

Tiny Hydraulics for Powered Orthotics

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Abstract—Untethered, powered orthotics require an actuation system with power supply and control, transmission line and actuator. Fluid power has unmatched force-to-weight and power-to-weight compared to electromechanical systems, but it is unclear if those same advantages hold for small systems in the 10 to 100 W range. A systems analysis approach suggests that a fluid power system will be lighter than an electromechanical system with the same output power and efficiency if the fluid power is run at pressures over about 200 psi. A theoretical analysis of small bore cylinders suggests that eliminating the piston seal will result in a higher efficiency actuator if the clearance gap is small. A demonstration, battery powered electrohydraulic actuator assembled from off-the-shelf components had the force and power suited to a powered ankle orthosis, but is too large and too heavy, suggesting the need to develop custom components.

Keywords—powered orthotics; fluid power

I. BACKGROUND AND SIGNIFICANCE

A. Powered Orthotics Can Assist People with Motor Impairments

Upper and lower extremity movement is a fundamental part of daily life and motor impairments can lead to a significant degradation in the quality of life. In the United States, approximately 36 million people report a physical disability [1], which in many cases will include mobility impairment. A particular concern is wounded soldiers returning from the Iraq and Afghanistan conflicts. From 2001 to 2006, 7,018 soldiers received a major lower limb injury that did not require amputation [2].

An orthosis is a medical device applied to a human limb to control or enhance movement [3] and can range from splints to immobilize joints during the repair of damaged bone, ligament or muscle to powered exoskeletons for paralyzed walking. Untethered powered orthotics are a recent development that offer significant promise for new strategies for restoring motion when the impairment to the muscle or neural system is significant and the user can only move the limb weakly or not at all under voluntary power.

Recent reviews describe the blossoming research in powered orthotics [4][5][6][7]. Daunting technical challenges define the field. Unlike powered prosthetics that replace a missing limb, orthotics are worn outside the body, eliminating the availability of internal volume for packaging components. Similar to prosthetics, the major technical challenges for untethered powered orthotics are: (1) a small, light power source that has sufficient stored energy for all day use, (2)

compact rotary or linear actuators to move the structural components that in turn push and pull against limb segments, (3) actuator control means that sits between the power supply and the actuators and can provide full control over actuator power at high efficiency and an appropriate bandwidth, and (4) packaging of components, interconnects and structure that is light and unobtrusive. **As one example of the challenge, a mere 2 kg on each foot of a healthy adult results in a 30% increase in oxygen uptake while 20 kg on the trunk has little impact [8].** In this paper we focus on untethered powered systems with modest amounts of power, the 10 to 50 W range, although similar issues arise in human amplifiers such as the Raytheon XOS 2 that operate at much higher power¹.

B. Fluid Power is an Appropriate Actuation Choice for Powered Orthotics

Electromechanical systems come in a range of powers, have good bandwidth, are easy to control and are clean. They also have inherent limitations. Human motion is characterized by relatively high torque, relatively low velocity actuation. Ordinary DC electric motors are the opposite: low torque, high velocity. Electric motors require a transmission, typically a rotary gear head or a rotary to linear ball screw, to match the actuator to the load requirements. That transmission must be co-located with the motor and is typically heavy, sometimes heavier than the motor.

Fluid power actuation systems have characteristics that overcome some of the limitations of electromechanical systems [9]. **The key advantages of fluid power are the high force-to-weight and force-to-volume ratios of the actuators eliminating the need for a transmission.** The pressurized fluid is transported to the actuator through flexible hoses that can be snaked over moving joints and placed in locations that are impractical for electric motors, including being integral with the structure. This allows great flexibility in component placement including locating only the light weight cylinder at a distal joint without sacrificing force or power. **Electromechanical systems carry power through flexible wires that can also be routed around joints but wire cannot be used to separate the actuator from the transmission.** Finally, unlike some high-ratio mechanical transmissions, fluid power actuators, to some extent, are back drivable within the limits of fluid drag forces.

