

# Immediate and Long-Term Effects of Ankle-Foot Orthosis on Muscle Activity During Walking: A Randomized Study of Patients With Unilateral Foot Drop

Johanna F. Geboers, MD, Maarten R. Drost, PhD, Frank Spaans, MD, PhD, Harm Kuipers, MD, PhD, Henk A. Seelen, PhD

**ABSTRACT.** Geboers JF, Drost MR, Spaans F, Kuipers H, Seelen HA. Immediate and long-term effects of ankle-orthosis on muscle activity during walking: a randomized study of patients with unilateral foot drop. *Arch Phys Med Rehabil* 2002;83:240-5.

**Objectives:** To determine (1) whether use of an ankle-foot orthosis (AFO) by patients with ankle dorsiflexor paresis leads to decreased muscle activity, immediately or 6 weeks after AFO use, and (2) whether this decrease (if present) differs between healthy and paretic subjects.

**Design:** Cross-sectional and longitudinal randomized case-control study.

**Setting:** Rehabilitation research center in the Netherlands.

**Participants:** Fourteen healthy persons and 29 patients with foot drop.

**Interventions:** Muscle activity was measured by surface electromyography. Electromyographic reproducibility was tested in 14 healthy volunteers walking with and without AFO. Acute changes in muscle activity from AFO use were compared between the 14 healthy persons and the 29 patients with foot drop. Adaptation effects of AFO use after 6 weeks were studied in 29 patients, randomly chosen 16 of whom had started using an AFO at the first measurement.

**Main Outcome Measures:** Amount of change in mean rectified electromyographic activity ( $\delta$  value) between walking with and without AFO. Follow-up measurements were conducted after 3 and 6 weeks.

**Results:** Correlation coefficients, reflecting within-subject reproducibility, varied between .68 and .96 (mean, .86). In patients and healthy subjects, tibialis anterior muscle activity decreased by 7% and 20% ( $P = .01$ ,  $P = .04$ ), respectively, when using an AFO. In patients, this decrease was measured in the overall activity during the gait cycle; in healthy subjects, it was measured in the first 15% of the gait cycle. Overall electromyographic activity did not change during 6 weeks;  $\delta$  values per muscle did not change during follow-up in the AFO group.

**Conclusion:** AFO use immediately reduced muscle activity of the ankle dorsiflexors. However, using an AFO for 6 weeks

did not lead to a generally lower electromyographic activity level nor did the amount of activity reduction accumulate in comparison with patients who did not use an AFO. It is, therefore, safe to use an AFO, even with recently paretic patients.

**Key Words:** Ankle; Electromyography; Foot; Gait; Orthotic devices; Rehabilitation; Walking.

© 2002 by the American Congress of Rehabilitation Medicine and the American Academy of Physical Medicine and Rehabilitation

**A**N ANKLE-FOOT ORTHOSIS (AFO) is frequently prescribed for patients with paretic ankle dorsiflexor muscles to improve walking ability and to prevent stumbling.<sup>1</sup> In subjects with paretic ankle dorsiflexors, an AFO prevents foot drop during the swing phase of gait and helps to control foot placement after heel strike. In treating patients with a fairly recent paresis, it is important to know whether their supported dorsiflexor muscles become less active from the partial immobilization. If they do, this might induce disuse effects during the period of orthosis use, thereby worsening the existing loss of strength and possibly delaying recovery.<sup>2-4</sup> Also, because patients often use an orthosis for several months, central adaptation effects may occur that gradually decrease muscle activity over time. Central adaptation of motor representation after peripheral changes such as amputation, spinal cord injury, or immobilization has been described by Bruelmeier et al,<sup>5</sup> Cohen et al,<sup>6</sup> Green et al,<sup>7</sup> and Kaas.<sup>8</sup> If, because of AFO use, the central stimulation of the dorsiflexors diminishes, this could result in delayed and decreased strength restoration of the paretic muscles after nerve recovery.

The tibialis anterior muscle in healthy persons shows a large burst of electromyographic activity around heel strike to control foot placement in gait.<sup>9</sup> A second burst is seen after toe off during the swing phase to prevent the foot and toes from dropping. The temporal reproducibility of this second burst of the tibialis anterior is lower than the first.<sup>10-12</sup>

AFO use diminishes the possibility for active plantarflexion, inversion, and eversion. Gait analyses in subjects with an AFO show alterations in the walking pattern (eg, the duration of stance phase, range of motion [ROM] of the hip and knee joint),<sup>13-19</sup> but in these studies no electromyography has been measured. It is conceivable that the supported muscles do show less activity, whereas the antagonistic muscles may increase their activity to overcome the restriction in ROM and the proximal muscle groups to compensate for the extra weight added to the leg. Diaz et al<sup>20</sup> and Cerny et al,<sup>21</sup> for example, found an increase in electromyographic activity of proximal leg muscles when subjects wore a knee brace that restricted knee extension. Bulthaupt et al<sup>22</sup> and Jansen et al<sup>23</sup> found an increase in proximal muscle activity and a decrease in the activity of the supported wrist extensor muscles in patients with wrist orthoses. However, these studies of muscle reaction to orthosis use were predominantly performed with healthy volunteers or

From the Institute for Rehabilitation Research, Hoensbroek & Atrium Medical Centre, Heerlen (Geboers, Seelen); Department of Movement Science, Maastricht University, Maastricht (Drost, Kuipers); Department of Clinical Neurophysiology, University Hospital Maastricht, Maastricht (Spaans), The Netherlands.

