Design of a Portable Hydraulic Ankle-Foot Orthosis

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Abstract— **Small-scale hydraulics is ideal for powered human assistive devices including powered ankle foot orthoses because a large torque can be generated with an actuator that is small and light. A portable hydraulic ankle foot orthosis has been designed and is undergoing preliminary prototyping and engineering bench test evaluation. The device provides 90 Nm of ankle torque and has an operating pressure of 138 bar (2,000 psi). The battery-operated hydraulic power supply weighs about 3 kg and is worn at the waist. The ankle component weighs about 1.2 Kg and connects to the power supply with two hoses. Performance simulation and preliminary bench testing suggests that the device could be useful in certain rehabilitation applications.**

I. Introduction

A. Background

An ankle-foot orthosis (AFO) is a device that assists a person's ankle by constraining and limiting the range of motion or assisting the muscles of the ankle though dorsi and plantar flexion of the ankle [1]. While the detailed motion of the human ankle joint is complex and is actuated by multiple muscles, most AFOs have a single-degree-of-freedom and operate within the range of normal motion, which is ankle plantar flexion is between and between 10° to 30° of dorsiflexion and 40° to 65° of plantar flexion [2].

AFOs can be separated into two categories, passive and powered. A passive AFO is used to constrain the motion of the ankle, but can also store the energy generated by the movement of the body in linear or rotary spring elements. The energy can be released to assist weak muscles in moving the ankle [1]. A powered AFO uses an actuator and energy from an external power source to assist the muscles in dorsi and plantar flexion of the ankle.

Current clinical AFOs are passive and used in physical therapy, rehabilitation and as assistive devices for people with chronic or temporary motor impairments that affect the ankle [1]. There are three types of clinical AFOs: solid ankle, leaf spring and articulated, each providing a different ankle stiffness. Two common applications for AFOs are to treat foot drop and ankle spasticity. Foot drop is the inability to dorsiflex the ankle during swing phase, while spasticity is characterized by poor muscle control and tight or stiff muscles. Foot drop and ankle spasticity are conditions that result after a variety of nerve injuries, brain and spinal disorders, and muscle disorders [3, 4].

In the future, powered AFOs will likely play a significant role in treating ankle conditions, but technology developed for powered AFOs could have applications beyond medical when extended to other joints. For example, the same technology could be used for load sharing for construction workers who must transport heavy or awkwardly shaped objects.

B. Previous Work

In 2005 researchers at the University of Michigan and the University of Washington designed and tested a powered AFO that used pneumatic artificial muscles. The AFO was capable provided 70 Nm of torque assistance in plantar flexion and 38 Nm in dorsiflexion. The limitation of the device was that it was tethered to a power source [5]. In 2011 researchers at the Center for Compact and Efficient Fluid Power designed and tested a portable CO_2 powered AFO. The device had a bidirectional rotary pneumatic actuator attached to the ankle and a CO_2 bottle with regulator attached at the waist. The strengths of the design were that the separation of the power supply and the actuator allowed some of the system weight to be positioned at the waist instead of the ankle. The limitation was that the AFO could only generate 9 Nm of torque assistance [6].

C. Objective

The objective of our project is to design and test a powered AFO that is light, compact and can replicate the angular velocity and torque seen by the ankle during normal gait. Because of its exceptional force-to-weight and power-to-weight characteristics, hydraulics was chosen for the prime mover. To minimize the weight carried at the ankle, an architecture was chosen with the hydraulic power supply at the waist and an actuator unit at the ankle connected by hoses. What we report in this paper is the conceptual design of the hydraulic AFO as well as some preliminary testing of a first prototype.

