The Effects of Tone-Reducing Orthotics on Walking of an Individual After Incomplete Spinal Cord Injury

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Purpose: Most literature about the efficacy of tone-reducing orthotics pertains to adults and children with central nervous system (CNS) pathology. There is relatively little mention of using this type of orthotic with adults after spinal cord injury (SCI). Therefore, the purpose of this study was to investigate whether tone-reducing orthotics have an effect on gait including electromyographic (EMG) activity, velocity, step length, time in double-limb support, and SCI-Functional Ambulation Inventory (SCI-FAI) scores for an individual with incomplete SCI and spasticity.

Methods: We used a single case design. The subject was a 25-year-old white male who was 16 months post-injury with a diagnosis of T6 left/T9 right sensory, L3 motor American Spinal Injury Association C incomplete SCI. Five different walking conditions were tested during each of two separate sessions: barefoot, shoes, foot plates, one ankle-foot orthosis (AFO) with a joint, and one with a tone-reducing AFO, and tone-reducing AFOs bilaterally. Surface EMG was used to record electrical activity of four muscle groups bilaterally. Step length, gait velocity, and time in double limb support were calculated for all five walking conditions. Gait parameters were further analyzed with video analysis using the SCI-FAI.

Results: Mean EMG was relatively constant in all muscle groups under all walking conditions with the exception of the gastrocnemius. In this muscle group, EMG activity with the use of tone-reducing orthotics was better modulated than the other conditions. Gait velocity and step length both increased with tone-reducing orthotics, whereas double limb support time decreased, thus improving the corresponding SCI-FAI score accordingly.

Conclusion: The subject showed improvement in the control of his lower extremities while wearing bilateral tone-reducing AFOs as evidenced by an increased step length and gait velocity and a decrease in the amount of time spent in double limb support. Electromyographic data were less conclusive, although activity in the left gastrocnemius muscle group was more erratic under alternative walking conditions when compared to the tone-reducing AFOs.

Key words: incomplete spinal cord injury, tone-reducing orthotics, walking

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INTRODUCTION

Approximately 11,000 people per year in the United States survive and subsequently live with a spinal cord injury (SCI). Incomplete injuries are becoming more common and currently exceed 50% of all SCI injuries.[1] With advances in trauma care coupled with new interventions, the proportion of patients with incomplete SCI will continue to increase.[2]

Eighty-six percent of patients with incomplete tetraplegia can be expected to recover some capacity for walking.[3] While some motor recovery after SCI is spontaneous, the training effect of early, task-specific rehabilitation enhances motor outcomes.[4–6] New neurological agents can be expected to further enhance these numbers.[7,8] Because of the increasing numbers of clients who have incomplete SCIs,[1,2,9–11] the question for physical therapists is less often whether an individual with an SCI will walk again, but more a question of how soon and how well.

Spasticity is a significant factor limiting successful rehabilitation outcomes.[12] In this case, spasticity is defined as muscle hypertonia and exaggerated tendon reflexes, including clonus.[13] The presence of ankle clonus coupled with a strong positive supporting reaction is particularly problematic. It is possible to inhibit clonus with strong loads,[14] which explains the gradual reduction or extinction of clonus with prolonged static weight-bearing. However, walking, with its cycle of weight-bearing and nonweight-bearing, often elicits a renewed bout of clonus with each step. The positive supporting reaction, often elicited with a sensory stimulus to the metatarsal heads in an individual with central nervous system pathology, is characterized by excessive knee extension and plantarflexion and can completely prevent standing and walking without regard for accompanying muscle weakness.[14] A positive supporting reaction can nearly triple the energy needed to initiate swing phase,[15] while reduced knee velocity and increased time in double limb support highly correlate with the degree of spasticity.[12] Since stride frequency is more important than stride length when attempting to increase walking speed,[16] extra time spent in double limb support is a limiting factor in long-term walking outcomes. Therefore, rehabilitation interventions should focus on improving the speed of alternating advancement of the lower extremities.[16]

Sensory feedback is commonly used in neurological rehabilitation approaches. For individuals who have incomplete spinal cord injuries, studies indicate that "appropriate" loading during stance can increase extension of the support leg and also can trigger swing phase in the contralateral

FIGURE 1. Bilateral tone-reducing orthotics.

limb.[17–19] Tone-reducing orthotics are designed to achieve the most appropriate loading possible, thereby decreasing reflexive muscle activation and improving the walking pattern. Whether improved walking with the use of tone-reducing orthotics is neurophysiological or mechanical, the result could possibly have a positive overall outcome on gait when considering recent knowledge of the plasticity of the spinal neural circuitry.[20]

Current clinical rehabilitation options fail to yield satisfactory results in controlling the specific spastic patterning elicited during weight-bearing. While the use of tone-reducing orthotics to address specific spastic movement patterns is discussed in stroke and cerebral palsy literature,[21–28] the SCI literature rarely mentions them. Atrice[29] briefly mentions incorporating tone-reducing modifications into ankle-foot orthoses (AFOs) in her review of lower extremity orthotic management of incomplete SCI and Barbeau et al[2] state that at the time of their report, there were no studies reporting possible therapeutic effects of orthotics after SCI.

