A Proposed Evidence-Based Algorithm for the Adjustment and Optimization of Multi-Function Articulated Ankle-Foot Orthoses in the Clinical Setting

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Abstract

Individuals with neuromuscular pathologies are often prescribed an ankle-foot orthosis (AFO) to improve their gait mechanics by decreasing pathological movements of the ankle and lower limb. AFOs can resist or assist excessive or absent muscular forces that cause tripping, instability, and slow inefficient gait. However, selecting the appropriate AFO with mechanical characteristics that limit pathological ankle motion in certain phases of the gait cycle, but allow the ankle to move effectively during other phases requires detailed clinical decision-making. The aim of this study is to propose an explicit methodology for the adjustment of Multi-Function articulated AFOs in the clinical setting. A secondary aim is to present the evidence upon which this method is based and to identify gaps in that evidence as opportunities for future research. An emerging class of AFO, the Multi-Function articulated AFO offers features that permit more comprehensive, iterative, and reversible adjustments of AFO ankle alignment and resistance to ankle motion. However, no standard method exists for the application and optimization of these therapeutic devices in the clinical setting. Here we propose an evidence-based methodology applicable to the adjustment of Multi-Function articulated AFOs in the clinical setting. Characteristic load-deflection curves are given to illustrate the idealized, complex resistance-angle behavior of Multi-Function articulated AFOs. Research is cited to demonstrate how these mechanical characteristics can help to ameliorate specific pathologic ankle and knee kinematics and kinetics. Evidence is presented to support the effects of systematic adjustment of high resistance, alignable articulated AFOs to address many of the typical pathomechanical patterns observed in individuals with neuromuscular disorders. Published evidence supporting most decision points of the algorithm is presented, and gaps in that evidence are identified. Finally, two hypothetical case examples are given to illustrate the application of the method to the optimization of articulated AFOs treating specific gait pathomechanics. This method is proposed as an evidence-based systematic approach for the adjustment of Multi-Function articulated AFOs, using observed gait deviations mapped to specific changes in AFO alignment and resistance settings as a clinical tool in the orthotic treatment of individuals with complex neuromuscular gait disorders.

1 Introduction

Ankle-foot orthoses (AFOs) are common assistive devices used to treat pathologic gait and help facilitate functional gait by improving ankle and knee motion in patients with neuromotor pathologies. In healthy individuals, efficient walking is accomplished by activating muscles to control the motion of the ankle and other joints to initiate or resist motion through the different phases of the gait cycle (1–5). The ankle must perform a complex series of tasks during walking (6, 7) and the function of the ankle during gait may be described by dividing the gait cycle into foot-centric phases called “3 rockers of gait” (1, 7, 8) (Fig. 1).
For individuals with compromised neuromusculoskeletal systems, disrupted motion and forces acting at the ankle result in pathologic deviations that are primarily observed in the 3 rockers of gait, but can also include pathological kinematics and kinetics at the knee and hip. Pathologic ankle biomechanics can be positively influenced by an AFO which resists/assists ankle motion to compensate for impaired muscle function (9–14). Research demonstrates that an AFO can assist the ankle in improving stability and enhancing walking competence, efficiency, and mobility.

The primary indication for AFO prescription is excessive plantarflexion in swing phase for individuals with foot drop. This can lead to an increased risk of the patient tripping (15, 16). A secondary, but related indication is toe-heel or flat foot gait at initial contact. This pathologic gait pattern severely disrupts the forward momentum of the body during ambulation (17). The position of the foot at initial contact, maximum plantarflexion in early stance, maximum ankle dorsiflexion during mid-stance, ankle push-off during terminal stance, and foot clearance in swing may all benefit from AFOs. Studies indicate that AFOs can improve joint kinematics and kinetics (18–22), walking speed (23), standing stability (23, 24), and energy efficiency (25, 26), leading to improved patient mobility and safety.

However, adjusting the mechanical properties of an AFO in the clinical setting to fully maximize these benefits for the patient is a complex task. This study proposes an evidence-based algorithm for the adjustment of articulated AFO mechanical characteristics to remediate specific pathologic gait deviations and improve ankle and knee kinematics and kinetics through the gait cycle. This work aims to assist clinicians in establishing a more consistent evidence-based clinical methodology for the adjustment of articulated AFOs. It is anticipated that this evidence-based methodology may establish a foundation for future research into the method itself, with future published evidence of the efficacy of this orthotic intervention.

There is a broad compendium of literature comparing the effectiveness of non-articulated and articulated AFOs in the treatment of gait deficits. Non-articulated AFOs are typically of the solid-ankle, Posterior Leaf Spring (PLS) or strut type. Articulated AFOs are typically known as hinged AFOs (23–25, 27) and typically employ metal springs to resist/assist ankle motion. Researchers have investigated the influence of these AFO types when treating pathologic gait deviations, and compared different AFO designs for different patient populations (18, 27–29). More recently, systematic reviews have been performed (23–25, 27) to compare gait with and without the use of an AFO, regardless of the AFOs mechanical characteristics or evidence of appropriateness for a given pathological gait disturbance.

Though many studies have taken into account the adjustment of AFO mechanical characteristics on the kinematics and kinetics of the ankle, knee, and hip (8, 10, 12, 14, 21, 30–42), a comprehensive method to adjust the mechanical characteristics of articulated AFOs to address specific observed pathological joint kinematic deviations has not yet been presented.

In clinical practice, there are two fundamental characteristics of an AFO that are commonly considered and adjusted to influence gait biomechanics. One is the AFO’s resistance to ankle motion and the other is its ankle alignment angle. AFO alignment angle is defined as the angle in the sagittal plane between
the sagittal plane axis of the footplate and tibial section without external force applied. A ‘neutrally-aligned’ AFO is defined as an AFO with a 90° ankle alignment angle. This alignment is also sometimes referred to in the common vernacular as a 0° alignment, which means that the sagittal plane tibial axis of the AFO is at 0° inclination with respect to vertical.

The resistance of an AFO is typically measured as the torque or bending moment given in Newton-meters (Nm) that the AFO applies to resist ankle motion. The terms resistance and stiffness are sometimes used interchangeably, however the stiffness of an AFO is more rigorously defined as the change of resistance per unit of ankle articulation and is typically measured in Newton-meters per degree (Nm/deg). Various devices have been developed to measure stiffness of AFOs (43). These three AFO mechanical characteristics: alignment, resistance, and stiffness influence ankle motion in distinct ways and if properly adjusted may help reduce pathologic gait abnormalities for patients with neuromuscular disorders (10, 11, 13).

Several recent studies have compared the biomechanical influence of AFOs with mechanical characteristics systematically adjusted to the unique needs of each individual patient (8, 10, 31–36, 40). Kobayashi et al. evaluated the influence of plantarflexion spring stiffness of articulated dorsiflexion assist-type AFOs and demonstrated a systematic influence on sagittal ankle position at initial contact and the subsequent ankle motion through the gait cycle in individuals post-stroke (10).

Kobayashi et al. assessed sagittal ankle and knee motion and moments during walking with the articulated dorsiflexion assist-type AFOs of different stiffnesses (36). Their work showed that for individuals post-stroke with knee hyperextension, this pathologic gait deviation could be ameliorated by increasing plantarflexion spring stiffness to encourage a heel-toe gait pattern at initial contact, resulting in an ankle position shifted toward dorsiflexion rather than plantarflexion, and a dorsiflexor moment at the ankle in early stance. Increased plantarflexion stiffness also reduced the peak knee flexor moment and knee hyperextension in single-limb stance (36). Their work also showed a systematic increase in both ankle dorsiflexion and knee flexion angles with increased plantarflexion resist spring stiffness throughout the gait cycle.

