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SPECIAL ISSUE

EXPERIMENTAL STUDY OF PNEUMATIC DRIVEN EXOSKELETON FOR REHABILITATION AND TRAINING

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ABSTRACT: This work investigates the pneumatic actuation of an upper limb exoskeleton intended for physical training and rehabilitation. In order to address specific requirements regarding transparency of movement, simplicity, natural safety and efficiency, in this study we examine the use of a pneumatic drive actuated with a combination of vacuum and pressurized air sources. To evaluate transparency, we measure the force of interaction between the patient and the exoskeleton in a passive mode. The experimentation of the interactions between the patient and exoskeleton is performed by harmonic movements created by the patient in a single shoulder joint with one degree of freedom system. The results of simulations and experiments are shown graphically. Finally, a conclusion and instructions for future works are made.

KEY WORDS: Rehabilitation exoskeleton, Pneumatic actuation, Vacuum pressure.

1 INTRODUCTION

Alternative to conventional manual phisical therapy of stroke patients aimed for improvement of motor function is the use of robotic exoskeletons for rehabilitation [1]. The rehabilitation exoskeleton must be able to create a high torque in order to independantly support, help and aim the movement of the upper limb of the patient in the early stages of recovery, it should also be able to freely follow and react to the movement the human arm without introducing resistance [2]. For this reason in the controll design of the rehabilitation exoskeletons there could be defined two ‘extreme’ ideal working modes, that cover the whole spectrum of theurepatic interventions: “robot in charge” and “patient in charge” [3]. In the “robot in charge” mode, it is important that the exoskeleton has high stregth and power in order to achieve the needed movement with relevantly high stiffness and impedance. In the “patient in charge” mode, it is important that the forces of interaction between the exoskeleton and human are low;

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in other words the impedance of the robot has to be low. The main characteristic here is transperancy.

In order to provide security and transperency with the interaction, there are two main methods for adjusting the mechanical impeance of the exoskeleton: active and passive. Electric motors and other active drive mechanisms are used for impedance controll of rehabilitational exoskeletons with an active approach. This controll method is based on the use of sensors and alorithums for driving the motor. The active controll of impedance successfully manages the interaction between the patient and exoskeleton in all modes of theurepatic intervention [4].

The passive method includes a natural and inherantly safety driving mechanisum. The pneumatic actuation has a natural compliance and allows for the realization of safety and transperancy in the process of rehabilitation in a passive way [5]. The pneumatic actuation also allows for a controll of impedance by an active aproach. There are different types of pneumatic actuation mechanisms. The most popular are the pneumatic cylinders and rotational vane drives. From one side they are charactertised with a big size, high weight and rigid construction, on the other side, when they are fixed on a stationary base, they provide multiple advantages of pneumatic drives.

Rotational pneumatic actuators have been developed, that transform the energy of pressurised air into rotational mechanical movement [6]. The use of pneumatic rotational mechanisums in theurepatic rehabilitation has gained popularity in the last decade, as different studies demonstrate their eficiency when used for helping patients with upper and lower limb disabilities [7, 8]. Studies show that they have a proven potential for providing controll and personalized help with mobility of patients recovering from injury of upper and lower limb or neurological disorders [9, 10]. These actuation mechanisms can be integrated into wearable devices or robotic systems to provide adjustable force, torque, and assist patient movement during therapy sessions [11]. Studies show that pneumatic actuation mechanisms can ease the functional recovery and motor learning with stroke patients, spinal cord injuries and neurological disorders [12, 13]. The eficiency of pneumatic actuators in rehabilitation aplications can be significantly increased by knowledge of the characteristics of the human body [14]. Created mathematical model of the human body, generated in a computer environment, can help mass-inertial parameters of all body segments to be calculated and to be used in control algorithums [15].

Pneumatic actuation mechanisms usualy work with higher than athmospheric pressures. Resently there were some soft pneumatic actuation mechanisms based on vacuum pressure [16]. Using the efect of mechanical deformation for generation of controlable force, there were succesfully developed soft robotic systems based on a vacuum actuated mechanisums [17]. Vacuum actuatuors have many advantages compared to high pressure actuators. For example this type of actuators can provide inherently safe work, since the output force is restricted by the magnitude of the atmospheric pressure [18], also this leads to a more reliable actuation mechanisums with longer service life and durability.

