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# BENCH TESTING OF A TUNABLE ANKLE-FOOT ORTHOSIS WITH ADJUSTABLE STIFFNESS AND NEUTRAL ANGLE

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## ABSTRACT

*Cerebral palsy is the most common childhood motor disability that effects 0.3% of children in the US and two-thirds of them have gait impairment. An ankle-foot orthosis (AFO) is commonly prescribed as a gait assistance. The function of an AFO is maximized when its stiffness and neutral angle are optimally prescribed to address each user's issue. However, the prescription process is not standardized and is subjective to the prescribing clinician. Only one-third of AFOs improved the user's gait while another one-third negatively affected the gait. A tunable AFO is developed to allow clinicians to test a range of stiffness and neutral angle of a passive AFO, making the prescription more likely to have a positive effect. The design of tunable AFO has a weight of about a typical plastic AFO and a dimension designed for children. It covers 90% range of stiffness and neutral angle of prescribed AFOs. It can withstand the torque applied during walking. Mechanisms of adjusting both parameters operate fast and are controlled by a microprocessor. A benchtop prototype was built to test the adjustment mechanisms. Both mechanisms were validated.*

Keywords: cerebral palsy, orthosis, objective prescription, gait assistance.

## 1. INTRODUCTION

Cerebral palsy (CP) is a childhood motor disability that impacts the ability to control muscle. It is estimated that 0.3% of children in the US have CP, and about two-thirds of children with CP experience some type of gait impairment. [2,3] An ankle-foot orthosis (AFO) is a plastic boot mounted on the user's calf and foot. It is commonly prescribed for children with CP to improve gait performance. Each AFO is customized to the user, not only for fit but also in setting the neutral angle of the ankle and the stiffness about the ankle. The performance is maximized when the two key parameters: stiffness and neutral angle are optimally set to address the condition of each user. [3] Stiffness is the compliance of the device in the dorsiflexion and plantar flexion direction. Neutral angle is the angle between the foot and calf when the device is unloaded. The AFO prescription process is not standardized and can depend on the subjective opinion of the prescribing clinician. Only 37% of AFO prescriptions improved gait quality, and 28% negatively impacted the gait pattern. [3]

Our lab is developing a tunable AFO, which is a device that allows clinicians to test a range of the stiffness and neutrals angle in the clinic to help prescribing a passive AFO that is more likely to have a positive outcome. The first generation of the tunable AFO used controlled hydraulics to emulate the different stiffness and neutral angle [7]. While this version worked, it required a walk-behind hydraulic power supply and controller, which is not feasible for practical use. The next generation device used tiny hydraulic cylinders to move the attachment point of a cantilever beam to achieve different stiffness and neutral angles [8]. Although this version was light and did not require a walk-behind cart, it was still significantly heavier than a plastic AFO and required thin hydraulic hoses from a waist pack to the ankle. From there, the design evolved to use lightweight electric motors to move the cantilever beam attachment points and reduced the overall weight [1]. A rendering of the current version is shown in Fig 1 and is estimated to weigh approximately 321 grams compared to the 350 grams of an average plastic AFO.

The purpose of this study was to fabricate a physical prototype of the current design and through bench testing to determine whether the system could modulate stiffness and neutral angle. The scope of this study was limited to bench testing and did not include experiments with users wearing the device.

## 2. MATERIAL AND METHOD

### 2.1 Design of the Device

Table 1 lists the key design requirement for the tunable AFO, which were derived from data collected at Gillette Children's Specialty Hospital (GCSH), a leading center for treating children with CP.

**TABLE 1:** DESIGN REQUIREMENTS

| # | Requirement | Value |
|---|---|---|
| 1 | Weight | <350g |
| 2 | Stiffness Range | 1-10 Nm/deg |
| 3 | Neutral Angle Range | 5° plantar flexion<br>to 15° dorsiflexion |
| 4 | Maximum Ankle Torque | Plantar flexion: 66Nm<br>Dorsiflexion: 21Nm |
| 5 | Adjustment Time | <30s |
| 6 | Height | <310mm |

The weight requirement comes from the need to weigh about the same as a typical plastic AFO. Stiffness and neutral angle are the two key parameters of an AFO. The ranges of stiffness and neutral angle capture 90% of current AFO prescriptions at GCSH. [4] The device must withstand the torque generated during walking. The adjustment time refers to the time required to change the stiffness or neutral angle from one end to the other. An upper limit of 30s ensures that the prescription process can be completed with a reasonable time. There is a limit to the height of the device since it should not hinder the gait of a child wearer. These design specs were realized in the model shown in Fig.1. A physical prototype (Fig 2) was built to determine if the mechanisms of controlling the key parameters are valid.