This research is supported by the Center for Compact and Efficient Fluid Power a National Science Foundation Engineering Research Center, funded under cooperative agreement number EEC-0540834

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978-1-4244-7929-0/14/$26.00 ©2014 IEEE

II. Mechanical Design

A. Design Requirements

The requirements defining the maximum torque generation, range of motion, and maximum angular velocity are based on gait data of an 80 kg male [7]. The powered AFO must be portable and un-tethered from power sources and computers, and must provide the average number of gait cycles that a person completes in a day [8] before recharge is needed. The ankle component must fit under a pant leg with the foot portion fitting in a shoe. Weight distribution is a crucial aspect. Studies on the oxygen consumption during normal and loaded gait have shown that placement of a 20 kg load on the trunk of a person causes little to no increase in the consumption of O_2. However, if a 2 kg weight is attached to a person's foot, the rate of oxygen consumption increases 30% [9]. Based on this data, we required the weight positioned at the ankle to be less than 1.2 kg and an overall system weight to be less than 3.5 kg. Because the device has high torques and operates at high hydraulic pressure, it must also be safe with appropriate safety shields and limit stops. The key design requirements are shown in Table 1.

TABLE I. Design Requirements of HAFO

Maximum Torque Generation	Plantar flexion	90 Nm
	Dorsi-flexion	10 Nm
Range of Motion	Plantar flexion	50°
	Dorsi-flexion	20º
Maximum Angular Velocity	250°/sec	
Gait Cycles Before Recharge	7000	
Weight Positioned on Ankle	< 1.2 kg	
Total System Weight	< 3.5 kg	

B. Design Description

The hydraulic ankle foot-orthosis (HAFO) is composed of a hydraulic power supply secured to the center of the lower back with a cushioned belt and a hydraulic ankle-foot actuator secured to the shin and foot with carbon fiber supports, straps, and a standard shoe. The power supply contains a 3300 mAh, 29.6 V lithium-ion polymer battery that powers a motor driver and the control electronics. A brushless DC motor drives a 3.7 to 1 gearbox connected to a hydraulic axial piston pump with a fluid displacement of 0.4 cc per revolution. The hydraulic axial piston pump supplies the hydraulic control circuit housed in an aluminum manifold. All components are connected to a plastic casing and cover to ensure safe use eliminating exposure to hydraulic leaks or pinch points (Fig. 1).

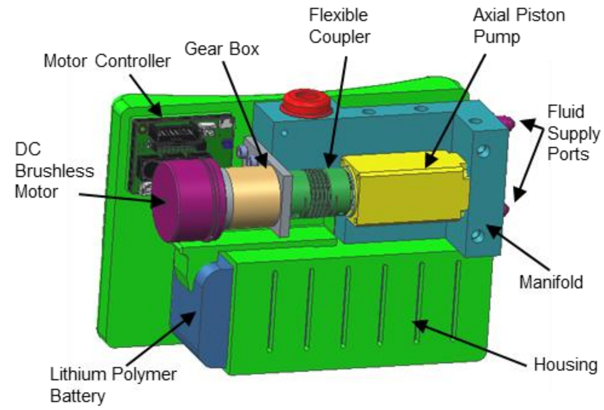

Figure 1. Hydraulic power supply.

The power supply connects to the ankle actuator with two high pressure hydraulic tubes. One tube supplies fluid power for dorsiflexion actuation and the other for plantar flexion actuation. The ankle actuator (Fig. 2) is composed of twin units positioned on the medial and lateral sides of the ankle. Each unit has three main parts: a hydraulic cylinder manifold, a foot support bracket and a shin support bar. The cylinder manifold is made of aluminum and houses two identical 1.27 cm. (0.5 in.) bore hydraulic cylinders where the fluid power is converted into a linear tension force. The cylinder pistons are attached to nylon coated steel cables that wrap around a pulley integrated into the aluminum foot support bracket. As the cable is pulled, torque is generated about the ankle. The use of a cable for the cylinder rod means that the overall length of the actuator is much less than that of a traditional cylinder with a rigid rod. The bottoms of the two foot support brackets are fused to a molded carbon fiber foot support that transfers the torque to the user's foot. The aluminum shin support bars connect the cylinder manifolds on the medial and lateral actuators to a carbon fiber shin support that is strapped to the front of the calf. Two Hall Effect sensors are attached to the outside plastic casing to measure the angular position of the ankle. Fig. 3 shows a functional block diagram of the HAFO illustrating the transfer of electrical, mechanical, and fluid power.

