiotalar dorsiflexion and plantar flexion</td>
<td>21.3 ± 7.4</td>
<td>17.8 ± 2.7</td>
<td>0.109</td>
<td>20.4 ± 4.7</td>
</tr>
<tr>
<td>Max. foot-tibia dorsiflexion</td>
<td>−5.1 ± 12.0</td>
<td>7.7 ± 3.0‡</td>
<td>&lt;0.001</td>
<td>4.6 ± 3.5</td>
</tr>
<tr>
<td>Max. foot-tibia planter flexion</td>
<td>−30.0 ± 9.6</td>
<td>−14.0 ± 5.6‡</td>
<td>&lt;0.001</td>
<td>−27.7 ± 6.2</td>
</tr>
<tr>
<td>Range of foot-tibia dorsiflexion and plantar flexion</td>
<td>24.9 ± 11.0</td>
<td>21.6 ± 3.1</td>
<td>0.291</td>
<td>32.3 ± 6.0</td>
</tr>
<tr>
<td>Mean medial arch</td>
<td>107.2 ± 11.1</td>
<td>118.9 ± 5.6‡</td>
<td>0.002</td>
<td>123.7 ± 5.9</td>
</tr>
<tr>
<td>Lateral standing radiograph (deg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcaneal pitch</td>
<td>25.1 ± 8.4</td>
<td>15.4 ± 6.3‡</td>
<td>0.009</td>
<td>10-20</td>
</tr>
<tr>
<td>Talometatarsal angle</td>
<td>20.9 ± 7.1</td>
<td>0.7 ± 12.8§</td>
<td>&lt;0.001</td>
<td>0</td>
</tr>
</tbody>
</table>

*The values are given as the mean and the standard deviation, or as the mean or the range. †Unpaired t test. ‡Significantly different, at the p < 0.01 level, from the preoperative value.
kinematics in conventional gait analysis. More recently, kinematic foot models have been introduced\textsuperscript{19-21} that permit evaluation of changes in foot and ankle function after corrective surgery in more detail. Only a few studies of the outcomes of foot deformity correction have included such a foot model analysis, and to our knowledge such an analysis has not previously been applied to cavovarus foot deformity. The major advantage of use of such a kinematic foot model is that forefoot equinus (cavus) does not influence the hindfoot results because hindfoot and forefoot motion can be evaluated separately.

The purpose of the present prospective study was to use three-dimensional foot analysis to evaluate the outcome of standardized tibialis posterior transfer to the dorsum of the foot as a part of cavovarus correction in patients with Charcot-Marie-Tooth disease. The study was intended to evaluate whether the transfer works as an active transfer or as a tenodesis.

Materials and Methods

Subjects

Fourteen patients with Charcot-Marie-Tooth disease and unilateral or bilateral cavovarus foot deformity with a foot drop component were enrolled prospectively as a sample of convenience. The patients were recruited at the special foot deformity outpatient clinic in our hospital if surgical correction was indicated. Inclusion criteria were the ability to walk independently without any assistive device, an age of seventeen to fifty years, and a diagnosis of foot drop. Patients with prior surgery involving the lower extremities, foot ulcerations, or gait disturbances due to concomitant hip dysplasia were excluded. All patients provided written informed consent, and the study was approved by the local ethical committee. Demographic details are summarized in the Appendix. A total of twenty-three involved feet were treated with tibialis posterior tendon transfer to the dorsum of the foot as a part of foot deformity correction. Five patients underwent unilateral treatment and nine underwent bilateral treatment; only one foot was analyzed in each of the latter patients.