Accepted in revised form February 8, 2001.

Supported by the Rehabilitation Foundation Limburg, Hoensbroek, and the Foundation De Drie Lichten, the Netherlands.

No commercial party having a direct financial interest in the results of the research supporting this article has or will confer a benefit upon the authors or upon any organization with which the authors are associated.

Reprint requests to Johanna F. Geboers, MD, iRv, Institute for Rehabilitation Research, PO Box 192, 6430 AD Hoensbroek, the Netherlands, e-mail: [m.geboers@zonnet.nl](mailto:m.geboers@zonnet.nl).

0003-9993/02/8302-6557\$35.00/0

doi:10.1053/apmr.2002.27462

sportsmen with orthopedic impairment (eg, instability of the ankle), but with nonparetic muscles.

In view of the previously mentioned studies, some important questions arise. The first is whether dorsiflexor muscles that are supported by an AFO decrease their activity during walking and whether adaptation effects occur after prolonged AFO use. The second question is whether paretic muscles react differently than do healthy muscles. In this study, the following specific research questions were posed: (1) What is the reproducibility of the electromyographic signal of the lower leg muscles in healthy persons walking on a treadmill with and without AFO during 2 consecutive measurement sessions?; (2) Do lower leg muscles show an immediate change in mean and initial activity after both healthy volunteers and patients don AFOs?; (3) Does the amount of immediate change in muscle activity ( $\delta$  value), during walking with or without an AFO, differ between healthy subjects and patients?; and (4) Is there a difference in the change in mean muscle activity ( $\delta$  value) of the lower leg muscles 6 weeks after initially donning the AFO between patients who do and not use an AFO?

## METHODS

### Subjects

Fourteen healthy volunteers (8 women, 6 men; mean age  $\pm$  standard deviation [SD],  $33.2 \pm 10.2y$ ) recruited from staff and students at our research institute and 29 patients (21 men, 8 women) with a recent unilateral peripheral paresis of the ankle dorsiflexors participated in all studies. Patients were recruited from regional hospitals. Because no exact SDs were available, sample size was not based on power analysis but on practical considerations (ie, availability of patients). Each subject met the following criteria: age  $\geq 18$  years; peripheral paresis of the foot dorsiflexors for 6 weeks to 1 year; Medical Research Council Scale<sup>24</sup> (MRC) strength scores from 1 to 4 (range, 0–5); no AFO use; no progressive neurologic disease, no contractures of the lower limbs; and no history of musculoskeletal, rheumatologic, or orthopedic problems in the lower extremities that prevented a subject from walking at least 500m. The healthy volunteers participated in the reproducibility study and the cross-sectional study; the patients participated in both the cross-sectional and longitudinal study. In table 1, the group composition is shown. For the longitudinal follow-up study to detect possible adaptation effects of AFO use, the patients were randomly assigned to 2 groups, with (AFO group) or without (no-AFO group) daily AFO use. No significant difference was found in the duration and severity of the paresis at the first measurement (T0) between the 2 patient groups. After the first measurement, the data collection was repeated after 3 weeks (T3,  $21 \pm 2.6d$ ) and again 3 weeks later (T6,  $22 \pm 3d$ ). The study was approved by the medical ethics committees of our research institute and participating hospitals. All patients and healthy controls gave their informed consent.

**Table 1: Demographic Characteristics of Groups**

Group	n	Age (y)	M/F	Duration Paresis T0 (wk)
Healthy subjects* <sup>†</sup>	14	$33 \pm 10$	6/8	NA
No-AFO group <sup>††</sup>	13	$44 \pm 13$	10/3	$28 \pm 8$
AFO group <sup>††</sup>	16	$57 \pm 17$	11/5	$19 \pm 13$

NOTE. Values are as n or mean  $\pm$  SD.

Abbreviations: M, males; F, females; NA, not applicable.

\* Reproducibility study.

<sup>†</sup> Cross-sectional study.

<sup>††</sup> Longitudinal study.

