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VARIABLE HYDRAULIC TRANSMISSION TO BE USED IN A BODY-POWERED WEARABLE ROBOT

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ABSTRACT

A body-powered wearable robot (BPWR) transmits power from one joint to another in an exoskeleton. A variable hydraulic transmission design using long-stroke rolling diaphragm cylinders and efficient on/off valves is suggested in this paper to be used in a BPWR. Using the new design, a high number of transmission ratios are achievable in a smooth mechanism. The number of transmission ratios with respect to the number of cylinders and the pressure drop across the transmission is assessed. The torque loss caused by the pressure drop is 5 percent using a proper conduit geometry.

Keywords: Hydraulic transmission, Rehabilitation, Body-powered wearable robot.

INTRODUCTION

A body-powered wearable robot (BPWR) is an internal force system where the body segment's power is transmitted to other segments by an exoskeleton. BPWR is targeted for both performances increasing and rehabilitative purposes. A variable transmission between joints enables the system to have a wide range of speeds and to operate close to the peak power and efficiency. Variable power transmission can be continuous (i.e., two joints with variable radii pulleys and a belt or a hydrostatic transmission) or discrete (i.e., digital hydraulics). Hydraulic transmission is a viable choice for wearable robots because of its high stiffness, lightweight, and capability of having a variable transmission ratio [1, 2]. Figure 1 shows the proposed hydraulic transmission for a BPWR. This device connects multiple joints to transmit power produced by the patient's strong segments to the stroke-affected ones.

A benchtop hydraulic transmission device was suggested in the previous study [3]. Long-stroke rolling diaphragm (LSRD) cylinders were used in the device offering low friction and high stroke length, which allow the transmission to have a smooth and high-bandwidth movement in a high range of motion [4]. Figure 2 shows the hydraulic circuit of the transmission equipped with two cylinders on each joint, and a transmission ratio of one to one between input and output shafts achieved by pre-pressurizing the system using a hand pump and closing the isolation valve.

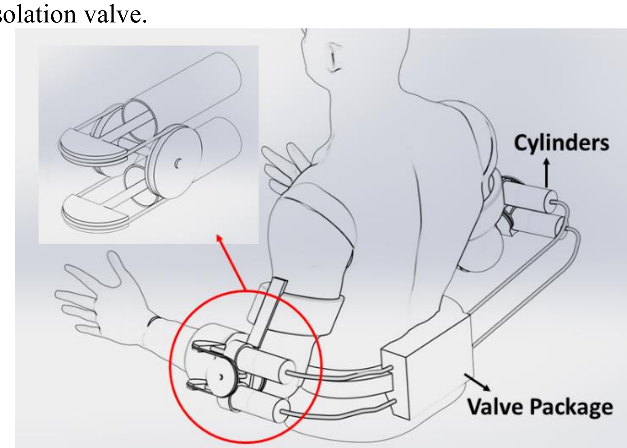

Figure 1. Body-powered wearable robot

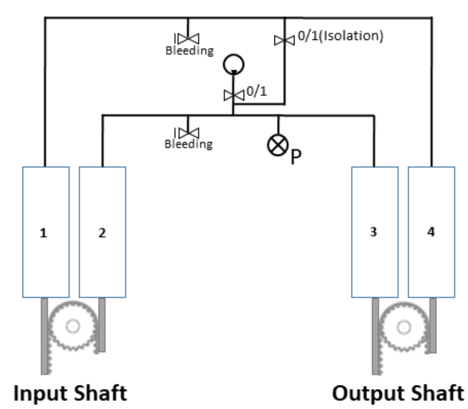

Figure 2. Antagonist transmission circuit with a 1:1 transmission ratio.

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Having a certain number of discrete transmission ratios is feasible using a digital hydraulic concept. Digital fluid power is controlling of system output using hydraulic or pneumatic components that are coupled to the system with switching valves. A digital fluid power system can be arranged in two configurations. One uses a parallel connection of several valves to have discrete outputs, and the other uses continuous pulse width modulation to maintain an infinite output value [5]. In this device, on/off valves were used on each cylinder in the transmission to connect/disconnect it to the closed system (Figure 3).

