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A Review of Actuators in Ankle-Foot Rehabilitation Therapy

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KEYWORDS

Pneumatic Artificial Muscle
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Servo Motor
Range of Motion (ROM)

ABSTRACT

Ankle injury is one of the physical injuries that commonly occur during physical related activities, especially in sports. Currently, there are established treatments for ankle rehabilitation at the hospital. This treatment involves range of motion exercises and endurance exercises. However, current treatment requires patients to visit to hospital frequently which is very repetitive in nature. Ankle rehabilitation robots are developed to enhance ankle strength, flexibility and proprioception after injury and promote motor learning and ankle plasticity in patients with drop foot. This article reviews the types of actuators used in ankle rehabilitation and discusses the evolution of industrial robotics towards rehabilitation.

1. INTRODUCTION

Ankle joint is one of the most important joints in human body as it helps to maintain body balance for lower limb movement [1, 2]. It is capable of rotational motion in all three anatomical planes while subjected to impact forces of up to several times of the body weight during normal daily activities. Consequently, the ankle has tendency to be injured if its movement is excessive. Previous researches showed that ankle injury is considered as one of the most common sports injuries as well as domestic related activities [3, 4]. Various types of ankle rehabilitation robots have been developed in the last years. One of the popular ankle rehabilitation robots is the Rutgers Ankle [5, 6]. Rutgers Ankle is a pneumatically actuated 6-degree-of-freedom (DoF) Stewart platform that allows patient to do his or her rehabilitation routine in virtual reality (VR) environment. Apart from pneumatic actuators, there are also electrical and shape memory alloy which are used as actuator for rehabilitation. Robot-assisted ankle rehabilitation presents many advantages in concerns of effectiveness and repeatability. Nevertheless, the solution existing on the market is still not convenient, in term of cost, dimensions or complexity [7]. This paper reviews and describes the types of actuator used for rehabilitation and range of motion obtained from the actuators used.

2. ANKLE JOINT

The foot and ankle are made up of the twenty-six individual bones of the foot, together with the long-bones of the lower limb to form a total of thirty-three joints. Although frequently referred to as the 'ankle joint', there are a number of articulations facilitating motion of the foot. The ankle joint has a very complex structure which is responsible for the up and down, side to side and medial to lateral motion of the foot as shown in Figure 1(a). Ankle joint is composed of three bones: the tibia, the fibula, and the talus. The subtalar joint is under the ankle joint, and it consists of the talus on top and calcaneus on

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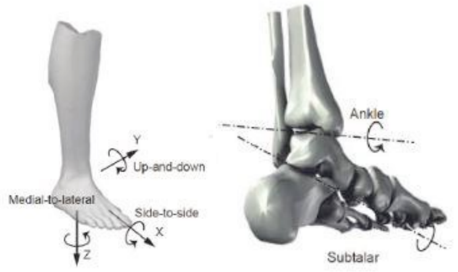
the bottom. The subtalar joint is responsible for the side-to-side motion of the foot as shown in Figure 1(b) [8].



(a) (b)

Fig. 1: a) Rotation direction, and b) Structure of ankle joint [8]

3. REHABILITATION DEVICES FOR ANKLE-FOOT

Over the many years all around the world, research and development concerning the design of more and more effective systems supporting rehabilitation of ankle have been conducted, and these resulted in creation of various equipment's. Moreover, significant improvements were observed in rehabilitation devices regarding range of motion, complexity of the devices and effectiveness over the years. Below describes the evolutionary of the rehabilitation devices.

3.1 Low complexity devices

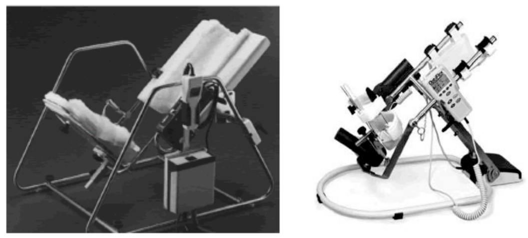
This Low complexity devices refer to devices that do not involve any mechanicals or actuators to operate those devices. These devices could be made very simply by using elastic bands, roller foams and wobble boards as shown in Figure 2(a)(b)(c). These devices are typically used in exercises that could be performed both in clinic and at home, they are easy to find in almost any physiotherapist shop. Elastic bands are the simplest devices, made of multi-shaped strips of resistive elastic intended for muscular strengthening. Roller foams act as unstable surfaces and are used to improve balance and proprioception. Wobble boards are circular discs with a hemispherical pivot in the centre of one of the sides, used to improve balance and proprioception too as shown in Figure 2.