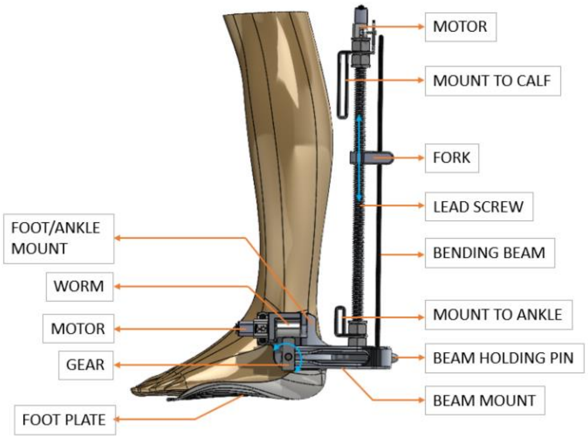

**FIGURE 1:** RENDERING OF THE TUNABLE AFO MOUNTING STRAPS ARE NOT SHOWN.

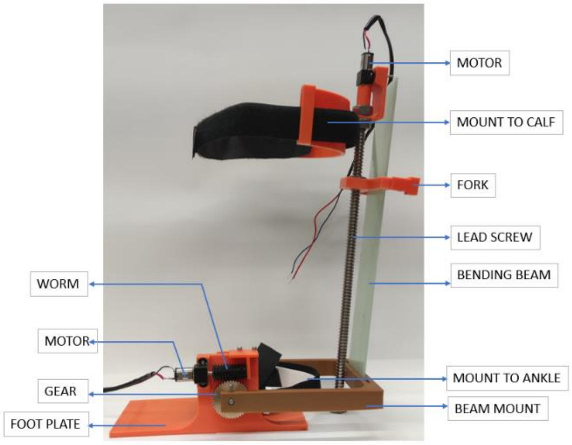

**FIGURE 2:** THE PHYSICAL PROTOTYPE.

The stiffness of the tunable AFO is controlled by the small electric motor at the top. As the motor rotates the lead screw, the fork moves up and down so that a changing portion of the cantilever beam at the rear bent during walking, therefore changing the effective stiffness of the beam. The beam is made of FR4/G10 glass fiber reinforced polymer (GFRP), whose geometry is designed to achieve the desired range of stiffness. [5] For the purpose of this bench test study, the beam was simplified to a rectangular 8cm-wide, 1/8-inch thick FR4/G10 sheet.

The neutral angle of the device is adjusted through a second gear motor driving a worm, so that the beam mount rotates with gear. The gear meshing with the worm has 80 teeth and is cut to only keep the portion needed to complete 20° of rotation required. The worm gear mechanism has a speed reduction of 80:1 and has the advantage that it cannot be back driven. The worm and gear were designed to withstand the required ankle torque. In the prototype, a 40-tooth bronze gear and a black-oxide 1045 carbon steel worm were used for testing.

The motors used were Pololu 1000:1 Micro Metal Gearmotor HPCB 12V motors. They are light and can produce the torque needed to adjust the parameters. The motors were controlled with Arduino Uno microprocessor and Pololu A4990 Dual Motor Driver Carrier using an open-source control library. [6] For the benchtop prototype shown in Fig. 2, most parts were 3D printed with ABS, given that the prototype would not be heavily loaded during the test protocol. The prototype was sized so that it could fit a small adult.