It remains unclear whether it is most advantageous for an AFO to provide sufficient resistance to plantarflexion to hold the ankle neutral throughout swing phase, while limiting the maximum plantarflexion resistance to some extent that will also allow ankle plantarflexion at initial (heel) contact where the ground reaction force increases the external plantarflexion moment at the ankle.

Waterval et al. studied the influence of Posterior Leaf Spring (PLS) AFOs with five different stiffnesses for 37 participants with neuromuscular disorders and non-spastic calf muscle weakness (14). PLS AFOs present zero initial resistance to ankle motion, deriving their resistance to ankle motion from the deflection of the footplate away from the ankle alignment angle. The stiffness of AFOs used in this study of optimal walking economy was highly individualized, with stiffness of $4.3 \pm 0.5$ Nm/deg most frequently demonstrating the best gait economy, but only for 11 of the 37 participants. The most economical gait resulted in AFOs with a stiffness of $2.8 \pm 0.4$ Nm/deg in 8 participants, $3.5 \pm 0.4$ Nm/deg
in 6 participants, 5.3 ± 0.7 Nm/deg in 5 participants and 6.6 ± 1.1 Nm/deg in 6 participants. The least efficient AFO stiffness was most frequently 6.6 ± 1.1 Nm/deg in 14 participants and 5.3 ± 0.7 Nm/deg in 12 participants. Their results demonstrated that AFO stiffness individualized for each participant in the study reduced the energy cost of walking by 11% when compared to the stiffest AFO. It was hypothesized that the stiffest AFO would produce the greatest push-off energy based upon bending moment hysteresis calculation of energy stored and lost, but the stiffest AFO did not result in significantly lower mean walking energy cost (14). These results suggested that individualized adjustment of PLS AFO stiffness for each individual patient is likely more beneficial than simply making an AFO stiffer. It should be noted that this study employed single stiffnesses for each of the different AFOs, with these single stiffnesses constant throughout the gait cycle. In practice, this approach is difficult to employ for individuals with complex neuromuscular pathologies demonstrating dysfunctional ankle motion at some points in the gait cycle but with functional ankle motion at other points in the gait cycle. Even if a set of prefabricated AFOs with a range of stiffnesses were available at fitting, an appropriate stiffness AFO would still be difficult to prescribe because the guiding outcome of this approach is gait economy, which requires complex metabolic testing with portable O$_2$ and CO$_2$ sensor systems. Therefore, it is unlikely that this approach would be applicable to routine orthotic care in the clinical setting due to its expense, time and effort, and limitations to the orthotist’s scope of practice and experience with respect to energy cost diagnostics. The method would also be fraught with errors, with confounding variables such as food consumed prior to the test and the difficulty of achieving a steady state during walking.

2 Optimal Mechanical Characteristics of AFOs

Customary Orthotic Practice and Challenges in AFO Optimization

Determining the optimal mechanical characteristics of an AFO is a complicated task for the prescribing physician, and for the orthotist who is responsible for providing orthotic care and adjusting the AFO to improve patient ambulatory function. AFO designs that employ an adjustable ankle joint rather than requiring an irreversible change to the orthotic design to alter stiffness offer the opportunity to quickly and reversibly alter the AFO’s mechanical characteristics in the clinical setting. These adjustable orthoses also facilitate the adaptation of those characteristics to the patient’s changing needs over time. Adjustability also offers the ability to change the AFO’s mechanical characteristics progressively, and iteratively to achieve specific functional objectives. However, optimization requires that the goals of adjustment are clearly defined. In practice, it is often also necessary to prioritize and reconcile optimization goals considering the myriad of competing concerns in orthotic patient management.

The overall aim of AFO optimization is to reduce specific pathologic gait deviations. It is reasonable to assume that the reduction of pathologic gait deviations will improve patient ambulatory function (23–25, 27), therefore normal gait is often used as a comparative reference for adjustment. The adjustment process is typically informed by subjective and objective clinical indicators, e.g. patient verbal feedback and observation of the patient walking respectively. It is widely accepted that three-dimensional
instrumented gait analysis including kinetic and kinematic data, is the gold standard of gait assessment. However, this type of motion analysis has limited availability and is costly, time-consuming, and complicated, which makes it impractical in many clinical settings. Customary orthotic practice relies upon basic clinical techniques for the evaluation of objective clinical indicators. One such indicator is the identification of gait deviations using observational gait analysis.

Several studies have demonstrated that observational gait analysis can result in substantial errors when used to identify gait deviations (44–47). However, studies also suggest that if the observer’s attention can be focused on a few discrete gait events and the assessment is repeated multiple times, the ability of the observer to reliably identify gait deviations may be improved (48). The use of slow-motion video as an adjunct to observational gait analysis may also help to improve the reliability of identifying gait deviations. Therefore, it is possible to improve the accuracy of identifying the orthotic influence on patient gait through iteration of AFO adjustments using repetitive observations of specific gait events with slow-motion video. This is typically done by stopping motion and scrolling the video repeatedly through the gait event. Establishing the reliability of observational gait analysis is essential if it is to be used to determine whether a specific gait deviation has been reduced or increased through the adjustment of AFO mechanical characteristics. Various gait assessment scales have been developed that utilize this concept (49). For example, the Edinburgh Visual Gait Score showed 69% agreement with 3D computerized gait analysis for maximum ankle dorsiflexion in stance, 83% agreement with maximum ankle dorsiflexion in swing, but only 47% agreement with peak knee extension in stance (49). While these observational gait tools are not as accurate or precise as the gold standard of instrumented motion analysis, they can potentially improve the reliability, sensitivity, and validity of visual gait analysis when instrumented analysis is not feasible.

Therefore, by focusing on a few key gait characteristics, the orthotist’s ability to identify a patient’s gait deviations reliably and validly may be improved, and by doing so, observational gait analysis may be adequate for the purpose of AFO adjustment and optimization of patient ambulatory function. However, it should be noted that substantial errors may be associated with the less than rigorous application of observational gait analysis to AFO optimization, therefore an iterative approach to the change of AFO mechanical characteristics with repetitive observation is essential to minimize observational errors if the assessment is to be applied to orthotic practice.

AFO Mechanical Characteristics

To reduce pathologic gait deviations, the intrinsic sagittal plane mechanical characteristics of an AFO should be adjusted. As aforementioned, these intrinsic mechanical characteristics are the AFO’s alignment, resistance, and stiffness. Non-articulated AFOs typically possess high structural stiffness, between 8 and 18 Nm/deg depending on the fabrication method and materials used (50). Following fabrication, the structural stiffness of a non-articulated AFO is fixed unless its shape is irreversibly changed. Though their stiffness may be high, the initial resistance of a non-articulated AFO is 0 Nm. However, the resistance of high stiffness AFOs increases rapidly with deflection of the AFO footplate.
contrast, traditional articulated AFOs use mechanical ankle joints to resist ankle motion. These orthotic components typically resist ankle motion by virtue of internal springs with stiffness that is significantly lower than the structural stiffness of a solid AFO. The stiffness of these traditional hinged AFOs may be on the order of 0.25 Nm/deg \((10, 34, 38)\). Traditional hinged AFOs also present 0 Nm of initial resistance to ankle motion, and because their stiffness is relatively low, may in some cases only be suitable for the management of swing phase gait abnormalities (e.g. foot drop), where the resistance required to influence pathologic gait is relatively low compared to stance phase.