a) b) c)

Fig. 2: (a) Elastic band (b) Roller foam (c) Wobble Foam [9]

3.2 Intermediate complexity devices

Intermediate complexity devices refer to electromechanical systems that allow patients to move and stretch the muscles and tendons gently. The movement is similar to basic ankle movement as shown in Figure 1(a) and it is able to obtain different ranges of motions for each rotation. Even though these devices considered as good for ankle rehabilitation but there are some limitations or drawbacks. One of the most important disadvantages nowadays is that they work in a Continuous Passive Motion (CPM) basis, in which the patient plays a rather passive role in the rehabilitation process. Figures 3 and 4 show some commercial systems offered on the market for helping with and promoting ankle rehabilitation; in both cases the patient could either be in a sitting or a lying position [10, 11].



(a) (b)

Fig. 3: (a) JACE Ankle A330 CPM system (b) Optiflex Ankle CPM system [9]

Table 1. Degree of freedom for intermediate complexity devices [12]

Intermediate complexity devices	Degree of Freedom
JACE Ankle A330 CPM system	1
Optiflex Ankle CPM system	2

3.3 High complexity devices

High complexity devices not only help in ankle rehabilitation but to promote rehabilitation in the entire lower limbs. One of these systems is product from Biodex as shown in Figure 4.

This system has high capabilities for data acquisition, storage, transmission, and written reports elaboration, allowing objective evaluation in patient progress throughout the rehabilitation therapy. Some of the disadvantages of these products consist in being expensive, bulky, needing a specialist who operates the systems and obviously are only suitable for clinical use.

Fig. 4: Biodex Multi-Joint System [13]

4. ACTUATORS

An actuator is a device that moves or controls some mechanism. An actuator turns a control signal into mechanical action such as an electric motor. Actuators may be based on hydraulic, pneumatic, electric, thermal or mechanical means, but are increasingly being driven by software. In this paper three types of actuators are discussed, which are Shape Memory Alloy (SMA) [14], Pneumatic Artificial Muscle [15] and Servo Motor used in ankle rehabilitation [16].

4.1 Shape Memory Alloy (SMA)

Shape Memory Alloys (SMAs) have been on the forefront of research for the last several decades. They have been used for a wide variety of applications in various fields. A shape-memory alloy (SMA, smart metal, memory metal, memory alloy, muscle wire, smart alloy) is an alloy that remembers its original shape and that when deformed returns to its pre-deformed shape when heated. This material is a lightweight, solid-state alternative to conventional actuators such as hydraulic, pneumatic, and motor-based systems [17].

Fig. 5: Shape Memory Alloy [16]

The advantages of Shape Memory Alloy (SMA) actuators are that it has highest power-to-weight ratio among light-weight technologies which means that they have a high potential for miniaturization. In addition, it's a silent actuation with noiseless operation, removing the vibration disturbances to other payloads that are normally associated with motor-driven deployment. On the other hand, one of the disadvantages of Shape Memory Alloy is that it has a low energy efficient. Besides, it has a strong relationship between the strain operation range and fatigue life [11].

4.2 Pneumatic Artificial Muscle (PAM)

Robots become significant to serve and assist human, especially for older people and disabled people. However, high rigidity of robot joints would be hazardous to a human as a human has soft arms and compliant joints activated by numerous muscles. Many researchers have motivated to study in this field due to the necessity for human-like actuators system and created the Pneumatic Artificial Muscle. The PAM is used for converting pneumatic power to pulling force and eventually causing movements of the mechanism. Besides PAM, it has another names which are Fluidic Muscle [18], Pneumatic Muscle Actuator [19], Air Muscle [20], Silk Pneumatic Artificial Muscle [21, 22] Tension Actuator [23], Fluid Actuator [24] and Fluid-Driven Tension Actuator [25].