### Materials

Electromyographic activity was recorded from the tibialis anterior, the extensor digitorum longus, the peroneus longus, the soleus, and the lateral head of the gastrocnemius muscle of the affected leg. The tibialis anterior and extensor digitorum longus were chosen because they are innervated by the peroneal nerve and specifically act as ankle dorsiflexors. The peroneus longus was measured because of its possible role in compensating foot drop by eversion in a paretic leg. The soleus and gastrocnemius muscles were measured for the effect of an AFO on the antagonistic muscles. Because electrode placement on the medial head of the gastrocnemius muscle was hampered by the AFO, the lateral head was chosen. Surface electromyography<sup>a</sup> was performed using Ag/AgCl surface electrodes<sup>b</sup> with a recording surface of  $1\text{cm}^2$ . Before applying the electrodes, the skin was cleaned with alcohol. A mold was used to ensure an interelectrode distance of 23mm during each measurement. Electrodes were placed over the thickest part of the muscle belly. Their location, together with some anatomic structures, were registered on a panty sock to facilitate correct reproduction of the electrode placement during the second and third measurements. Heelstrike was recorded by a microswitch imbedded in the most posterior part of the heel of a regular, off-the-shelf-type shoe (available in 10 sizes). In this study, muscle activity is represented by the mean rectified electromyographic activity during 1 step cycle and the initial activity of the dorsiflexors (tibialis anterior, extensor digitorum longus) by the first 15% of the gait cycle because of the specific electromyographic burst expected. Also, the mean electromyographic activity of the step cycle as a whole was calculated for all 5 muscles measured. To test the reliability of our measurement protocol, reproducibility of the electromyographic measurement was tested in healthy volunteers before the study.

AFO group participants used their own plastic orthoses during the measurements; the healthy controls and the patient control group used a standard, off-the-shelf, plastic AFO weighing 125g, set at  $90^\circ$ , with a posterior trimline to allow some flexibility in ankle movement throughout the gait pattern. The AFOs<sup>c</sup> were available in 3 sizes.

### Test Procedures

Reproducibility of the electromyographic test procedure was measured in 14 healthy persons before the clinical study. They were studied twice, 1 week apart. For the longitudinal study, 29 patients were investigated 3 times with a 3-week interval between sessions. Table 2 presents an overview of the measurement sequences.

Muscle activity was measured while subjects walked on a level treadmill (fig 1) with and without an AFO, in random order. Patients were asked to walk at a comfortable speed. This speed was also used during the next measurements. If patients normally used a walking aid, they used the treadmill's side bar for support. After a warm-up of approximately 2 minutes, the subjects' muscle activity and heelstrike were recorded during 5 trials of 20 seconds each at a sample rate of 1000Hz.

### Data Analysis

The electromyographic signal was full wave rectified and filtered using a Butterworth second-order, low-pass filter with a cutoff frequency of 5Hz. The MATLAB software package<sup>d</sup> was used. A similar procedure was used in gait analysis by Winter.<sup>25,26</sup> The electromyographic signal was standardized to the gait cycle using heelstrike as a reference. Mean electromyographic activity of each muscle was calculated over the total number of steps in all 5 trials. This mean electromyographic activity ( $\mu\text{V}$ ) was considered an indicator of the effort

Table 2: Measurement Scheme

	T0	T2	T3	T6
Healthy subjects	RS, CSS	RS		
No-AFO group	CSS, LS		LS	LS
AFO group	CSS, LS		LS	LS

Abbreviations: RS, reproducibility study; CSS, cross-sectional study; LS, longitudinal study.

the muscle delivered during the walking test. The effect of AFO use on muscle activity of each person was expressed as the percentage of change in muscle activity ( $\delta$  value) when walking with an AFO compared with when walking without an AFO. The first 15% of the step cycle after heelstrike was considered the most consistent period of eccentric activity of the ankle dorsiflexors. For all electromyographic calculations, the mean, the 95% confidence interval of the mean, and the median are given.

All statistical analyses were performed with SPSS software.<sup>6</sup> The within-group values were analyzed with the Wilcoxon signed rank test, and the between groups values were tested with the Mann-Whitney *U* test.

In the healthy volunteers, reproducibility of the electromyographic measurement protocol was determined within each subject for the consecutive measurements for each of the 5 registered muscles.

**Error analysis.** All measurements of the healthy control group were used. In the paretic group, 2 patients had bad registration caused by signal recording problems. Their data were excluded from further analysis. These 2 patients were both from the AFO group. Thus, comparison between the patient groups was performed with 13 subjects in the no-AFO group and 14 in the AFO group.

## RESULTS

### Reproducibility

The differences in mean electromyographic production between the first and second measurement sessions were calculated for each muscle with and without AFO use. Electromyographic



Fig 1. A patient walking on a level treadmill with electrodes on the tibialis anterior, extensor digitorum longus, peroneus longus, soleus, and the lateral part of the gastrocnemius muscle (below the AFO). The patient wears the standard AFO and shoe.