### 2.2 Benchtop Testing

The objective of this study was to test if the mechanisms for controlling the stiffness and neutral angle are valid. To test the stiffness adjustment mechanism, the bending stiffness with the fork at different heights was measured. The prototype was mounted onto a flat surface. The calf and ankle mount were attached to a foam cylinder whose base was touching the foot plate. A piece of tape was attached to the cylinder as a mark. A force gauge was connected to the plastic cylinder between the motor and lead screw. The fork was moved to three different positions by controlling the motor. With each position of the fork, the force gauge was moved horizontally in the direction away from the foot plate, and a video was taken to show the position of the system and the display of the force gauge. Video recordings were analyzed with software Kinovea to determine the rotation angle of the AFO. The rotation of the tape mark on the cylinder was measured to represent the bending of the beam. The torque applied to the beam was determined from the reading of the force gauge and the distance from the top of the beam mount to the force gauge attachment point.

The mechanism of adjusting the neutral angle was validated by showing that the neutral angle could be controlled by the motor when the prototype was unloaded.

## 3. RESULTS AND DISCUSSION

Bending stiffness of the beam results with the center of fork at 15cm, 18cm and 21cm above the top of the beam mount are shown in Fig 3. It took average 9s to make the adjustment with the motor operating at 90% of the maximum speed. The fork of the device can move with a 195mm range; therefore, the total adjustment time was estimated to be 45s. This is significantly longer than the desired and can be improved by using a different set of lead screw and nuts.

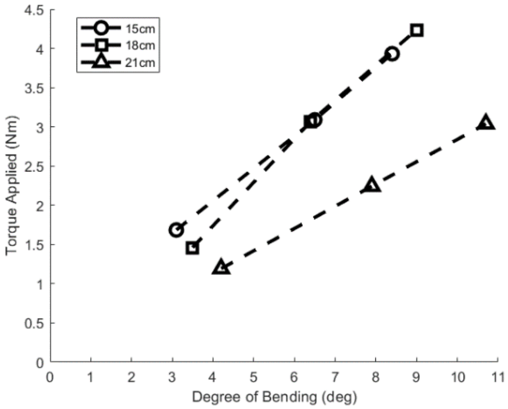

**FIGURE 3:** BENDING STIFFNESS TEST RESULT. THE STIFFNESS IS THE SLOPE OF EACH LINE.

The bending stiffness was estimated by fitting the data shown in Fig. 3 to a straight line passing through the origin with the results shown in Table 2. The data proved that this mechanism is valid.

**TABLE 2:** BENDING STIFFNESS WITH DIFFERENT FORK POSITIONS.

| Fork Position | Bending stiffness |
|---:|---|
| 15cm | 0.48 Nm/deg |
| 18cm | 0.47 Nm/deg |
| 20cm | 0.34 Nm/deg |

Fig. 4 shows the prototype with neutral angle at 8.5° dorsiflexion, 0°, and 11.5° plantar flexion. It took 4s to change the neutral angle from 0° to each of the other two positions with the motor operating at 90% of the maximum speed. The total adjustment time for the required range of 20° was estimated to be 7.2s. This mechanism is therefore proven to be valid and the desired adjustment time is achieved.

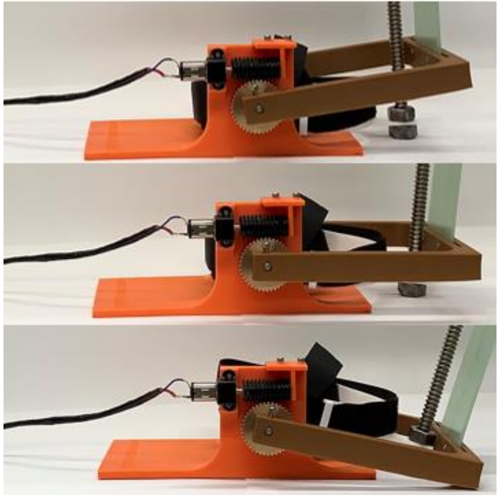

**FIGURE 4:** THE PROTOTYPE WITH A NEUTRAL ANGLE OF 8.5° DORSIFLEXION (TOP), 0° (MIDDLE), AND 11.58° PLANTAR FLEXION (BOTTOM).

## 4. CONCLUSION

The tunable AFO is a device that helps determines the stiffness and neutral angle of a plastic AFO. It is expected help to improve the treatment outcomes of AFO prescriptions. The mechanism for adjusting the stiffness and neutral angle was validated.

## ACKNOWLEDGEMENTS

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