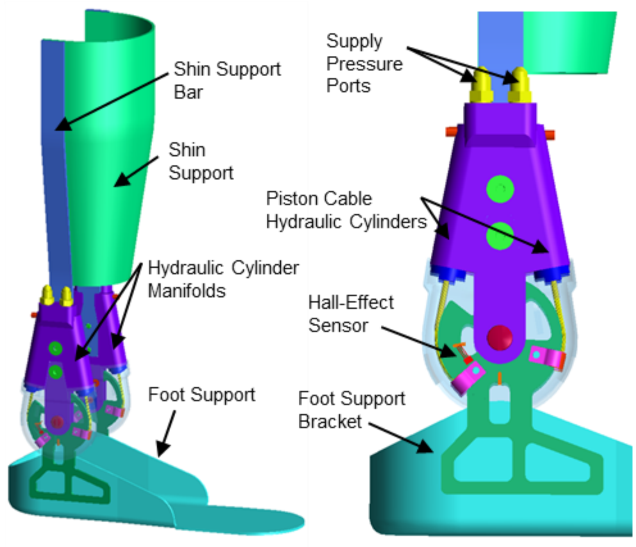

Figure 2. Hydraulic ankle-foot actuator.

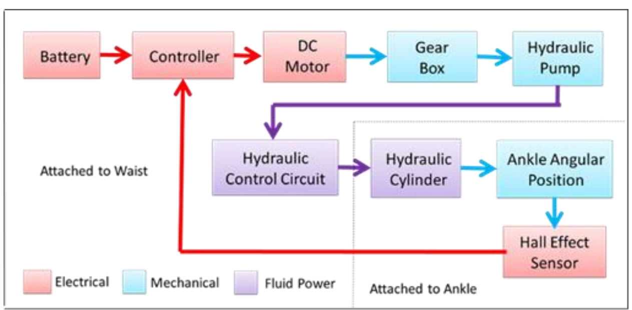

Figure 3. Block diagram of HAFO.

C. Hydraulics

The AFO uses hydraulics rather than electric motors because of the high power density of hydraulics [10]. Based on the results shown in [11], the hydraulics must operate at pressures above 34 bar (500 psi) to achieve a higher power density compared to electromechanical systems for systems that produce 100 W of mechanical power. Hydraulic cylinders are often used for low velocity and large linear force generation as opposed to electric motors that operate efficiently at high angular velocities and low torque and require a gearbox to bring velocities down to human range. In addition, hydraulics systems have the ability to separate the power generation from the actuator through the use of hoses. This allows the actuator attached to the ankle to be light and ensures that the weight of the AFO does not negatively impact gait dynamics.

The HAFO was designed to operate at or below 138 bar (2000 psi) and generate torque assistance of about 90 Nm. All of the components, excluding small hardware and sensors, are composed of an aluminum alloy7075-T6 due to its high strength to weight machinability. Finite element analyses were conducted on the main components of the actuator to ensure that the strength of the components have an adequate safety factor for the expected loads and hydraulic pressures.

D. Hydraulic Control Circuit

The hydraulic circuit in the power supply is composed of a bi-directional pump, two pilot operated check valves, and a reservoir (Fig. 4). The hydraulic circuit of the ankle actuator is composed of two hydraulic cylinders and an air vent to atmosphere to ensure air pressure does not build behind the pistons. As the red or yellow lines in Fig 4 are pressurized, a pilot operated check valve prevents fluid from flowing back into the reservoir from the high pressure line, while the other pilot operated check value allows fluid from the low pressure line to flow back into the reservoir and pump.