An emerging class of articulated ankle-foot orthosis with features that facilitate improved control over AFO mechanical characteristics has been recently introduced to the orthotics profession. The first of these devices was the Neuro Swing double acting ankle joint introduced by Fior & Genz in 2013. In 2016 Becker Orthopedic introduced the Triple Action Multi-Function ankle component and in 2019 Otto Bock Healthcare introduced Nexgear Tango. These advanced orthotic components differ slightly in their feature set, but all possess the defining characteristics of Multi-Function orthotic ankle components. Multi-Function articulated AFOs are more suitable for the management of both swing phase and stance phase gait deficits by virtue of their high resistance to ankle motion and adjustability. The resistance and stiffness of Multi-Function articulated AFO springs are typically much higher than traditional articulated AFOs. In addition, Multi-Function articulated AFOs can be more precisely adjusted with mechanical characteristics that are de-coupled from one another, facilitating the independent adjustment of mechanical characteristics in a way that is more multifaceted than traditional articulated AFOs. The stiffness of component springs can be changed to accommodate a broader range of patient weights, and these devices possess the unique feature of presenting a resistance threshold, or pre-load torque (Nm) to ankle motion. The resistance threshold of a Multi-Function articulated AFO is the minimum torque necessary to move the AFO footplate away from its alignment angle. When the torque applied to the AFO footplate is below the resistance threshold, the Multi-Function articulated AFO presents the high structural stiffness of the orthosis to resist ankle motion and the footplate deflects as would a much higher stiffness non-articulated AFO. However, when the external ankle moment exceeds the resistance threshold of the ankle component, the footplate begins to move away from its ankle alignment angle and the resistance of the AFO continues to increase at the rate determined by the stiffness of the ankle joint springs. This stiffness is typically less than the structural stiffness of a non-articulated, e.g. solid AFO but higher than the stiffness of a traditional articulated AFO. The maximum range of ankle motion is also adjustable, and when this motion limit is reached the AFO again presents high structural stiffness to resist ankle motion (Fig. 2). Therefore, the total resistance that a Multi-Function articulated AFO applies to influence ankle motion is determined by its structural stiffness, resistance threshold, and dorsiflexion and plantarflexion spring stiffness. This mechanical behavior results in a complex resistance vs. angle curve resembling a sigmoid which exhibits varying resistance through specific and adjustable ankle ranges of motion (Fig. 3).

---Place Fig. 2 about here---
This demonstrates the complex features of a Multi-Function articulated AFO to allow functional ankle motion while resisting motion through dysfunctional ranges. The Multi-Function articulated AFO also facilitates the independent adjustment of ankle alignment angle without altering the resistance or stiffness settings (35, 39).

3 Development of an Evidence-Based Algorithm

Evidence-Based Algorithm for the Adjustment of Multi-Function articulated AFOs in the Clinical Setting

There is a dearth of orthotic adjustment algorithms in orthotic practice. One orthotic algorithm described by Owen et al. involves the optimization of AFOs combined with shoe outsole modification to improve patient ambulatory function. The AFO footwear combination (AFO-FC) is clinically “tuned” by modifying the shoe outsole shape to improve gait in children with cerebral palsy (51). This method of adjusting the AFO-FC has also been described by Jagadamma et al. for use in post-stroke adults with hemiplegia (21). The method initially focuses on determining the ankle alignment angle by evaluation of the patient’s passive range of ankle dorsiflexion before fabrication of the rigid AFO. With the rigid AFO and shoes donned to the patient, optimization for standing balance and knee position is accomplished by adjustment of the heel height of the shoe. The shape of the heel and forefoot rockers of the shoe outsole are subsequently adjusted by abrasive grinding to ‘tune’ the shape of the outsole, reducing pathologic shank and thigh kinematics in early and late stance phases of gait. Stiffness of a footplate of an AFO may affect gait patterns as well (52). Owen’s method thus focuses on the reduction of pathologic shank and thigh gait deviations with an emphasis on observing these limb segments with respect to the vertical axis.

In contrast to Owen’s work, the adjustment algorithm proposed in this present work aims to preserve functional ankle motion while reducing pathologic ankle and knee gait deviations. This algorithm is novel as it is focused on the adjustment of the mechanical characteristics of a Multi-Function articulated AFO to associate with and systematically influence specific events throughout the gait cycle (8, 10, 35–41, 53, 54).

Multi-Function articulated AFO mechanical characteristics have been found to systematically influence gait kinematics and kinetics of the ankle and knee (8, 10, 32–38, 40). Studies demonstrate that changes to the AFO ankle alignment angle influences ankle angle throughout the gait cycle (8, 10, 32, 33). Studies also demonstrate that resistance to ankle plantarflexion systematically influences ankle and knee sagittal kinematics and kinetics through swing phase and in the first rocker of gait (30, 38). Resistance to ankle dorsiflexion systematically influences the second rocker of gait, midstance to pre-swing (35). Evidence also suggests that this influence is mostly isolated, facilitating the association of specific AFO adjustments with specific phases of the gait cycle. Therefore, the algorithm was developed to exploit this isolated influence of AFO adjustments to help establish a clear pathway toward optimization, providing guidelines to associate observed gait deviations with specific Multi-Function articulated AFO
adjustments while remediating undesirable, iatrogenic consequences of the orthotic treatment. Examples of the adjustments that can be made to a Multi-Function articulated AFO are shown in Fig. 4, where each resistance threshold value is adjusted in response to an observed gait deviation.

The algorithm was developed to be used in the clinical setting, where access to a sophisticated gait lab is typically not available. The method relies on observational gait analysis augmented by repeated observation of specific gait events using slow-motion video to increase the reliability of observations and indicated adjustments. Contemporary smartphones equipped with high-resolution slow-motion cameras make this feasible in a clinical setting. Observational gait analysis may be further improved by capturing video from different perspectives, e.g. both the sagittal and coronal planes, which may also be helpful to detect changes in gait characteristics as well as to estimate joint angles or step lengths.

A specific and clinically relevant set of gait events was selected for the adjustment algorithm (Supplementary File 1) based upon reliability of identification as well as clinical utility:

1. Knee position and shank inclination in static weight bearing
2. Perceived weight line with respect to ankle, knee, and hip joint anatomical axes in static weight bearing
3. Toe clearance in mid swing
4. Knee extension at terminal swing
5. Foot position at initial contact
6. Knee kinematics through 1st rocker
7. Tibial progression through 2nd rocker
8. Heel rise at terminal stance through 3rd rocker
9. Knee kinematics after midstance
10. Step length and step length symmetry

Pathologic deviations of these specific gait events inform associated adjustments to Multi-Function articulated AFO mechanical characteristics. Evidence to support the systematic effects of AFO adjustment intended to influence specific gait characteristics is supported by cited literature in the text and Figs. 5–13.

Throughout the subsequently described process, the term alignment signifies changing the AFO ankle alignment angle without adjustment of AFO resistance threshold or stiffness, while the term adjustment is used to indicate a change of resistance threshold or component stiffness with or without a change of alignment. As previously described, the resistance threshold of the Multi-Function articulated AFO is adjusted by pre-compressing, or preloading, the component springs within the ankle joint. AFO component stiffness is adjusted by installing different springs or combinations of springs in the ankle joint, and may serve to scale the resistance threshold adjustment range to the weight and biomechanical deficits of the patient. Steps 4 and 5 in the following procedure initially involve setting the AFO
The Multi-Function articulated AFO Adjustment Algorithm

Step1: Bench Adjustment

Bench adjustment involves setting the mechanical characteristics of the orthosis to an initial condition in preparation for optimization. The term and procedure are similar in some respects to the more familiar “bench alignment” originally coined by prosthetists. Prosthetic bench alignment of a transtibial prosthesis refers to the process of adjusting the initial alignment of the prosthetic socket with respect to the prosthetic foot (Fig. 5). While there is an accepted standard for prosthetic bench alignment, accommodation is typically made to the socket angle in cases where the patient has a flexion contracture or atypical joint alignment of the residual limb, and for the anticipated heel height of the shoe.

