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A PORTABLE 3D PRINTED 2DOF ARM EXOSKELETON FOR REHABILITATION

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ABSTRACT

Traditional rehabilitation treatments for stroke patients are often limited in their scope; the location, availability and capacity of a physiotherapist in addition to methods of quantifying treatment effectiveness may all be restricting factors yet are also crucial in providing a successful therapy to patients. Rehabilitation robotics is an evolving field with the potential to increase therapeutic effectiveness. We thus have developed a portable robotic arm orthosis (RAO) capable of actuating a user's arm in 2 Degrees of Freedom (2DOF), namely elbow flexion and extension and forearm pronation and supination. The exoskeleton is fabricated from lightweight materials, 3D printed ABS and carbon fibre, and is battery operated. Motion sensors incorporated in the RAO allow movement control and analyses. The paper will review the mechanical properties and performance of the device. Several tests are performed to confirm the design parameters are met. Finally we suggest treatment alternatives as well as future orthoses advancements.

Keywords: Exoskeleton, rehabilitation robotics, stroke, control

INTRODUCTION

Over recent years the need to offer treatments and support to individuals stricken by neuromuscular disorders such as stroke and Spinal Cord Injury (SCI) is becoming evident [1]. Many technologies vying to augment traditional therapies are being developed. Upper limb robotic/exoskeleton devices are one prime example. Many designs are fixed-based (non-ambulatory) and aim to serve in a clinic facility, hospital or connected to a mobile structure such as a wheelchair [2][3][4][5], while others are designed to be portable [6][7][8]. The number of joints served also varies significantly [9]. The higher the Degree of Freedom (DOF) of the device, the heavier and less likely it is to be ambulatory.

Several moderately lightweight upper limb exoskeletons have been developed. Vanderniepen et al have developed a compliant elbow orthosis [10]. It uses a dual actuation system and a spring element, and is able to generate 10 Nm of torque and movement frequency of 0.5 Hz. The total weight is 1.1 Kg. Vitiello et al have developed an elbow exoskeleton called NEUROExos which offers a passive joint aligning mechanism. It is capable of generating 15 Nm of torque and weights 2.3 Kg [11].

This paper presents a 3D printed 2 DOF upper limb exoskeleton designed to be implemented in a rehabilitation setting. The focus of the design was to develop a low cost, customizable and portable device that would be easy to don and operate. In the next section the hardware design will be discussed followed by control and performance discussion. Finally applications and conclusion section will be elaborated.

HARDWARE DESIGN

The design of the RAO focused on two upper arm joints, namely elbow flexion/extension and forearm pronation/supination. Both of these joints play a significant role in most activities of daily living (ADL) such as reaching and picking/holding tasks [12]. Furthermore we are developing wrist devices that attach to the RAO to create a full upper arm 4 DOF device.

The fabrication process utilized almost exclusively a rapid prototype, ABS derivative, material (Axis Prototypes "NEXT" material) and carbon fibre placed in specific high stress areas.

The elbow joint is actuated with a 24 Volt brushless DC motor from Maxon (EC 45 flat, 50W). The motor itself is capable of producing 84.3 mNm of continuous torque at 5260 rpm and 822 mNm of torque at stall. It was chosen to construct a custom gearbox in order to reduce cost and weight while enabling customization. The gearbox, consisting of 4 stages shown in Figure 1, was designed in-house and master gears were rapid prototyped by Axis Prototypes. Once assembled the 120:1 gearbox combined with the motor is theoretically capable of producing a continuous torque of 9.92 Nm at 44 rpm and a 130 Nm torque at stall. These values were of course practically limited by the material properties of the plastic 3D-printed gears. The range of motion of the elbow assembly is mechanically limited to 110 degrees as a safety feature.

