Soft Wearable Orthotic Device for Assisting Kicking Motion in Developmentally Delayed Infants[1]

Kriti Subramanyam
Harvard School of Engineering and Applied Sciences, Cambridge, MA 02138

Emily Rogers
Harvard School of Engineering and Applied Sciences, Cambridge, MA 02138

Mateusz Kulesza
Harvard School of Engineering and Applied Sciences, Cambridge, MA 02138

Donal Holland
Harvard School of Engineering and Applied Sciences, Cambridge, MA 02138;
Wyss Institute for Biologically Inspired Engineering, Boston, MA 02115

Joshua Gafford
Harvard School of Engineering and Applied Sciences, Cambridge, MA 02138;
Wyss Institute for Biologically Inspired Engineering, Boston, MA 02115

Eugene Goldfield
Wyss Institute for Biologically Inspired Engineering, Boston, MA 02115;
Boston Children's Hospital, Boston, MA 02115

Conor Walsh
Harvard School of Engineering and Applied Sciences, Cambridge, MA 02138;
Wyss Institute for Biologically Inspired Engineering, Boston, MA 02115

1 Background

Cerebral palsy is diagnosed in 1 out of 3000 people in the U.S. Nearly half of affected children have a limited ability to crawl and walk and a majority of them rely on the use of assistive devices for mobility [1]. Exploratory kicking motion in infants is essential for developing the coordination between the knee and hip joints, which leads to crawling and eventually the development of a coordinated gait [2]. Because infants with cerebral palsy tend to exhibit very little independent motion during the kicking stage, they often have gait deficiencies that limit their ability to walk when they reach adulthood [3].

Cerebral palsy is typically not diagnosed until the age of two, when a child starts walking and abnormal gait patterns become apparent. At that point, the abnormalities are difficult if not impossible to correct without costly and invasive treatment methods. On the other hand, several well-known factors are associated with an increased probability of developing cerebral palsy, most notably premature birth [1]. In these cases, early intervention treatment can be administered during the infant stage and has the potential to stimulate the formation of neuromuscular connections that would otherwise not develop due to the onset of the impairment [3]. However, the high cost and scarcity of such methods limit their current utility as potential therapies. There is a need for early intervention treatment methods that can improve infants' motor coordination before they begin walking; such treatments would likely reduce gait deficiencies and dependence on assistive devices later in life.

The soft, wearable kicking device presented in this paper actively assists kicking in infants at the hip and knee joints in all relevant planes of motion. By stimulating kicking motion, the device may help build nerve connections in the infants' legs, thereby improving the development of motor control and proper gait.

2 Methods

Functional requirements for an assistive device for infants were identified through interviews with clinical collaborators and observation of an infant kicking study. A target age range of 3–9 months was chosen to specifically address the opportunity for early intervention treatment to reduce symptoms of cerebral palsy prior to official diagnosis. The device was designed to be a wearable system that assists hip adduction, abduction, hip flexion, and knee flexion, and is appropriately sized, comfortable, and safe for an infant to wear. The final design (Fig. 1) consists of soft fiber-reinforced pneumatic actuators on the hip and knee, a fabric attachment interface with Velcro straps, and a control system.

In order to match the active range of motion of infants, the device assists hip flexion to 18 deg, hip abduction and adduction to 60 deg, and knee extension to 146 deg [4]. Based on force calculations for the average weight of an infant's leg, the device was designed to produce a 1.6 Nm torque at the hip and 0.5 Nm torque at the knee to achieve this range of motion. For the hip actuators, fiber-reinforced actuators were fabricated by molding hollow tubes of elastomer (Elastosil M4601, Whacker Silicones, Adrain, MI). The actuators were then wrapped with strain limiting thread (Kevlar thread, KEV693NATL00S, The Thread Exchange, Weaverville, NC) to prevent radial expansion. A flexible strain layer (Fiberglass cloth, FG-C0427S, U.S. Composites, West Palm Beach, FL) was adhered to the bottom to constrain longitudinal expansion on one side of the actuator, thereby producing a bending motion. Gaps in the strain layer allowed sections of the actuator to extend in the axial direction. Preliminary testing determined that in order to extend over the flexed hip, extension segments of 9.5 cm were needed to achieve a total extension of 4 cm when pressurized.

Four actuators were placed on the bottom of each leg, two on the inside of the thigh and two on the outside. This attachment configuration requires the inner actuators to twist from the anchoring point on the infant's back to the anchoring point on the knee, a motion achieved by wrapping segments of the actuators with

Fig. 1 Final device attached to infant mannequin showing attachment interface that holds hip and knee actuators in place

[1]Accepted and presented at The Design of Medical Devices Conference (DMD2015), April 13–16, 2015, Minneapolis, MN, USA.
DOI: 10.1115/1.4030549
Manuscript received March 3, 2015; final manuscript received March 17, 2015; published online July 16, 2015. Editor: Arthur Erdman.

Fig. 2 (*a*) Hip actuator attachment and (*b*) knee actuator attachment

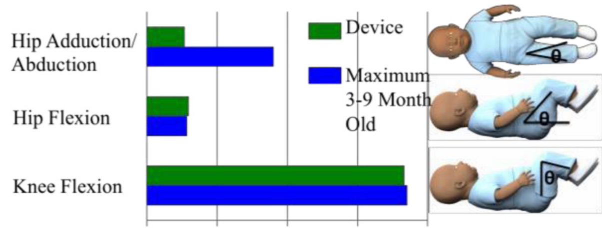

Fig. 3 Joint angle analysis of device compared with maximum angles achieved by 3–9 month-olds [4]

Kevlar thread in a unidirectional pattern as opposed to a double helix pattern [5]. By pressurizing, different combinations of the actuators, hip adduction, abduction, and flexion are achieved. The knee actuators are hollow cylindrical tubes of elastomer (Elastosil M4601, Whacker Silicones, Munich, Germany), which expand radially when pressurized. Constraining the expansion inside a pocket made of inextensible fabric causes the actuators to stiffen and become rigid when pressurized. When not pressurized, these actuators can bend easily in all directions. Two actuators were placed on the back of the leg with the two ends of the actuators anchored just above and below the knee joint. This allows for the knee to remain in a flexed position without causing any discomfort. When pressurized, the actuators stiffen underneath the knee and cause the leg to straighten, producing knee extension.

