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Pneumatically Powered Hydraulic Rescue Shears for Firefighter Operations

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For severe traffic accidents, rapid occupant extrication is crucial. Firefighter hydraulic rescue shears, while essential for this task, are hindered by bulky hydraulic hoses which reduce maneuverability. This research investigates powering these tools with compressed air from a firefighter's self-contained breathing apparatus (SCBA) cylinder. The proposed system utilizes a compact, mobile hydraulic power unit driven by this pneumatic source. A hydraulic rescue shears and review of market solutions are reviewed, and a typical cutting loads are defined. A model of a small, mobile hydraulic power unit powered by an SCBA cylinder is proposed and its performance validated via simulation. This study aims to enhance rescue efficiency and ergonomics by potentially eliminating traditional hydraulic hose constraints.

Keywords:
hydraulic shears,
hydraulic power unit,
pneumatic source,
model,
simulation

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1 Introduction

In the critical moments following a severe vehicular accident, the time to extricate a trapped occupant is a major determinant of survival and recovery outcomes. The concept of the "golden hour", the period immediately after traumatic injury during which there is the highest likelihood that prompt medical and surgical treatment will prevent death, places immense pressure on emergency responders to act with speed and precision [1]. Vehicle extrication, the process of cutting away a damaged vehicle to free a trapped person, is a foundational and often complex task for fire and rescue services. The success of these operations hinges on the effectiveness of the tools at their disposal.

For decades, hydraulic rescue tools (HRTs), often colloquially known as the "Jaws of Life," have been the standard for vehicle extrication. These tools utilize high-pressure hydraulic fluid, generated by a dedicated power unit, to actuate cutters, spreaders, and rams capable of severing the high-strength steel components of modern automobiles [2]. While undeniably powerful, the conventional design of these systems presents significant logistical and ergonomic challenges. The tools are tethered by heavy, cumbersome hydraulic hoses to a bulky, engine-driven power unit. This configuration can impede a firefighter's maneuverability, limit access to vehicles in precarious positions (e.g., down an embankment or in a narrow alley), and increase the time required to set up and deploy the equipment at the scene. These limitations can introduce delays and increase the physical strain on rescuers, potentially compromising the efficiency of the entire operation.

To address these shortcomings, this research investigates a different approach for powering hydraulic rescue shears by leveraging a piece of equipment already carried by every firefighter into a hazardous environment: the self-contained breathing apparatus (SCBA). Modern SCBA systems operate with high-pressure air cylinders, typically at pressures up to 300 bar and volumes up to 10 liters, representing a significant and readily available pneumatic energy source [3]. The proposed solution involves the development of a compact, portable hydraulic power unit that is driven by compressed air from an SCBA cylinder. This would effectively untether the rescue tool, granting the operator complete freedom of movement and drastically reducing setup time.

This paper aims to establish the feasibility of this concept. It begins with a comprehensive overview of existing firefighter hydraulic rescue shears and defines the typical cutting forces and energy requirements encountered during vehicle extrication. Subsequently, a fluid power model for a small-scale, air-powered hydraulic unit is proposed. The performance of this model is then validated through simulation to determine its capacity to meet the operational demands of rescue cutting tasks. Ultimately, this study seeks to present a viable, innovative solution that enhances the mobility, efficiency, and ergonomics of firefighter rescue operations, potentially representing the next step in the evolution of these life-saving tools.

2 Existing rescue tool technologies

The evolution of vehicle extrication tools has been driven by the concurrent evolution of automotive manufacturing. As car designers have incorporated high-strength steels (HSS) and ultra-high-strength steels (UHSS) to improve passenger safety and fuel efficiency, the demands placed on rescue tools have increased exponentially [4].

2.1 Conventional hydraulic rescue systems

The most common rescue systems in use by fire departments worldwide are traditional hydraulic tools. These systems consist of three primary components:

- **The power unit:** A gasoline or diesel engine, or an electric motor, drives a hydraulic pump. This unit is typically heavy and is placed at a safe distance from the incident vehicle.
- **The hoses:** High-pressure, non-conductive hydraulic hoses, often in coaxial or "twin-line" configurations, connect the power unit to the tool. These hoses are typically 15 to 30 meters long and operate at pressures up to 720 bar.
- **The tool:** This can be a spreader, a cutter (shears), a combination tool, or a ram. The tool contains a hydraulic cylinder that actuates the arms or blades.