By contrast, orthotic “bench adjustment” in the algorithm implies setting the initial AFO ankle alignment angle to slightly incline the patient’s shank with the AFO and shoe donned (Fig. 5) and adjusting the resistance of the AFO to ‘lock’ the ankle joint, simulating the mechanical characteristics of a high stiffness, non-articulated AFO. This is done to achieve maximum stability and safety for the patient during “Static Alignment”.

Step 2: Static Alignment

Static alignment is performed with the AFO and shoes donned to the patient in quiet standing (Fig. 6) and the AFO ‘locked’ to simulate a non-articulated AFO. Static alignment changes the ankle angle with concomitant change to knee flexion. The goal of this step of the algorithm is to adjust the initial ankle alignment angle to achieve slight shank inclination and improve the patient’s subjective sense of balance in quiet standing. If accommodation is necessary for a plantarflexion contracture to position the ankle within its passive range of motion, a heel lift under the AFO may be advantageous. During Static Alignment, an objective measure of 10° to 12° of shank inclination, e.g. 11° shank to vertical (SVA) angle may be used as a starting point. This angle was determined by Owen to be the average shank to vertical angle for optimal gait kinematics and kinetics for their method (51). Consideration should also be given to the position of the patient’s weight line with respect to the imaginary line joining the Trochanter, Knee, and Ankle (TKA). The patient’s subjective feedback is a critical aspect of static alignment, and the patient’s subjective sense of balance, stability and comfort is assessed as part of this process. Again, a parallel can be drawn to the static alignment of a transtibial prosthesis, which includes anteriorly tilting the prosthetic socket and aligning the knee center anterior to the ankle axis such that the patient’s weight line passes through the middle third of the foot (55).
Step 3: Swing Phase Alignment

When satisfied with the static alignment, the patient is asked to walk to adjust swing phase alignment (Fig. 7–9). This step of the algorithm is also performed with the ankle joint adjusted to simulate a non-articulated AFO. Published data show that sagittal ankle angle is systematically changed with ankle alignment of the Multi-Function articulated AFO. The goal of swing phase alignment is to optimize ankle alignment to improve toe clearance in mid-swing, foot position and foot position symmetry at initial contact and knee extension at terminal swing. These three gait events are observed and prioritized during swing phase alignment with the following guidelines. During mid-swing, toe clearance is evaluated with a goal of achieving at least 1 cm of clearance between the shoe and the floor (Fig. 7). A minimum toe clearance of 1–2 cm has been suggested for the young and elderly adults (15, 16). Ankle alignment may be adjusted toward dorsiflexion to increase toe clearance and assuming the structural stiffness of the orthosis is high enough, the kinesiological response to this adjustment has been found to be systematic.

The angle between the shoe outsole and the floor at initial contact i.e. foot-to-floor angle has been described by Perry in normal gait to be 25 degrees at the time of heel strike (6), and Vette et al. show 15–20 degrees of foot-to-floor angle at initial contact (56). Therefore, a range of 10–25 degrees is used as the goal for swing phase alignment of foot position at initial contact and foot position symmetry (Fig. 9). Ankle alignment is optimized to achieve this goal by adjusting ankle alignment towards dorsiflexion and plantarflexion to increase or decrease the foot-to-floor angle respectively.

After alignment for toe clearance, and foot position at initial contact, knee extension at terminal swing is observed and compared with the normative value of 175 degrees of knee popliteal angle, or 5 degrees of knee flexion at terminal swing (Fig. 8). If the knee does not fully extend at terminal swing, there may be restriction by a knee flexion contracture or shortened gastrocnemius, exacerbated by excessive ankle dorsiflexion alignment. If the knee does not achieve full extension, the previous objectives may need to be reconciled by further iterative adjustment of ankle alignment to achieve overall optimization. However, it should be noted that this last objective of full knee extension is not well-supported by the published literature. Anecdotal clinical observations do suggest that it may have utility for orthotic optimization, therefore it is included in the algorithm with the caveat that the measure should be cautiously utilized. However, the clinician should not rely solely upon this observation for definitive decision making during AFO optimization.

To summarize, static and swing phase alignment is performed with the Multi-Function articulated AFO adjusted to its maximum resistance settings (against the dorsiflexion and plantarflexion motion limiting stops), therefore any pathologic gait deviations observed during the adjustment of swing phase alignment are reduced by optimization of ankle alignment to balance and prioritize concerns among the
observed gait deviations. Toe clearance in mid-swing and foot position at initial contact are prioritized. However, if there is observed restriction of knee extension in terminal swing with increasing dorsiflexion alignment of the AFO, and this observation can be associated with a shortened gastrocnemius, then toe clearance and/or foot position at initial contact may need to be sacrificed by plantarflexing the ankle alignment to increase knee extension.

Iteration between AFO settings for “Static Alignment” and “Swing Phase Alignment” may be necessary to reconcile competing concerns between these two steps of the adjustment algorithm and to achieve the optimal alignment setting for balance in quiet standing with improved swing phase gait mechanics. There may be a point of diminishing benefits to this compromise in reduction between gait deviations as the ankle alignment angle is changed. The algorithm relies on clinical judgment and iteration of changes to alignment and careful, repeated observations to identify the optimal compromise between these potentially competing concerns.

**Step 4: Early Stance Phase Adjustment**

During static and swing phase alignment, the plantarflexion resistance threshold had been previously adjusted (during bench adjustment) to ‘lock’ the ankle simulating a non-articulated AFO. In this configuration there was no concern that the orthosis would present inadequate resistance to prevent ankle plantarflexion through swing phase because the orthosis presents the high structural stiffness of a non-articulated AFO to the ankle. However, with the patient walking in a maximally supportive AFO with high resistance to plantarflexion, undesirable rapid knee flexion in 1st rocker may be observed (10, 33, 36, 38). This iatrogenic gait deviation is mitigated by reducing the plantarflexion resistance threshold in the next step of the algorithm (Fig. 10–11).

Early Stance Phase Adjustment involves reducing the plantarflexion resistance threshold to allow ankle plantarflexion in 1st rocker when the ground reaction force from initial contact to loading response exceeds that resistance. When making this adjustment, it is important to maintain the plantarflexion resistance threshold high enough to maintain the ankle position at the ankle alignment angle through swing phase until initial contact. Unpublished research suggests that there exists a resistance threshold setting that, if high enough will maintain the ankle angle of an articulated AFO through swing phase and so the resistance threshold setting should also maintain toe clearance in mid-swing. The goal of adjusting the AFO resistance threshold for early stance phase is to encourage controlled knee flexion by permitting resisted ankle plantarflexion through 1st rocker. Therefore, the plantarflexion resistance threshold setting should permit ankle plantarflexion from initial (heel) contact to loading response to facilitate controlled knee flexion as the foot moves to the floor. If the patient presents with genu recurvatum in early stance, in some cases reduction of the plantarflexion resistance threshold may permit knee hyperextension before midstance (38). In such cases, the plantarflexion resistance threshold may need to be increased and iteration of this adjustment may be necessary to determine the best setting to resist knee hyperextension while permitting ankle plantarflexion as much as possible in
early stance. The final setting of the plantarflexion resistance threshold should therefore balance and prioritize these concerns and the clinician must decide upon the principal gait deficit to be treated while prioritizing the reduction of other gait deviations.

