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Research paper

Development of Ankle-Foot Orthosis with Vibration Stimulator using Energy Harvesting Source for Cerebral Palsy Children

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Abstract

Background/Objectives: Recently, studies on the effects of vibration stimulation on the stiffness, strength, motion function, gait, and various daily activities have been conducted in patients with nervous diseases like Parkinson's disease, stroke, cerebral palsy (CP) and human multiple sclerosis(MS).
Methods/Statistical analysis: Although a variety of ankle-foot orthosis (AFO) is generally used to increase the efficiency of gait and normalize movement patterns with spastic CP in clinic, it was no AFO combined with vibration stimulator to improve the gait. Therefore, we aim to develop AFO that can give local vibration stimuli to improve walking of children with CP.
Findings: Therefore, it is possible to expect smooth gait and posture maintenance ability by applying vibration stimulus while wearing a short leg support, regardless of time and place when walking or standing.
Improvements/Applications: The vibration stimulator uses a vibration motor equipped with an eccentric rotor. The power source of the vibration stimulator is combined with the energy harvesting technique using the piezoelectric element.

Keywords: *Ankle-foot orthosis, Cerebral palsy, Frequency, Piezoelectric, Vibration stimulator.*

1. Introduction

Cerebral palsy (CP) refers to a disorder caused by non-progressive brain damage with clinical characteristics such as impairment of movement and postural control[1]. Children with CP have a variety of motor impairments, such as spasticity, decreased muscle strength, poor balance, and loss of selective motor control, depending on the location and degree of the damage in the central nervous system[2]. In particular, about 90% of children with spastic CP have deformities of the foot and ankle, caused by muscle weakness, coordination problems, and joint contracture associated with spasticity. In spastic CP, a representative deformity of the foot and ankle is equinus, with shortness of ankle plantar flexors. This deformity leads to excessive ankle plantar flexion in the stance phase, associated with a decreased step length, gait velocity, and cadence during gait[3]. Most therapeutic interventions focus on reducing spasticity in the calf muscles to improve postural control and gait[4,5,6]. Medications, botulinum toxin injections, and orthopedic surgery are traditional interventions for reducing spasticity[7]. These interventions can have negative side effects, including systematic deconditioning, pain, and long-term immobilization[7]. To decrease these effects, conservative treatments such as thermal therapy, muscle stretching, and electrical stimulation are often performed in clinics.
Recently, many researchers have investigated whether vibration stimulation is effective not only to reduce muscle spasticity, but also to improve muscle strength, gait, and various activities of daily living in various neurological diseases such as CP, stroke, and multiple sclerosis and Parkinson's disease [4]. Vibration stimulus has the advantage that it is easy to apply and can facilitate the proprioceptive nervous system as a noninvasive method[8]. Many researchers have addressed the physiological mechanisms of the effects of vibration stimulation. The first mechanism is the tonic vibration reflex where the vibration stimulus activates the primary muscle spindle endings, causing Ia afferent impulses to be conducted to alpha motor neurons that produce involuntary contractions in the vibrated muscle[9]. The second mechanism is that Ia inputs can alter the excitability of the corticospinal pathway by increasing excitability of primary motor cortex. The third mechanism is that excitation of the Golgi tendon organs activates a reflex by which the vibrated muscle is forced to relax and the antagonist is forced to contract]. A vibration stimulus can be applied as whole-body vibration or segmental muscle vibration (SMV). Katusic et al. (2013) reported that whole-body vibration significantly reduced spasticity and improved motor functions in children with CP[8]. Dickin et al. (2013) reported that vibration stimulation increased the dynamic ankle joint range of motion, stride length, and walking speed in children with CP[5]. However, whole-body vibrations do not selectively stimulate spastic muscles. Also, vibration stimulation therapy is limited in number of treatments and cannot be used during gait in clinic.
A variety of orthoses have been used to increase walking efficiency and normalize exercise patterns with spastic CP. In children with CP, the purpose of orthotic management in ankle foot orthoses (AFOs) is to improve walking pattern by positioning distal joints in a way that reduces abnormal reflex patterns or by preventing pathological movement of the joints. Although a wide variety of AFOs are used in clinic, it was no AFO with vibration stimulator to improve the gait. Therefore, we would like to

develop a vibration stimulator with energy harvesting technology that can be used in any place. It will be possible to expect smooth gait and maintenance of normal posture by applying continuous vibration stimulation while wearing the AFO without regard to time and place when gait or standing.