The primary advantage of these systems is their immense and sustained power output, capable of handling the most demanding cutting and spreading tasks. However, as noted, the operational constraints imposed by the hoses are a significant drawback. The setup time, potential for entanglement, and the need to move the heavy power unit to reposition for different cuts all detract from efficiency [5].

2.2 Battery-powered hydraulic rescue systems

In recent years, battery-powered (or "e-draulic") rescue tools have gained significant market share. These tools integrate the pump and a small electric motor directly into the tool's body, powered by a high-capacity rechargeable lithium-ion battery. This design eliminates the need for external power units and hoses, granting the operator complete freedom of movement.

Key advantages include rapid deployment (simply turn it on) and superior maneuverability. However, limitations exist. The power output, while sufficient for many applications, may not match the highest-end conventional systems for cutting through the most advanced UHSS. Battery life is a critical consideration; multiple batteries are required for extended operations, and their performance can degrade in extreme temperatures. Furthermore, the integrated design makes the individual tools heavier and bulkier than their hosed counterparts [6].

2.3 Pneumatic power in rescue operations

Compressed air is already a staple in rescue operations, primarily for lifting bags and powering pneumatic chisels or impact wrenches. These tools are valued for their lightweight design and simple operation [7]. However, pure pneumatic tools lack the force generation capabilities required for the heavy-duty cutting and spreading performed by hydraulic systems. The concept of using compressed air to *drive* a hydraulic system is also available on the market [8], however those systems require stable pressured air source and also requires hoses.

Therefore, the core innovation explored in this paper is a hybrid approach that seeks to combine the portability and ready availability of a pneumatic source (the SCBA cylinder) with the unparalleled force multiplication of hydraulics. To our knowledge, a comprehensive feasibility study of powering primary hydraulic extrication shears from a firefighter's SCBA cylinder has not been previously undertaken. This research aims to fill that gap by providing a foundational analysis of such a system.

3 System modeling and calculation

To assess the feasibility of an SCBA-powered hydraulic system, a theoretical model was developed and its performance parameters were calculated in this section.

3.1 System Components

Figure 1 show pneumatic and hydraulics schematic of power unit and a tool. The proposed power unit consists of a standard firefighter SCBA cylinder, a pressure regulator to step down the SCBA pressure to the motor's operating pressure, the pneumatic motor itself, a high-pressure hydraulic pump, and a compact hydraulic low and high pressure reservoirs. For this study, we proposed a common 10-liter carbon-fiber cylinder pressurized to 300 bar. This represents a finite, but readily available, energy source at any fire scene. The interface between the compressed air and the hydraulic pump is a pneumatic motor which is mechanically coupled to the hydraulic pump. The system is designed to power a standard hydraulic rescue shear, which requires a hydraulic pressure of 700 bar for maximum cutting force.