The authors of this study have developed an upper limb exoskeleton with soft pneumatic muscles. The exoskeleton is aimed towards education and rehabilitation, assisted by interactions inside virtual reality scenes [19]. Besides pneumatic muscles, there was and exoskeleton actuated by pneumatic cylinders. The pneumatic cylinders allow both the use of high and vacuum pressure. The efficiency of the pneumatic cylinder based exoskeleton was studied with different suppling pressures [20].

This study is a continuation of our previous works in a scenario, where the exoskeleton is actuated by a rotational pneumatic actuator, with a vacuum pressure and compared with different combination methods using higher than atmospheric pressures. The purpose of the work is on one side to evaluate the movement of the exoskeleton in regards to transparency and natural safety and efficiency on another side.

2 Materials and Methods

The main focus of the experiments is a prototype of a simplified exoskeleton, including an active rotational joint with a rotational pneumatic drive, fastened to the shoulder joint of the upper limb.

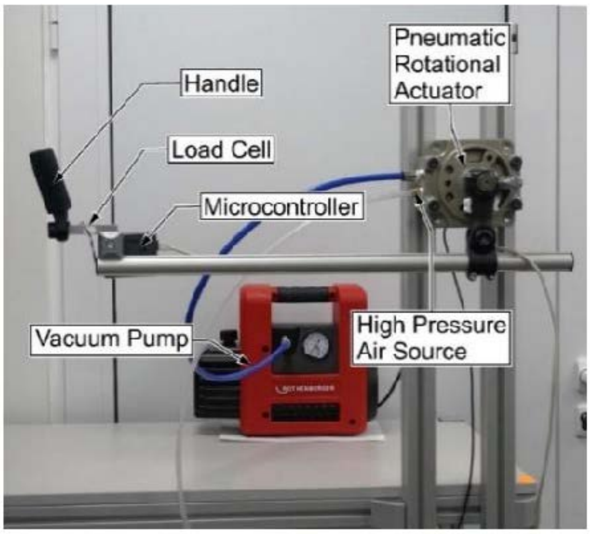


Fig. 1. Real prototype of one-handed exoskeleton with one degree of freedom.

It represents an adjustable and personalizable device for rehabilitation of the patient's upper limbs with capabilities for active or passive rehabilitation with possible single or multiple muscle groups stimulation and an interface communication between a microcontroller and computer applications

2.1 Mechanical system

Figure 2 shows a schematic of the rehabilitation device, that consists of a rotary actuator fixed to a stationary base and two adjustable levers (Lever 1 and Lever 2) coupled to the rotor of the actuator.

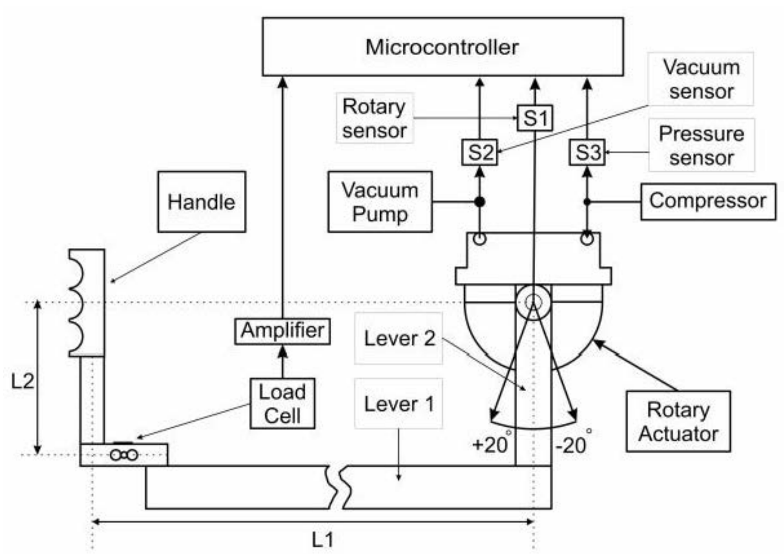


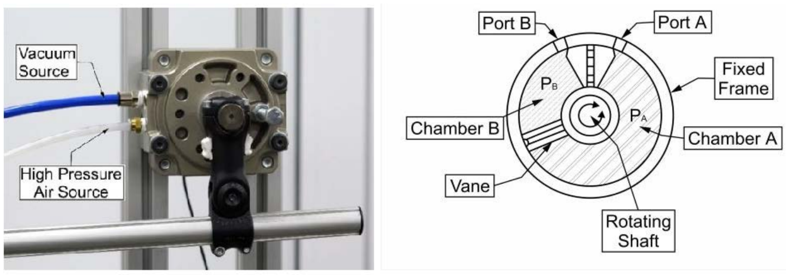
Fig. 2. Schematic of the different components in the exoskeleton.