Table 3: Differences in Mean Electromyographic Activity of 14 Healthy Subjects at 2 Measurement Sessions for Walking With and Without AFO

	TA (%)	EDL (%)	SOL (%)	GAS (%)	PL (%)
Without AFO	0 ( $\pm 13$ )	-9 ( $\pm 23$ )	2 ( $\pm 14$ )	-17 ( $\pm 53$ )	-6 ( $\pm 23$ )
With AFO	2 ( $\pm 27$ )	-13 ( $\pm 31$ )	-0 ( $\pm 16$ )	4 ( $\pm 39$ )	-3 ( $\pm 27$ )

NOTE. Values expressed as  $(T2-T0)/T2 \times 100\%$  ( $\pm$ SD).

Abbreviations: TA, tibialis anterior; EDL, extensor digitorum longus; SOL, soleus; GAS, gastrocnemius; PL, peroneus longus.

graphic activity between T0 and T2 was not significantly different (table 3).

Reproducibility of the electromyographic patterns in healthy subjects, expressed as the correlation coefficient, was very good when walking without an AFO (ie,  $r \geq 0.9$ ; table 4). With the exception of the peroneus longus, walking with an AFO resulted in a lower reproducibility (ie,  $r \leq .81$  for all muscles). The gastrocnemius muscle showed the lowest value.

### Immediate Changes in Electromyographic Activity After Donning an AFO

There were large interindividual differences in patients' electromyographic patterns. In most patients, for example, the activity of the tibialis anterior did not show the typical pattern of an initial burst in the first 15% of the gait cycle that was seen in the healthy group (fig 2).

The mean immediate changes in electromyographic activity after subjects donned an AFO are shown in figures 3 and 4 for all muscles for the healthy and paretic subjects. When an AFO was used by healthy subjects, electromyographic activity of the tibialis anterior and extensor digitorum longus decreased during the first 15% but not during the step cycle as a whole. In contrast, these activities in paretic subjects decreased during the step cycle as a whole but not specifically during the first 15%.

### Differences in Immediate Electromyographic Changes Between Subjects

Between the groups, no differences were found in the amount of electromyographic change for any muscle, either in the step cycle as a whole or in the first 15% (figs 3, 4, respectively). The healthy group seemed to show a larger decrease in activity of the tibialis anterior and extensor digitorum longus than did the paretic group, especially in the first 15% of the step cycle. However, the difference was not significant.

### Differences in Muscle Activity Changes Between Both Patient Groups at 6-Week Follow-Up

The total amount of electromyographic activity did not change between T0 and T6 for either patient group in both conditions. Also, the amount of muscle reaction ( $\delta$  value) after putting on an AFO did not change significantly between or within groups from T0 and T6. Electromyographic activity changes were calculated

Table 4: Median Correlation Coefficient of the Electromyographic Patterns in 14 Healthy Subjects While Walking With and Without AFO for Each Muscle

	TA	EDL	SOL	GAS	PL
Without AFO	.96 $\pm$ .26	.91 $\pm$ .28	.96 $\pm$ .26	.90 $\pm$ .29	.90 $\pm$ .25
With AFO	.81 $\pm$ .51	.79 $\pm$ .48	.80 $\pm$ .28	.68 $\pm$ .33	.93 $\pm$ .44

NOTE. Values are mean  $\pm$  SD.