Although most AFOs have some tone-reducing benefits,[21,28] a tone-reducing AFO uses a more deliberate approach to achieve an intensified outcome. A tone-reducing AFO, as depicted in Figure 1, uses a metatarsal pad and a great toe extension feature. Toe extension is accomplished by building a toe shelf under the great toe accompanied by an extension shelf to abduct the remaining four digits. The metatarsal pad and toe shelf used together take the weight off the metatarsal heads while extending the toes.

There is anecdotal evidence that even slight extension of the toes has a neurological tone-reducing effect on abnormal extensor responses in the lower extremity.[30] Other tone-reducing qualities are thought to include (1) continuous pressure at the point of a muscle insertion specifically the gastrocnemius/soleus attachment[31]; (2) mechanical stabilization of a joint, which reduces tone through static immobilization[31]; and (3) materials considered "passive fields," defined as cool, rigid, and smooth (most thermoplastics), which tend to produce inhibition of muscle tone when applied in full contact with muscle bellies.[31]

The purpose of this study was to investigate whether tone-reducing orthotics have an effect on gait parameters including electromyographic (EMG) activity, step length, gait velocity, time in double-limb support, and SCI-Functional Ambulation Inventory (SCI-FAI)[32] scores in an individual with incomplete SCI and spasticity. We hypothesized that the use of tone-reducing orthotics would change the abnormal electrical activity of lower extremity muscles and improve gait characteristics when compared to other walking conditions.

METHODS

Subject

The subject was a 25-year-old white male rancher with a diagnosis of T6 American Spinal Injury Association (ASIA) C[33] incomplete paraplegia as a result of a motor vehicle accident 16 months before the study. Immediate postinjury emergency department records documented that there was no sensation below the nipples, no voluntary movement below the level of injury, and decreased rectal sphincter tone consistent with a diagnosis of T4 ASIA A complete paraplegia. When the subject was admitted to inpatient rehabilitation six weeks post-injury, he had intact pinprick sensation throughout, intact light touch to T9 on the right and T6 on the left, and absent light touch below L3 with the exception of the sacral segments. The subject demonstrated visible and palpable muscle contractions in the long toe extensors and ankle plantar flexors as well as voluntary anal contraction and a positive anal wink. Throughout his course of rehabilitation, his strength steadily improved and his diagnosis was upgraded to T9 right, T6 left sensory, L3 motor ASIA C, incomplete paraplegia. His manual muscle test (MMT) scores reflected this improvement and are reported in Table 1. Plantar flexion is not reported, however, because spasticity was triggered each time manual resistance was applied or weight-bearing occurred through the plantar surface of his foot, thus invalidating any standardized MMT results.

The subject exhibited problematic spasticity throughout his rehabilitation. Modified Ashworth[34] scores were typically grade four in the lower extremities bilaterally with consistent findings of sustained clonus. The subject began taking oral baclofen prior to inpatient rehabilitation admission. His dose at the time of this study was stabilized at 30 mg three times daily. He also received a one-time dose of botulinum toxin[35] injected into the left and right hamstrings at approximately 10 weeks post-injury with the stated intent of alleviating flexor spasms, which were thought to be compromising the safety of his emerging sliding board transfer skills.

