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Comparing Plantarflexor Power and Function using Carbon Fiber Versus Traditional Thermoplastic Ankle Foot Orthoses: Case Series

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Abstract

Background: Thermoplastic ankle foot orthoses (TAFO) control the foot during swing and initial contact of walking. Carbon fiber AFOs (CAFO) has the added ability to store and return energy at push off. The purpose of this report is to determine if plantarflexor power and function can be improved with a CAFO compared to a TAFO and identify factors that may be related to plantarflexor power improvement in two adults with reduced ankle muscle performance.

Case Descriptions: Two participants with reduced ankle muscle performance completed a gait analysis and the 6 minute walk (6MW) test wearing each AFO. Physical function was higher in Participant 1 compared to Participant 2 as measured by the Foot and Ankle Ability Measure and walking speed.

Outcomes: Participant 1's 6MW distance and plantarflexor power improved wearing the CAFO compared to the TAFO (6MW distance: TAFO=427 m, CAFO=553 m and Plantarflexor power: TAFO=1.16 W/kg, CAFO=1.56 W/kg). Participant 2 showed similar outcomes in both AFO conditions (6MW distance: TAFO=290 m, CAFO=276 m and plantarflexor power: TAFO=0.89 W/kg, CAFO=0.60 W/kg).

Discussion: A CAFO increased walking speed and plantarflexor power compared to a TAFO in a person with a relatively high level of physical function but not in a person with a relatively low level of physical function. These preliminary results suggest a sufficiently high level of physical function is required to "engage" the CAFO and benefit from its energy storing capabilities.

Keywords: Kinetics; Orthotic devices; Braces; Power; AFO; Ankle foot orthosis.

Introduction

Ankle muscle performance is affected in 10-20% of those who have had a stroke [1] and ankle muscle performance impairment is a common residual from trauma, multiple sclerosis [2] and neurological injury and illness [3-5]. Loss of ankle muscle performance results in an inefficient walking pattern [6] and increases the risk of falling [1,7]. Loss of ankle dorsiflexor muscle performance results in a foot drop during the swing phase of walking and at initial contact with the ground, increasing the risk of falls as a consequence of a functionally longer leg. Loss of ankle plantarflexor muscle performance results in poorly controlled tibial progression over the planted foot during stance and lack of push off (ankle power) at the end of stance. Overall, in those with impaired ankle function, walking speed is slower, step length is decreased, and ability to perform dynamic activities often required in daily life is limited (e.g. fast walking or jogging to cross the street safely, walking on uneven surfaces and up hills) [6,8].

Traditional thermoplastic (polypropylene) ankle foot orthoses (TAFO) are often prescribed to prevent foot drop and provide tibial control during walking. Improved limb stability results in increased walking speed and step length [9-11]. However, the TAFO reduces the ability to use residual active plantarflexor muscle power and the material used in fabrication has poor energy storing and return capabilities. The result is limited ankle plantarflexor power production, limiting both walking speed and higher level activities such as running and climbing hills and stairs [10,12].

In contrast, carbon fiber is a lightweight material that is able to store and return energy and has been incorporated into AFOs (CAFO). In children, the CAFO improved ankle plantarflexor power by 15-97%, [10,13,14] increased walking speed by 7-30%, [13,15] and increased stride length by 9% [13] as compared to a TAFO. In adults, use of a CAFO, compared to no orthosis, increased walking speed 10-20% [16,17] decreased energy cost and improved function (e.g. timed stair climb, sit to stand) [18]. Ankle plantarflexor power has not been well studied in adults wearing a CAFO, and the only report found indicates no improvement in plantarflexor power with a CAFO after a stroke [17].

The current, but limited research, suggests potential to increase plantarflexor power during walking in some but not all users. Variability in power production capability was recognized by the prosthetic community when first introducing carbon feet. Ambulation and activity ability/potential was divided into 5 levels, called K levels, to assist in guiding prosthetic component choices. (K0-K4 describing lowest to highest activity ability/potential) (Table 1). Carbon prosthetic components are reserved for those defined as K3 or higher

[19]. An important next step in CAFO prescription is to determine if a similar system can identify patients who can successfully engage the CAFO, increase plantarflexor power production, and improve their physical function.