(a) (b)

Fig. 6: Pneumatic artificial muscle (a) before contraction (b) after contraction [25]

PAMs have very lightweight because their main element is a thin membrane. This allows them to be directly connected to the structure they power, and this is an advantage when considering the replacement of a defective muscle. Another advantage of PAMs is their inherent compliant behavior, when a force is exerted on the PAM, it gives in, without increasing the force in the actuation. The disadvantages of using pneumatic artificial is its inherent dry friction and threshold pressure. Because of these, accurate position control is difficult to achieve. Additionally, warm muscles behave different from cold ones as friction temperature affects muscle operation [18].

4.3 Servo motor

A servomotor is a rotary or linear actuator designed for precise positioning, velocity, and acceleration. They're ideal for many applications; from simple DC servomotors used in toys to modern AC servo variants which are common in automation control, robotics, and electric vehicles. It consists of a suitable motor coupled to a sensor for position feedback. Servo motors are not a specific class of motor although the term servomotor is often used to refer to a motor suitable for use in a closed-loop control system [26].

Fig. 7: Servo Motor [26]

The advantage of using servo motor is that if a heavy load is placed on the motor, the driver would increase the current to the motor coil as it attempts to rotate the motor. Moreover, high-speed operation is possible by using servo motor. The disadvantages of using this actuator are that since the servomotor tries to rotate according to the command pulses, but lags, it is not suitable for precision control of rotation. When stopped, the motor's rotor continues to move back and forth one pulse, so that it is not suitable when there is vibration.

5. Actuator and Range of Motion of Ankle-Foot

Different types of actuators have been used for rehabilitation devices over the years. Each of the actuators gives different range of motion depending on the design and sizes of the devices. Table 2 shows the range of motions obtained from the different actuators.

Table 2. Range of motion of different actuators [27]

Year	Author	Actuator	Range of Motion	DOF
2000 – 2012	Rutgers Ankle	Pneumatic actuator	45° - Plantar/dorsiflexion 80° - Abduction/adduction 40° - Inversion/eversion	6
2006	Liu et al.	Electric motor	41.9°-Plantarflexion 43.8°-Dorsiflexion 53.8°-Inversion 44.1°- Eversion	3
2006	Yoon et al	Pneumatic actuators	50°-Plantar/dorsiflexion 55°-Inversion/eversion	2
2007	Lin et al	Electric motor	20°-Plantar/dorsiflexion	1
2015	Alaa AbuZaiter	Shape Memory Alloy	30°-Plantar/dorsiflexion 30°-Inversion/eversion	6

6. CONCLUSION

This paper reviews the different types of actuators in Ankle-Foot rehabilitation therapy. Nearly all lower extremity injuries benefit from rehabilitation programs that include therapeutic exercise. These robots use various actuation mechanisms, sensors, and control strategies with sole purpose of improving patient's ankle condition. In several studies, these robots were rigorously tested and successfully demonstrated positive treatment outcomes. Despite meeting numerous challenges, stability and dynamic characteristics of ankle rehabilitation robots continually improve, resulting in safer compliant robots with better actuation mechanism and natural compliance, higher backdrivablity and safer use. These features are accompanied by the installation of various sensors as feedback to the controller. These improvements would also progress alongside the advancement of medical science and biomechanics as scientists and medical practitioners gain better insight on the optimal movement tasks to improve foot and ankle plasticity and strength

REFERENCES

[1] Fong, D.T.-P., et al., A systematic review on ankle injury and ankle sprain in sports. Sports medicine, 2007. 37(1): p. 73-94.

[2] Kim, H.Y., et al., A surgical ankle sprain pain model in the rat: effects of morphine and indomethacin. Neuroscience letters, 2008. 442(2): p. 161-164.

[3] Saglia, J.A., et al., A high-performance redundantly actuated parallel mechanism for ankle rehabilitation. The International Journal of Robotics Research, 2009. 28(9): p. 1216-1227.

[4] Lamb, S., et al., Mechanical supports for acute, severe ankle sprain: a pragmatic, multicentre, randomised controlled trial. The Lancet, 2009. 373(9663): p. 575-581.

[5] Girone, M., et al., Orthopedic rehabilitation using the" Rutgers ankle" interface. Studies in health technology and informatics, 2000: p. 89-95.

[6] Deutsch, J.E., et al., Post-stroke rehabilitation with the Rutgers Ankle System: a case study. Presence: Teleoperators & Virtual Environments, 2001. 10(4): p. 416-430.