The subject was evaluated for possible walking potential prior to inpatient discharge/outpatient admission at ap-

TABLE 1. Lower Extremity Manual Muscle Testing from Chart Review

	4 Months Post-injury		6 Months Post-injury		9 Months Post-injury	
	Right	**Left**	**Right**	**Left**	**Right**	**Left**
Hip flexion	1+	2	2+	3+	4−	4
Hip abduction	1−	1+	1−	2+	2−	3
Hip extension	*	*	3	3	2+	2
Hip adduction	*	*	5	5	*	*
IR	2	1−	*	*	2	2
ER	1	1−	*	*	1−	1−
Knee extension	3	2	4	4	5	5
Knee flexion	*	*	2	3	2	3+
Dorsiflexion	1	1−	1−	3	2	3
Ankle eversion	*	*	*	*	0	1+
Ankle inversion	*	*	*	*	1−	2
Toe extension	*	*	3	3	*	*

* Data not available in patient records.
Abbreviations: ER, external rotation; IR, internal rotation.

proximately three months post-injury. At that time, he demonstrated the ability to walk 10 feet using a high platform four-wheeled walker and bilateral knee immobilizers with moderate to maximal assistance of two assistants. Because of spastic paretic movement patterns during weight-bearing, which for our subject included toe-walking coupled with a scissoring gait pattern, the rehabilitation team decided to include tone-reducing features in his initial knee-ankle-foot orthoses (KAFOs) as well as use a design that allowed for reduction of the KAFOs to AFOs when appropriate. By attempting to control and reduce hyperreflexive patterning during weight-bearing activities, the intention was to facilitate emergent walking by controlling spasticity.

Upon discharge from outpatient physical therapy at approximately 14 months post-injury and during the time of this case study at 16 months post-injury, the subject was able to use bilateral tone-reducing AFOs to walk distances of greater than 300 meters with a front-wheeled walker, including the negotiation of uneven surfaces including grass, gravel, ramps, curbs, and stairs. He was able to walk shorter distances with the more challenging Loftstrand forearm crutches and used walking functionally to load his wheelchair into the back of his pick-up truck and less often to negotiate inaccessible buildings. For most of this subject's day-to-day activity, however, he used a wheelchair, chose to forego the orthotics, and transferred with shoes alone.

During the course of outpatient therapy, various orthotics were tried; however, after clinical observation of his reduced walking ability with these devices, the rehabilitation team decided to continue the use of the tone-reducing orthotics.

Procedures

Prior to initiating this study, the subject granted us both verbal and written consent to participate and share the results via a dissemination format of our choosing. We also obtained Institutional Review Board approval from University of North Dakota, St. Alexius Medical Center, and the University of Mary.

The subject was selected for this single case design because he fit the criteria of ongoing problematic spasticity during walking after incomplete SCI. Furthermore, since the subject had previously been fit with several types of orthotics during the course of his rehabilitation, we had a variety of custom-fit orthotics available for testing. The subject was willing to participate with no contraindications related to the procedures.

Five walking conditions were tested during two separate sessions conducted one week apart. The walking conditions were barefoot, shoes, footplates, jointed AFO on the left and tone-reducing AFO on the right, and tone-reducing AFOs bilaterally. These walking conditions are further detailed in Table 2. During each of the two sessions, the subject walked six 18-foot segments for each of the five walking conditions, resulting in a total of 30 walking segments for each session.

The same examiners prepared the subject for each testing session with one assessing the level of spasticity (tonic

TABLE 2. Walking Conditions

Barefoot	The subject wore no shoes or socks. Testing took place on a smooth, cool, uncarpeted surface.
Shoes	The shoes worn without orthotics were flat, rubber-soled athletic shoes that had a built-in arch support with trim lines that ended just below the malleoli bilaterally.
Foot plates	The tone-reducing foot plates were fabricated similarly to the tone-reducing AFOs but contacted only the plantar surface of the foot and extended only one half inch up the sides. There was no dorsal strap or contact with the Achilles tendon. The foot plates were held in place by regular shoes.
AFO with joint on left, tone-reducing AFO on right	The jointed left AFO was made of 3/16 to ¼ inch copolymer but with the tone-reducing metatarsal pad and toe shelves placed after casting using expanded polyethylene foam. The joint was made of polymer with a 90-degree plantar flexion stop and free dorsiflexion. The dorsal strap was internal, similar to a "T" strap, to limit plantarflexion within the brace.
Tone-reducing AFOs	The tone-reducing AFOs consisted of orthopedic-grade 3/16 to 1/4 inch copolymer plastic cast into three degrees of dorsiflexion[43] with solid ankles, trim lines anterior to the malleoli bilaterally and finger formed into intimate contact with the Achilles tendon. During casting, we used an Orthomerica prefabricated foot plate with some adjustments made with heat that provided a divided, elevated, and extended toe plate and a built-in metatarsal pad. Carbon struts were added for extra sagittal support. The anterior Velcro dorsal strap was padded with foam. Shoes worn with the tone-reducing orthotics were flat, rubber-soled athletic shoes two full sizes larger than the subject's usual size to accommodate the extended toe plates.

Abbreviations: AFO, ankle-foot orthosis.