K-Level 0	No potential/ability to transfer safely with or without assistance. Prosthesis doesn't enhance quality of life or mobility.
K-Level 1	Potential/ability to ambulate or transfer with prosthesis in level surfaces at a fixed cadence. Household ambulatory.
K-Level 2	Potential/ability for ambulation, can transverse low-level environmental barriers. Limited community ambulatory.
K-Level 3	Potential/ability for ambulation with variable cadence. Community ambulatory.
K-Level 4	Potential/ability for ambulation beyond basic needs. No limits.

Table 1: K level description of functional ability.

The purposes of this case report were to: 1) compare selected gait parameters and measures of physical function in two adults with impaired ankle muscle performance while wearing their shoe, the TAFO and the CAFO and 2) examine the impact of measures of physical function on the ability to engage the CAFO and increase plantarflexor power. To meet these goals we tested one participant with a relatively high level of physical function (K4) and one participant with a relatively low level of physical function (K2).

Methods

Participants

Participant 1 (age: 55 years, height: 1.69 m, weight: 79.9 kg) had partial muscle performance loss in all leg compartments bilaterally from a left personal nerve injury 36 years prior to testing and a first lumbar vertebra compression fracture with spinal cord injury, 26 years prior to testing. Participant 1 wore bilateral TAFOs for 10+ years and received bilateral CAFOs 5 months prior to testing. Ankle dorsiflexion strength, measured with a hand dynamometer, was reduced compared to normative data (5.9 kg vs norm=29 kg [20]), the participant could not complete a single heel rise through a full range of motion, but had protective sensation on the plantar surface of the foot as tested using the 5.07 Semmes-Weinstein monofilament [21]. The left side was tested for this report as it had the most severe loss of muscle function. Self-report of function was measured with the Foot and Ankle Ability Measure (FAAM) [22]. The Activities of Daily Living subscale has 21 activities of daily living (i.e. home responsibilities, recreational activities) and the Sport subscale has 8 sport activities (i.e. running, jumping). (1-100%, 100% is full function) Participant 1 had FAAM-Activities of Daily Living subscale of 74% and a Sport subscale of 44% (K4 level).

Participant 2 (age: 41 years, height: 1.78 m, weight: 68 kg) had right lower extremity muscle performance loss requiring use of a TAFO for the past 8 years. The origin of the weakness remained unknown until 2 years prior to the testing occasion when he was diagnosed with multiple sclerosis. He received the CAFO two weeks prior to testing. He had a greater reduction in ankle dorsiflexion strength (3.6 kg) compared to participant 1, could not complete a single heel rise through a full range of motion, and had protective sensation on the plantar surface of the foot [23]. His FAAM-Activities of Daily Living subscale was 51% and the Sport subscale was 1% (K2 level).

AFO design

The TAFOs and CAFOs (Figure 1) were custom designed by form fitting the orthoses material around a plaster mold of the participant's lower leg. The TAFOs were fabricated of high temperature thermoplastic, polypropylene homopolymer (Guard Industries, Inc, St. Louis MO). The CAFOs were fabricated of 18 layers of preimpregnated expoy unidirectional carbon fiber (Adhesive Prepregs for Composites Manufacturers, Plainfield CT).

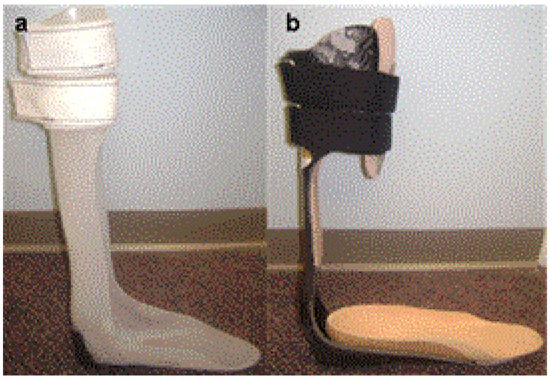

Figure 1: a) Traditional ankle foot orthosis made of polypropylene homo-polymer. b) Carbon fiber AFO made of layer of carbon fiber.

The vertical strut length and shape and the foot plate size and shape were determined by the participants' leg and foot size and used the following landmarks. The posterior proximal trim line for the struts of the TAFOs and CAFOs were distal to the medial hamstring insertion when the knee was flexed to 90 degrees. The struts for the TAFOs encompassed the medial and lateral malleoli, while the struts for the CAFOs remained posterior to the malleoli. The TAFO and CAFO footplates extended distally on the foot ending proximal to the 1st and 5th metatarsal heads. The footplate trim lines for the TAFOs and CAFOs extended a sufficient amount toward the dorsum of the foot to restrict inversion and eversion foot motion without irritating bony prominences. The proximal trim line of the pre-tibial shell for the CAFOs was even with the posterior proximal trim line of the strut and 4 inches in length.