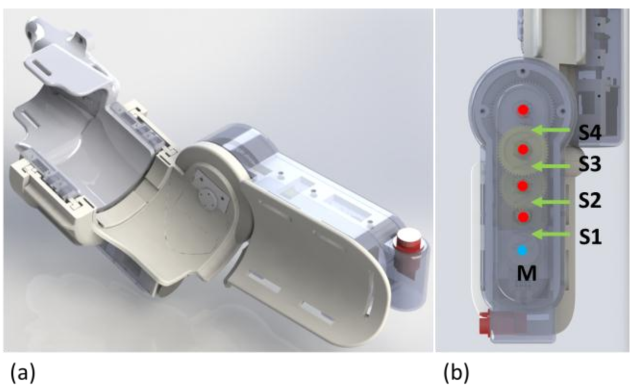

Figure 1 - (a) RAO (b) M-motor, S#-stage 1 to 4

The pronation/supination mechanism consists of two concentric semi-cylinders where the inner one is connected to the user forearm and the outer to the upper arm section of the device. A Polyurethane transmission chain (Posi-Drive Belt) and aluminum sprockets are used to transfer a 12V DC motor with a 50:1 stock planetary gearbox (Lynxmotion) motion as shown in Figure 2. The stock motor is capable of 870 mNm of continuous torque at 120 rpm. The chain sprocket assembly of the forearm joint creates a gear reduction of 5:1 that enables a theoretical continuous torque of 4.4 Nm at 24 rpm. The system is capable of producing 75 degrees of rotation in both pronation and supination for a total of 150 degrees of movement.

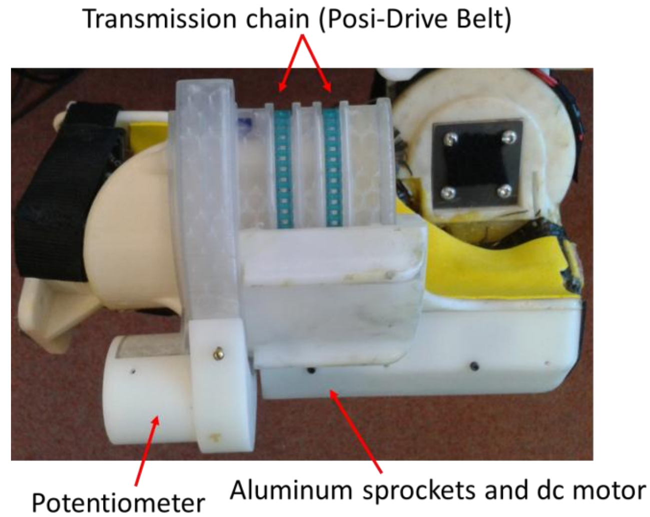

Figure 2 - Pronation/supination mechanism

The total weight of the device including the actuators and strapping material is 1.7 Kg. A safety button that cuts off power to the device has been embedded on the upper arm section. Strapping the device involves two straps for the upper arm and two for the forearm. This increases the contact area and therefore reduces misalignment between the limb and the device. Donning the device takes less than 30 seconds when aided by another party and less than 60 seconds unaided. The design allows resting and manipulating the arm with little interference between the RAO and the user's body. The RAO does not assist shoulder motion as it is designed for individuals with some shoulder mobility. A shoulder strap across the torso helps support the device as shown in Figure 3.

Figure 3 – Demonstrating wearing the RAO

A Structural Analysis using SolidWorks Simulation was performed to the forearm main load-bearing component in order to locate weak regions. Consequently the part was partially wrapped with carbon fibre to improve the structural strength as shown in **Figure 4**.

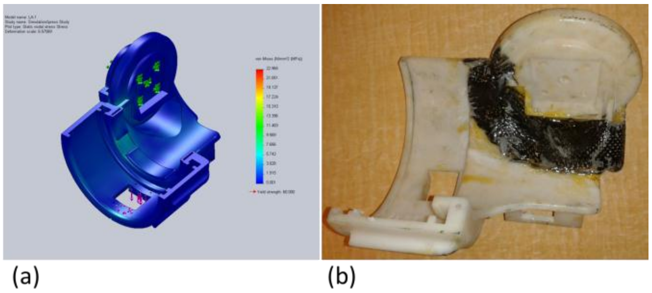

Figure 4 – (a) Elbow joint structural analysis (b) Reinforcing with carbon fibre wrapping

CONTROL AND PERFORMANCE

To examine the capabilities of the device we perform several tests evaluating the performance of the elbow joint mechanism. A Maxon controller (ESCON Module 50/5) is used. The controller can be set to operate in open or closed loop velocity control modes as well as current control.