Fluid power is broadly split into pneumatics and hydraulics. Pneumatics is clean because the pressurized fluid is air, and does not require a return line, which minimizes system weight.

¹ http://www.raytheon.com/newsroom/technology/rtn08_exoskeleton/

Drag through small hoses and valve orifices is smaller. Hydraulic systems, however, can operate at much higher pressures for superior force per volume and have high stiffness, which simplifies control. For example, unlike electric motors, the actuator can be locked with zero input power by blocking the flow with a valve.

While fluid power dominates in heavy equipment [9], there are significant technical challenges when considering tiny, low power hydraulic systems suitable for portable, wearable applications such as a powered orthosis. The fundamental problem is that as size goes down, the friction losses in cylinders and pumps and the drag losses in conduits go up because of surface area to volume scaling. In fact, it is not obvious whether the force-to-weight and power-to-weight advantage of fluid power continue to hold as the system gets tiny. A second complication is that the hydraulic fluid is at a minimum messy and at a maximum toxic, which means leaks are not tolerated even if water is used for the pressurized fluid. A third complication is that off-the-shelf tiny hydraulic components do not exist. Commercial cylinders, pumps, motors, valves and conduits are targeted to the industrial high power market and are completely unsuitable for wearable applications. Despite the promise, there has been little research on tiny hydraulics, with the notable exception of preliminary work by Love [10] and Kargov et al. [11]. The project described in this paper is designed to close this gap.

II. POWERED ANKLE FOOT ORTHOSIS AS A TEST BED

The Center for Compact and Efficient Fluid Power (CCEFP)² is charged, among other things, with developing new knowledge and new technology in compact fluid power. One of the four test beds in the center is a portable powered ankle foot orthosis (AFO). The AFO is a rich test bed for validating tiny fluid power concepts because healthy ankle function is well-defined, the power is reasonable and there are strict packaging and weight requirements for clinical acceptance.

Fig. 1 shows the kinematics and dynamics of the healthy ankle. These are the targets to hit if the AFO is to provide gait assistance equal to that of the normal ankle. The average power at the ankle is about 13 W, but power peaks to almost 200 W just before toe off. The power peak presents an interesting design challenge that for fluid power systems could be met by rapidly discharging a small accumulator. Energy is about 14 J per step.

Longevity is determined by desired daily use with active people taking 10,000 steps per day and sedentary people less than 5,000 steps per day [12]. For minimal interference with gait, the AFO should be less than 1 kg and packaged to fit inside loose pants.

Research at the CCEFP has produced a prototype pneumatic portable powered ankle orthosis [13]. The ankle is driven by a small air motor and the power supply is a 9 oz. tank of compressed CO₂. The system can provide up to 12 Nm of plantar- and dorsiflexor torque. The maximum torque and power of the pneumatic system is limited and for full ankle

function a tiny hydraulic system is contemplated. The next section takes a system analysis approach with the objective of guiding the design of tiny hydraulic systems suitable for untethered powered orthotics

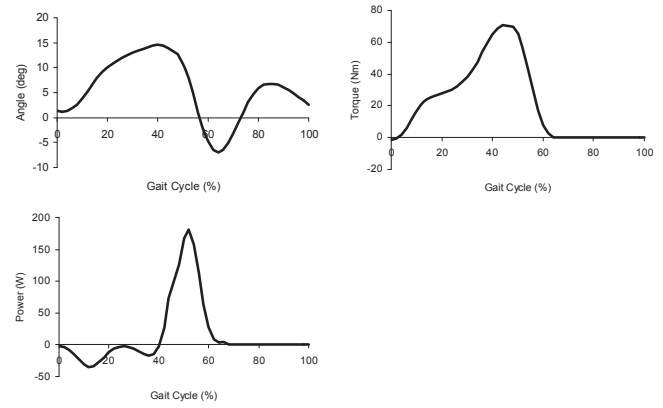


Figure 1. Ankle kinematics and dynamics for 85 kg person walking [14].