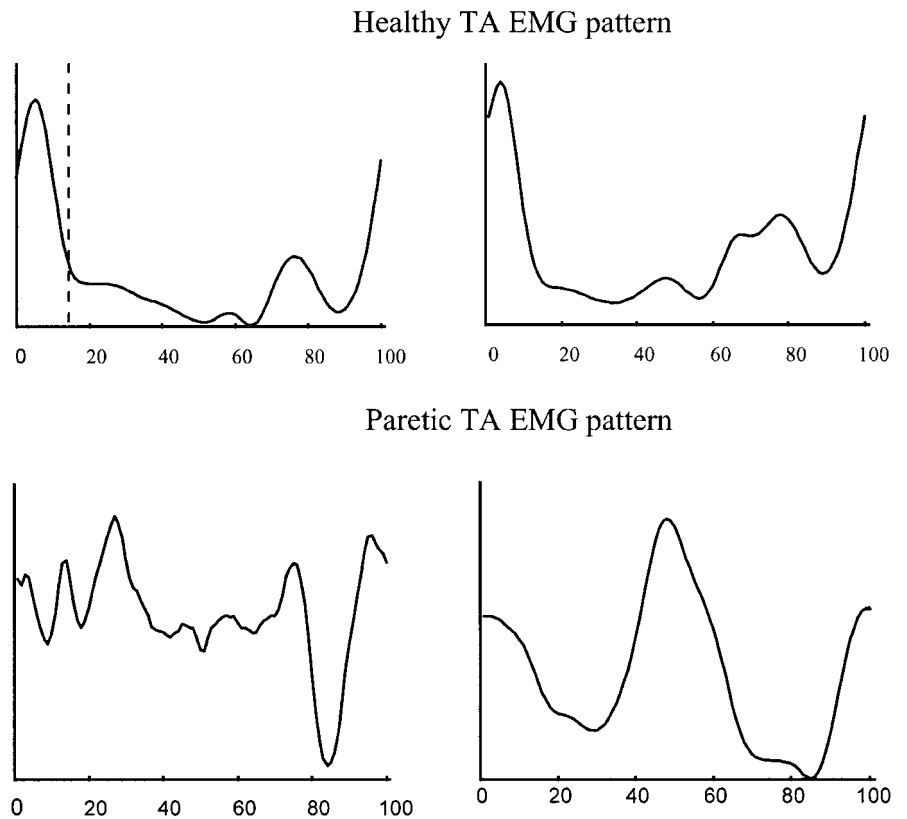


Fig 2. Random example of mean rectified filtered electromyographic (EMG) pattern of tibialis anterior (TA) during a step cycle for 2 healthy and 2 paretic subjects. The 15% border is indicated.

for the step cycle as a whole. Measurements of the first 15% of the step cycle were not represented because in the paretic subjects this specific first electromyographic burst was not found consistently. Figure 5 shows the fairly consistent reaction pattern over the 3 measurement sessions. This means that no adaptation effect of AFO use could be shown.

isting paresis. In a case of foot drop, an AFO is often prescribed to restore a more normal and safe walking pattern. In this study, we evaluated the effect of AFO use on electromyographic activity of 5 lower leg muscles in healthy and recent paretic subjects. We found a significant decrease of 7% and 20%,

**DISCUSSION**

In clinical practice, the question often arises whether an orthosis diminishes muscle activity, thereby worsening an ex-

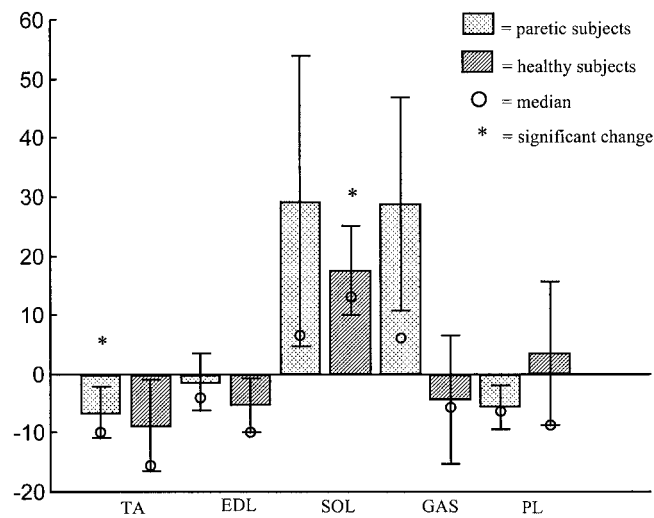


Fig 3. Mean immediate change in muscle activity with AFO use per muscle, for paretic and healthy subjects, standard error of the mean (SEM) and median.

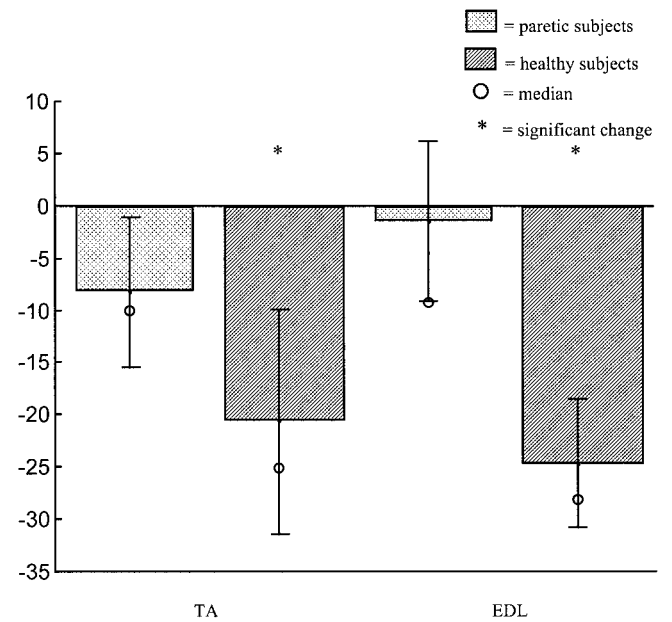


Fig 4. Mean immediate change in muscle activity in the first 15% of the gait cycle for, respectively, paretic and healthy dorsiflexors, SEM, and median.