2. Energy Harvesting Technique using Piezoelectric Device

2.1. Piezoelectric (PZT) Effect

Piezoelectric elements are devices that exhibit piezoelectric phenomena. Typical examples are crystal, tourmaline, and rustrates. It is also called a piezoelectric element. Crystals such as quartz, barium titanate, ammonium dihydrogenphosphate, and ethylenediamine-tartarate have recently been used as piezoelectric elements. Piezoelectricity is a phenomenon in which positive and negative electric charges proportional to external force appear on both sides of a plate when a certain kind of crystal plate is pressed in a certain direction. In 1880, Jacque Curie and Pierre Curie : 1859 ~ 1906) Brother first discovered it. It is known that the piezoelectricity appearing on a single crystal plate is weak, but the amount of piezoelectricity is greatly increased when multiple sheets are inserted while inserting a metal foil. It has also been found that there is inherent vibration in the crystal plate, and when the elastic vibration and the electric vibration are in agreement, they are combined with the piezoelectric vibration to generate stronger vibration. And various inventions using these phenomena followed. As a result, crystals and barium titanate are widely used as piezoelectric elements in the pick-up of a microphone or a full-axis, a speaker of a telephone or a radio, an ultrasonic detector, a vibrator of a crystal watch, a broadcasting device. The principle of power generation using piezoelectric elements is shown in Figure 1.

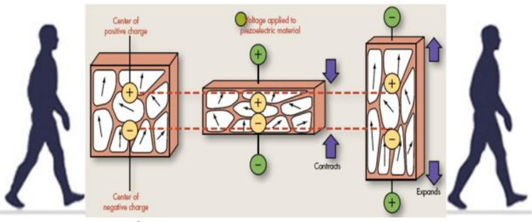


Figure 1: Principle of Electric source generation in Piezoelectricelement

2.2. Energy Harvesting Technology

Energy harvesting is a series of processes where energy is produced from external energy sources and stored in a small power devicey that is used in mobile and portable electronics. The energy source of the energy harvester is supplied from the surrounding space and can be freely used. An example of an energy source for harvester are vibration, wind, wave, thermal temperature gradients, and piezoelectric elements. Here, we focus on vibration and piezoelectric elements as a typical source that can be converted to electric power in the environment.

Vibration of the body is a very charming energy source because it is abundant. Some vibrating circles in nature have a wide variety of frequencies and amplitudes, including rotation of electric motor, wind, waves of the sea, car motion, human body motion, and earthquake vibration. Vibration energy can be collected using several ways, such as piezoelectric, static electric and electro-magnetic conversion. Piezoelectric energy harvesters provide a high output power and are more efficient for relatively high vibration frequencies[10].

The energy harvesting technique can be introduced in this study because it does not require stimulation at all times in the case of anankle-foot orthosis equipped with a vibration stimulator. Also, since the displacement and the stress (compression) of the human body are mounted on the greatest foot when a person moves, the mechanical energy that can be converted into electrical energy can be easily secured. Figure 2 shows the concept of energy harvesting process using piezoelectric element.

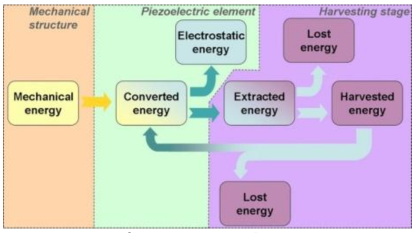


Figure 2: Concept of Energy harvesting process using Piezoelectricelement

2.3 Adoption of Vibration Stimulator

The vibration stimulator selects the vibration mode according to the amplitude, frequency and duration time of the required vibration according to the patient's condition. Generally, vibration is generated by using a vibration motor and an actuator. There are vibration motors that connect the eccentric load to the rotor of the motor and cause unbalanced rotation when the motor rotates. And, an actuator vibrates the drive rod with the interaction force (magnetic force) between the permanent magnet and the power coil. Figure 3 shows the two types of vibrator according to vibration generation method. The two types according to the vibration type are shown in Table 1by comparing the power source, vibration source, vibration type, and advantages and disadvantages.