Functional measures

Orthosis satisfaction was measured using the Monitor Orthopaedic Shoes pre post questionnaire [24], with modification to improve

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specificity for the TAFO and CAFO. The distance walked in six minutes [25], was measured in both the TAFOs and CAFOs.

Kinetic, kinematic, spatiotemporal data acquisition

An 8-camera video-based motion capture system (Vicon, Los Angeles, CA) and force platform (Bertec K80301, Bertec Corporation, Columbus, Ohio) were used to acquire three-dimensional lower extremity spatiotemporal, kinetic and kinematic data. Participants walked at a self-selected speed in their shoes, TAFOs, and CAFOs. Reflective markers were attached as described previously by Hastings et al. [26] for the shank and foot although the foot markers were attached to the shoe.

Five walking trials were collected. The three trials with the highest plantarflexor power were chosen and the variables of interest for these three trials were averaged (i.e. peak ankle dorsiflexion motion, peak ankle plantarflexor moment and power, energy stored, energy returned, and step length). Energy stored was the area above the negative component of the power curve as the tibia advanced over the foot during walking. Energy returned was the area under the positive component of the power curve during push off. All motion capture data were post processed using Visual3D software (Cmotion, Inc., Rockville, MD).

Results

Participant 1 reported that the CAFO improved his ability to walk inside and outside of the house and perform daily activities and work responsibility compared to the TAFO (Monitor Orthopaedic Shoes questionnaire). Participant 1 also reported the CAFO was superior to the TAFO regarding cosmesis and a cooler temperature of his leg. Participant 2 reported the primary benefit of the CAFO was prevention of knee hyperextension that could not be controlled with the TAFO. In addition he reported that the temperature of his leg was cooler wearing the CAFO compared to wearing the TAFO. There was no reported difference between the CAFO and the TAFO in ease of putting on and taking off the orthosis and walking on uneven surfaces remained challenging regardless of the AFO used.

Participant 1 walked further in six minutes when wearing the CAFO (553 m; walking speed=1.54 m/s) compared to the TAFO (427 m; walking speed=1.19 m/s). Participant 2 walked a similar distance in six minutes wearing the TAFO compared to the CAFO (290 m; walking speed=0.80 m/s and 276 m; walking speed=0.77 m/s respectively).

Participant 1 had the greatest peak plantarflexor power in the CAFO condition and least in the shoe only condition. Participant 2 had the greatest peak plantarflexor power in the shoe only condition with least in the CAFO condition (Table 2 and Figure 2). The greatest energy stored and returned for participant 1 occurred in the CAFO walking condition. The greatest amount of energy stored and returned for participant 2 occurred in the TAFO walking trial (Table 2). Walking speed during kinematic and kinetic data collection did not influence kinetic results for Participant 1as there was essentially no difference is walking speed between conditions(shoe=1.15 ± 0.03, TAFO=1.16 ± 0.05, and CAFO=1.09 ± 0.04 m/s, respectively). Walking speed was also not related to power production in Participant 2 as the fastest speed was recorded for the CAFO condition yet power was least in this condition (CAFO 0.90 ± 0.04, shoe=0.66 ± 0.03, TAFO=0.85 ± 0.03 m/s).