Lever 1 and lever 2 have a specific length, shown in Fig. 2, which can be adjusted depending on the anthropomorphic parameters of the patient. Lever 1 is directly fastened to the rotor of the pneumatic drive, and Lever 2 is perpendicularly fastened to Lever 1. Depending on the length of the levers, the system can exert different forces at the operation handle (end effector), allowing for greater flexibility and adaptivity towards different muscle groups. There are included end stoppers comprised of mechanical limiter fasteners, that are inserted before the beginning of the experiment in order to limit the rotational movement, reassuring safety to the patient operator.

2.2 Control system and actuation

Control measurement System of the device includes the following components: Bourns AMS22B Analog magnetic Rotary encoder Sensor (S1); Pfeiffer Vacuum PKR 261; Vacuum sensor (S2); Honeywell 40 PC Series 100g pressure sensor (S3); STM32 microcontroller with a 12-bit ADC; Hx711 Amplifier for 10kg load cell; SMC CRB1BW100-180S rotary actuator; Magnus GA-81 Compressor with Aignep T020-MINI Air pressure Regulator; Aluminum extrusions and mechanical fasteners.

The rotary actuator SMC CRB1BW100-180S represents a cylindrical inner housing divided into two chambers A and B. A general view and scheme of the pneumatic rotary actuator is shown in Fig. 3 (a) and (b). The compressor and vacuum pump supply different air pressures to the two chambers by using direct or regulated airflow connected with air hoses and quick couplings. The control measurement system receives input data from the pressure and vacuum sensors (S2 and S3) connected to port A and port B of the pneumatic rotary actuator as well as from the rotational sensor (S1) coupled to the motor shaft. Additionally, at the end effector, there is a handle coupled with a load cell and digital signal amplifier measuring patient interaction force. These measurements are processed by the microcontroller, which features a 12-bit Analogue to digital converter (ADC) for high-resolution measurements. The pressure sensors (S2 and S3) and load cell monitor the air pressure and output forces within the system, providing real-time data to the microcontroller. This information allows for adjustments to maintain the desired force at the end effector for calibration.



(a) (b)

Fig. 3. Single vane pneumatic rotary actuator: (a) general view; (b) schematic of rotary pneumatic actuator.

The pneumatic actuator is controlled by supplying compressed air through port A and port B. In this way, the control is carried out in both directions of rotation. Depending on the applied pressure difference in the two chambers of the drive mechanism, a torque is generated, which is transmitted to the patient's arm through the Lever 1 and Lever 2 as an application of a corresponding force.

2.3 Exoskeleton-patient interaction force

The subject of the present work is to evaluate the interaction between the patient and the exoskeleton in the ”patient in charge” mode, where it is important that the interaction forces between the exoskeleton and the person are low. In this mode, the exoskeleton does not generate active forces, the resistive forces are determined only by the mechanical impedance of the exoskeleton. The resistance force applied to the operator's hand is determined by the inertial, frictional and gravitational forces, as well as the elastic forces of the pneumatic actuator.

The resistive force F_g applied perpendicular to the end of the operator's hand (Fig. 4) depends on the torque of the resistive forces in the exoskeleton joint Q_h according to the equation

$$F_h = Q_h/L1\,, \tag{1}$$

where $L1$ is the length of Lever 1 of the exoskeleton (Fig. 2) and the torque of the resistance forces Q_h represents the sum:

$$Q_h = Q_J + Q_{fr} + Q_g + Q_p\,. \tag{2}$$

Above: Q_J presents the torque created by the motor and the transmissions inertia as well as the exoskeleton inertia; Q_{fr} represents the friction torque which is mainly the result of the friction forces generated in pneumatic actuators; Q_g is the torque created by the exoskeleton gravity; Q_p is the torque produced by the pneumatic.