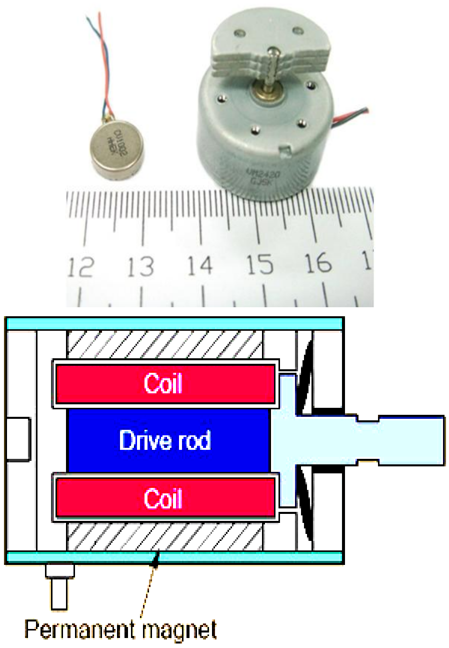


Figure 3: Type of Vibrator according to Vibration generation method

Table 1: Advantages and Disadvantages of Vibration system

Division	Vibration motor type	Actuator type
Power	Rechargeable battery	Rechargeable battery
Principle of vibration	Vibration due to eccentric rotation	Motion of a magnetic body by magnetic force
Vibration type	Oscillating type	Straight type
Advantages	Easy to control - Small size	- Strong vibration -Relatively weak vibration - Constant vibration
Disadvantages	-Relatively weak vibration	Relatively large volume

3. Implementation of Ankle-Foot Orthosis

3.1 Design of Power Source

A rectifier using a bridge circuit and a circuit for charging the rechargeable battery should be designed in order to rectify the AC power input from the piezoelectric element and supply it to the DC vibration stimulator. The PZT Pad design maximizes the energy conversion by analyzing the gait patterns of children with cerebral palsy by optimizing the placement of the piezoelectric pads and the circuit connections on the bottom of the orthosis. Adoption of a capacitor analyzes the correlation between the amount of walking children and the use time of a vibration stimulator, and installs a capacitor with a suitable capacitance. Charging circuit design is to design and install a charging circuit capable of full wave rectification because the power source is reversed when the brace is on and off. The detailed circuit diagram of the power supply circuit is shown in Figure 4. Also, Figure 5 is the appearance of piezoelectric pad on foot plate of ankle-foot orthosis.

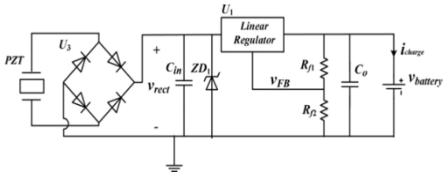


Figure 4: Power Chargingcircuit of Vibration stimulator using Bridge circuit

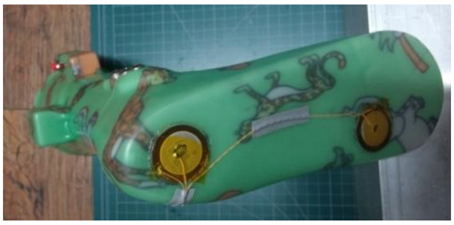


Figure 5: Appearance of Piezoelectricpad on Foot plate of Lower leg orthosis

3.2 Design of Vibration Stimulator

Since the amplitude, frequency, and duration of vibration are different according to the patient's condition, the control circuit is designed to be adjustable within a certain range. As a result of comparing the vibration motor with the actuator, it was easy to install the eccentric vibration motor and the relatively high vibration frequency was obtained, and the vibration motor was selected as the vibration stimulator. Figure 6 shows the vibration motor with eccentric rotor as vibration stimulator. Also, Table 2 and Table 3 are the characteristics of vibration stimulator and specification of vibration motor for vibration stimulator.

a) Side view b) Front view

Figure 6: Vibration motor with Eccentric rotor as Vibration stimulator

Table 2: Characteristics of Vibration stimulator

Division	Characteristics
Source	Rechargeable battery and piezoelectric element power are mixed
Rotor	Eccentric body about the weight of the motor
Vibration	Unbalanced rotation vibration
Control	Voltage control

Table 3: Specification of Vibration motor for Vibration stimulator

Specification	Values	Specification	Values
Rated voltage	3 [V]	Axial length	15 [mm]
Rated current	520 [mA] Max.	Diameter	12 [mm]
Rotation speed	13000 ± 1300 [rpm]	Diameter of eccentric rotor	6 [mm]
Starting voltage	1.0 [V]	Height of eccentric rotor	8 [mm]
Axial interval	0.02-0.5 [mm]		

3.3 Design Parts

The ankle-foot orthosis requires a vibration stimulator, a power control switch, a lamp, a power jack, and a battery. Table 4 shows the specifications of the other components like Figure 7.The switch uses the push button method, and when it is OFF, the energy harvesting power is also cut off. The charging jack can charge the battery of the vibration stimulator using an external power source. Piezoelectric pads were placed in the two most stressed areas when the patient walked. The power source of the vibration stimulator was a rechargeable AA type rechargeable battery which can be charged and recharged using a general charger. Unlike general-purpose disposable batteries, which cannot be reused once, they have the same shape and performance, and can be reused using a conventional charger. The charging lamp uses DC LED, lights up when charging, and turns off when charging is complete. In the rectifying circuit, a Whitestone bridge was used to convert the alternating current generated in the piezoelectric pad into a direct current by full wave rectification.