**Step 5: Late Stance Phase Adjustment**

The last step of the algorithm involves adjustment of the dorsiflexion resistance threshold for late stance phase of the gait cycle. This adjustment is intended to permit resisted ankle dorsiflexion with knee stability through 2nd and 3rd rockers (Fig. 12–13). It has been expected that the resistance of an AFO to dorsiflexion encourages knee extension after midstance and may also help to control forward tibial progression through 2nd rocker. The Multi-Function articulated AFO will begin resisting dorsiflexion as the ankle attempts to dorsiflex beyond the ankle alignment angle. Resistance to dorsiflexion is essential to compensate for plantarflexor and quadriceps weakness and to encourage full knee extension after midstance. However, excessive resistance to dorsiflexion may also result in undesirable knee hyperextension in terminal stance (35). In this step of the algorithm, tibial progression and knee stability are observed from midstance through pre-swing. The timing of heel rise is also observed after midstance and at 3rd rocker. It is generally accepted that the appropriate timing of heel off occurs prior to initial contact of the contralateral foot, but after the contralateral foot swings past the stance foot in the sagittal plane (57). Evidence suggests that the timing of heel off may also be affected by ankle dorsiflexion range of motion (58). Excessive knee flexion or late heel off after midstance is suggestive of insufficient dorsiflexion resistance threshold. If these gait deviations are observed, dorsiflexion resistance threshold should be increased. Conversely, the observation of excessive knee hyperextension or early heel off after midstance suggests that the dorsiflexion resistance threshold should be decreased.

4 Hypothetical Case Studies

The Multi-Function Articulated AFO Adjustment Algorithm (Supplementary File 1) is applicable to the orthotic treatment of a broad range of complex neuromotor pathologies. To illustrate the application of this algorithm, two hypothetical clinical cases are presented. These cases are based on the generalized clinical presentation and treatment outcomes of an ensemble of actual patients treated using Multi-Function articulated AFOs with the adjustment algorithm and by order of a prescribing physician.

**Example 1**

A Patient with myelomeningocele (MMC)

Imagine the hypothetical patient is a 15-year-old adolescent male who presents to clinic with myelomeningocele. The underlying pathology results in the functional deficit of absent volition of the plantarflexors with other motor function mostly preserved. Because of the plantarflexor deficit, the
patient exhibits no push-off in late stance phase of gait, and walks with persistent knee flexion throughout stance phase. It is important to keep these deficits in mind when reviewing slow-motion video during the optimization process. The patient has an orthotic treatment history of non-articulated plastic AFOs that he uses with athletic footwear and native outsoles, however the iatrogenic gait abnormality of excessive knee flexion in 1st rocker is observed and the persistent knee flexion throughout stance is untreated in the orthotic design. The goals of orthotic treatment will be to improve the patient’s stance phase gait mechanics while minimizing restriction of the ankle to preserve ankle motion in 1st and 2nd rockers, to reduce knee flexion in 1st rocker of gait, and to achieve full knee extension without knee hyperextension in late stance phase.

The patient is molded for bilateral Multi-Function articulated AFOs (Fig. 14). The negative casts are corrected before pouring the positive model, to correct the sagittal ankle angle of the AFOs to a position that would encourage slight shank inclination when fit to the patient with shoes donned. The AFOs incorporate features intended to resist the pathologic foot and ankle postural abnormalities.

STEP 1: Bench Adjustment

Prior to fitting, the orthoses are bench adjusted. Bench adjustment is performed by adjusting the ankle alignment angle to its neutral setting (at the angle of fabrication which slightly inclines the shank when fit with the shoes) and the resistance threshold of the Multi-Function articulated AFO ankle joints to their maximum setting, effectively configuring the AFOs as solid ankle-foot orthoses.

STEP 2: Static Alignment

The patient is seen for orthotic fitting, and the orthoses and shoes are donned. The fit of the orthoses is evaluated and adjusted to provide comfort and postural support without irritation.

The patient is asked to stand, and the ankle alignment angles are adjusted with the patient in static weight bearing. It is observed that the patient’s knees are excessively flexed, therefore the static alignment angle is adjusted toward plantarflexion to slightly recline the shank and provide improved standing balance. Reclining the shank is perceived to shift the visualization of the weight line (TKA line: trochanter-knee-ankle line) posteriorly. This patient’s knee flexion is observed to be very responsive to the adjustment of ankle angle and is easily optimized during static alignment.

STEP 3: Swing Phase Alignment

The patient is asked to walk at a comfortable pace while the clinician uses a smart phone to record slow motion, sagittal plane video. Slow motion video captures at the high frame rate of 240 frames per second, resulting in high resolution video that improves the clarity of stop-motion and scrolled images. The clinician reviews the video, slowly scrolling the image left and right to analyze toe clearance in mid swing and foot-to-floor angle at initial contact. This assists in identifying the pathologic gait
abnormalities. Through the analysis of multiple steps of the patient walking, it appears that the toe clearance is greater than 2 cm in mid swing, but the foot position at initial contact appears symmetric between sides. It is also observed that the foot-to-floor angle is excessive and greater than 25 degrees. The ankle alignment settings of the AFOs are adjusted toward plantarflexion to decrease the foot-to-floor angle at initial contact. The walking trial is repeated, and slow-motion smart phone video confirms that the new alignment setting encourages heel contact with decreased dorsiflexion at initial contact and a foot-to-floor angle of about 20°. There does not appear to be any effect of the adjustment on knee extension at terminal swing. The patient’s standing balance is again evaluated in static weight bearing. Shank inclination appears slightly reduced, but the knees do not appear hyperextended, and the ankle alignment setting is verified as the best compromise overall that improves standing balance and the patient’s sense of stability in ambulation. The final, best-compromise Multi-Function articulated AFO alignment setting is 0 degrees.

**STEP 4: Early Stance Phase Adjustment**

During initial adjustment of the AFO, the plantarflexion and dorsiflexion were locked to simulate a non-articulated AFO with high stiffness. Therefore, it is suspected that the high resistance to plantarflexion might result in the iatrogenic gait abnormality of rapid knee flexion in 1st rocker. Slow motion video confirms this suspicion.

To improve early stance phase knee kinematics, the Early Stance Phase Adjustment procedure is performed. Because the patient’s dorsiflexion strength is preserved, it was anticipated that a lower stiffness, high compliance spring resisting plantarflexion might be appropriate for the patient. Therefore, a spring of 0.2 Nm/deg stiffness had been installed in the component’s plantarflexion-resist channels prior to Bench Adjustment. The plantarflexion resistance threshold of the Multi-Function articulated AFOs are adjusted to 1 Nm permitting 15 degrees of ankle plantarflexion relative to the ankle alignment angle before encountering the plantarflexion stop.

The patient is again asked to walk, and slow-motion video confirms that the toe clearance in mid swing and foot-to-floor angle at initial contact are unchanged after the reduction of the plantarflexion resistance threshold. The excessive knee flexion in 1st rocker is again observed and appears reduced following this adjustment but is still present. Therefore, the plantarflexion resistance threshold is further decreased to 0.6 Nm, increasing the compliance of the AFO in plantarflexion. Video analysis is repeated and reveals that this adjustment appears to significantly reduce the rapid knee flexion in the 1st rocker of gait. Foot position in swing phase and at initial contact remains unchanged, and ankle plantarflexion is clearly observed from initial contact to foot flat. The patient now ambulates with improved foot position through swing phase and at initial contact and with significantly improved knee kinematics and visible ankle plantarflexion through 1st rocker.

**STEP 5: Late Stance Phase Adjustment**
Having remediated the iatrogenic gait abnormality of rapid knee flexion in 1st rocker, Late Stance Phase Adjustment is performed. A stated goal of orthotic treatment was encouraging full knee extension in late stance phase. The orthosis had been bench adjusted for high structural resistance to dorsiflexion and this setting has not yet been changed. Therefore, the orthosis had been configured to block ankle dorsiflexion beyond the ankle alignment angle which occurs at midstance. While achieving full knee extension was a stated goal, knee hyperextension is observed and considered an iatrogenic gait abnormality, therefore the resistance threshold to ankle dorsiflexion must be decreased.

