

The 1st Pneumatic Fluidic muscles based Exoskeleton Suit in the U.A.E

Abdulla Almomani, Faisal Miqdadi, Mustafa Hassanin, Mustafa Samy, and Mohammed Awadallah,
IEEE

Abstract— Team Excelsoir's Prototype is a fully functional wearable exoskeleton arm that moves in sync with the operator's motion within 3 DOFs. Thanks to this device the user will no longer feel any fatigue in carrying heavy loads for long time periods. Recyclable, light and enduring materials are used in this project in order to fulfill safety and environmental concerns. Pneumatic muscles are placed cloning the human anatomy to provide absolute synchronization with ordinary human motion. Biceps, triceps and deltoids are assisted by the device and limited according to their allowable angles of motion. The exoskeleton arm can specifically be used in physiotherapeutic treatment and to aid people with difficulties in mobility and also in the heavy industry. The project officially precedes the Middle-Eastern market record by being the first of its kind. This project is sponsored by Festo. Festo is a worldwide leading supplier of pneumatic and electrical automation technology.

I. INTRODUCTION

The senior design course gives an experience to senior students through enhancing their skills in solving real world issues in a team work approach. Teams are expected to work on a project for two consecutive semesters following the design pyramid in which they start by stating the problem, follow up by designing and then finalize by embodying the design. Thus, our team is dedicated to building a unique, functional and beneficial project following a set timeline (see Appendix A). This report is stating a detailed description of a project the team decided to build. This project will definitely aid: civil defense, industry, society and medical organizations.

II. Project description

Excelsoir's exoskeleton suit, also known as powered exoskeleton, exoframe, or exosuit, is a mobile machine consisting primarily of an outer framework worn by a person, and a powered system of pneumatic artificial muscles (fluidic muscles) that delivers at least part of the energy for limb movement. Thanks to this device the user will no longer feel any fatigue in carrying heavy loads (up to 100 Kg) for long periods of time. Recyclable, light and enduring materials are used in this project in order to fulfill safety and environmental concerns.

The main function of the exoskeleton suit is to assist the wearer by boosting their strength, endurance and

durability. They are commonly designed for military use, to help soldiers carry heavy loads both in and out of combat. In civilian areas, similar exoskeletons could be used to help firefighters and other rescue workers survive dangerous environments. The medical field is another prime area for the exoskeleton technology, where it can be used for enhanced precision during surgery or as an assist to allow nurses to move heavy patients.

Moving to the technical part, the exoskeleton suit structure is made mainly from a combination of steel and aluminum. The power system is delivered through a set of Fluidic Muscles. In this prototype, 6 DMSP, 20 mm diameter, 400 mm stroke with a radial, at one end, pneumatic connection Fluidic Muscles are used. All positioned at the back of the structure so that the user feels no restrictions in the motion. Each Fluidic Muscle, which is provided by FESTO, can handle a load up to 1200 N (120 Kg) through the 25% contraction permitted. Also, 6 proportional pressure regulators VPPE are used to control the fluidic muscle flow rate in and out. Moreover, 6 mm high pressure plastic tubing, G1/8-6 mm fittings for VPPE, a 2.5 m cable for VPPE, G1/8 Silencers for VPPE, G3/8-6mm fittings for the fluidic muscles, and 6 mm T-connections have been used.



Figure 1: Full CAD drawing of the Exoskeleton Suit

The Exoskeleton suit is going to have different angles of motion depending on the human muscle group aided i.e. biceps, triceps, shoulders and legs. A pulley system resembling the human joints is used in order to attain the required range of

motion. More importantly, the team will focus on health and safety through the motion limitation of the fluidic muscles while the operator is using the exoskeleton suit. Kill switches "safety switches" are added to the design for such purposes. The procedure of making our project safe is complete in theory but it might change during the final manufacturing phases.

At last, the project officially precedes the United Arab Emirates market record by being the first of its kind. Furthermore, the project is sponsored by FESTO, a worldwide leading supplier of pneumatic and electrical automation technology. Founded in 1925, FESTO is a privately owned German industrial control and automation company. FESTO not only provided the team the generous discount of all the items purchased, but also supported the project in the technical aspects as well.

A. Exoskeleton Benefits

The product in general will allow users to lift weights outstanding the human ability. The exoskeleton arm can specifically be used in physiotherapeutic treatment (physical therapy) and to aid those who have difficulties in mobility.

Other useful uses can be listed as follow:

- Rescue missions (specifically road accidents)
- Heavy maintenance procedures

In fact, the exoskeleton will allow the wearer to function in any working field replacing man-power without decreasing the proficiency of the task in hand.