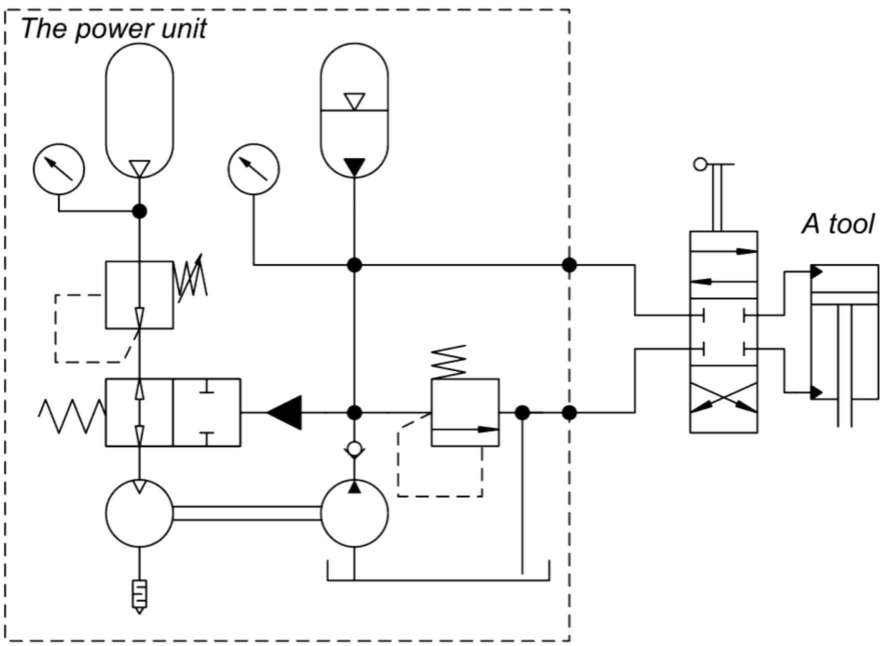

Figure 1: Schematic of the power unit and a tool.

Source: own

To save air and energy, a hydraulically controlled 2/2 pneumatic valve was added to the system. This valve interrupts the air flow if the hydraulic pressure exceeds the operating pressure, thus preventing the hydraulic safety valve from opening.

The RM 110 Piston Air Motor was selected for this study. Its operating characteristics at air pressure of 6 bar are shown in Figure 2 [9]. Figure 2a presents the motor's torque characteristic as a function of rotational speed. The motor has a starting torque of 6.8 Nm, which is slightly lower than its maximum torque of approximately 9 Nm, achieved at a speed of about 200 rpm. As the rotational speed increases, the torque decreases, reaching a value of 4.5 Nm at 2400 rpm. The air consumption, expressed in normal liters per second (NL/s), is shown in Figure 2b. It exhibits an approximately linear increase in relation to the rotational speed. Maximum air consumption is 29 NL/s at 2400 rpm.

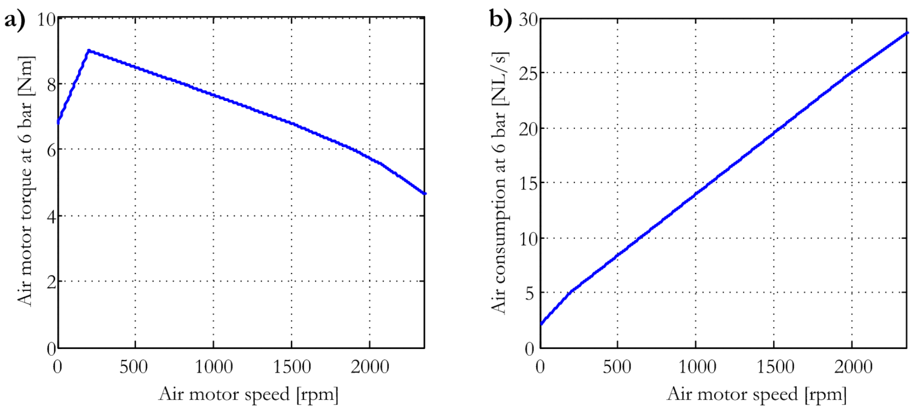

Figure 2: Air motor torque a) and air consumption b) at 6 bar pressure.
Source: derived from [9]

According to [10], the selected high-pressure pump is a radial piston pump (Type R) with a displacement of 0.43 cm^3/rev and is capable of achieving a pressure of 700 bar. It has a volumetric efficiency of 98 % and a hydromechanical efficiency of 82 %. The required torque (τ) for this pump can be calculated using the following equation:

$$\tau = \frac{pD}{2\pi\eta_{hm}}, \quad (1)$$

where p is the operating pressure in Pa, D is the pump displacement, and η_{hm} is the hydromechanical efficiency. Using the specified pump parameters, the required torque to achieve 700 bar is calculated to be 5.84 Nm. The maximum torque of the air motor exceeds this value for speeds below 2000 rpm (as shown in Figure 2a). Therefore, the chosen air motor is capable of powering the proposed high-pressure pump.