A 0.3 Nm/deg stiffness spring had initially been installed in the component’s dorsiflexion resist channel to provide assertive resistance to ankle dorsiflexion over a shorter range of motion substituting for the absent plantarflexors. The dorsiflexion resistance threshold is changed to 0.6 Nm which permits a maximum of 16 degrees of dorsiflexion range of motion relative to the ankle alignment angle before encountering the dorsiflexion stop. The patient is asked to walk, and slow-motion video confirms that the knee hyperextension has decreased after midstance, but repeated observations reveal that at this dorsiflexion resistance threshold, full knee extension is achieved only intermittently. Therefore, the dorsiflexion resistance threshold is increased to 1.4 Nm and the patient is again asked to walk. With this adjustment, video confirms that the patient achieves reliable, full knee extension with smooth tibial progression through mid-stance without knee hyperextension or early heel rise.

After completion of the algorithm, the patient’s gait pattern is comprehensively reviewed to determine whether there are additional opportunities for improvement through iteration of Multi-Function articulated AFO component settings.

Example 2

A Patient with Charcot Marie Tooth (CMT)

Imagine a hypothetical 76-year-old elderly male patient with history of Charcot Marie Tooth, presents to the clinic with a plantarflexion contracture with maximum dorsiflexion of 0 degrees and quadriceps weakness. The patient’s ambulatory function is impaired with several pathologic gait abnormalities including poor foot clearance in swing phase, steppage gait, short step length, and slow walking. Without use of an assistive device, the patient walks with an anterior trunk lean and instability. The patient’s chief complaint is decreased activity level and an increased number of falls.

The primary goal of orthotic treatment is to provide support for the quadriceps and decrease the risk of falls. Secondary goals are to improve standing balance in static weight bearing, and to improve toe clearance in swing phase while minimizing restriction of the ankle to preserve ankle motion in 1st and 2nd rockers.

The patient is molded for fabrication of bilateral Multi-Function articulated AFOs (Fig. 15). Prior to fabrication, the negative casts are corrected to neutral (0 degrees) dorsiflexion which would facilitate
approximately 5 degrees of shank inclination when donned with shoes. This ankle angle is the patient’s maximum passive dorsiflexion range of motion.

----------Place Fig. 15 about here----------

**STEP 1: Bench Adjustment**

Prior to fitting, the orthoses are bench adjusted. Bench adjustment is performed by adjusting the ankle alignment angle to its neutral setting (at the angle of fabrication) and the resistance threshold of the Multi-Function articulated AFO ankle joints to their maximum resistance setting, effectively configuring the AFOs as solid ankle-foot orthoses.

**STEP 2: Static Alignment**

The patient is seen for orthotic fitting and the orthoses and shoes are donned. The fit of the orthoses is evaluated and adjusted. After achieving the appropriate fit to provide comfort and postural support without irritation, the patient’s AFOs are optimized using the evidence-based algorithm.

The patient is asked to stand in the orthoses and the ankle alignment angles are adjusted with the patient in static weight bearing. Because the patient’s ankle dorsiflexion range of motion is limited, heel lift insoles are added to his shoes plantar to the orthoses to accommodate the contractures and maintain the position of the ankles within their passive range of motion. This facilitates optimization of shank inclination while avoiding alignment of the ankle angle to the patient’s end of anatomic dorsiflexion range of motion. The shank inclination is evaluated, and patient feedback is solicited regarding his sense of stability in quiet standing. The final ankle alignment setting is 2 degrees dorsiflexion. This static alignment results in the patient standing in slight knee flexion. Because the orthoses present high resistance to dorsiflexion (with dorsiflexion blocked at bench adjustment), the patient has the sense of improved standing balance which is objectively observed in a more relaxed and erect trunk and arm position. When solicited for feedback, the patient expresses a feeling of improved stability and comfort.

**STEP 3: Swing Phase Alignment**

The patient is asked to walk at a comfortable pace. A smart phone is used to record slow motion video to assist in identifying pathologic gait abnormalities.

Through this analysis it is observed that when walking, the patient has improved toe clearance and foot position at initial contact with the initial bench adjustment, though foot position at initial contact and step length appear slightly asymmetrical between the left and right sides. The ankle alignment settings of the AFOs are adjusted to improve symmetry while ensuring that the foot-to-floor angle is maintained at approximately 10 degrees at initial contact. Following this adjustment, the patient expresses the feeling of greater stability while walking and this is reflected by the observed decrease in anterior lean and reduced trunk sway during gait. The patient’s sense of standing balance is again evaluated in static
weight bearing and the ankle alignment setting is verified as the best compromise that overall provides the best standing balance and sense of stability while the patient is walking.

**STEP 4: Early Stance Phase Adjustment**

After the pathologic gait abnormalities of foot clearance in mid swing, knee extension at terminal swing, foot position at initial contact, and step length symmetry in early stance have been remediated with static and swing phase alignment, it is anticipated that the high resistance to plantarflexion of the Multi-Function articulated AFOs might result in the iatrogenic gait abnormality of rapid knee flexion in 1st rocker. This is confirmed by observation. To improve early stance phase kinematics, the Early Stance Phase Adjustment procedure is performed.

It was anticipated that a high stiffness spring resisting plantarflexion was appropriate for the patient, due to the patient’s weight and the nature of their biomechanical deficits, therefore, a spring of 1.5 Nm/deg stiffness was installed in the component’s plantarflexion resist channels prior to Bench Adjustment.

The plantarflexion resistance thresholds of the Multi-Function articulated AFOs are adjusted to 4.3 Nm facilitating 5 degrees of plantarflexion range of motion relative to the ankle alignment angle before encountering the plantarflexion motion stop. However, it is observed that knee flexion is still exaggerated in 1st rocker from initial contact to loading response at this plantarflexion resistance threshold setting. Therefore, the plantarflexion resistance threshold is further reduced to 1 Nm. The evaluation is repeated and this change in component settings appears to result in improved knee stability in 1st rocker with controlled knee flexion through early stance, while maintaining the position of the foot in swing to initial contact.

**STEP 5: Late Stance Phase Adjustment**

Having optimized knee kinematics in 1st rocker, attention is lastly focused on Late Stance Phase kinematics. Tibial progression through midstance and knee kinematics at terminal stance are evaluated using slow motion video.

It was anticipated that a high stiffness spring resisting dorsiflexion would be appropriate for the patient, due to the patient’s weight and the weak quadriceps, therefore, a spring of 1.5 Nm/deg stiffness had been installed in the component’s dorsiflexion-resist channels prior to Bench Adjustment. With the AFOs still adjusted to block dorsiflexion, repeated observations using slow-motion video of the patient walking, confirm that while knee stability appears improved and gait speed is higher, tibial progression is interrupted in 2nd rocker near the static alignment angle.

Therefore, the resistance threshold to dorsiflexion is decreased to 5 Nm to allow resisted ankle dorsiflexion past the ankle alignment angle after midstance, facilitating 4 degrees of resisted dorsiflexion range of motion beyond the ankle alignment angle. Resisted dorsiflexion is intended to support the quadriceps and keep the knee more extended through midstance while improving tibial
progression in 2nd rocker until the structural stiffness of the orthosis is encountered at the end of dorsiflexion range of motion.

After completion of the algorithm, the patient’s gait pattern is comprehensively reviewed to determine whether there are additional opportunities for improvement through iteration of Multi-Function articulated AFO component settings.

5 Discussion

The overarching goal of this AFO adjustment algorithm is to mitigate pathologic gait deviations while minimizing restriction of ankle motion throughout the gait cycle. It is assumed that the mitigation of pathologic gait deviations will improve overall patient function and the least possible ankle restriction will facilitate the most beneficial therapeutic outcome. However, the evidence upon which the method is based is limited to the biomechanical influence of Multi-Function articulated AFOs rather than the efficacy of orthotic treatment due to the paucity of orthotic efficacy research.