B. Design Process

The team observed other products in order to keep the originality of the design and also to seek what other products lacked and work on compensating missing functions and integrate that in a fully new design made by the team. Self-studies on human abilities in terms of the degrees of freedom of each muscle group were done. The Team meetings were held discussing several design probabilities and all the power drives needed to allow the wearer to have excess aiding force on number of muscles as:

Table 1: Design probabilities and power drives.

Biceps/Triceps	1 power drive	1 degree of freedom
Shoulders	2 power drives	2 degrees of freedom

The team also aims to build an exoskeleton arm within minimal costs compared to other products worldwide. The team made several analyses on the load to be lifted versus the weight of the exo-arm itself in order to provide a satisfying experience the wearer. The team took safety in consideration along every step of the design. Many sketches have been drawn and many brainstorming have been done. The extraction of these ideas brought the team into three final designs. The sketches and the analyses of each design are provided in the conceptual design section. Each design differs in its own

mechanic and technique. Power driving sources were examined theoretically to decide which of them shall be used in the final product. More comprehensive testing preventive and corrective examination will be held throughout the manufacturing process starting in late December.

III. 4.0 Specifications and constraints:

1. Increases the human strength, agility and endurance
2. Allow the wearer to lift heavy objects at a ratio of 2:1.
3. Made of light material.
4. Expected to weigh about 20kg.
5. Utilizes a combination of controllers, sensors and actuators.
6. Resistive to environmental challenges.
7. Cost is under 10000 AED.
8. Safe, comfortable and easy to control.

IV. 7.0 THEORETICAL BACKGROUND

Although autonomous robotic systems perfectly perform in structured environments such as factories, integrated human-robotic systems are superior in un-structured environments that require instantaneous adaption [1].

The technology of Exoskeletons is divided into two parts, lower extremity exoskeletons and upper extremity exoskeletons. The reason behind separating the two parts is that people can envision great applications for either part. Also, the technology of exoskeleton and human power augmentation is still in its early stage. Therefore, further research is required to ensure that both the upper and lower extremities function well independently before having an attempt to integrate them.

In the early 1960s, the Defense Department of the United States expressed their interest in the development of a powered suit of armor that would make soldiers lift and carry heavier weights (Figure 1).

From 1960 to 1971, General Electric developed and tested a prototype called the "Hariman" which is a set of overlapping exoskeletons controlled by an operator. The outer suit followed the motions of the inner suit which in turn followed the motion of the operator. However, using all these overlapping exoskeletons with difficulties in human sensing and the complexity of the system made it not practical (Figure 1) [1].



Figure 2: Hardiman

Seireg created an exoskeleton system for paraplegics where only the hip and knee were powered by hydraulic power unit consisting of a battery-powered direct-current (DC) motor, pump, and accumulator. A bank of servo-valves drives the actuators at the knee and hip. The device was controlled to follow a set of joint trajectories without the use of any sensory system from the operator (Figure 3) [1].



Figure 3: An exoskeleton system designed for paraplegics by Seireg

Later on, the University of Tsukuba developed the hybrid assisted limb (HAL). A 15kg battery powered suit that detects muscle myoelectric signals from the skin surface by sensors and sent to a computer that translates the nerve signals into signals of its own for controlling the electric motors of the exoskeleton. In addition to the electromyography (EMG) signals, the exoskeleton also includes potentiometers for measuring joint angles, force sensors for measuring ground reaction forces, a gyroscope and accelerometer for measuring the angle of the torso (Figure 4) [1].



Figure 4: HAL, an exoskeleton system designed by the University of Tsukuba

Moreover, Yamamoto created an exoskeleton for assisting nurses with patient handling where lower limbs include pneumatic actuators for flexing and extending the hips and knees. The pneumatic power is provided by air pumps mounted directly onto each actuator. Operators input is determined by force sensing resistors (FSR) attached to the operator's skin. These measuring resistors along with other information such as the joint angles are used to determine the input torques required for various joints (Figure 5) [1].