III. SYSTEM ANALYSIS OF TINY HYDRAULICS

A. Choices for System Architecture

Fig. 2 illustrates the choices a designer has for configuring a complete mechanical drive system for a portable application. The top row is the generic configuration containing an energy source, control means, power transmission line and actuator system. The second row shows the electromechanical solution. Note that the mechanical transmission (e.g. gear head or ball screw) is co-located with the motor at the point where power is applied to the joint. There are some exceptions, for example when a cable drive is used to distance the transmission from the joint. Cables present problems, however, if they pass over several joints.

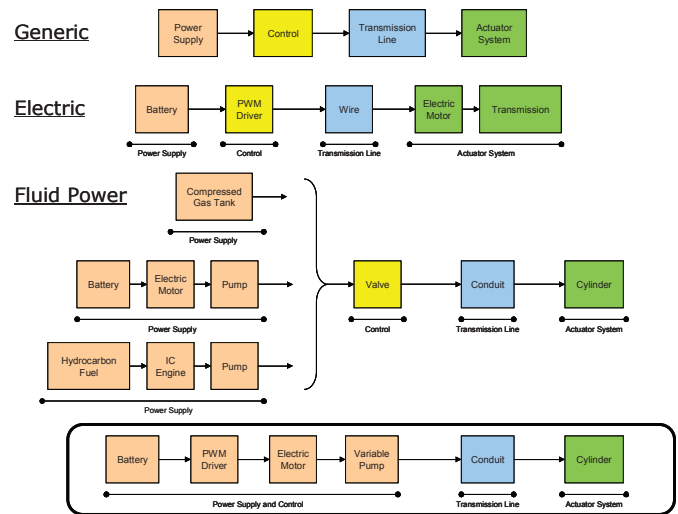


Figure 2. Architectures for configuring a mechanical drive system.

² <http://www.ccefp.org/>

The bottom section of Fig. 2 illustrates various configurations for realizing a fluid power actuation system. For pneumatics, the power supply can come from a tank of compressed gas as was done in [13]. The second option is to create the pressurized fluid locally using a pump. As indicated in the figure, the pump can be driven by a battery and electric motor combination or by a hydrocarbon fuel and internal combustion engine combination. The pump plus electric motor solution could be a piezoelectric pump [15] and the battery could be replaced by a fuel cell [15]. Two control means are shown, one uses a flow-control valve and the other uses a PWM drive to control the electric motor.

The energy source can be a battery or hydrocarbon fuel. While fuel has a much higher energy density, the conversion to mechanical power through a combustion engine is not efficient. Research is ongoing to develop efficient tiny engines for fluid power supplies [16][17][18]. Because relatively high energy density batteries and reasonably power dense electric motors are available off the shelf, our short-term approach is the one circled in Fig. 2.

B. Hydraulics Will Be Lighter Than Electromechanical Only at High Pressures

To further understand the engineering trade-offs between hydraulic and electromechanical solutions for low power systems, we conducted a series of system analyses. The first analysis was designed to answer the question, "For equal efficiency, which is lighter a fluid power or an electromechanical system?" For a tiny system this question cannot be answered by intuition. Details of the analysis are in [19]. The benchmark system used for analysis is shown in Fig. 3 and excludes the power supply.

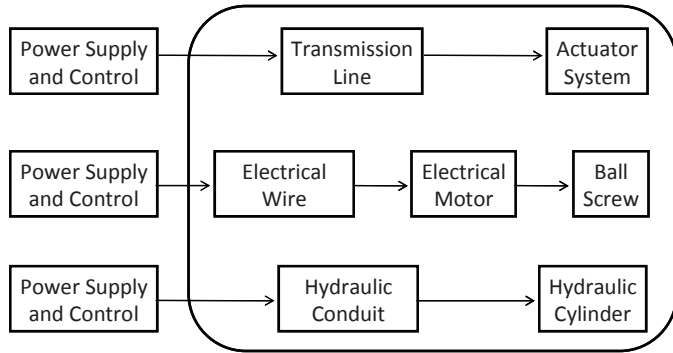


Figure 3. Configuration for comparison system analysis.

