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Development of a novel compact hydraulic power unit for the exoskeleton robot

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ABSTRACT

Exoskeleton robots require powerful and lightweight power supplies. Because of its high power-to-mass ratio and fast response, hydraulic systems can meet the requirement for locomotion robots. In this paper, a novel compact hydraulic power unit (CHPU) is proposed. A two-stroke IC engine, with a rated power of 2.4 kW at 13,000 rpm, is used as the prime mover. The engine drives a high speed (10,000 rpm) piston pump to allow the engine to operate at high power. A spring loaded reservoir has been developed to prevent the pump intake from cavitation and contamination. The payload flow rate is indirectly estimated using the displacements of the actuator. A Ragone plot analysis shows that the CHPU can maintain a high specific power over a long duration. A dynamic model for the CHPU has been developed based upon simplified engine operating characteristics and a set of experimentally identified parameters. A prototype of the CHPU has been constructed with a rated power of 1.45 kW and a weight of 16.6 kg. Experimental testing of the prototype confirms the dynamic model and the output capacity of the CHPU.

1. Introduction

Exoskeleton robots can play an important role in many occasions by enhancing the wearer's strength and endurance. Many exoskeleton robot prototypes have been successfully developed such as BLEEX [1,2], HULC and XOS [3,4] for field use as well HAL [5], LOPES [6], NeXOS [7], energy harvesting exoskeleton [8] and Octopus inspired Robot [9,10] for normal life use and rehabilitation.

In many applications, high load carrying capacity, long working hour, as well as fast energy supply are necessary. Therefore exoskeleton robot requires a powerful, lightweight and easily supplied power unit. Several kinds of actuations have been used in the exoskeleton robot. Using the electromotor is a convenient way to drive the joints, but the output driving torque won't be very large for the limitation of the size of the motor. Besides, the joint structure will be swollen with the motor and the speed reducer. Pneumatic is another way to drive the robot joint, however, the accurate position control of the pneumatic muscle is difficult and the big air source is hard to integrate into the robot either. Hydraulic system has high power-to-mass ratio, fast dynamic response and large force output. These advantages make it provide the high load carrying capacity and many locomotion robotics such as Bigdog [11] and HyQ [12,13] use hydraulic systems as their drive system.

The XOS exoskeleton robot uses an external hydraulic power unit located on the ground, so that the total mass of the robot is decreased and the energy can be quite enough for a long working time, however the XOS cannot work far from the power unit as the result of the limitation of the length of the hoses. A hydraulic-electric power unit (HEPU) based on an engine was built and demonstrated on the BLEEX. The HEPU prototype weighs 27 kg and produces 2.52 kW total power. HEPU uses a solenoid valve to regulate the hydraulic system. However, due to rapid transient of the hydraulic power demand, sudden increase of the engine load torque often happens causing the engine stall. In addition, a part of high-pressure hydraulic flow goes directly to the reservoir, producing energy waste and excessive heat. The HULC exoskeleton robot uses a battery as the prime mover of the hydraulic power unit. However, due to the low specific energy of the battery, it is hard to achieve long working time. Furthermore, as a robot applied in battlefield, battery charging may be a tough problem for HULC.

Table 1 shows several power sources possible used in the robotic field. The gasoline engine has very high actual energy density even though its efficiency is low (15.8% in this paper). The actual energy density of Li-ion battery is much lower than the engine [14], and so as to the free piston hydraulic pump (FPHP) based on monopropellants developed at UC Berkeley [15]. Fuel cells can provide very high energy density and efficiency [16], but

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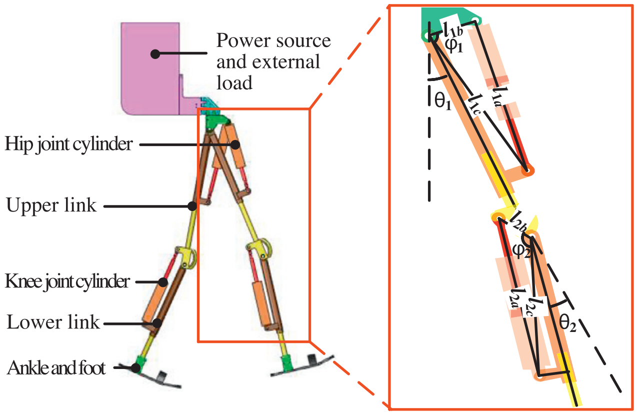
Table 1
Energy density of different power sources.

Power sources	Gasoline engine	Li-ion battery	Fuel cells	FPHP
Energy Density (MJ/kg)	44	0.72	Decided by the fuel	1.2
Efficiency	15.8%	90%	Up to 90%	90%
Actual energy density (MJ/kg)	7	0.648	Only electric energy	1.08



(a) (b)

Fig. 1. (a) Lower extremity exoskeleton robot structure; (b) Right leg of the exoskeleton robot.