3.2 Simulation model

In the model, the speed-dependent torque (shown in Figure 2a) developed by the air motor is used to both build up hydraulic pressure in the pump and accelerate the combined inertia (I_{eq}) of the motor, pump, and shaft. Therefore, the following equation can be written:

$$\tau_m(\omega) = \dot{\omega} I_{eq} + \frac{pD}{2\pi\eta_{hm}}, \tag{2}$$

where ω is angular velocity of air motor and hydraulic pump in rad/s, and combined inertia is chosen heuristically to be 0.02 kgm^2. Hydraulic flow Q is determined by the pump angular speed, its displacement and volumetric efficiency (η_{vol}) according to:

$$Q = nD\eta_{vol} = \frac{30\omega}{\pi} D\eta_{vol} \, . \tag{3}$$

The duration of the air motor's normal operation is determined by the total volume of available air (in normal state), which is calculated using the following expression:

$$V_N = \frac{p_t - p_m}{p_N}\left(\frac{T_N}{T_t}\right) V_t, \tag{4}$$

where p_m is air motor operating pressure, p_t, T_t and V_t are pressure, temperature and volume of SCBA cylinder, while p_N and T_N are pressure and temperature of air in normal state, respectively. For example, a 10 L SCBA cylinder containing air pressurized to 300 bar at a temperature of 20 °C holds a volume of 2704 normal liters (NL). This amount of air is sufficient to allow the air motor to operate for 93 seconds at its maximum speed of 2400 rpm, where the air consumption is 29 NL/s (see Figure 2b).

As shown in Figure 3, the simulation model for the power unit is built on the air motor's torque characteristic from Figure 2a, which provides the maximum torque (τ_m) as a function of rotational speed. The motor's torque is opposed by the load torque from the high-pressure hydraulic pump. The difference between these torques accelerates the pump and motor. The rotational speed is then found by integrating the angular acceleration. This new rotational speed is subsequently used to calculate the air consumption and the motor's torque for the next iteration. Furthermore, the rotational speed also dictates the oil flow rate (Q) through the pump. The simulation proceeds until the entire normal air volume (V_N) is depleted. A necessary conversion is included in the model, as the motor's characteristics are given in revolutions per minute (rpm), while the rotational speed (ω) is calculated in radians per second.

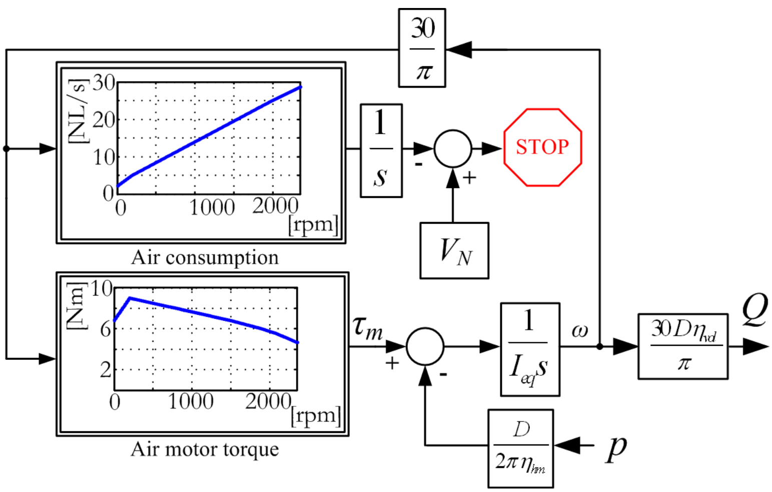

Figure 3: Simulation model.

Source: own

4 Simulation results

As shown in Figure 4a, the air motor (and the hydraulic pump) successfully accelerates despite the extremely high load torque resulting from the hydraulic system being set to its maximum operating pressure of 700 bar. After a few seconds, the motor reaches a steady-state speed of 1963 rpm. At this speed, the motor develops a torque of 6 Nm, which is precisely what is needed to maintain this steady-state condition, as seen in Figure 4b.

The motor's characteristics (Figure 2a) show that a higher torque is available at lower speeds. This allows for a faster initial acceleration, and this increase in torque is clearly visible in the first few seconds of Figure 4b. Air consumption, shown in Figure 4c, has an approximately linear relationship with the rotational speed of the air motor. The simulation runs until the motor consumes the entire available air volume, which occurs after 111 seconds.