1) Hydraulic System Analysis

The first part of the analysis was to estimate the weight of the ideal hydraulic cylinder shown in Fig. 4 based on principles of fluid mechanics and solid mechanics. The thickness of the cylinder wall was based on thin-walled pressure vessel analysis and the thickness of the end walls was developed from the thin plate formula. The rod diameter was calculated using Euler and JB Johnson buckling formulas based on the applied load. Cylinder force and volumetric efficiencies were developed from approximations describing seal friction and leakage for a rubber o-ring seal.

To validate the procedure used to estimate total cylinder weight, catalog data for 187 commercial hydraulic cylinders was mined. The pressure, bore, stroke, material properties (stainless steel was assumed) and safety factor (2 was assumed) was entered into the theoretical model to determine theoretical wall thickness, rod diameter, material volume and a theoretical weight, which was compared to the actual weight. Fig. 5 shows the comparison. The theory generally was able to predict the weight, but as the inset shows, practical cylinders are heavier than predicted for the lightest cylinders, likely because the analysis neglected the weight of fittings.

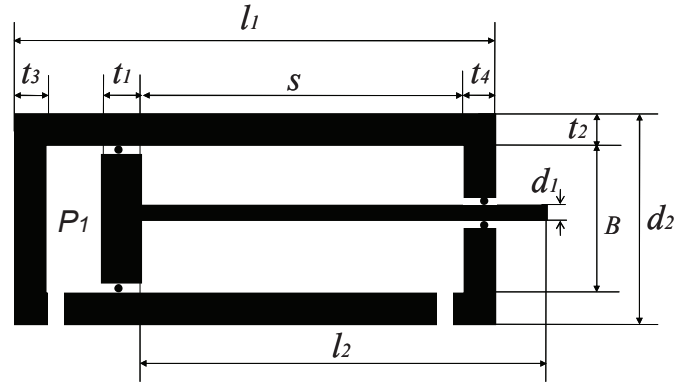


Figure 4. Ideal cylinder used for estimation of theoretical weight and efficiency.

The weight of the conduit was estimated from the thin-walled cylinder formula and the conduit efficiency was estimated from the simplified theory of the pressure drop in smooth pipes with laminar or turbulent flow. The properties of tiny conduits are very sensitive to diameter as a small increase can greatly increase the flow for fixed pressure drop.

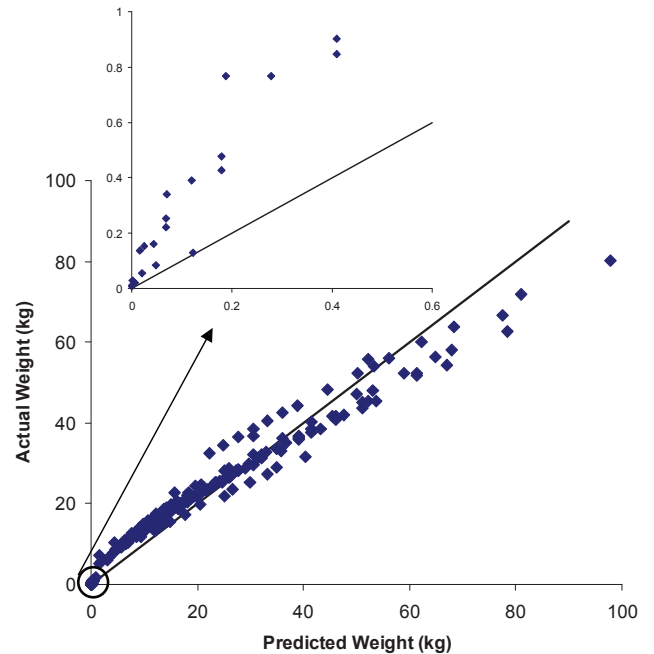


Figure 5. Comparison between actual and predicted weight of 187 commercial cylinders. Upper inset expands the data for light weight cylinders.