V. CONCEPTUAL DESIGN

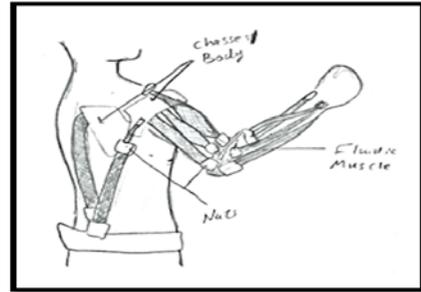


Figure 5: Conceptual Design

The third design is inspired by nature and uses devices that are analogical to the human muscular model. The concept is similar to the 1st design but instead of using actuators it is powered by artificial muscles. The muscles, a product of Festo (a worldwide leading supplier of pneumatic and electrical automation technology), are found in industrial applications under the name of "Fluidic Muscles". These fluidic tubes are of elastomer (a polymer with viscoelasticity/elasticity) reinforced with aramid fibers, a man-made organic polymer. They use pressurized gas to produce mechanical motion. When a Fluidic tube is filled with compressed air, its diameter increases and it is at the same time shortened. This behavior acts as a linear actuator and can deliver motion to two joints connected together. Also, this artificial muscle has enormous starting power, and its dynamic behavior is similar to that of a human muscle. Having said that, it can be shaped into the different muscles needed and provide extra power to them. One great advantage over its human counterpart is that when shortened, it doesn't require any supply of energy.

Any weight once lifted by the tubes can stand a long period of time. Moreover, with such technology, the force applied and the amount of shrinkage the tubes does can be all precisely metered. This can be done with highly new proportional valves from the same company Festo. Thus, for a reliable fluidic tube control a combination of pressure and length sensors are used to accurately quantify the values of force and contraction needed. A pressure tank is proposed to be placed at the back to provide the pressure needed. The volumetric flow rate formula is a multiplication of the flow velocity and the cross-sectional vector area. This implies that the smaller the radius of the tubes are the higher the pressure and thus the faster the contraction. Using pressure sensors and valves as stated above, proper values of flow will be set.

Throughout the design process of the exoskeleton, Excelsior team of engineers resolved economical, ethical and contemporary issues.

VI. 10.0 CONCEPT AND OPERATION OF THE MUSCLE TUBE

According to [2] PAMs are linear motion generators operated by gas pressure (air). The basic structure is composed of a flexible reinforced closed casing attached at both extremes to fittings where the mechanical load is transformed. When gas is sucked out of the membrane, it gets squeezed. With this radial expansion the membrane contracts axially and therefore exerts a pulling force on the load attached.

Two basic experiments will be discussed explaining the behavior of the tube when load is attached and air is applied to the tubes.

A. 10.1 In single situation

As Figure 6 shows, a constant mass M is attached and the pressure difference across the membrane is increased from an initial value of zero ($P=0$). When the pressure is zero the tube has a minimal volume, V_{min} , and a maximal length, l_{max} . If air is compressed and the muscle is pressurized to P_1 , the tube will start to lump and also develop a pulling force. As a result, the mass M will be lifted. The membrane's volume will then have grown to V_1 and its length shortened to l_1 . Increasing the pressure further to p_2 will continue this process. [2]

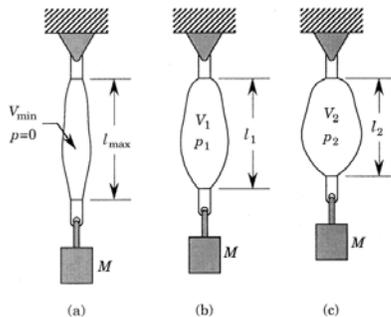


Figure 6: Muscle tube volume variation

The basic muscle tube behavior rules deduced from the experiment:

- 1) The muscle tube shortens by increasing its enclosed volume.
- 2) It will contract against a constant load if the pressure is increased.

B. 10.2 In pair situation

The fluidic muscles are devices that can be contracted generated linear motion (in one direction). In order to generate bidirectional motion, two muscles must be coupled together. As on tube inflates and contracts, the other tube gets expanded and elongated. This opposite connection of the muscles is

usually referred to as the antagonistic set-up. Figure 7 shows some examples of such antagonistic configuration. [2]

However, and most importantly, this set-up is analogical to the behavior of the muscles in the human body. Perhaps a good example would be the Biceps-Triceps pair. They both act in opposite manner delivering this rotational motion of the arm. When the Biceps is contracted, the Triceps is inflated and arm is lifted upward. This analogy is very helpful as our fluidic muscle designs are based on such antagonistic behavior. [2]

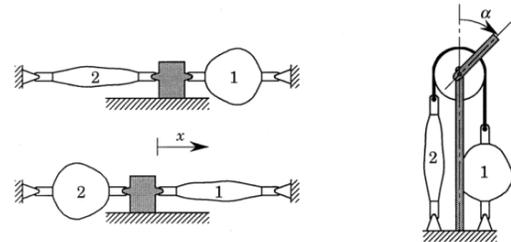


Figure 7: Antagonistic set-up.