A variable hydraulic transmission device using commercial solenoid valves has been examined [6]. Because there is no additional power source in the system, the hydraulic components must preserve the power. The pressure drop in the commercial solenoid valves increased the power loss through the transmission in the previous studies. A valve analysis was done to find a valve mechanism with the lowest pressure drop [7]. Ball and butterfly valve mechanisms have the lowest pressure drop in their open positions. Using these valve mechanisms and LSRD cylinders ensures the highest mechanical efficiency through the transmission.

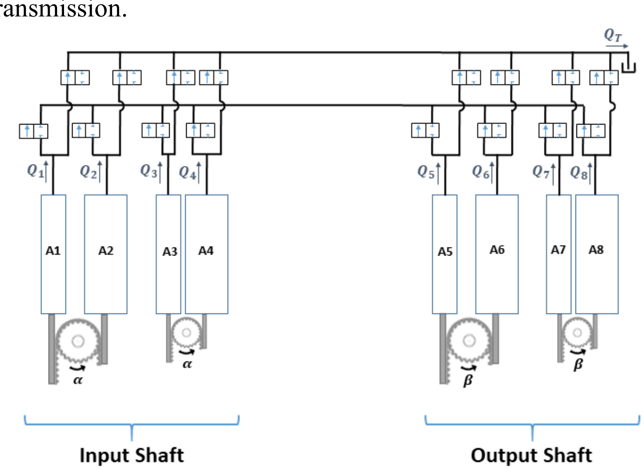

Figure 3. Variable hydraulic transmission with eight cylinders and sixteen valves

The previous study included a calculation method for transmission ratios [6]. A smoother mechanism with a higher number of transmission ratios was achieved by adjusting the design of the system. A higher number of transmission ratios was reached by adding unique sized pulleys and cylinders to each joint. In this paper, the maximum number of unique transmission ratios for a specific number of cylinders and valves was investigated. Furthermore, an analysis of the effect of pressure drop on the performance of the transmission in a BPWR was conducted.

METHODS

1.1 Variable hydraulic transmission

Figure 3 shows the variable hydraulic transmission device with eight LSRD cylinders, four pulleys, and sixteen valves. Pulleys connected to the joint shafts allow all cylinders to affect the transmission ratio. A cable loop was used to attach a pulley pair to the cylinder pair (Figure 1). The cable gets tensioned by pre-pressurizing the system. Each cylinder can be either connected to the common closed manifold or the open reservoir using the on/off valves.

The previous study evaluated the transmission ratio in a variable hydraulic transmission by analyzing the flow rate in the system [6]. Similar analysis was performed for this device. Having a higher number of unique sized cylinders and pulleys on each joint increases the number of unique transmission ratios.

1.2 Pressure Drop

The valve architecture chosen for this transmission device has the same open diameter as the hose, the pressure drop in the transmission device comes from the diameter change from cylinder to the hose and along the hose.

The pressure drop due to the change in diameter from cylinders to the hoses and from the hoses to the cylinders is negligible due to the low flow rate in this application. Assuming the elbow flexion/extension of 90 degrees in a minimum of 1 second, 50 mm of pulley diameter, and 25 mm of cylinder diameter, the flow rate in the cylinders is less than 20 cm3/s (0.32 gpm) and the pressure drop due to this change in diameter is less than 50 Pa [8].

The pressure drop along the tube depends on the geometry of the tube and fluid properties. The Darcy-Weisbach equation was used to calculate the pressure drop along the tubes.

$$\Delta p = 128\,\frac{\mu L Q}{\pi D^4} \qquad (1)$$

where Δp is the pressure drop, μ is the dynamic viscosity of the fluid, L is the length of the tubes, Q is the flow rate, and D is the tube diameter.

RESULTS AND DISCUSSION

2.1 Variable hydraulic transmission

The transmission ratio for each valve configuration was calculated using the analysis in the previous study [6]. With four cylinders and eight valves, assuming that the two large cylinders have twice the area of the two small cylinders and that the pulleys have the same radius, $16(2^4)$ transmission ratios are available; however, seven are redundant, leaving nine unique variable transmission ratios ranging from -2 to 2 including zero, positive, and negative infinity (Figure 4.)