2) Electromechanical System Analysis

Unlike hydraulics, electromechanical components for tiny systems are commercially available. Rather than using first order principles to estimate the weights of motor and transmission, empirical equations for bounds were developed based on catalog data. Fig. 6 plots power and efficiency as a function of weight for 192 brushless DC motors from two suppliers of high end motors. Power was calculated from the product of catalog nominal speed and nominal torque. The data shows a large spread, up to a factor of five, in power-to-weight ratio of motors. The solid lines on the plots are the bounding equations surrounding the data, which were developed empirically.

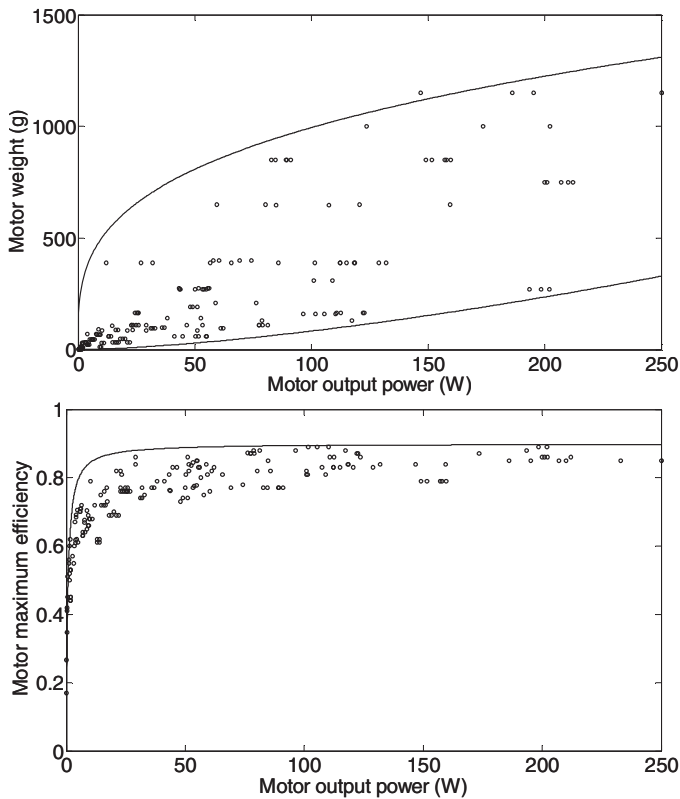


Figure 6. Weight (top) and efficiency (bottom) as a function of power for 192 DC brushless motors. The lines are empirical bounding curves used for system analysis.

The analysis assumed the transmission was a ball screw, which has excellent power-to-weight and high efficiency. An empirical bounding equation for ball screw weight as a function of rated load and stroke length was developed from catalog data for 82 models from one supplier of high performance ball screws. The ball screw efficiency was assumed to be 90%.

The weight and efficiency of the wire was also considered. The wire efficiency was fixed at 99% to reduce the number of system parameters. The weight was calculated from the resistivity and density of copper for a diameter that produced the target efficiency at the current required for the design problem. The weight of the insulation was not considered.

3) Comparing Hydraulic to Electromechanical

To compare the two systems, a design problem was established by specifying system power, force and linear excursion. The electrical system was designed based on the empirical models described above and the efficiency calculated. The weight of the motor was taken from the lower bounding curve shown in Fig. 6. A hydraulic system was designed to match the same design requirements and the same efficiency. The system efficiency determines the run time for a given amount of energy input. We assumed that the input energy was the same for the two solutions and by matching efficiencies we guaranteed that the output energy was the same, which is the fair comparison. If only power/weight was optimized without regard to efficiency, the two systems might have very different run times. The weight of the hydraulic system was then compared to the weight of the electromechanical system.