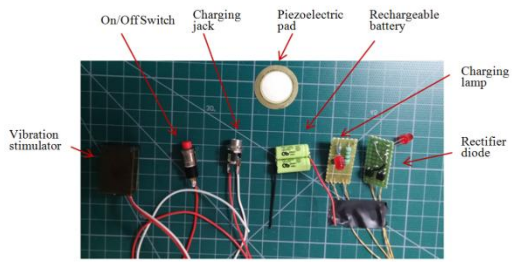


Figure 7: Electronic devices for Manufacturing Vibration stimulators

Table 4: Specification of Design parts for Ankle-foot orthosis

Parts	Spec. & Values	Piezoelectricpad	Spec. & Values
Power switch	Push button type Rating: 3A/125 VAC Contact resistance.: 50 mΩ	Resonant frequency Resonant impedance Max. input voltage	7,200 ± 300 Hz 300 Ohm 30 V
Bridge rectifier	Full wave rectification	Capacitance @ 1kHz	10,000 ± 30% pF
Power jack	DC-025 A	Plate material	Stainless steel
Charging lamp	T-1 3/4 Standard 1.0	Operating temp.	-20 ~ 60 ℃

3.4 Manufacturing Process

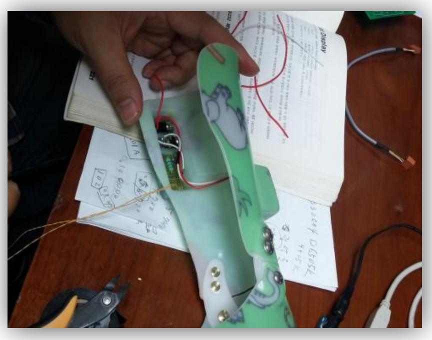
The orthosis with the vibration stimulator was fabricated through the manufacturing process as shown in Figure 8.The orthosis model should be tailored to the foot size and symptom severity of patients with cerebral palsy. A pediatric orthosis model was embossed with appropriate size as a sample. The orthosis model was designed considering the position of vibration stimulator, switch, rectifier circuit and piezoelectric element. The vibration stimulator was mounted on the back because it needed to eliminate the interference of both legs and stimulate the calf when walking.

The switch and charge jack utilize the side of the attachment of the vibration stimulator and are designed not to protrude to the side. The rectifier circuit was installed on the outside so as not to cause interference when walking, and was installed close to the vibration stimulator as much as possible. The piezoelectric pad was attached to the heel and the forefoot to strengthen the contact force. The two pads were connected in series and connected to the bridge of the charging circuit.

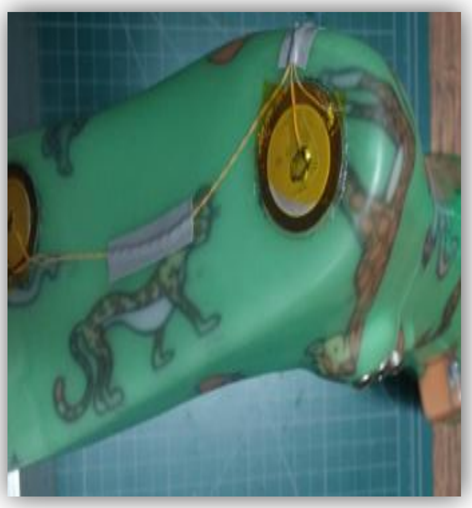
a) Orthosis model making

b) Insertion of vibration stimulator

c) Charging jack and switch installation



d) Rectification circuit mounting



e) Piezoelectric pad attachment

f) Orthosis with vibration stimulator

Figure 8: Manufacturing process of Ankle-foot orthosis withVibration stimulator

4. Conclusion

Vibration can be divided into whole-body vibration and focal vibration. Although whole - body vibration has been proven to be effective in most neurological diseases such as stroke, cerebral palsy, spinal cord injury and multiple sclerosis, there have been few studies using local oscillations in children with cerebral palsy. Thus, ankle-foot orthosis equipped with a vibration stimulator using an eccentric rotor vibration motor was developed. The energy harvesting technique using the piezoelectric element was applied as a power source for driving the vibrator. This should be used in conjunction with an external rechargeable garden to enhance the effectiveness of ankle-foot orthoses.

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