TABLE 3. Modified Ashworth Scores and Clonus for Subject Prior to Each Session

	Session 1		Session 2	
	Left	Right	Left	Right
Adductor	3	4	3	3
Quadriceps	1	1	1	1
Hamstrings	4	4	4	4
Gastrocsoleus	4	4	4	4
Clonus	Present sustained	Present sustained	Present sustained	Present unsustained

stretch reflex) using the Modified Ashworth Scale and another attaching the electrodes. The Modified Ashworth Scale was administered after the subject was resting comfortably in the supine position. Hip adduction, knee flexion, and knee extension were tested with the examiner placing one hand on the posterior limb slightly proximal to the knee with the other hand supporting the leg near the ankle. Plantar flexion was tested with the examiner stabilizing the limb at the ankle with the testing hand resting under the metatarsal heads of the foot. The examiner moved the limb through the appropriate hip, knee, or ankle range of motion within one second. Results of the subject's Modified Ashworth scale are reported in Table 3. To prepare for electrode attachment, the electrode sites were shaved and rubbed with alcohol. The electrodes were taped directly over the motor points and oriented parallel to the muscle fibers of the medial gastrocnemius, vastus lateralus, adductor longus, and medial hamstrings bilaterally. Immediately prior to initiating the walking sequences, a set of two maximal voluntary contractions (MVCs) for each tested muscle group were recorded in a seated position.

The five walking conditions were tested using identical procedures during each session, with the exception of the walking condition sequence, which was deliberately changed from the first session to the second. The sequence during the first session was (1) shoes, (2) barefoot, (3) bilateral tone-reducing AFOs, (4) jointed AFO left and tone-reducing AFO right, and (5) bilateral foot plates. During the second session, the sequence was (1) barefoot, (2) foot plates, (3) shoes, (4) jointed AFO left and tone-reducing AFO right, and (5) bilateral tone-reducing AFOs.

For each of the five walk segments that were performed each testing session, stand-by guarding was provided. A NorAngle (Noraxon USA Inc., Scottsdale, AZ) biaxial goniometer was manually triggered at both heel strike and toe off to mark the EMG record with the start and end of stance phase. The goniometer was triggered by one of the examiners who was positioned at midpoint of the walkway at a location that provided a clear view of the subject's feet.

We used a stationary video camera to record the walking trials from a sagittal view. In this way, we obtained six sets of data to calculate step length and gait velocity and four sets of data to record EMG activity for stance and swing gait phases for each walking condition. Between conditions, the subject rested in his wheelchair for a minimum of three minutes.

EMG Measurement

The bilateral surface EMG of the rectus femoris, medial hamstrings, gastrocnemius, and adductor muscles were concurrently recorded during four of the six segments for each walking condition. To measure EMG activity, we used bipolar dual silver chloride electrodes that are one centimeter in diameter and have a fixed interelectrode space of two centimeters between recording surfaces. Each of the dual electrodes was connected with cables to an eight-channel Noraxon Myosystem 1200 EMG (electrodes and Myosystem, Noraxon USA, Inc.). This system has a sensitivity of ± 100 μV, a differential input impedance of greater than 10 MΩ, a common mode rejection ratio of greater than 100 dB at 60 Hz, and a frequency response of 10 to 500 Hz. The Myosystem was connected with a computer via a 16-channel, 12-bit A/D card (KPCMCIA-12AI-C, Keithley Instruments, Inc., Cleveland, OH). The sampling rate was 1000 Hz for each channel, which was the frequency most appropriate for our instrumentation. The EMG activity of the eight muscle groups was continuously monitored as the subject completed each of the 18-foot gait segments. The EMG data for each testing condition were saved for analysis.

Data Analysis

EMG data were processed and analyzed using MyoResearch 2.0 software. The EMG signal was filtered using a 60-Hz Butterworth filter, rectified and integrated for data analysis. Because the amplitude of the electrical activity elicited during the subject's MVC was too small for analysis, it was discarded. For each of the target muscle groups, the EMG processing software calculated the mean EMG for the stance phase and the swing phase of each walking segment. Subsequently, we entered the mean EMG microvolt reading per 18-foot segment for each muscle, for each walking condition, and for both the stance and swing phases into SPSS software to calculate the combined mean EMG microvolt reading of the four segments, both for the stance and swing.