The method was developed to assist in the optimization of articulated Multi-Function articulated AFOs in the orthotic treatment of pathologic gait secondary to stroke, cerebral palsy (CP), traumatic brain injury (TBI), myelomeningocele (MMC), multiple sclerosis (MS), Charcot-Marie-Tooth (CMT) disease and other neuromotor pathologies. By adopting the modest ambition of developing a preliminary adjustment algorithm focused on the reduction of pathologic gait deviations when compared to normal gait, the algorithm is intended to serve as a preliminary guideline for the adjustment of AFO mechanical characteristics to streamline the process of AFO adjustment and improve the consistency of the clinician’s approach in reducing the pathologic gait deviations that may result from a broad range of underlying pathologies.

Evidence from published research that supported the development of the algorithm, suggests that the method could potentially be used to systematically reduce pathologic gait deviations to improve the gait, daily activities, and quality of life of patients with a broad range of underlying pathologies. The focal influence of specific mechanical characteristics of Multi-Function articulated AFOs on some kinesiological variables, and the reliability of observational gait analysis augmented by repeated observations of specific gait events using slow motion video were established and provide the foundation for the method (8, 10, 25, 30, 35, 38, 39, 44–49, 53, 54). However, some observations employed by the algorithm are less well supported including toe clearance in mid swing and knee extension at terminal swing. Additional research is required to validate the utility of these clinical observations for orthotic adjustment. There is also insufficient evidence to support the efficacy of AFOs in general in the treatment of patients with pathologic gait abnormalities (59, 60). Multi-site studies using an ensemble of metrics including patient activity level, kinesiological measurements, and validated survey instruments to determine patient satisfaction and quality of life could overcome these limitations.

Identification of pathologic gait deviations plays an important role in our proposed algorithm. Though there have been significant advances in motion analysis technology, a cost-effective and clinically viable...
means to quickly and accurately assess gait performance remains unrealized. In clinical practice, orthotists rely heavily on observational gait analysis to assess the impact of orthotic treatment. However, evidence also suggests that the reliability of observational gait analysis may be influenced by the clinician's skill level and personal experience (44, 46). There is also evidence to suggest that this reliability may be improved by focusing the clinician's observations on specific gait events, with repetitive trials using slow-motion video (45, 47–49). A thorough validation of the algorithm is necessary in future studies with a large sample size.

The published research does not support application of a single AFO stiffness to treatment of the complex gait pathologies that we observe (38, 61). Therefore, our case examples illustrate how the method could be applied to adjust the mechanical characteristics including stiffness and the resistance threshold of an AFO to the unique needs of the individual patient to achieve the best possible results. This method was developed to be effectively implemented in the clinical setting, by orthotists familiar with the basic techniques of customary orthotic practice. Real-world functional gait data that demonstrate the efficacy of orthotic treatment and AFOs optimized using the method is not available, however this limitation could be overcome by conducting large-scale clinical trials with comprehensive evaluations of a variety of patient populations (62).

Future applications of the algorithm (Supplementary File 1) might be to create an explicit methodology for orthotic clinical care that could inform research through the standardization of orthotic practice, facilitating the isolation of variables essential to experimental design. This research could also focus on efficacy, leading to improvements in the delivery of care, orthotic design and patient outcomes.

Declarations

Ethics statement

The algorithm presented in this study was developed based on literature review and clinical experiences of the team. The "Hypothetical case studies" were presented based on hypothetical patients.

Conflict of Interest

N. LeCursi and B. Janka are employees of Becker Orthopedic, Inc., manufacturer of the Triple Action Multi-Function ankle joint.

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Author Contributions
Data availability

All data generated or analyzed during this study are included in this published article.

References


Figures
The 3 Rockers of gait are essential for

1\textsuperscript{st} rocker: maintaining forward momentum in early stance,
2\textsuperscript{nd} rocker: creating support against gravity in single limb stance, and
3\textsuperscript{rd} rocker: providing propulsive impulses during push-off in late stance.

![Sagittal Ankle Motion Diagram]

The 3 Rockers of gait are defined by the minima and maxima of sagittal ankle motion. Sagittal ankle motion of individuals with post stroke often have reduced ankle range of motion, and delayed minima and maxima (red dashed lines with red arrows) due to slow walking speed resulting an elongated stance phase and shortened swing phase (7, 42).

Figure 1

The 3 Rockers of gait are defined by initial contact to first peak plantarflexion (1\textsuperscript{st} Rocker; Heel Rocker), peak plantarflexion to peak dorsiflexion (2\textsuperscript{nd} Rocker; Ankle Rocker), and peak dorsiflexion to second peak plantarflexion (3\textsuperscript{rd} Rocker; Forefoot Rocker) (7, 42)
The Complex Resistance-Angle Curve of an Adjustable Multi-Function Articulated AFO

Combined view of all angular ranges and stiffness values. Three stiffness levels in five adjustable regions; The highest stiffness (12 Nm/deg) is fixed, and due to AFO construction techniques; the other stiffnesses are adjustable, as are the ranges of each stiffness.

Figure 2

A resistance (torque, Nm) versus angle (deg) plot of an example Multi-Function articulated AFO with five adjustable ranges with different stiffnesses. Two of these stiffnesses are adjustable, and the high stiffness is due to fabrication methods. The AFO cartoon in the upper left shows the total range of the AFO with specific ranges colored to represent different stiffnesses.
A typical Multi-Function articulated AFO's Resistance vs. Angle curve results in a specific sagittal ankle kinematic curve. The limits to motion caused by the highest stiffness are represented in red (12 Nm/deg) mainly during swing phase in the curve, with blue representing a low stiffness of 0.3 Nm/deg in early stance, and green representing a low stiffness of 0.6 Nm/deg in mid- and terminal stance. The red stiff region as the ankle crosses neutral provides stability in single limb stance, but allows ankle motion in both dorsiflexion and plantarflexion as the ankle angle changes. Abbreviations: DF, dorsiflexion; PF, plantarflexion.

Figure 3

Three specific regions of pathological ankle motion are restricted by high stiffness (Red), while lower stiffness values (Blue and Green) allow the ankle to move functionally during specific periods of the gait cycle.
Example Adjustments in a Multi-Function Articulated AFO to Improve Specific Observed Pathologic Motions

Figure 4

A demonstrated series of adjustments to stiffness and range of motion of a Multi-Function articulated AFO to treat specific observed pathologic ankle motions. The overall outcome is a stiffer AFO with narrower bands of low stiffness ranges. Abbreviations: DF, dorsiflexion; PF, plantarflexion; ROM, range of motion.
Figure 5

Step 1: The bench adjustment of a Multi-Function articulated AFO at the start of the optimization process. The AFO is set at an incline of 11° of shank to vertical angle (SVA) (51) to accommodate a typical shoe. The plantarflexion (PF) resistance threshold and dorsiflexion (DF) resistance threshold are adjusted to maximum.
Step 2: Static Alignment
Adjust ankle alignment with AFO Solid (ROM = 0°)

**AFO Adjustment**
Dorsiflex alignment to incline shank and shift weight line toward mid foot

Linear relationship between AFO alignment and ankle angle in standing (63).

**Gait Deviation**
Shank reclined with knee extended and weight line toward heel

**AFO Adjustment**
Plantarflex alignment to recline shank and shift weight line toward mid foot

Linear relationship between AFO alignment and knee angle in standing, but each individual likely has a unique slope (63).