A software PID control loop has been implemented and a response to a step position command is performed as is shown in **Figure 5**. The system achieves a rise time of about half a second. The steady state error is less than 1 deg and reduces even further after a few more seconds. Additionally NI Labview 2010 system identification toolbox was utilized to evaluate the open loop model for the elbow joint assuming a linear time-invariant system. A velocity triangle signal was set and the response recorded as shown in **Figure 6**. Consequently the following transfer function was obtained.

$$\frac{Y(s)}{U(s)} = \frac{0.4s + 1.24}{1.64s^2 + 1.8s + 1}$$

This model may later be used to implement a closed loop controller analytically.

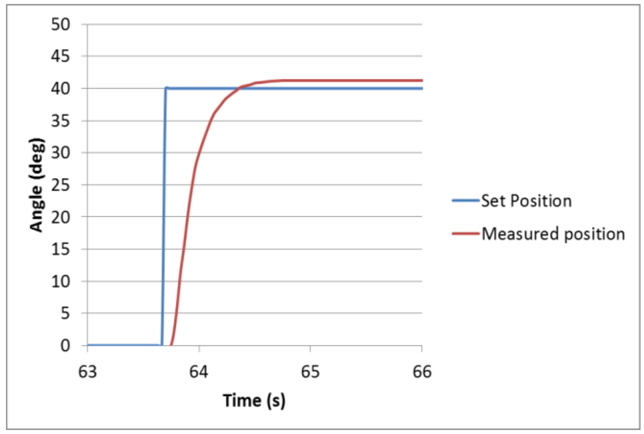

Figure 5 – PID position step response

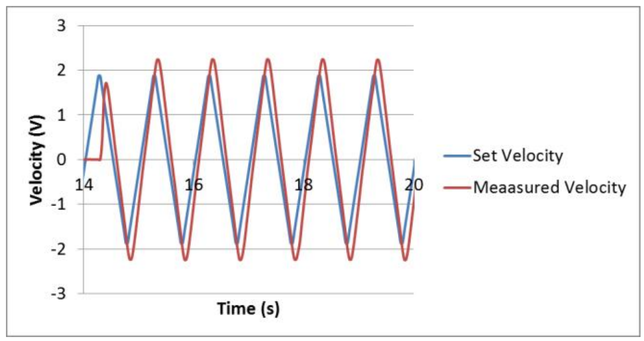

Figure 6 - System identification input and response

Depending on the application, the current performance may suffice or require improvement. Generally in rehabilitation training very accurate position and fast response may not be necessary or even desirable; whereas making the user comfortable and safe is a high priority. However, utilizing the embedded velocity controller will likely enhance the performance.

APPLICATIONS

Broadly speaking, applications for an upper arm exoskeleton can be considered for assistance or rehabilitation. The former generally refers to devices that are used to assist in performing ADL. Such activities may involve eating and drinking, dressing or the ability to be independently mobile.

Rehabilitation devices may help regain functionality and ability of these same activities. Rehabilitation aims to reduce disabilities following neurological or musculoskeletal injuries and improve physical and mental capacity.

CONCLUSION

The RAO has been designed with both assistive and rehabilitation of the elbow and forearm in mind. It is therefore relatively lightweight and powerful. All but the complete device was manufactured using 3D printing technologies which shows promise and functionality. Future versions will look at reducing material further as well as potentially rapid prototyping with a combination of materials. Successful testing with volunteers using the device has been performed in functional and rehabilitative applications, and additional testing will ensue.

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