All six segments for each walking condition were averaged for each session to calculate the average time and step length. Using these averages, step length was calculated by dividing the average number of steps into 18 feet, and velocity was calculated by dividing the 18-foot distance by the average time. Double limb stance time was calculated for the first session only because the subject demonstrated greater spasticity than in the second session, which would allow the use of tone-reducing orthotics a chance to demonstrate a greater effect than when the subject had less spasticity. The time in double limb support was calculated from the EMG record based on the period during which both limbs were in stance phase and also when one limb was in swing phase as indicated by their respective heel strike–toe off markers. Therefore, the examiners decided that using a sample for this gait parameter would be sufficient for this parameter and hand-counting the time in double limb support from the computer printout would not be necessary. Twelve of the clearest double limb support phases of gait from the first two segments of the experiment for each walking condition were averaged for time and compared.

The quality of the subject's gait, including the ability to shift weight onto the limb during stance, attain sufficient abduction to allow the swing leg to clear the stance leg during limb advancement, maintain symmetrical step rhythm, achieve adequate step length, toe clearance during stepping, and heel strike, was assessed via video analysis and graded according to the parameters of the SCI-FAI.[32]

RESULTS

The mean EMG activity in most muscle groups was relatively constant when comparing walking conditions; however, there was variability in the left gastrocnemius during both sessions for stance phase and in the first session for swing phase. The least EMG activity in the gastrocnemius during both sessions occurred with the use of tone-reducing orthotics, whereas the most activity occurred during the barefoot and shoes conditions. The mean gastrocnemius EMG activity was less during stance phase under all conditions in session 2 as compared to session 1. A comparison of means and standard deviations for the stance and swing phases for four trials of all walking conditions and all muscle groups are recorded in Tables 4 and 5, respectively. Table 6 contains mean EMG data of the left gastrocnemius for each 18-foot segment and is included to show the extent of variability during both sessions for stance phase and the first session for swing phase.

The average step length and gait velocity increased and time in double limb support decreased with the use of tone-reducing AFOs when compared to other walking conditions during session 1. The data were not as convincing in session 2 as tone-reducing orthotics were similar to those for shoes in the step length and velocity parameters (Table 7). Video analysis using the parameter section of the SCI-FAI reflected these improvements as higher scores were achieved with tone-reducing orthotics than with any other walking condition (Table 8).

DISCUSSION

The purpose of this study was to determine whether tone-reducing features built into lower extremity orthotics have a measurable effect on EMG activity and other gait parameters in a subject with spastic paresis after incomplete SCI when compared to other walking conditions. The results of this study are consistent with our hypothesis that functional walking can be improved with the use of tone-reducing AFOs. Velocity and step length generally increased and the length of time in double limb support decreased when the subject was using tone-reducing orthotics. We did not see the expected differences in the mean EMG activity among various walking conditions, however.

For all conditions, our subject's swing phase was very short, making the double limb support phase much longer than the normal 60% of the gait cycle.[36] Increased time in double limb support seems to be the limiting factor in improving the speed of alternating the advancement of the lower extremities.[31] Data reported in Table 7 are only from the first two segments of the first trial, which is a limitation of this study, but these data are an indication that for this subject, the amount of time spent in double limb support decreased with the use of tone-reducing orthotics. In the sample used, the subject spent 1.2 seconds less time per step in double limb support using the tone-reducing AFOs than when he was walking barefoot. In other words, in tone-reducing orthotics, this subject was able to increase the duration of single limb support, demonstrating progress toward a more normal walking pattern. Therefore, we might

TABLE 4. Average and Standard Deviations of Mean EMG Activity (μV) for the Stance Phase for Four Segments of All Walking Conditions and All Muscle Groups