CVA: cerebrovascular accident; MS: multiple sclerosis

**Figure 6**

Step 2: Static alignment. With the AFO range set to 0° of plantarflexion and 0° of dorsiflexion, the alignment angle of the AFO is set so that the center of mass weight line falls at the middle of the foot (red line). The grey line shows when the AFO is too plantarflexed (left) or dorsiflexed (right). Previous research has shown that the standing ankle angle responds systematically to AFO alignment angle changes, accounting for > 99% of the participant’s variance (63). The knee also shows a linear relationship to AFO alignment angle ($R^2 > 0.96$), but each individual likely has a unique slope of knee position in standing as AFO alignment angle is altered (63).
Step 3A: Swing Phase Alignment
Iteratively adjust ankle alignment with AFO Solid (ROM = 0°)

**Gait Deviation**
Not enough toe clearance in mid swing

**AFO Adjustment**
Dorsiflex alignment to increase toe clearance

**Mid-Swing**
Published evidence of toe clearance during gait shows a value of 1-2 cm is reasonably safe for most individuals (15).

Published data show that sagittal ankle motion is systematically shifted into dorsiflexion with each successive 2° alignment change (0°, 2°, 4°, 6°) (32).

**Figure 7**
Step 3A: Swing phase alignment. The AFO alignment should be dorsiflexed to create 1-2 cm of toe clearance in mid stance (15). Published data show that sagittal ankle motion is systematically shifted into dorsiflexion with each successive 2° alignment change (0°, 2°, 4°, 6°), adapted from reference (32). Abbreviations: ROM, range of motion.
Step 3B: Swing Phase Alignment
Iteratively adjust ankle alignment with AFO Solid (ROM = 0°)

Gait Deviation
Not enough knee extension at terminal swing with or without shortened step length

AFO Adjustment
Plantarflex alignment to increase knee extension and make step length equal left and right

Terminal Swing

This is a difficult and perhaps unobtainable goal for individuals with knee flexion contractures. It is worth attempting, but it may not be possible.

Anecdotal evidence suggests that limited ROM of gastrocnemius may restrict knee extension and plantarflexing ankle alignment may facilitate increased knee extension.

There is not yet published evidence that this AFO tuning step is possible for all individuals.

Figure 8

Step 3B: Swing phase alignment. The AFO should be aligned to encourage near full knee extension at initial contact. This is a challenging goal, and there is not yet published evidence to support this goal in optimization of AFOs. Abbreviations: ROM, range of motion.
Step 3C: Swing Phase Alignment
Iteratively adjust ankle alignment with AFO Solid (ROM = 0°)

Gait Deviation
Foot to floor angle too low at initial contact

AFO Adjustment
Dorsiflexion alignment. Make foot to floor angle symmetrical for left and right foot

Gait Deviation
Foot to floor angle too high at initial contact

AFO Adjustment
Plantarflex alignment. Make foot to floor angle symmetrical for left and right foot

10-25° foot floor angle is supported by (6) and (56). Improving weight acceptance and preserving forward momentum is necessary to maintain gait economy (17).

Figure 9

Step 3C: Swing phase alignment. The AFO alignment should be adjusted to create a 10-25° between the foot and the floor at initial contact. 10-25° foot floor angle is supported by references (6, 56). Lower angles than this are observed in pathological individuals leading to foot-flat or toe-heel contact (56) that can disrupt weight acceptance and forward momentum preservation in early stance (17). Abbreviations: ROM, range of motion.
Step 4A: Early Stance Phase Adjustment

Adjust plantarflexion resistance threshold. If foot to floor angle at initial contact decreases with decreased PF resistance threshold, then return to the previous resistance threshold setting. If maximum resistance threshold does not correct deviation, increase spring stiffness. (DF ROM = 0°)

**Gait Deviation**
Rapid knee flexion in 1st rocker with limited ankle plantarflexion

**AFO Adjustment**
Decrease plantarflexion resistance threshold to reduce rapid knee flexion in 1st rocker

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**Figure 10**

Step 4A: Early stance phase adjustment. The AFO plantarflexion range should be adjusted or the spring stiffness changed to allow 1st rocker with controlled knee flexion. Published data have demonstrated that sagittal ankle motion can be systematically shifted into plantarflexion or dorsiflexion by altering plantarflexion resist spring stiffness (38). To control rapid knee flexion in early stance, either decrease plantarflexion resistance threshold or choose a less stiff spring (3 Nm/deg à 0.6 Nm/deg à 0.3 Nm/deg). Abbreviations: DF ROM, dorsiflexion range of motion.
Step 4B: Early Stance Phase Adjustment

Adjust plantarflexion resistance threshold. If knee hyperextension is observed before mid stance, increase PF resistance threshold. If maximum resistance threshold does not correct deviation, increase spring stiffness. (DF ROM = 0°)

Figure 11

Step 4B: Early stance phase adjustment. Published data have shown that a more compliant spring can shift the knee to more extension in early stance (38). To control knee hyperextension in early stance, either increase plantarflexion resistance threshold or choose a stiffer spring (0.3 Nm/deg à 0.6 Nm/deg à3 Nm/deg). Abbreviations: DF ROM, dorsiflexion range of motion; PF, plantarflexion.
Step 5A: Late Stance Phase Adjustment
Adjust dorsiflexion resistance threshold.

Published evidence supports the effect of AFO dorsiflexion resistance on knee flexion and extension (35).

Gait Deviation
Excessive knee flexion after mid stance

AFO Adjustment
Increase dorsiflexion resistance threshold to reduce knee flexion after mid stance

Gait Deviation
Knee hyperextension after mid stance

AFO Adjustment
Decrease dorsiflexion resistance threshold to reduce knee hyperextension after mid stance

Figure 12

Step 5A: Late stance phase adjustment. To reduce excessive knee flexion in stance, the dorsiflexion (DF) resistance threshold should be increased; to control knee hyperextension in single limb stance the dorsiflexion resistance threshold should be decreased. This approach is supported by data from reference (35).
Step 5B: Late Stance Phase Adjustment
Adjust dorsiflexion resistance threshold.

This is an area of AFO adjustment that does not yet have sufficient data to support this intervention, although it has been observed in some clinical cases that making this resistance threshold adjustment appears to be effective. In non-involved individuals, smaller triceps surae plantarflexor passive range of motion reveals earlier heel rise, suggesting that this mechanistic approach may be effective (58).

Figure 13

Step 5B: Late Stance Phase Adjustment. If heel rise occurs too early in the gait cycle, decrease the dorsiflexion (DF) resistance threshold. If the individual exhibits late heel rise with hyperdorsiflexion, increase the dorsiflexion resistance threshold (58). There is not yet published evidence which supports or refutes this adjustment.
A hypothetical case study of the adjustment algorithm for a 15-year-old adolescent male with sacral level myelomeningocele (MMC). With highly active dorsiexors and absent plantarexors, the Multi-Function articulated AFO is adjusted to have low stiffness through 15° of plantarexion and then encounters the high stiffness of the AFO structure. A brief period of high stiffness is set around neutral (0°) for stance phase stability, with a moderate spring stiffness into ~4° of dorsiexion where the high stiffness of the AFO was encountered to prevent excessive dorsiexion in late stance phase, and improve knee extension in mid stance.
Figure 15

A hypothetical case study of the adjustment algorithm for a 76-year-old elderly male with Charcot Marie Tooth (CMT). The patient’s pathologic gait deviations are the result of bilateral plantarflexion contractures at 0° and quadriceps weakness. After optimization, the ankle alignment angle for balance in static weightbearing, the Multi-Function articulated AFO is adjusted using the algorithm to allow 8° of resisted plantarflexion against stiff springs. The resistance threshold to dorsiflexion is adjusted to permit 2nd rocker against high resistance springs to stabilize the knees before encountering the high structural stiffness of the AFO at 5° dorsiflexion.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementalFileRS.pdf