Fig. 7 illustrates the key result, which is that a tiny hydraulic system will be lighter than the equivalent electromechanical system if the fluid pressure is high. For example, looking at the points for 100 W of output mechanical power, the electromechanical system is predicted to weigh 428 g. A hydraulic system at 100 psi is predicted to weigh 625 g, but one at 500 psi would weigh 125 g and only 63 g at 1000 psi.

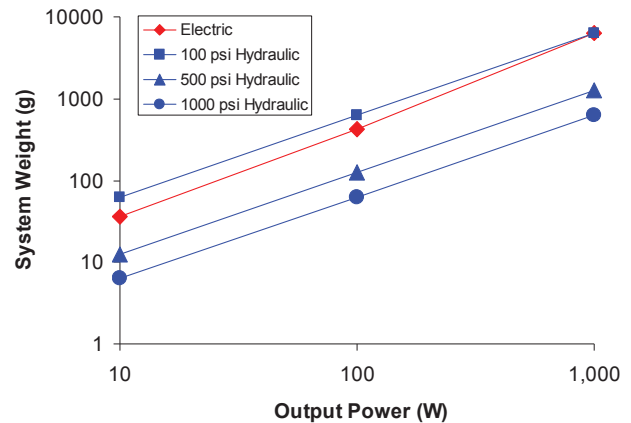


Figure 7. Compares predicted weight of ideal fluid power system to an electromechanical system of the same power and efficiency.

C. Tiny Cylinders May Be More Efficient Without Piston Seals

Because friction dominates behavior as cylinder bore gets smaller, we conducted a system analysis study of the efficiency of four hydraulic cylinder configurations with cylinder bore size between 1 and 10 mm. The analysis details are in [20]. The configurations were: (1) no piston seal, no rod seal; (2) no piston seal, rod seal; (3) piston seal, no rod seal; (4) piston seal, rod seal. A leakage and friction model based on a compliant o-ring seal was used. Fig. 8 shows the simulation results for efficiency versus bore size for a piston gap of 10 μm . Comparing the two traces with the rod seal (no rod seal would mean fluid leaking into the environment) and with and without the piston seal shows that removing piston seals can improve

hydraulic cylinder overall efficiency if the clearance gap is small. The benefits of removing seals become significant as bore size decreases. If the gap size is 20 μm , it is better to leave the seal in, but the overall efficiency is lower than the smaller gap with no seal.

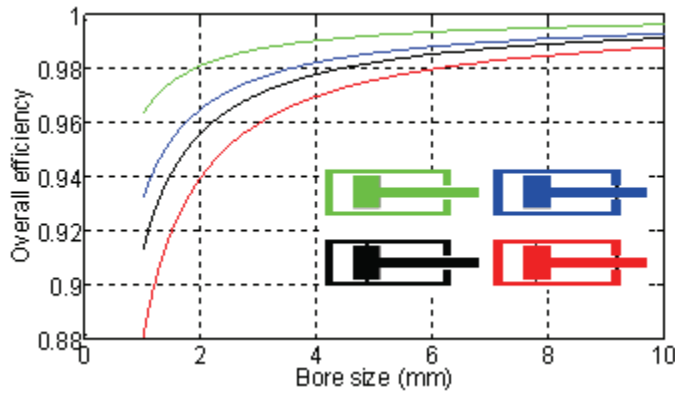


Figure 8. Cylinder efficiency versus cylinder bore for four seal configurations. Green: no piston or rod seal. Black: no rod seal. Blue: no piston seal. Red: both seals.