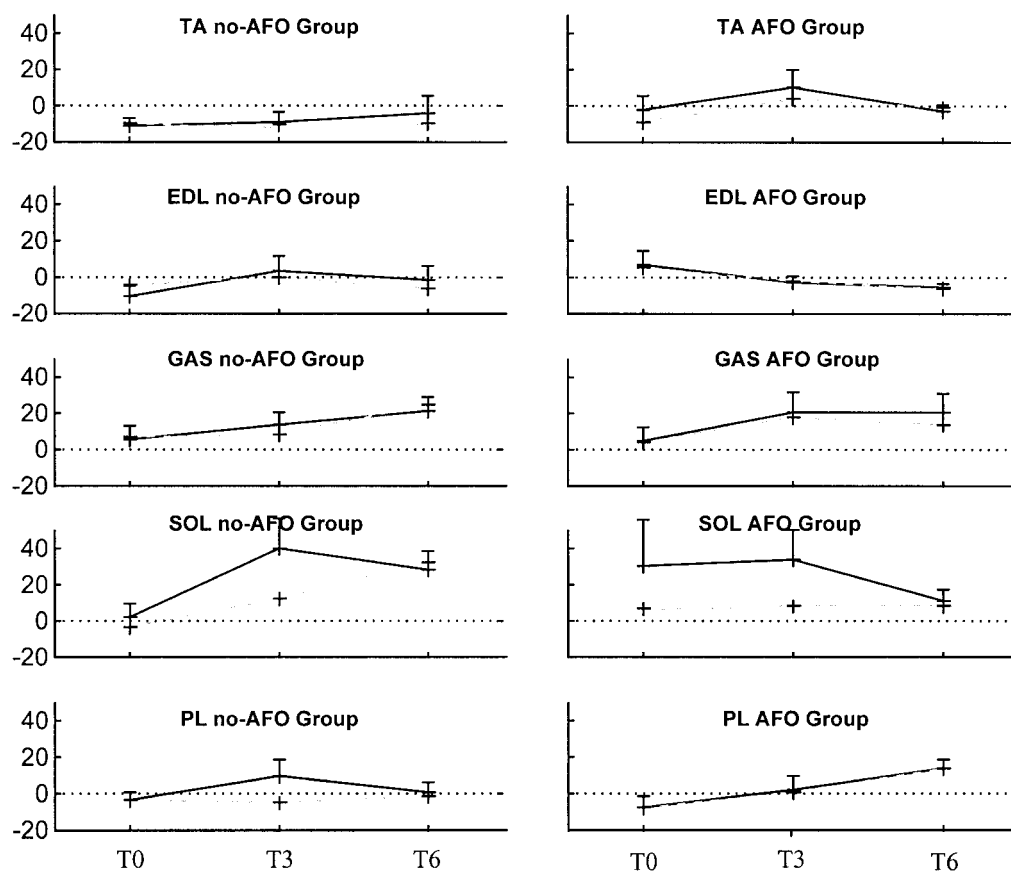


Fig 5. Relative change in electromyographic activity of the tibialis anterior (TA), extensor digitorum longus (EDL), gastrocnemius muscle (GAS), soleus (SOL), and peroneus longus (PL) in the no-AFO group and AFO group at T0, T3, and T6. NOTE. Mean (solid line), SEM, and median (broken line).

respectively, in paretic and healthy subjects in tibialis anterior activity when an AFO was used but during different phases of the gait cycle. In the paretic group, electromyographic activity decreased when calculated over the step cycle as a whole, and it decreased in healthy subjects in the first 15%. We could not show an adaptation effect during 6 weeks of AFO use in the patient group. This study addressed the problem through 4 separate questions discussed later.

Our first question focused on the reproducibility of the electromyographic measurements in healthy volunteers. The reported correlation coefficient for the within-subject reproducibility proved to be good for most muscles and is in accord with Winter and Yack.<sup>27</sup>

Second, we wanted to know whether there was a change in muscle activity when people with or without paresis used an AFO. We found a significant decrease of tibialis anterior muscle activity in healthy persons in the first 15% of the gait cycle and in paretic muscles during the entire gait cycle. However, the variability in motor patterns during the gait cycle was much larger in the paretic group, causing the first 15% of the gait cycle to be not specific for the tibialis anterior. For the calf muscles in the healthy subjects, there was also a significant decrease of the overall activity of the soleus muscles in the AFO condition. The gastrocnemius muscle in all subjects showed a large variability in activity levels in its reaction to AFO use. This corroborated the observation that while walking on the treadmill, several persons tried to plantar flex their ankles during toe-off, although they were restricted in this direction by the AFO. These differences in reacting to the ROM restriction of the ankle in all subjects can explain the large inter-individual variety in electromyographic changes with AFO use, which is reflected in the large SD for the calf muscles.