Surgery

In all patients, the tibialis posterior tendon transfer was performed according to a standardized surgical technique (total split posterior tibial tendon transfer, T-SPOTT)\textsuperscript{10} as part of a surgical intervention in which all components of the foot deformity were corrected. The concomitant soft-tissue and osseous procedures are summarized in the Appendix. In our surgical routine, tendon transfers are prepared first, then hindfoot and midfoot deformities (cavovarus) are corrected by Chopart arthrodesis and/or osteotomies, followed by correction of the first ray (Jones procedure and/or extension osteotomy). After the foot is corrected and stabilized with Kirschner wires, the ankle is assessed for the presence of hindfoot equinus and, if necessary, aneurotic calf muscle lengthening or Achilles tendon lengthening is performed to correct the equinus. Finally, the tendon transfers are anchored under tension and sutured with number-1 Vicryl (Ethicon). Other than Kirschner wires, the only other type of internal fixation used was locking plates for the supramalleolar tibial derotation osteotomies performed in two patients (see Appendix).
The Heidelberg Foot Measurement Method (HFMM) was introduced by Simon et al.\(^{19}\). This method involves the placement of markers at specific anatomic landmarks, such as the lateral and medial malleoli (LML and MML [not shown]), lateral and medial aspects of the calcaneus (CCL), navicular (NAV), proximal and distal ends of the first metatarsal (P1MT and D1MT), hallux (HLX), distal end of the second metatarsal (D2MT), and distal and proximal ends of the fifth metatarsal (D5MT and PSMT). (Reproduced, with permission of Elsevier, from: Simon J, Doederlein L, McIntosh AS, Metaxiotis D, Bock HG, Wolf SI. The Heidelberg Foot Measurement Method: development, description and assessment. Gait Posture. 2006 Jun;23[4]:411-24. Epub 2005 Sep 12. Copyright [2006]. http://www.sciencedirect.com/science/journal/09666362.)

**Fig. 2 A**: Placement of markers in the lateral and medial epicondyles (LEP and MEP [not shown]), tuberosity (TTU), two points on the medial side of the shin (SH1 and SH2), lateral and medial malleoli (LML and MML [not shown]), lateral, dorsal, and medial aspects of the calcaneus (CCL), navicular (NAV), proximal and distal ends of the first metatarsal (P1MT and D1MT), hallux (HLX), distal end of the second metatarsal (D2MT), and distal and proximal ends of the fifth metatarsal (D5MT and PSMT). (Reproduced, with permission of Elsevier, from: Simon J, Doederlein L, McIntosh AS, Metaxiotis D, Bock HG, Wolf SI. The Heidelberg Foot Measurement Method: development, description and assessment. Gait Posture. 2006 Jun;23[4]:411-24. Epub 2005 Sep 12. Copyright [2006]. http://www.sciencedirect.com/science/journal/09666362.)

**Fig. 2 B**: Tibiotalar flexion parameter (flexion between the tibia and the talus, represented by the motion of the calcaneus and navicular) is calculated as the rotation around the malleolar line. Positive values indicate dorsiflexion and negative values indicate plantar flexion. This parameter was chosen to evaluate ankle function independently of the midfoot and forefoot.

**Fig. 2 C**: The foot-tibia flexion parameter (flexion between the tibia and the medial longitudinal foot axis) is determined by the line between the calcaneus and the distal end of the first metatarsal (D1MT in Fig. 2-A). Positive values indicate dorsiflexion and negative values indicate plantar flexion. This parameter describes the sagittal motion between the whole foot and the tibia, and it is influenced by the severity of the cavus deformity. **Fig. 2-D**: The medial arch is measured as the absolute angle between the first metatarsal (MT1) and a line from the marker in the medial calcaneus to the navicular. A smaller angle indicates a higher arch. This parameter provides information regarding the severity of the cavus deformity.

**T-SPOTT Surgical Technique (Fig. 1)**

The complete tibialis posterior tendon is released, split in half, and transferred anteriorly through the interosseous membrane to the dorsum of the foot. One tendon half is transferred to the tibialis anterior tendon, and the other half is transferred to the peroneus brevis or tertius tendon.

**Postoperative Care**

Non-weight-bearing plaster casts were used postoperatively for a period of five to six weeks because of the concomitant osseous procedures. After the Kirschner wires were removed, a weight-bearing cast was used for an additional six weeks, followed by use of an ankle-foot orthosis for an additional three months. Physiotherapy (two to three times a week) was begun at nine weeks postoperatively and consisted of passive and active mobilization of the ankle and concentric and eccentric strength training to strengthen dorsiflexion and plantar flexion. All patients received at least six months of regular physiotherapy.

**Evaluation**

All patients were examined preoperatively and postoperatively according to a standardized protocol. The mean duration (and standard deviation) of follow-up after the intervention was 28.8 ± 12.8 months. Clinical examination and instrumented three-dimensional gait analysis (Vicon, Oxford, United Kingdom) with use of a validated foot model\(^{20}\) (Heidelberg Foot Measurement Method, HFMM) were performed in all patients. Seventeen reflective markers were placed at well-defined osseous landmarks of the leg and the foot (Fig. 2). A heel alignment device was used to standardize the placement of the calcaneal markers. The patient was asked to walk barefoot along a 7-m walkway. At least ten valid strides were collected, and the trajectories of the markers were analyzed with use of custom MATLAB (MathWorks, Natick, Massachusetts) software (MoMo, written by Jan Simon, University of Heidelberg).