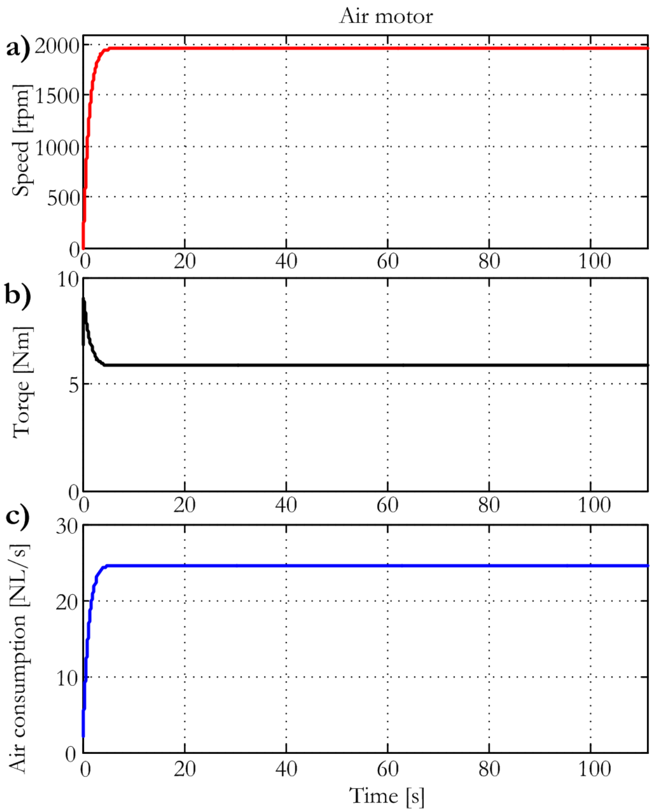

Figure 4: Simulation results of air motor speed a) torque b) and air consumption c).
Source: own

Figure 5a illustrates the oil flow rate of the pump, which is a linear function of its rotational speed (see Figure 4a). The time-based accumulation of the total volume of pressurized oil transferred by the hydraulic pump is depicted in Figure 4b. The simulation determined that this system, when powered by a 10 L compressed air tank at 300 bar, can deliver a total of 1.51 L of oil at a pressure of 700 bar.

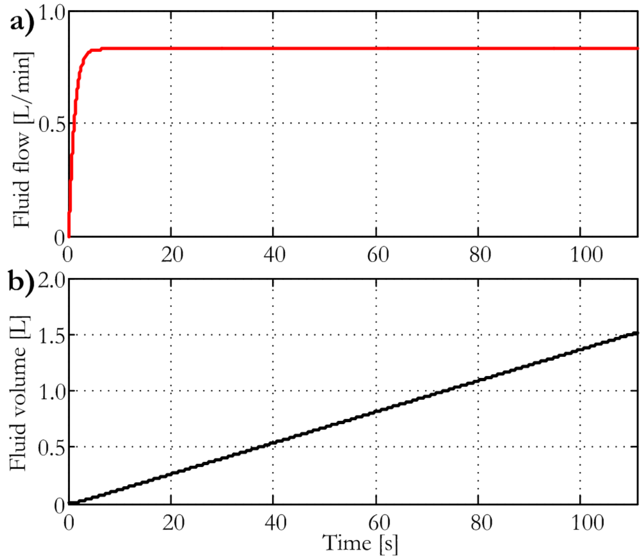

Figure 5: Simulation model.
Source: own

5 Discussion

The simulation results confirm the feasibility of a pneumatic-to-hydraulic drive system powered by a firefighter's SCBA cylinder. The model shows that the air motor can successfully accelerate and maintain a hydraulic pressure of 700 bar despite the extremely high load torque from the pump. This high pressure is essential, as it enables hydraulic shears, such as the CU 5030 CL, to achieve their maximum cutting force.