As stated the vane of a rotary pneumatic actuator divides its inner chamber into two separate chambers A and B. When pressurized air is introduced into the chambers, the vane rotates, thereby generating a torque represented by the sum

$$Q_p = Q_{pa} - Q_{pb}\,, \tag{3}$$

where Q_{pa} and Q_{pb} are the torques produced of chambers A and B, supplied with pressures p_a and p_b.

3 Experimental Results

In the present study we evaluate the force of interaction at the end effector of the exoskeleton, depending on higher or lower input pressures at the pneumatic actuator. The following cases are evaluated: first, when the chamber is opened to atmospheric pressure ($p_a = p_{\text{atm}}$) and the pressure p_b in chamber B is smaller than atmospheric (vacuum pressure); second when the pressure p_a in the chamber A is bigger than atmospheric and chamber B is opened to atmospheric pressure ($p_b = p_{\text{atm}}$); third, a combination of pressures, when the pressure p_a in the chamber A is bigger than atmospheric pressure and the pressure p_b in the chamber B is smaller than atmospheric (vacuum).

Experiments have been conducted to assess the force of the interaction in the recovery phase of patients when they are able to initiate complex independent movement in a relatively safe and transparent manner. This is the so-called "patient in charge" stage, where it is important that the forces of interaction between the exoskeleton and the patient are low.

To assess the forces of interaction, dynamic experiments were performed with harmonic movement in one joint of the exoskeleton. All joints are locked, and the arm is controllable, where flexion-extension in the shoulder is performed. The operator moves the exoskeleton arm as shown in Fig. 4.

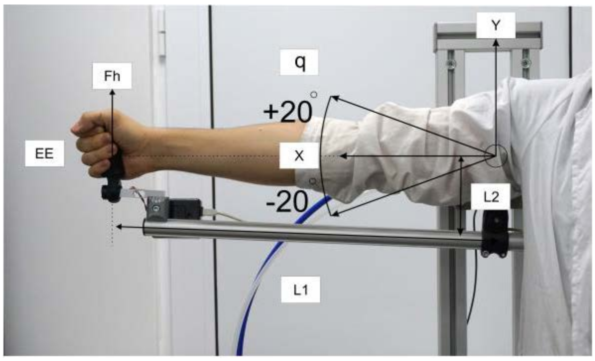


Fig. 4. Harmonic motion imposed by the operator on the exoskeleton shoulder joint.

On the end effector, there is a force sensor installed, where the operator applies a force F_h (on a distance of $L1 = 0.656$ m) evaluating the interaction. The angle q at the shoulder joint defines the rotational position of the arm, where it is assumed that the arm is horizontal when $q = 0$. The operator performs harmonic movements from the start position $q = 0$ with equal amplitude q_m and constant frequency of rotation.

3.1 Experiments by pneumatic drive with vacuum pressure

In order to evaluate the use of lower pressures for actuation of the exoskeleton arm a vacuum pump "Rothenberger rovacro air 3.0", was used to create 1 kPa. The arm is first held horizontally, without applying any external air pressure, measuring only forces corresponding to the weight of the aluminum lever. When a vacuum pressure of 1 kPa is applied to the first chamber of the rotational actuator, and atmospheric pressure of $p_{\text{atm}} = 101.325$ kPa is applied to the second chamber, an interaction force is observed at the end effector, shown in Fig. 5.

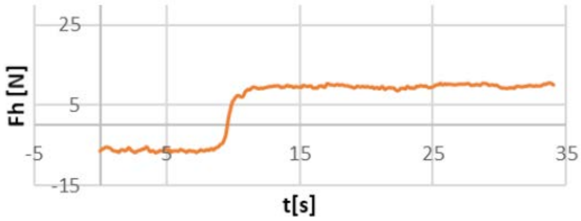


Fig. 5. End-effector interaction forces, before and after turning on the vacuum pump.