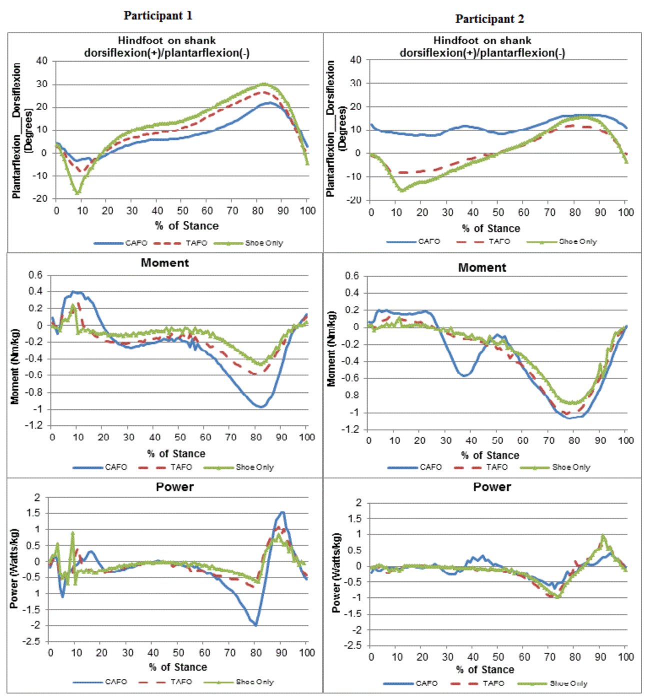

Figure 2: Walking stance phase kinematic and kinetics summarized for patient 1 in the left column and patient 2 in the right column for hindfoot dorsiflexion/plantarflexion (a), moment (b), and power(c). The Carbon ankle foot orthosis (CAFO) is the blue solid line, the traditional ankle foot orthosis (TAFO) is the red dashed line, and the shoe only is the green line with triangles.

Ankle moment was greatest in the CAFO for participant 1. There was little difference in ankle moment between conditions for participant 2 (Table 2 and Figure 2). Peak dorsiflexion range of motion during stance phase of walking, for participant 1, was lowest for the CAFO and greatest for the shoe condition. Participant 2 had similar dorsiflexion in the shoe only and CAFO conditions and less in the TAFO (Table 2 and Figure 2).

The longest step length for participant 1 was in the CAFO with little difference in step length between the shoe only and TAFO conditions. The step length for participant 2 was greatest in the AFO conditions and least in the shoe only condition (Table 2).

Discussion

These two cases provide interesting insights into the potential usefulness of CAFO's. Of greatest importance, participant 1 demonstrated that use of a CAFO enhanced physical function within the home and community, walking speed, and power during push off. However, as demonstrated with participant 2, not all individuals will be capable of engaging the CAFO to improve power at push off, although other benefits may indicate appropriate use of the CAFO (i.e. improved knee hyperextension control). Additionally, energy return with the carbon orthosis was only 37%, even in participant 1. We do not know the maximum orthosis efficiency that can be attained. Future work must examine the interactions between the patient and specific orthosis features and the ability of physical therapy to train individuals to optimally engage the orthosis to store and release the energy, enhancing power return and function.

	Peak Ankle Power (W/kg)			Ankle Moment (Nm/kg)			Peak Ankle Dorsiflexion (degrees)			Energy Stored (W/kg)			Energy Return (W/kg)			Step Length (m)		
Participant	Shoe Only	TAFO	CAFO	Shoe Only	TAFO	CAFO	Shoe Only	TAFO	CAFO	Shoe Only	TAFO	CAFO	Shoe Only	TAFO	CAFO	Shoe Only	TAFO	CAFO
1	0.9 (0.0)	1.2 (0.2)	1.6 (0.1)	-8.6 (0.2)	6.2 (0.2)	0.71 (0.02)	30 (1)	27 (1)	22 (0)	-8.6 (0.2)	-14.1 (0.2)	-26.8 (0.6)	6.2 (0.2)	8.8 (0.3)	9.9 (0.5)	0.71 (0.02)	0.69 (0.03)	0.80 (0.02)
2	1.2 (0.1)	0.9 (0.1)	0.6 (0.11)	-13.6 (0.3)	6.2 (0.3)	0.47 (0.06)	16 (1)	12 (1)	17 (0)	-13.8 (0.3)	-15.4 (0.3)	-10.2 (0.2)	6.2 (0.3)	6.5 (0.2)	2.9 (0.1)	0.47 (0.06)	0.56 (0.02)	0.53 (0.02)

Table 2: Walking kinematics and kinetics. Values are given as the mean (standard deviation). TAFO: Traditional Ankle Foot Orthosis; CAFO: Carbon Fiber Ankle Foot Orthosis.

Plantarflexor power during walking with the CAFO increased 34% compared to the TAFO and 80% compared to the shoe only condition for participant 1. In contrast plantarflexor power was not improved with use of the CAFO for participant 2. An increase in plantarflexor power between 15-97% has been reported with the use of a CAFO compared to a plastic or hinged orthosis in children [10,13,14] Very few reports have documented adult use of the CAFO and currently there is no support for improved plantarflexor power in adults. Bregman et al. [17] examine plantarflexor power during walking in a CAFO in a group of adults who had a stroke. The average plantarflexor power decreased 31% during walking in the CAFO compared to a no orthosis condition. Perhaps these individuals, like participant 2, were unable to adequately engage the CAFO.