The simulation reveals that a single 10 L SCBA cylinder, pressurized to 300 bar, can maintain a maximum operating pressure for 111 seconds. During this period, the hydraulic pump transfers a total of 1.51 L of pressurized oil. Given that the CU 5030 CL shears require 0.155 L of oil per cutting cycle [11], the system is capable of performing approximately nine cuts. According to [12], this capacity is often sufficient for a single technical intervention, as a typical extrication may require between five and ten cuts. To extend the operating time and increase the number of available cuts, a two-bottle system, also called Twinpack System [13] could be implemented. This would increase the available air to 13.6 L, providing 2.06 L of pressurized oil and enabling up to 13 cuts.

The results of this study strongly suggest that powering hydraulic rescue shears from a firefighter's SCBA cylinder is not only feasible but also offers compelling advantages over traditional systems. The most significant benefit is the elimination of bulky hydraulic hoses, which untethers the firefighter and allows for unrestricted movement around a vehicle. Rescuers can more easily access components from any angle, navigate through debris, and operate in confined spaces without the risk of hose entanglement. The compact and mobile nature of the power unit means it could be carried by a single firefighter or placed on a small trolley, significantly reducing the physical strain and setup time associated with conventional gasoline-powered units.

By utilizing a power source that is already on-scene and carried by personnel, the time from arrival to the first cut can be dramatically reduced. There is no need to start a gasoline engine or run lengthy cables and hoses. In the time-critical context of vehicle extrication, saving these crucial minutes can directly impact patient outcomes. While modern battery-powered tools also offer untethered operation, the SCBA-powered system presents a different logistical paradigm. Fire departments already have a robust infrastructure for refilling SCBA cylinders on-site. An empty cylinder can be swapped for a full one in seconds, ensuring continuous operation. This contrasts with battery management, which requires charging stations, rotation schedules, and the eventual replacement of expensive batteries as they age. The performance of the SCBA system is also independent of ambient temperature, whereas extreme cold can degrade battery performance.

This study is a theoretical and simulation-based analysis and has several limitations that must be addressed through future work. The next logical step is to build a physical prototype of the compact pneumatic-to-hydraulic power unit. This prototype must be rigorously tested to validate the simulation results and assess its durability, reliability, and noise levels in a controlled environment. The final weight and dimensions of the prototype are also critical. Future work should also be focused on creating a unit that is significantly more portable than traditional power units, making it practical for a single rescuer to carry and operate. This study used a specific motor for its calculations. Future research could explore different pneumatic motors to optimize air consumption and overall system efficiency.

Ultimately, the system should be tested in realistic training scenarios with experienced firefighters to evaluate its ergonomics, usability, and effectiveness in complex extrication drills.

6 Conclusion

This study successfully demonstrates, through simulation, the feasibility of a novel pneumatic-to-hydraulic drive system for rescue shears that is powered by a firefighter's SCBA cylinder. The model confirms that the proposed system can maintain the required hydraulic pressure of 700 bar, which is essential for generating the maximum cutting force of the shears. The analysis indicates that a single 10 L SCBA cylinder provides sufficient power for approximately nine cuts, a capacity that is often adequate for a typical vehicle extrication. Furthermore, the system's operational time can be extended to support up to 13 cuts with a two-bottle configuration.

The results strongly suggest that this concept offers significant advantages over both traditional and battery-powered rescue tools. The most compelling benefit is the elimination of bulky hydraulic hoses, which grants firefighters unprecedented freedom of movement, improves access in confined spaces, and drastically reduces the risk of entanglement. By leveraging a power source that is already carried on-scene, the system also minimizes the time from arrival to the first cut, a critical factor in time-sensitive rescue operations. From a logistical standpoint, the system capitalizes on the robust SCBA refilling infrastructure already present in fire departments, offering a more dependable and low-maintenance solution compared to the complexities of battery management.

In summary, this research confirms that using an SCBA cylinder to power hydraulic shears is a viable and highly promising approach. It offers a powerful combination of portability, speed, and logistical simplicity that could revolutionize vehicle extrication. While the simulation results are compelling, the next logical step is to validate these findings through the prototyping and physical testing of a compact, real-world unit. This future work will be critical to fully assess the system's performance, ergonomics, and effectiveness in practical rescue scenarios.

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