	Barefoot	Shoes	Footplates	Jointed AFO/L	Tone-reducing AFOs
Session 1					
R vastus	37.65 ± 07.67	26.85 ± 03.79	27.03 ± 02.91	28.16 ± 09.68	25.57 ± 03.07
L vastus	52.00 ± 11.72	39.22 ± 11.60	42.18 ± 05.39	38.00 ± 07.13	29.15 ± 04.94
R hip add	15.87 ± 01.53	14.40 ± 03.49	15.09 ± 00.28	14.32 ± 00.46	14.99 ± 00.71
L hip add	15.49 ± 00.09	17.94 ± 03.83	15.49 ± 00.28	15.33 ± 00.25	15.51 ± 00.08
R HS	22.99 ± 02.95	19.57 ± 02.00	21.37 ± 01.02	18.54 ± 01.40	19.77 ± 02.37
L HS	19.31 ± 00.92	17.25 ± 01.41	15.86 ± 00.38	15.12 ± 01.68	16.35 ± 01.81
R gastroc	77.96 ± 10.62	80.07 ± 11.83	81.30 ± 03.07	78.17 ± 06.73	86.24 ± 16.09
L gastroc	89.29 ± 19.94	174.74 ± 158.00	76.97 ± 10.14	78.61 ± 06.93	68.97 ± 16.97
Session 2					
R vastus	21.79 ± 00.86	25.67 ± 01.24	22.33 ± 02.91	21.46 ± 01.08	22.21 ± 01.78
L vastus	40.35 ± 08.04	52.09 ± 08.81	40.45 ± 00.37	44.83 ± 08.36	40.35 ± 05.18
R hip add	57.03 ± 03.34	40.05 ± 03.16	41.39 ± 06.90	30.85 ± 03.14	29.77 ± 02.24
L hip add	22.30 ± 00.76	25.29 ± 01.81	22.91 ± 00.88	23.64 ± 01.17	22.30 ± 01.17
R HS	17.22 ± 01.81	17.33 ± 02.04	15.96 ± 00.66	15.44 ± 01.48	16.22 ± 01.98
L HS	24.70 ± 00.78	24.87 ± 00.74	24.50 ± 01.39	22.22 ± 01.89	20.89 ± 01.09
R gastroc	68.13 ± 06.92	71.09 ± 04.68	65.59 ± 01.86	70.41 ± 07.43	68.13 ± 06.92
L gastroc	48.48 ± 08.27	120.21 ± 60.27	47.95 ± 08.23	51.53 ± 08.53	49.48 ± 08.27

Values are mean ± SD.

Abbreviations: add, adductor; AFO, ankle-foot orthosis; EMG, electromyography; gastroc, gastrocnemius; HS, heel strike; L, left; R, right.

TABLE 5. Average and Standard Deviations of Mean EMG Activity (μV) for the Swing Phase for the First Four Segments of All Walking Conditions and All Muscle Groups

	Barefoot	Shoes	Footplates	Jointed AFO/L	Tone-reducing AFOs
Session 1					
R vastus	17.84 ± 06.42	23.68 ± 05.71	19.88 ± 04.23	17.73 ± 05.03	22.00 ± 03.61
L vastus	35.87 ± 18.61	72.84 ± 49.45	45.65 ± 29.10	95.18 ± 46.30	65.71 ± 47.50
R hip add	18.33 ± 29.56	41.29 ± 08.84	41.51 ± 01.64	44.47 ± 04.49	45.77 ± 06.67
L hip add	18.33 ± 08.54	21.02 ± 09.74	16.53 ± 07.18	25.19 ± 09.59	17.94 ± 09.45
R HS	15.79 ± 09.68	19.97 ± 13.92	17.19 ± 11.04	22.87 ± 09.61	20.77 ± 12.31
L HS	20.96 ± 03.83	26.62 ± 03.28	24.93 ± 04.05	24.18 ± 03.33	24.05 ± 04.90
R gastroc	55.26 ± 06.70	68.70 ± 19.69	64.06 ± 17.26	69.85 ± 22.90	74.96 ± 22.12
L gastroc	164.26 ± 139.20	67.17 ± 43.81	48.12 ± 35.65	73.79 ± 24.92	51.03 ± 8.53
Session 2					
R vastus	36.47 ± 10.45	21.87 ± 07.33	27.53 ± 13.99	26.76 ± 19.82	26.93 ± 09.68
L vastus	51.94 ± 30.98	39.74 ± 17.71	53.35 ± 37.61	56.69 ± 44.37	53.96 ± 31.24
R hip add	13.16 ± 01.17	10.56 ± 03.10	12.95 ± 01.99	10.39 ± 01.65	10.72 ± 01.98
L hip add	08.87 ± 01.66	14.84 ± 04.51	06.98 ± 01.11	05.59 ± 01.14	06.05 ± 00.59
R HS	18.46 ± 07.39	19.47 ± 03.97	17.47 ± 06.59	19.33 ± 05.02	20.65 ± 07.64
L HS	17.62 ± 04.51	15.41 ± 02.79	15.70 ± 06.61	16.47 ± 04.96	16.98 ± 04.71
R gastroc	66.13 ± 11.29	93.17 ± 51.87	97.78 ± 53.78	92.03 ± 47.12	88.38 ± 39.29
L gastroc	29.04 ± 136.34	77.79 ± 66.95	80.51 ± 59.56	87.87 ± 46.32	70.81 ± 45.90

Values are mean ± SD.
Abbreviations: add, adductor; AFO, ankle-foot orthosis; EMG, electromyography; gastroc, gastrocnemius; HS, heel strike; L, left; R, right.