Table 2
Specification of the lower extremity exoskeleton.

Joint (i)	(l_{ib}, l_{ic}) (mm)	φ_{i0} (°)	(D_i, d_i, l_{i0})(mm)
Hip (i=1, 3)	(87.2, 318.0)	102.3	(20, 15, 250)
Knee (i=2, 4)	(63.5, 312.3)	138.3	(20, 15, 250)

only electric energy. The transmission to hydraulic power will be heavy and decrease the overall efficiency. Besides, this technology is still not matured enough to be integrated in a wearable robot. From the above, the internal combustion engine is employed in the CHPU for its high specific energy and the fast refueling.

This paper presents a novel compact hydraulic power unit (named CHPU) powered by an internal combustion engine. The CHPU has a high specific power and can be easily integrated. In the transmission chain, a high speed pressure-compensated piston pump with 10,000 rpm is used for improving the power density highly. Meanwhile, the engine stall and the power waste caused by the switching valve regulation in [1] are also avoided by the pump. The spring loaded reservoir employed in the CHPU assists the high speed pump working well and reducing the reservoir dimensions. Finally, the dynamic model of the CHPU is built and the performance of the CHPU is validated by the prototype test.

The remainder of this paper offers the following:

Section 2 presented the analysis of pressure and flow rate requirement based on a lower extremity exoskeleton.
Section 3 presented the overview and main characteristics of the CHPU.
In section 4, model of the CHPU was built and the physical parameters were identified by using least square method.
Section 5 showed the tests result carried out on the CHPU prototype. Section 6 concludes.

2. Load requirements

2.1. Lower extremity exoskeleton structure

A lower extremity exoskeleton structure is shown in Fig. 1(a), where four actuators are used to drive the hip and knee joints while the ankle joints are passive. Each actuator consists of a double-acting hydraulic cylinder and a servo valve.

To facilitate the presentation, the hip and knee joints on the right leg are defined as joints 1 and 2, and on the left leg 3 and 4 respectively. The hip joint angles θ_i (i=1,3) are measured as the positive counterclockwise displacement of the distal upper link from the torso link (zero in the standing position); while the knee joint angles θ_i (i=2,4) are measured as the positive clockwise displacement of the distal lower link from the upper link (zero in the standing position). The maximum payload is 40 kg (not including the power unit) and the maximum stride frequency is 1 Hz.

The right leg details are zoomed in, displayed in Fig. 1(b). Angle φ_i changes as a function of θ_i: $\varphi_i = -(\theta_i - \varphi_{i0})$, where φ_{i0} is the initial value of φ_i in standing position. l_{i0} is the cylinder initial length, D_i is the cylinder diameter and d_i is the rod diameter. So the displacement of the cylinder rod l_{ia} can be formulated as (1). The values of the lower limb physical parameters are shown in Table 2.

$$l_{ia} = \left(\sqrt{l_{ib}^2 + l_{ic}^2 - 2 l_{ib} l_{ic} \cos\varphi_i)} - l_{i0}\right) i = 1, 2, 3, 4 \tag{1}$$

2.2. Pressure requirement

There are three main concerns in determining the system pressure, i.e. the load capacity, the compactness of the components, and the transmission efficiency, defined as the ratio of the power delivered to the actuators divided by the power produced by the hydraulic pump. On one hand, when a high pressure level is adopted, larger force could be exerted by a certain actuator, the hydraulic flow rate required by the system could be reduced, and components with smaller size, such as valves, actuators and hoses could be adopted. On the other hand, high system pressure results in more leakage in the pump and valves, thus reduces the transmission efficiency. High pressure also causes wear of the sealing parts, and increases the safety risk to the wearer of the exoskeleton.

As a result of the compromise between efficiency and compactness, the maximum system pressure is determined to be 9 MPa.

2.3. Flow rate requirement

2.3.1. Method

Flow rate requirement depends much on the stride frequency. An indirect method was used to calculate the flow rate without using a flowmeter. Based on the kinematics of the exoskeleton (1), the flow into each cylinder q_i can be calculated by (2), where v_{ia} is the velocity of the cylinder rod.

$$q_i = \begin{cases} v_{ia} \dfrac{\pi D^2}{4} v_{ia} \geq 0 \\ -v_{ia} \dfrac{\pi \left(D^2 - d^2\right)}{4} v_{ia} < 0 \end{cases} \tag{2}$$

As the leakage of the pump used in the CHPU can be ignored when the maximum system pressure is 9 MPa, the leakage of the system mainly comes from the servo valves. The leakage of one