[7] Krishnan, S., et al., Rehabilitation For Foot/Ankle-Continuous Passive Motion (Cpm) Using Shape Memory Alloy (Sma) Actuated Stewart Platform. ARPN J. Eng. Appl. Sci, 2016. 11: p. 22.

[8] Takemura, H., et al., Design and control of a wearable stewart platform-type ankle-foot assistive device. International Journal of Advanced Robotic Systems, 2012. 9.

[9] Alcocer, W., et al., Major trends in the development of ankle rehabilitation devices. Dyna, 2012. 79(176): p. 45-55.

[10] Abdul-Rani, A.M., et al. Early Mobilization Using Heat Treated Shape Memory Alloy (SMA) for Rehabilitation Phases. in Key Engineering Materials. 2017. Trans Tech Publ.

[11] Nagarajan, T., et al. A Novel Approach of Using SMA Wires Actuated Stewart Platform for Continuous Passive Motion (CPM) of Ankle Rehabilitation Therapy. in Advanced Materials Research. 2015. Trans Tech Publ.

[12] Alcocer Rosado, W., et al., Major trends in the development of ankle rehabilitation devices. Dyna; Vol. 79, núm. 176 (2012); 45-55 DYNA; Vol. 79, núm. 176 (2012); 45-55 2346-2183 0012-7353.

[13] Girone, M., et al., A Stewart platform-based system for ankle telerehabilitation. Autonomous robots, 2001. 10(2): p. 203-212.

[14] Amirtham, V., et al., SMA Actuation for Wrist Motion with Split-tube Flexures. Asian Journal of Scientific Research, 2013. 6(3): p. 615.

[15] Krishna, S., T. Nagarajan, and A. Rani, Review of Current Development of Pneumatic Artificial Muscle. Journal of Applied Sciences, 2011. 11(10): p. 1749-1755.

[16] Kumar, P. and D. Lagoudas, Introduction to shape memory alloys, in Shape memory alloys. 2008, Springer. p. 1-51.

[17] Abdul-Rani, A.M., et al. Inverse Kinematics-Stewart Platform Actuated by Shape Memory Alloy for Immobilization of Ankle-Foot Rehabilitation. in Key Engineering Materials. 2017. Trans Tech Publ.

[18] Andrikopoulos, G., G. Nikolakopoulos, and S. Manesis. A survey on applications of pneumatic artificial muscles. in 2011 19th Mediterranean Conference on Control & Automation (MED). 2011. IEEE.

[19] Daerden, F. and D. Lefeber, Pneumatic artificial muscles: actuators for robotics and automation. European journal of mechanical and environmental engineering, 2002. 47(1): p. 11-21.

[20] Daerden, F. and D. Lefeber, The concept and design of pleated pneumatic artificial muscles. International Journal of Fluid Power, 2001. 2(3): p. 41-50.

[21] Krishnan, S., et al. Silk Pneumatic Artificial Muscle (SPAM) construction for bio-medical engineering application. in Business Engineering and Industrial Applications Colloquium (BEIAC), 2012 IEEE. 2012. IEEE.

[22] Nagarajan, T., et al., Experimental Investigation-Natural Fiber Braided Sleeve for Pneumatic Artificial Muscles Actuation. Asian Journal of Scientific Research, 2013. 6(3): p. 596.

[23] Jobbágy, B., et al., Robotic arm with artificial muscles in rehabilitation. Procedia Engineering, 2014. 96: p. 195-202.

[24] Laksanacharoen, S. Artificial muscle construction using natural rubber latex in Thailand. in The 3rd Thailand and Material Science and Technology Conference. 2004.

[25] Lee, Y.K. and I. Shimoyama. A skeletal framework artificial hand actuated by pneumatic artificial muscles. in Proceedings 1999 IEEE international conference on robotics and automation (Cat. No. 99CH36288C). 1999. IEEE.

[26] Ouyang, P., et al., Micro-motion devices technology: The state of arts review. The International Journal of Advanced Manufacturing Technology, 2008. 38(5-6): p. 463-478.

[27] Khalid, Y.M., D. Gouwanda, and S. Parasuraman, A review on the mechanical design elements of ankle rehabilitation robot. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 2015. 229(6): p. 452-463.