TABLE 6. Left Gastrocnemius Mean EMG Activity (μV) for Each of the Four Walking Segments for Two Sessions (Stance) and One Session (Swing)

	Barefoot	Shoes	Foot Plates	Jointed AFO/L	Tone-reducing AFOs
Session 1 stance phase					
Walking segment					
1	118.94	409.12	67.99	71.89	89.54
2	75.69	120.19	69.57	74.30	76.18
3	81.59	63.92	89.55	86.51	53.61
4	80.9	105.76	80.79	81.76	56.58
Session 2 stance phase					
1	77.13	147.94	35.83	48.62	48.76
2	35.93	192.10	48.06	43.64	38.10
3	218.39	71.20	52.94	63.61	54.56
4	318.05	69.61	53.55	50.27	56.62
Session 1 swing phase					
1	44.09	114.12	62.91	75.68	92.96
2	46.23	94.80	91.48	87.71	75.89
3	309.71	27.43	22.56	38.13	17.96
4	257.01	32.36	15.53	93.63	17.32

Abbreviations: AFO, ankle-foot orthosis; EMG, electromyography; L, left.

infer that tone-reducing AFOs are important in facilitating a more functional gait pattern for the individual affected by incomplete SCI with spasticity.

Our initial intent was to use a percentage of the MVC as the baseline for comparison of walking conditions. Because the EMG showed little activity during MVC testing, we were unable to use this approach for data analysis. We speculate that the subject's actual voluntary muscle activity was not sufficiently strong enough to be recorded within the EMG sensitivity parameters. If that were the case, all motor activity recorded during gait would be related to the subject's positional change from sitting and nonweight-bearing to standing and weight-bearing. Limb loading during stance has been shown to increase EMG amplitude in individuals with SCI and muscle activation during unilateral stepping.[37,38]

Because we were unable to use a percentage of the MVC, we used the mean EMG, which is justified in the literature. Soderberg and Knutson[39] found that subjects in

TABLE 7. Comparison of Walking Conditions Regarding Average Step Length (in Feet); Gait Velocity (in Feet/Second), and Time in Double Limb Support (in Seconds)

	Barefoot	Shoes	Footplates	Jointed AFO/L	Tone-reducing AFOs
Step length (feet)[a]					
Session 1	1.06	1.06	1.06	1.13	1.16
Session 2	1.06	1.24	1.11	1.24	1.24
Velocity[a]					
Session 1	0.55	0.57	0.66	0.70	0.76
Session 2	0.59	0.80	0.67	0.78	0.82
Double limb support time[b]	3.7	3.3	3.0	2.7	2.5

[a] Step length and velocity are averaged for both sessions and all six segments.
[b] Calculated from the first two segments of session 1 measured in seconds.
Abbreviation: AFO, ankle-foot orthosis.

TABLE 8. Spinal Cord Injury Functional Ambulation Inventory Parameter Scores

Device	Session 1	Session 2
Tone-reducing AFOs	16/20	16/20
Jointed AFO Left	13/20	13/20
Barefoot	13/20	14/20
Shoes	11/20	15/20
Foot plates	13/20	12/20

Abbreviation: AFO, ankle-foot orthosis.

EMG trials can be considered their own controls if EMG data are collected the same day without the electrodes having been moved or adjusted. Soderberg and Knutson also suggest that several alternative trends for normalization of EMG data have emerged in the past 15 years, one of which allows the use of the mean EMG values obtained during a dynamic activity.

Although there was little difference in the mean EMG activity in most muscle groups tested, data indicate that bilateral tone-reducing AFOs had a modulating effect on the left gastrocnemius muscle. This effect in the gastrocnemius seems reasonable as the majority of tone-reducing features are intended to target this muscle group. Previous investigations of gastrocnemius muscle activity during walking in individuals with SCI[6] have shown that activity is lower in amplitude and poorly modulated compared to individuals who did not have neurological impairments. Our subject had poorly modulated EMG activity, which did improve using the bilateral tone-reducing orthotics (Table 6). Although other muscles, especially the quadriceps, did vary somewhat, the changes were not consistent enough to infer a pattern.

The jointed AFO also had a toe extension feature, albeit this was an add-on and not molded into the footplate. We considered the solid and molded ankle features of the tone-reducing orthotics to be part of the tone-reducing features in addition to the toe extenders.[31] Research in the pediatric literature[21] does not establish a difference in outcomes between a jointed versus a solid tone-reducing AFO with children who have spastic cerebral palsy; however, it is has been discussed that using any kind of AFO is better than using none.[21] There is limited evidence[40] that a dynamic AFO, which holds the ankle in a subtalar neutral position, can increase the velocity of individuals who have hemiplegia from a cerebral vascular accident. Our subject had improved gait parameters when both the solid ankle and toe extension were used.