Passive ankle range of motion was assessed in knee extension and at 90° of knee flexion during the clinical examination. The AOFAS (American Orthopaedic Foot & Ankle Society) ankle-hindfoot score\(^{21}\) was assessed in all subjects before and after the surgery; however, it should be noted that the AOFAS scale is not a validated instrument. All examinations were performed by a physiotherapist and a study nurse who have specialized in gait and foot analysis techniques for more than ten years.

**Data Analysis**

Three parameters from the three-dimensional foot analysis were chosen to study the effects of tendon transfer surgery on ankle dorsiflexion. Tibiotalar dorsiflexion or plantar flexion describes the motion of the hindfoot in relation to the tibia in the sagittal plane. This parameter was chosen to evaluate ankle function independently of the midfoot and forefoot. Foot-tibia dorsiflexion or plantar flexion describes the sagittal motion of the whole foot in relation to the tibia. This parameter is influenced by the extent of the cavus deformity. The medial arch angle indicates the severity of the cavus deformity (Fig. 2). These three parameters were evaluated during the stance and swing phases of the gait cycle. Within each gait phase, the mean, maximum, minimum, and range were calculated for each parameter.

One side of each of the patients with bilateral involvement was randomly selected for analysis, resulting in a total of fourteen analyzed feet in the study. Descriptive statistics were used to summarize each parameter of interest. Unpaired Student t tests were used to evaluate changes over time. A p value of <0.01 was considered significant.
Source of Funding
No external source of funding was used for this investigation.

Results

Clinical Examination
Passive ankle dorsiflexion, measured at 90° of knee flexion and in knee extension, had increased significantly \((p < 0.001)\) at the time of the follow-up examination, at a mean of twenty-nine months postoperatively (Table I). Passive plantar flexion had decreased slightly \((p = 0.031)\) but remained at a mean of 36° (Table I). The AOFAS score improved significantly from 55 to 76 \((p < 0.001)\), indicating an overall improvement after foot deformity correction.

Three-Dimensional Gait and Foot Analysis (HFMM)
Significant increases in tibiotalar dorsiflexion and foot-tibia dorsiflexion during the swing phase \((p < 0.001)\) occurred between the baseline and postoperative time points (Fig. 3 and Table I). The postoperative mean values were within the normal ranges of an age-matched reference group. These changes were accompanied by significant reductions in maximum plantar flexion (minimum dorsiflexion) at the stance-swing transition \((p < 0.001)\) (Fig. 3), but the total ranges of dorsiflexion-plantar flexion during the stance and swing phases did not change significantly. The entire flexion curves in Figure 3 were thus shifted toward dorsiflexion, with an improvement during swing phase but at the cost of plantar flexion at push-off. The mean medial arch angle increased significantly from 107.2° to 118.9° \((p = 0.002)\), indicating that the cavus deformity had been corrected.

Radiographic Results
The calcaneal pitch angle and talometatarsal angle decreased significantly after surgery \((p = 0.009\) and \(p < 0.001, \) respectively) (Table I).

Discussion
Tendon transfer surgery is commonly used to correct neurogenic foot deformities. Whether the tendon of a muscle transferred to another site can provide an active substitution has always been a matter of concern, especially when the muscle is normally an antagonist to the one requiring support. In a patient population such as individuals with Charcot-Marie-Tooth disease who potentially are able to relearn function, an active substitution is superior to a simple tenodesis since tenodesis would reduce function, especially during activities that require a large range of motion and a fast switch from extension to flexion of the involved joint. Foot drop poses a particular problem as the number of muscles providing foot and ankle dorsiflexion is smaller than the number providing plantar flexion. In patients with Charcot-Marie-Tooth disease, the tibialis anterior muscle is often degenerated and the long toe extensors are often concomitantly involved. Thus, none of the dorsiflexors that are active during the swing phase of gait are available as substitutes, and other muscles need to be considered. In these patients, the tibialis posterior tendon is commonly transferred to the dorsum of the foot. However, the question of whether the transfer can function as an active substitution during gait has not yet been adequately answered.