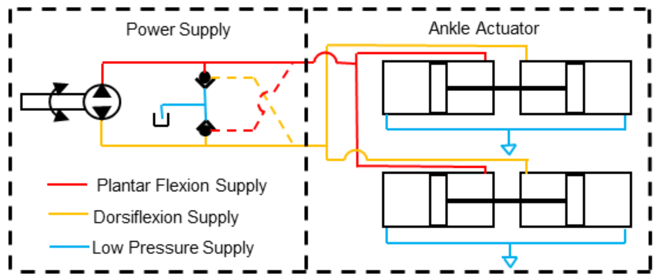

Figure 4. Fluid power circuit.

The selection of the components for the hydraulic power supply were based on the required pressures and flow rates that correspond to the gait dynamics [7]. Figure 5 illustrates the pressure and flowrate needed from the power supply to replicate the torque and angular velocity dynamics of a gait cycle for an 80 kg male. The operation of the power supply is intermintent, so the motor was sized using the root mean square of the torque-time profile, which takes into account the heat dissipation [12].

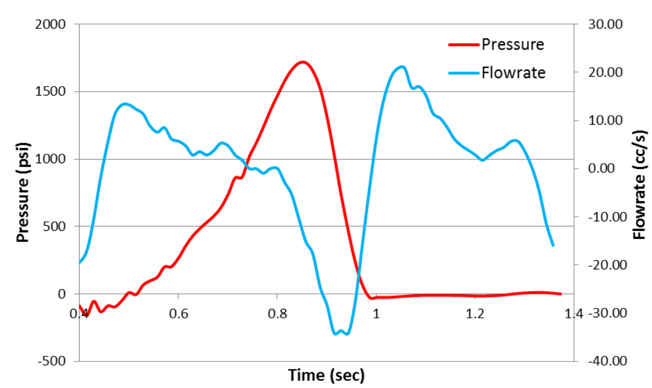

Figure 5. Simulated pressure and flow rate of power supply during one gait cycle.

III. PROTOTYPE AND TESTING

A preliminary prototype was fabricated (Figs. 6-7) and is undergoing bench testing. One actuator has been successfully leak tested to 145 bar (2100 psi) and the power supply has been operated up to 97 bar (1400 psi). The steady state efficiency of the power supply (defined as the ratio of fluid power generated by the pump to the electrical energy drained from the battery) was measured with the results shown in Fig. 8.

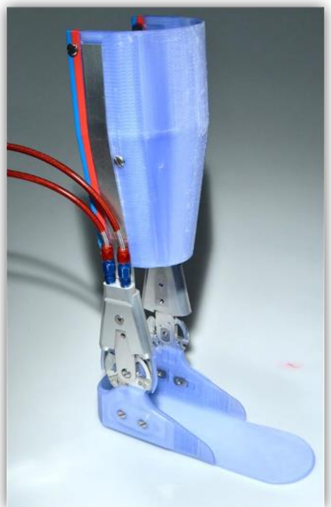

Figure 6. Ankle unit prototype.

Figure 7. Power supply prototype.

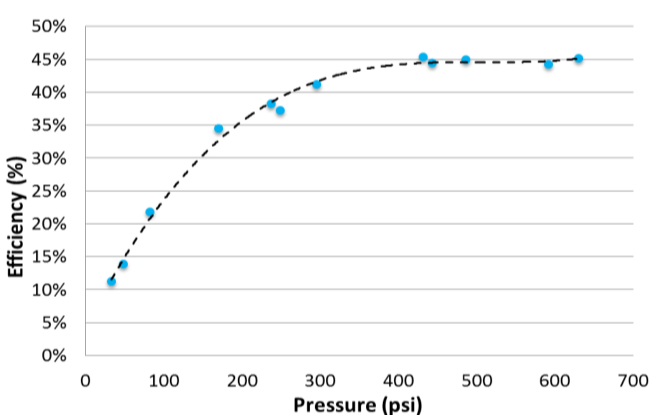

Figure 8. Power supply efficiency.

IV. DISCUSSION

The HAFO illustrates the high power density of hydraulics and the ability to separate the power supply and the actuator for optimal weight distribution. Early testing has demonstrated that the concept appears feasible. The compact design of the actuators including the cable-rod piston enables the unit to easily fit under a pant leg while still delivering the required 90 Nm of torque.

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