IV. DEMONSTRATION MODEL USING OFF-THE-SHELF COMPONENTS

To demonstrate the concept of small-scale hydraulics, an electro-hydraulic actuator (EHA) was prototyped using high performance off-the-shelf components (Fig. 9). The energy source is a lithium polymer battery (TP-2250-6SP30, Thunder Power, 22.2 V, 2250 mAh, 350 g). A brushless DC motor (370426, MAXON motor, 260 g) driving a fixed displacement axial piston pump (642654, Parker Oildyne, 190 g) transmits pressurized fluid to a cylinder (H-091-DZ, Bimba, 500 psi, 1.0625 in. bore, 2.0 in. stroke, 400 gms). The cylinder pulls on a load through a cable-pulley assembly and can lift an 85 kg person at 2.5 cm/s for an output power of 21 W. The pump produces 12.5 cc/s at 241 psi and is over-powered for an ankle orthosis. The system weight excluding the plastic base plate is 2750 gms. Of that about one-half (1500 gms) is the pump manifold, fittings, hoses, speed control potentiometer, electronics enclosure and wires, which clearly indicates the need for custom, tiny fluid power components and integrated systems that eliminate discrete hoses and manifolds. Another reason for integrating components is that hoses containing high pressure fluid are stiff and will add mechanical resistance if routed around moving joints.

V. CONCLUSIONS

The system analysis indicates a clear opportunity for applying tiny hydraulics to untethered powered orthotics. It is equally clear from the system analysis and the demonstration model that current off-the-shelf components are too large and too heavy. Technical development, guided by theoretical analysis, is needed to create a new generation of tiny, efficient pumps and cylinders. Components integrated into the structure of the orthosis will be needed to further reduce the size and weight. Control algorithms must be developed that account for

the nonlinear properties of pressurized oil passing through channels and orifices and the time delay of pressure waves, limited by the speed of sound, traveling through hoses. Current research by our group is addressing these problems.

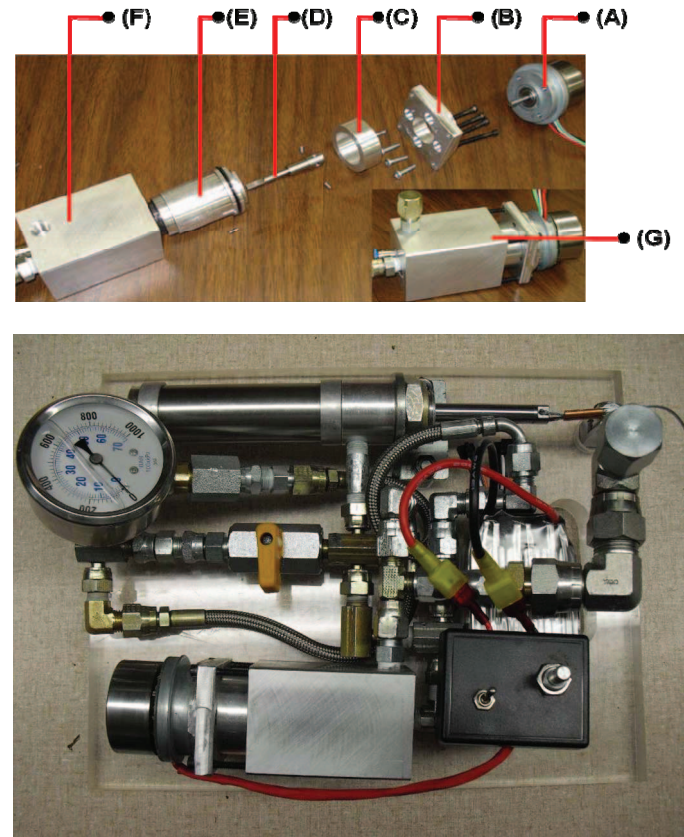


Figure 9. Small, self-contained electrohydraulic actuator using off the shelf components. Top image is an exploded view with DC brushless motor (A), mounting plate (B), compression ring (C), coupling shaft (D), fixed displacement axial piston pump (E), manifold (F). Bottom image is assembled system, including battery, that has the footprint of a sheet of paper.

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