In the present study, significant increases in tibiotalar and foot-tibia dorsiflexion during swing phase were found at a mean of two years after the transfer surgery. The objective, computerized data presented demonstrate that tibialis posterior tendon transfer was an effective procedure to correct the foot drop component of the cavovarus foot deformity in patients with Charcot-Marie-Tooth disease. However, the increase in dorsiflexion was accompanied by a significant reduction in peak plantar flexion at the stance-swing transition without any clinically relevant loss of active range of motion compared with the normal range, indicating that the entire motion curve was shifted toward dorsiflexion, which...
may indicate a potential tenodesis effect. The passive ankle dorsiflexion measured in knee flexion and extension, however, increased significantly without any relevant loss of passive plantar flexion. Thus, ankle excursion during walking was reduced at the end of the stance phase (push-off) despite the fact that the transferred muscle allowed passive stretching of the ankle over nearly normal plantar flexion ranges after surgery.

If the transferred tibialis posterior muscle was active during its former phase of the gait cycle (when it worked as a plantar flexor at the same time that the calf muscles were activated to initiate push-off’), this activity would counteract the push-off motion, resulting in reduced plantar flexion during late stance phase. In this case, the transfer would be working as a tenodesis. Alternatively, if the transfer does not work actively, a neutral ankle position would remain during the swing phase without a further increase in ankle dorsiflexion until terminal swing. Since dorsiflexion increased further during the swing phase, this suggests that these postoperative measurements may represent active dorsiflexion. This hypothesis is strengthened by the observation of improved function of the first rocker during the loading response at the beginning of the stance phase, when the tibialis anterior muscle is important for controlling plantar flexion. If a tenodesis effect had been present, this plantar flexion would have been counteracted; however, our results showed harmonious plantar flexion motion after the transfer (Fig. 3). On the basis of these observations, the activation pattern of the tibialis posterior muscle potentially changed after the transfer, a finding that has not been reported previously to our knowledge. However, the presence of an active transfer cannot ultimately be proven by the results of the present study, and further investigations to confirm these findings should therefore focus on dynamic electromyography of the tibialis posterior muscle and calf muscles during walking following transfer surgery.

Another possible explanation for the decrease in active plantar flexion is weakness of plantar flexor muscles after the surgery, resulting in impaired push-off. Various conditions may cause plantar flexor weakness. It may result from calf muscle lengthening surgery, which is needed in rare cases of cavovarus foot. In the present study, however, only one Achilles tendon lengthening and one aponeurotic calf muscle lengthening procedure were performed. The progression of the Charcot-Marie-Tooth disease may have influenced plantar flexor muscle strength. Use of a cast over a period of nearly three months should also be taken into consideration. Finally, since the position of the calcaneus in the sagittal plane affects the triceps surae, the reduction in tension of the gastrocnemius-soleus complex following correction of calcaneal pitch (Fig. 4) may aggravate plantar flexor weakness. Calcaneal pitch decreased significantly after surgery in the present study because of Chopart arthrodesis and plantar fascia release.

Postoperative physiotherapy should focus on coordinating the plantar flexors and the transferred muscle, on early mobilization (active and passive range of motion), and on early strength training to improve calf and dorsiflexor muscle strength. In our opinion, surgical lengthening of the calf muscles should be avoided in some patients, especially those who present preoperatively with calf muscle weakness. Surgical calf muscle lengthening should be limited to the very rare cases of persistent hindfoot equinus after correction of the cavus deformity. In these patients, three-dimensional gait analysis with use of a multisegmental foot model provides important information about the severity of the cavus deformity and the true degree of hindfoot equinus.

The variety of concomitant procedures performed in addition to the tibialis posterior tendon transfer represents a weakness of this study with respect to determining the isolated effects of the tibialis posterior tendon transfer. In particular, the modified Jones procedure (in which the extensor hallucis longus tendon insertion is transferred proximally to the first metatarsal) can have a potential influence on ankle dorsiflexion during the swing phase.

In conclusion, tibialis posterior tendon transfer was effective at correcting the foot drop component of cavovarus foot deformity in patients with Charcot-Marie-Tooth disease. The tendon transfer appeared to function as an active substitution. Although passive plantar flexion was not limited after surgery, active plantar flexion at push-off was significantly reduced. Further studies should investigate whether this reduction is an effect of tenodesis or of calf muscle weakness, the cause of which may be multifactorial.
Appendix

A table summarizing patient demographics and surgical procedures is available with the online version of this article as a data supplement at jbjs.org.

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References