Third, we questioned whether the amount of change in reaction to AFO use differed between paretic muscles and healthy muscles. We found no significant differences in the amount of change. However, the healthy subjects did specifically show a decrease in electromyographic activity during the first burst of the tibialis anterior immediately after heelstrike, whereas the paretic subjects showed a decrease in overall electromyographic activity during the step cycle. This means that results of studies of muscle activity patterns in healthy subjects cannot be extrapolated to patients without careful consideration. A possible difference in reaction pattern, and especially a much larger variety, must be expected in paretic muscles.

Finally, we asked whether an adaptation phenomenon occurred in the amount of activity of the supported paretic muscles in a 6-week follow-up period. We found no significant changes during that period in the amount of electromyographic change after putting on an AFO within or between the groups at the first and last measurement (ie, an adaptation effect over time was not found). The immediate drop in electromyographic activity of the tibialis anterior in AFO use may have accumulated after a longer period of orthosis use, thus enlarging the  $\delta$  value between T0 and T6. Or, if the muscle had adapted to the lower electromyographic activity level during AFO use, walking with or without AFO would generate the same values, lowering the  $\delta$  value between T0 and T6. However, because this was not shown, AFO use by recently paretic patients seems not to induce significant changes in muscle reaction after 6 weeks of daily use, compared with the immediate reaction. If, however, patients are more active with an AFO because they feel safer, or because walking is easier than it is without AFO,

this might have a stimulating effect on nerve recovery, as shown by van Meeteren et al<sup>28</sup> in a rat model.

Differences in walking velocity between the subjects were not taken into account as a variable to explain our data because the walking velocities during the different measurements were nearly identical. Earlier studies by McCulloch et al<sup>29</sup> and Yang and Winter<sup>30</sup> showed no significant changes in electromyographic patterns in subjects walking at different speeds. Because the relative changes were used to compare between subjects, no significant influence of walking speed was expected.

Also, it is not likely that AFO use would significantly influence the muscle patterns because of its weight. The weight of a standard AFO is only 125g. For a man of 80kg, the moment of inertia for the leg is raised by only 3.4%, from .291 to .301kg/m<sup>2</sup>.<sup>31</sup>

Finally, the strict inclusion criteria (ie, only subjects with a recent peripheral paresis MRC Scale scores from 1 to 4) resulted in a relatively small sample size. This might have caused small changes to not be identified as statistically significant, although some statistically significant differences were found. Also, we used only 1 type of AFO to limit variances in electromyographic activities that might be caused by the use of different materials or shapes. The ultimate effect of AFO use on strength production after 6 weeks is reported in a separate article.<sup>32</sup>

### CONCLUSION

Although AFO use significantly reduces electromyographic activity of the tibialis anterior in healthy subjects (20% during the first 15% of the step cycle), and in paretic subjects (7% calculated over the step cycle as a whole), the reduction does not accumulate over time. This decrease in electromyographic activity during AFO use is easily compensated for by an increase in total walking activity facilitated by AFO use. Therefore, even in recent paretic subjects, no contraindication exists for AFO use to enhance walking safely.