VII. Procedure for Paper Submission

A. 12.2 Suit Components

The suit structure is very simple and exposes many parts of the human body. It consist of an forearm cover, biceps and triceps cover, back and shoulders cover, joints, sensor rings, pressure source and control chips. Each component is briefly explained as follow:

1) 12.2.1 Joints

The first joint in the suit is the one connecting the forearm and the biceps cover. The motion in this at this joint is limited due to the fixed angle the forearm can move. This joint will provide momentum and thrust while lifting of the load. Hence, minimizing friction at this joint is of great importance. The second joint is the one that represents the shoulder, connecting the biceps part with the upper shoulder one. Structure wise, the design does not include any physical connection between them due to the variety of the motion degrees at that joint (shoulder). Instead, the fluidic muscles extremes will be placed each part taking the shape of the human body muscles. For example, the three deltoids will be represented as three fluidic tubes starting from the upper shoulder bit till the biceps cover.

2) 12.2.2 Forearm cover structure

The forearm cover was designed in a way that enables size variability. The structure is composed of a thin plate covering the lower part of the forearm with belts on top that the user when wearing them can adjust. Pins connecting the fluidic muscles where attached at the top and bottom of the structure so they connect the tubes with the desired orientation

3) 12.2.3 Biceps and Triceps cover structure

The biceps and triceps structure is similar to the forearm cover. It is a partially open structure with belts in the open part that enables adjustability for the user.

4) 12.2.4 Back and Shoulders cover structure

The back design was made with high focus on minimizing weight. It is a simple structure that has bents on top which rest on the shoulders, and a bent lower part that surrounds and support the wrist of the user.

5) 12.2.5 Pressure source

The pressure source proposed is a scuba tank. A gas cylinder that can be placed at the back of the user in which delivers the required pressure to the fluidic muscles.

6) 12.2.6 Sensor rings

Controlling the fluidic muscles motion will be done using a sensor ring. The ring has four sensors placed similar to a compass structure (north, south, west and east). The user when raising his forearm will trigger a sensor and with that will make the structure move due to the contraction of the muscles. Two sensor rings are used, one at the forearm and one at the biceps.



Figure 8: Sensor ring

7) 12.2.7 Control chips

Some micro-controlling chips will be located at the back of the suit in order to control the motion of the fluidic muscles.



Figure 9: Control chips

VIII. 15.0 MECHANICAL POWER CALCULATION

Power (P) is referred to as work per time and work (W) can be derived from the area under the curve of a force (F) vs. displacement (x) trend. Hence, work per time is similar to saying force multiplied by distance per time. Power is then

can be derived as Force multiplied by velocity or the torque times the angular velocity [6].

Given below an equation of how a work can be found if an object that made a displacement equal to C under the effect of a force F.

$$W_C = \int_C \mathbf{F} \cdot d\mathbf{x}$$

And can simplify to the following equation in case the path is linear:

$$\int \mathbf{F} \cdot \mathbf{v} dt,$$

Knowing that the force is the negative gradient of the potential energy and applying that to the first equation we get:

$$W_C = U(B) - U(A)$$

Where A and B correspond to values of x along the path

The power is the time derivative of the third equation and is shown as following:

$$P(t) = \frac{dU(B)}{dt} - \frac{dU(A)}{dt}$$

In the fluidic muscle system the pressure correspond to power through the following formula thus the amount of pressure needed to apply certain can be calculated easily:

$$P(t) = pQ,$$

Where p is pressure in pascals, or N/m² and Q is volumetric flow rate in m³/s in SI units. [6]

IX. CALCULATION AND ANALYSIS

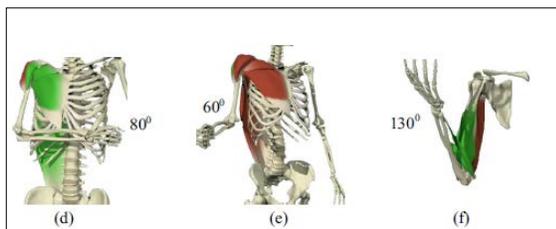
Below is the set of equations that the team will use to analyze and assist the robotic arm:

$$\begin{aligned} d' &= \sqrt{\sigma^2 + \sigma_y^2 - 2\sigma\sigma_y} \\ d' &< S_y \text{ - Safe} \\ N &= \frac{S_y}{d'} \approx 2,3 \\ \sigma_x &= \frac{F}{A} = \frac{PA}{2Lt} = \frac{PLD}{2Lt} = \frac{PD}{2t} \\ P &= \frac{d'}{t} \gg E = Pt \\ \text{Energy} &= \text{Pressure} \times \text{Volume} \\ \sigma_x &= \frac{F}{A} = \frac{P \pi D^2}{\pi \left(\frac{D+2t}{4} - \frac{D^2}{4} \right)} \\ P &= \sum FV \end{aligned}$$

$$\begin{aligned} \text{Power} &= \text{Force} \times \text{Velocity} = 500 \times 0,5 = 250 \text{ w} \\ \frac{N}{m^2} \times m^2 &= N \cdot m = J \\ P_{max} &= 4 \times 250 = 1 \text{ KW} \\ PV &= mRT = E \\ E &= P_r \times \text{Volume} = P_r V \end{aligned}$$

X. The muscle analogy to the human body

The shoulder joint anatomy is of major focus. The muscles that are involved in the abduction movement are the supraspinatus, deltoid muscle and teres minor. The supraspinatus muscle is a relatively small muscle of the upper back that runs from the supraspinatus to the scapula. It is one of the four rotating muscles which holds the humerus in place and keeps it from dislocating. It also performs the first 15 degrees of arm abduction. The deltoid muscle is the muscle forming the rounded contour of the shoulder. It is made up of three distinct set of fibers, the posterior, lateral and anterior. The deltoid is the primary abductor of the arm. It can abduct the arm up to 90 degrees from the torso. Lastly the Teres minor which is a narrow elongated muscle of the rotator cuff which aids the arm in adduction movement or in lowering the arm parallel to the torso.



XI. FINANCE

In order for our team to get all the equipment needed, several shops and stores were visited. Our team decided to build the actuators instead of buying them, this can help us to reduce the budget required. The team started searching for the equipment required in Mussafah and then Dubai. The main issue faced in all visited stores that they don't have the raw material required to build such actuators. So we decided not to build and start buying the required equipment from FESTO Company. Equipment prices were as follows:

Item	Designation	Type code	Qty
1	Fluidic Muscles	DMSP-20-400N-RM-CM	6
2	Proportional pressure regulator	VPPE-3-1-1	6
3	Plastic tubing 6 mm O.D	PUN	5 meter
4	Fittings for VPPE G1/8 - 6 mm	QS-1/8-6	12
5	Cable for VPPE 2.5 m	SIM-M12-5GD-2,5-PU	6
6	Silencer for VPPE G1/8	U-1/8	6
7	Fittings for Fluidic Muscles G3/8 - 6 mm	QS-3/8-6	6
8	T connection 6 mm	QST-6	5

XII. REFERENCES

- [1] H. Kazeroni, "Exoskeleton for human performance augmentation", *Springer Handbook of Robotics*, pp: 773-782
 [7] Z. Al Hassani. (September 5, 2012), *Dubai health survey to help cater for disabled* [Online]. Available:

<http://www.thenational.ae/news/uae-news/health/dubai-health-survey-to-help-cater-for-disabled>

[8] Wikipedia. (November 19, 2013), *List of countries by carbon dioxide per capita* [Online]. Available:

http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions_per_capita

[9] Wikipedia. (March 7, 2013), *List of countries by greenhouse gas emissions per capita* [Online]. Available:

http://en.wikipedia.org/wiki/List_of_countries_by_greenhouse_gas_emissions_per_capita

[2] F. Daerden, D. Lefeber, "Actuators for robotics and automation", *Pneumatic Artificial Muscles*, Vrije Universiteit Brussel, Department of Mechanical Engineering, Pleinlaan 2, B-1050, Brussels

[3] Images Scientific Instruments, *Air Muscle Actuators – Brio-Robotics* [Online]. Available:

<http://www.imagesco.com/catalog/airmuscle/AirMuscle.html>

[6] Wikipedia. (December 1, 2013), *Power (physics)* [Online]. Available: [http://en.wikipedia.org/wiki/Power_\(physics\)](http://en.wikipedia.org/wiki/Power_(physics))

XIII. APPENDIX



In pictures: UAE innovators display their wares at Abu Dhabi exhibition

Read more: <http://www.thenational.ae/uae/in-pictures-uae-innovators-display-their-wares-at-abu-dhabi-exhibition#ixzz2vXfqDiWX>

Follow us: [@TheNationalUAE on Twitter](https://twitter.com/TheNationalUAE) | [thenational.ae on Facebook](http://thenational.ae)