There are a number of participant and orthosis factors that may work together to determine the plantarflexor power produced with use of the CAFO. In order to engage the orthosis, the strut of the orthosis must bend over the foot plate component, measured as peak dorsiflexion range of motion. The peak dorsiflexion range of motion during walking in the CAFO was 22° for participant 1 and 17° for participant 2. This might indicate a critical value of orthosis deflection required for plantarflexor power production. This hypothesis is supported by Bregman et al. [17] who report no increase in plantarflexor power associated with 17° of dorsiflexion and Wolf et al. [14] who reported an increase in power with 21° of dorsiflexion. However, both Desloovere [10] and Bartonek [13] report an increase in plantarflexor power with peak dorsiflexor values below 20°. What was not measured in our study or others is the total deflection, from the initial position of the orthosis which is often in slight plantarflexion to maximum dorsiflexion, and would be most clearly related to energy storage and thus energy return. Future work must include a more comprehensive evaluation of total orthosis deflection during walking in order to understand and maximize plantarflexor power return.

Walking speed is likely a critical factor in identifying those adults that are capable of enhanced plantarflexor power with use of a CAFO. Walking speed is directly related to plantarflexor power [8]. Participant 1 walked faster (1.09 m/s) than Participant 2 during kinetic data collection. However, participant 1's walking speed was only slightly faster than the walking speed of 1.04 m/s in the adult study that found no improvement in plantarflexor power with a CAFO [17]. Average walking speeds of 1.21 [10] and 1.22 m/s [15] were reported for the studies measuring improved plantarflexor power with a CAFO in children. Future work must examine a variety of walking speeds and determine its contribution to plantarflexion power production with a CAFO.

The self-report of physical function using the FAAM, together with walking speed, could be a useful tool in characterizing a person's level of function and determining potential for enhanced plantarflexor power with use of the CAFO. Successful power production with the CAFO was association with FAAM scores indicating a high level of function with limitations related to activities such as quick starting and stopping and lateral movements (Participant 1: ADL=74% and Sport=44%). The low FAAM scores reported by Participant 2 (ADL=51% and Sport=1%) indicate a high level of disability with limited or no ability to complete community activities like walking up and down hills, going up and down stairs, walking on uneven surfaces, or walking 15 minutes or greater. Although additional research is required, we hypothesize that ability to produce ankle power using a CAFO can be predicted using the K-Level criterion and suspect that successful CAFO use will be associated with a K3 level or higher.

The mechanical efficiency of the CAFO, defined as the percentage of energy returned compared to stored, was 30 to 37%. We do not know the maximum potential efficiency of the orthosis but believe there are at least two important areas to explore in the goal of improving plantarflexion power at push off. The first is to match orthosis stiffness to the size and activity level of the user. An orthosis that is too stiff will be difficult to engage, while an orthosis that is too flexible will not store as much energy and is likely to break [27]. With additional research a simple algorithm can be developed that assists the orthotist in determining the number of carbon fiber layers and appropriate stiffness for the individual. The second area is to assess if physical therapy intervention can assist the user in learning to engage the orthosis through increasing dorsiflexion while keeping the hip and knee extended and timing the energy release to optimize plantarflexor power return at push off.

Of critical importance to patients, orthotists, and physical therapists is that these results suggest a translation of improved plantarflexor power to improved activities of daily living. Not only did participant 1 walk faster with the CAFO but also reported improved ability to walk inside and outside of the house and perform daily activities and work responsibility. Previous work in this area has not included outcome measures related to function, an important step in justifying and defining use of CAFOs in a health care economy striving for prudent use of health care resources. Finally, although plantarflexor power production is important, there are likely other indications and benefits of CAFOs (i.e. knee hyperextension not controlled by a TAFO). Future CAFO research must identify and define these in order to minimize patient pain and maximize function.

Future studies should address the primary limitations of this current work. Additional participants, with a variety of disability levels would assist in defining and confirming our suspicion that a K-level type assessment would be a useful screening tool to assist in determining who might benefit from the CAFO. Future studies must also include mechanical testing and modeling to assist in formulating an algorithm that matches orthosis stiffness with patient size and function. Finally, future work must test whether physical therapy intervention with the CAFO can improve energy storage and return.

Conclusion

A CAFO increased walking speed and plantarflexor power compared to a TAFO in a person with a relatively high level of physical function but not in a person with a relatively low level of physical function. These preliminary results suggest a sufficiently high level of physical function is required to “engage” the CAFO and benefit from its energy storing capabilities.

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