To attach the actuators to the body, a wearable harness containing pockets that hold the actuators in place at their precise anchoring points on the body was designed (Fig. 2).

The harness design consists of a waist strap and thigh straps that attach securely to the infant with a Velcro closure. The hip actuators are encased in spandex pockets, which are anchored on each side to the waist and thigh straps and capped with inextensible fabric to prevent the actuators from sliding out of the pockets as they extend.

A reinforcing band that straps around the actuators was added at the thigh, to ensure that their bending moment is applied directly across the infant's hip. The knee actuators are encased in inextensible fabric pockets and sewn directly onto the attachment bands.

3 Results

Preliminary testing was performed by attaching the device to a model with the dimensions and mass of a 3-month-old's hip and leg. Visual markers were placed on the joints to track motion and images were taken with the device fully pressurized (60 psi) and fully relaxed. Abduction/adduction was measured as a range from full adduction to full abduction rather than a deviation from a neutral position. Hip flexion was measured as the angle between ground and the thigh. Knee angle was measured with the straight leg equal to 180 deg and knee flexion causing a decrease in knee angle. An open source image processor (ImageJ, National Institutes of Health, Bethesda, MD) was used to measure the joint angles from the captured images and determine the range of motion achieved by the device.

Measuring the joint angles in the sagittal and coronal planes shows that the device is able to assist and initiate motion within the average range of motion of 3–9 month-olds. Figure 3 shows that joint angles for hip flexion and knee extension were almost identical to those measured on healthy infants with the device achieving 26.7 deg of the desired 18 deg of hip flexion and 165 deg of the desired 146 deg knee extension. The device achieves 24.1 deg of the full 60 deg range of motion of a real child in the abduction/adduction plane.

The assistance provided by the device can be varied by changing the pressure used to inflate the actuators or by changing the valve timing, reflecting the customizability of the therapy provided by this device. The actuator pressure can be modulated so as to provide graded actuation even in changing contexts of resistance with spasticity. When initially used on an infant, the device could be used at full pressure (60 psi) in order to provide maximum assistance in all degrees of freedom. However, as the child developed more coordination and strength, the effective pressure could be decreased.

4 Interpretation

This paper presented a device that could aid in the development of coordination between the knee and hip joints during kicking in 3–9 month-old infants through assisted kicking motion. Stimulation of infant kicking may allow necessary neural connections to form in the lower body, leading to improved motor control, particularly during gait development. Ultimately, the device has the potential to decrease dependence on assistive mobility devices and gait-correction treatments later in a child's life. As the first active device designed specifically for infants, this device would be used for infants at risk for cerebral palsy, including those with clinically obtained perinatal neuroimaging evidence of white matter damage. Thus, this therapy could improve access to early intervention care for infants at risk for cerebral palsy and other developmental delays. Future work will include interfacing the actuator suit with a previously designed sensing suit [6]. This integrated device will allow for smart control of the device, using the actuators to assist kicking if the detected change in joint angle is less than 5 deg/s.

Acknowledgment

This work was performed in ES 227, a course at the Harvard School of Engineering and Applied Sciences (SEAS) taught by one of the authors (CW) with two of the authors (DH and JG) acting as support teaching staff. Funding for this work was provided by SEAS, the Wyss Institute for Biologically Inspired Engineering, and a Course and Program Grant from the National Collegiate Inventors and Innovators Alliance. The final fabrication of the actuator attachment module was performed by Leanne Luce.

References

[1] CDC, 2013, "Cerebral Palsy," Centers for Disease Control and Prevention, Atlanta, GA, http://www.cdc.gov/ncbddd/cp/causes.html

[2] Jensen, J. L., Ulrich, B. D., Thelen, E., Schneider, K., and Zernicke, R. F., 1994, "Adaptive Dynamics of the Leg Movement Patterns of Human Infants: The Effect of Posture on Spontaneous Kicking," J. Mot. Behav., **26**(4), pp. 303–312.

[3] Damiano, D. L., 2006, "Activity, Activity, Activity: Rethinking Our Physical Therapy Approach to Cerebral Palsy," Phys. Ther., **86**(11), pp. 1534–1540.

[4] Harris, M. B., Simons, C. R., Ritchie, S. K., Mullett, M. D., and Myerberg, D. Z., 1990, "Joint Range of Motion Development in Premature Infants," Pediatric Phys. Ther., **2**(4), pp. 185–191.

[5] Maeder-York, P., Clites, T., Boggs, E., Neff, R., Polygerinos, P., Holland, D., Stirling, L., Galloway, K., Wee, C., and Walsh, C., 2014, "Biologically Inspired Soft Robot for Thumb Rehabilitation," ASME J. Med. Devices, **8**(2), p. 020933.

[6] Rogers, E., Polygerinos, P., Goldfield, E., and Walsh, C., 2015, "Smart and Connected Actuated Mobile and Sensing Suit to Encourage Motion in Developmentally Delayed Infants," ASME Design of Medical Devices Conference. Minneapolis, MN, Apr. 13–16, ASME Paper No. DMD2015-8701.