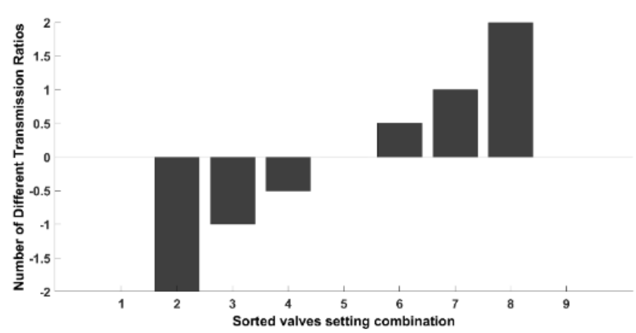

Figure 4. Transmission ratios using four cylinders and eight valves

Figure 5 shows the transmission ratios for a system using eight cylinders, two pulley pairs on each joint, and sixteen valves (Figure 3). Assuming the radius of the larger pulley is twice that of, the smaller and that the large-bore cylinders have twice the area as the small-bore cylinders, 45 unique transmission ratios ranging from -6 to 6 can be reached (including zero, positive, and negative infinity).

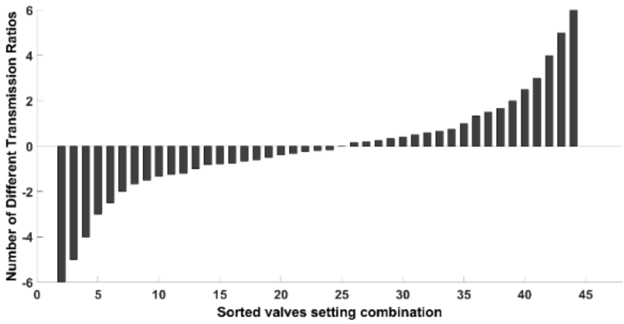

Figure 5. Transmission ratios using eight cylinders and 16 valves

The number of transmission ratios increases with the number of cylinders; however, it gets to a higher number of valves in the system. Figure 6 shows the number of different transmission ratios and the number of valves concerning the number of cylinders for two cases. The first case uses one size of the large cylinder for the larger cylinders and one size of the small cylinder for the smaller ones with the same set of pulleys for input and output, including a unique radius size for each pulley. The second case uses a unique bore size and radii for each cylinder and pulley in the system.

The number of transmission ratios can be increased further by relaxing the assumption of restricting cylinders to two bores and output pulleys to have the same size as input pulleys.

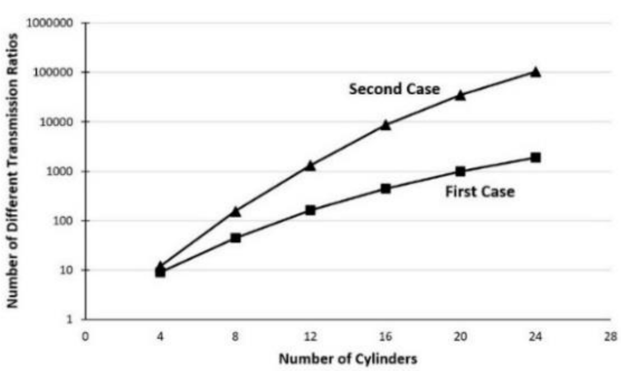

Figure 6. The number of unique transmission ratios with respect to the number of cylinders for two assumptions; first assumption: similar cylinder sets with the output pulley sizes similar to the input pulley sizes, second assumption: unique size for all cylinders and pulleys in the system.

2.2 Pressure Drop

The pressure drop for a meter of 3 mm diameter hose using mineral oil is 100 kPa (15 psi). This pressure drop will increase the required torque to move the forearm of an average person (80 kg weight and 170 cm height) [9] by 40 percent using 50 mm pulleys in the transmission. There is only a 5 percent increase in required torque to move the forearm of the same person using the same device with a meter of 5 mm diameter hose. This shows the importance of the conduit geometry in the performance of this transmission device.

CONCLUSION

The number of transmission ratios was assessed for the device for a number of the cylinders. A high number of unique transmission ratios are made available by having a unique sized for the cylinders and pulleys in the system, which can be designed compact enough for the robot. The pressure drop across the transmission increases the required torque to move the stroke-affected joint. This torque increase can be as low as 5 percent using a 5 mm diameter hose.

ACKNOWLEDGMENTS

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