### References

1. Jaivin JS, Bishop JO, Grant Braly W, Tullos HS. Management of acquired adult dropfoot. *Foot Ankle* 1992;13:98-104.
2. Appell H. Muscular atrophy following immobilisation. A review. *Sports Med* 1990;1:42-58.
3. Tropp H, Norlin R. Ankle performance after ankle fracture: a randomized study of early mobilization. *Foot Ankle Int* 1995;16:79-83.
4. Geboers JF, van Tuijl JH, Seelen HA, Drost MR. Effect of immobilization on ankle dorsiflexion strength. *Scand J Rehabil Med* 2000;32:66-71.
5. Bruelmeier M, Dietz V, Leenders KL, Roelcke U, Missimer J, Curt A. How does the human brain deal with a spinal cord injury? *Eur J Neurosci* 1998;10:3918-22.
6. Cohen LG, Bandinelli S, Topka HR, Fuhr P, Roth BJ, Hallett M. Topographic maps of human motor cortex in normal and pathological conditions: mirror movements, amputations and spinal cord injuries. *Electroencephalogr Clin Neurophysiol Suppl* 1991;43:36-50.
7. Green JB, Sora E, Bialy Y, Ricamato A, Thatcher RW. Cortical sensorimotor reorganization after spinal cord injury: an electroencephalographic study. *Neurology* 1998;50:1115-21.
8. Kaas JH. The reorganization of somatosensory cortex following peripheral nerve damage in adult and developing mammals. *Ann Rev Neurosci* 1983;6:325-56.
9. Dubo HI, Peat M, Winter DA, et al. Electromyographic temporal analysis of gait: normal human locomotion. *Arch Phys Med Rehabil* 1976;57:415-20.
10. Basmajian JV, DeLuca CJ. *Muscles alive: their function revealed by electromyography*. Baltimore: Williams & Wilkins; 1985.
11. Shiavi R. Electromyographic patterns in adult locomotion: a comprehensive review. *J Rehabil Res Dev* 1985;3:85-98.
12. Kameyama O, Ogawa R, Okamoto T, Kumamoto M. Electric discharge patterns of ankle muscles during the normal gait cycle. *Arch Phys Med Rehabil* 1990;71:969-74.
13. Lehmann JF, Condon SM, de Lateur BJ, Smith JC. Gait abnormalities in tibial nerve paralysis: a biomechanical study. *Arch Phys Med Rehabil* 1985;66:80-5.
14. Lehmann JF, Condon SM, de Lateur BJ, Smith JC. Ankle-foot orthoses: effect on gait abnormalities in tibial nerve paralysis. *Arch Phys Med Rehabil* 1985;66:212-8.
15. Lehmann JF, Condon SM, de Lateur BJ, Price R. Gait abnormalities in peroneal nerve paralysis and their correction by orthoses: a biomechanical study. *Arch Phys Med Rehabil* 1986;67:380-6.
16. Lehmann JF. Push-off and propulsion of the body in normal and abnormal gait, correction by ankle-foot orthoses. *Clin Orthop* 1993;288:97-108.
17. Perry J. *Kinesiology of lower extremity bracing*. Clin Orthop 1974;102:18-31.
18. Perry J. *Gait analysis*. Thorofare (NJ): Slack; 1992.
19. Balmaseda MT, Koozekanani SH, Fatehi MT, Gordon C, Dreyfuss PH, Tanbonliong EC. Ground reaction forces, center of pressure, and duration of stance with and without an ankle-foot orthosis. *Arch Phys Med Rehabil* 1988;69:1009-12.
20. Diaz GY, Averett DH, Soderberg GL. Electromyographic analysis of selected lower extremity musculature in normal subjects during ambulation with and without a Protonics knee brace. *J Orthop Sports Phys Ther* 1997;26:292-8.
21. Cerny K, Perry J, Walker JM. Effect of an unrestricted knee-ankle-foot orthosis on the stance phase of gait in healthy persons. *Orthopedics* 1990;13:1121-7.
22. Bulthaupt S, Cipriani DJ, Thomas JJ. An electromyography study of wrist extension orthoses and upper-extremity function. *Am J Occup Ther* 1999;53:434-40.
23. Jansen CW, Olson SL, Hasson SM. The effect of use of a wrist orthosis during functional activities on surface electromyography of the wrist extensors in normal subjects. *J Hand Ther* 1997;10:283-9.
24. Medical Research Council. *Aids to the examination of the peripheral nervous system*. London: Her Majesty's Stationery Office; 1976.
25. Winter DA. Pathologic gait diagnosis with computer-averaged electromyographic profiles. *Arch Phys Med Rehabil* 1984;65:393-8.
26. Winter DA. Linear envelope EMG as a biomechanical variable in the assessment of human movement. In: Anderson PA, Hobart DJ, Danoff JV, editors. *Electromyographical kinesiology*. Amsterdam: Elsevier Science; 1991. p 197-200.
27. Winter DA, Yack HJ. EMG profiles during normal human walking: stride-to-stride and inter-subject variability. *Electroencephalogr Clin Neurophysiol* 1987;67:402-11.
28. van Meeteren NL, Brakkee JH, Hamers FP, Helden PJ, Gispen WH. Exercise training improves functional recovery and motor nerve conduction velocity after sciatic nerve crush lesion in the rat. *Arch Phys Med Rehabil* 1997;78:70-7.
29. McCulloch MU, Brunt D, Vander Linden D. The effect of foot orthotics and gait velocity on lower limb kinematics and temporal events of stance. *J Orthop Sports Phys Ther* 1993;17:2-10.
30. Yang JF, Winter DA. Surface EMG profiles during different walking cadences in humans. *Electroencephalogr Clin Neurophysiol* 1985;60:485-91.
31. Winter DA. *Biomechanics and motor control of human movement*. 2nd ed. New York: John Wiley; 1990.
32. Geboers JF, Janssen-Potten YJ, Seelen HA, Spaans F, Drost MR. Evaluation of effect of ankle-foot orthosis use on strength restoration of paretic dorsiflexors. *Arch Phys Med Rehabil* 2001;82:856-60.

### Suppliers

- a. K-Lab Kinesiology, Lorentzkaade 34 2014 CA Haarlem, Amsterdam.
- b. Medi-Trace®; The Ludlow Co LP, a Tyco Healthcare Co, 2 Ludlow Park Dr, Chicopee, MA 01022.
- c. Otto-Bock Orthopedic Industry GmbH & Co, Max Näderstr 15, 37115 Duderstadt, Germany.
- d. The MathWorks Inc, 24 Prime Park Way, Natick, MA 01760.
- e. SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.