The use of bilateral tone-reducing AFOs was the third tested walking condition in the first session and the last walking condition tested in the second session. During the second session, tone-reducing orthotics should have been tested first to eliminate the possibility of accommodation, which is a limitation of this study. The subject had not previously accommodated to the tone-reducing orthotics due to typical everyday use, however, because this subject preferred to use only shoes without orthotics for everyday transfers and limited locomotion.

The subject's overall spasticity level was one level greater in the right adductor during session 1 than session 2 as reflected in the Ashworth scores. This increased spasticity appears to be further reflected in the differing results found in the subject's speed and velocity performance as well as in the SCI-FAI parameter data. The difference in spasticity levels between the two sessions might be due to the influence of a reported bladder infection during the first session or otherwise influenced by the subject's increased familiarity with the testing procedures during the second session.

The importance of controlling spasticity during emergent walking becomes imperative when considering research that indicates an inverse relationship between voluntary and involuntary neurological pathways during acute SCI recovery. Little et al[4] state that reducing hyperreflexia may enhance motor recovery in patients with spastic SCI and that continuing motor recovery can and does reduce hyperreflexia. Maynard and colleagues[41] concur that as cortical control improves, a reduction of problematic spasticity is also often observed, which lends credence to their observation that individuals with ASIA B and C SCI tend to have more severe spasticity than those who have ASIA D lesions.

Unfortunately, the converse is also true. Developing spasticity may be problematic to the recovery of function.[42] The presence of this inverse relationship, coupled with the neuronal mechanisms of recovery, suggests that synapse growth by descending motor and reflex inputs grow in direct competition with each other.[4] If this is true, it is imperative for clinicians to provide early and aggressive spasmolytic treatment accompanied by active exercise during the critical period of regrowth. Our subject was tested 16 months post-injury, a time when most individuals with SCI have reached a relative plateau in their expected neurological and voluntary motor improvement.[9] It is probable that the intensity of the effect this subject's spasticity had on his gait performance should have moderated over time as his voluntary muscle strength improved. Therefore, results obtained with any tone-reducing orthotic at 16 months post-injury could be expected to be reduced in significance from those that might have been obtained earlier in the rehabilitation process.

Even with the increased voluntary muscle strength and the use of the tone-reducing AFOs, the subject's gait was altered compared to normal. This was especially true of the gastrocnemius muscle groups bilaterally as they continued to demonstrate EMG activity during swing phase. In fact, there was comparable activity during swing and stance phase in the quadriceps and hamstrings as well. Normally, these muscle groups are quiescent during the first part of swing phase.[36]

The SCI-FAI parameters show that the tone-reducing AFOs had a positive effect on step length and velocity. The subject was able to shift his weight appropriately during all trials but was never able to contact the floor with his heels first. Toe drag varied from device to device. The areas where the subject improved the most while using bilateral tone-reducing AFOs were step rhythm and step length. With the bilateral tone-reducing AFOs in place, the swing phase began more quickly, in less than one second, and step length was increased to the point where the heel of the swing foot routinely landed in front of the stance foot toe, thus explaining how the subject's recorded speed and velocity were able to show an increase.

CONCLUSION

Although there has been little research on the use of tone-reducing AFOs in adults with increased spasticity after incomplete SCI, the results of this study indicate that the use of tone-reducing AFOs could be beneficial. Further, these results provide rationale for similar research with a larger number of subjects. Our subject showed improvement in the control of his lower extremities while wearing tone-reducing AFOs as evidenced by an increased step length and gait velocity and a decrease in the amount of time spent in double limb support. EMG data were less conclusive, although activity in the left gastrocnemius muscle group was more erratic under alternative walking conditions when compared to the tone-reducing AFOs.

Clinicians should consider the early and ongoing use of tone-reducing AFOs in the treatment of their clients with spasticity after incomplete SCI. The use of tone-reducing AFOs is a noninvasive, relatively inexpensive intervention that might be effective in decreasing abnormal tone during weight-bearing, subsequently enhancing normal movement patterns during emergent walking. Controlling spasticity during weight-bearing provides for a more appropriate loading posture during stance contributing to a more appropriate swing phase, which could increase overall voluntary motor return after incomplete SCI.

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