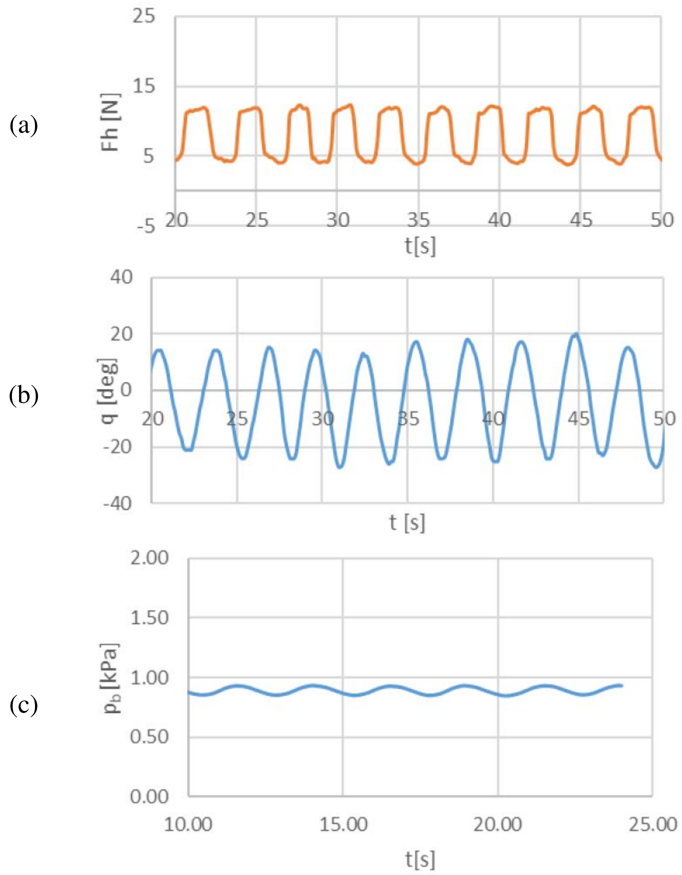


Fig. 6. (a) End-effector interaction forces at supply pressure $p_a = p_{\text{atm}}$; $p_b = 1$ kPa; (b) Measuring rotational changes at supply pressure $p_a = p_{\text{atm}}$ and $p_b = 1$ kPa; (c) Measuring pressure changes p_b in the vacuum chamber B at supply pressure $p_b = 1$ kPa and $p_a = p_{\text{atm}}$.

When the exoskeleton arm starts harmonious movements with amplitude $q_m = \pm 20^\circ$ from a horizontal position with vacuum pressure $p_b = 1$ kPa applied to the first chamber of the rotational actuator, and atmospheric pressure $p_a = 101$ kPa to the second chamber, the interaction force of the end effector varies as shown in Fig. 6(a) The rotational interaction takes place at $q_m = \pm 20^\circ$ around the horizon line with a constant frequency and amplitude. The measured angle is shown in Fig. 6(b) and the vacuum pressure p_b in chamber B is shown in Fig. 6(c).

The experiment show that the vacuum pressure does not affect the harmonic movements applied to the rotational actuator. The force of interaction changes by 8 N (from 4 N up to 12 N, the average force is 8 N). This change is not very big, and is mainly due to pneumatic resistance, friction, change in gravitational forces and others.

3.2 Experiments by pneumatic drive with a pressure greater than atmospheric pressure (positive pressure)

The next experiment was performed in order to compare the force interaction with the exoskeleton, actuated with higher pressure. In this experiment the exoskeleton arm is actuated with $p_a = 200$ kPa in pressure chamber A, and $p_b = p_{atm}$ in pressure chamber B. The arm is harmonically driven by the patient, with rotational interactions taking place at $q_m = \pm 20^\circ$ around the horizon line with a constant frequency and amplitude. The measurement of the force interaction at the End effector is shown in Fig. 7(a). In Fig. 7(b) is shown the measurement of the angle rotation, and in Fig. 7(c) is shown the change of air pressure p_a in chamber A.

In this case there is another additional pneumatic source of resistance that is combined with the others. The pressure in chamber A changes drastically as shown in Fig. 7(c). The force of interaction is mainly due to elastic forces in the pneumatic actuator chamber, where the compression of the air acts as a nonlinear spring, as seen in Fig. 7(a). The experiment shows that the force changes around 19 N (from 5 N to 24 N, average of 14.5 N), as the pressure in the chamber varies from 189 to 270 kPa.

If the force of interaction from this experiment is compared to the force of interaction in the experiment from chapter 3.1, the results show a big difference of fluctuations, when the average force is equal to 8.04 N powered with vacuum pressure and 14.5 N when powered with higher pressure.

An experiment is made where the higher pressure in chamber A, was carefully reduced to $p_a = 190$ kPa, in which the average force value of 7.7 N is close to that generated by vacuum pressure, (8.04 N) as shown in Fig. 8. The results show a clear difference in fluctuation amplitude, where the higher pressure system shows larger compression spikes compared to the vacuum powered system.

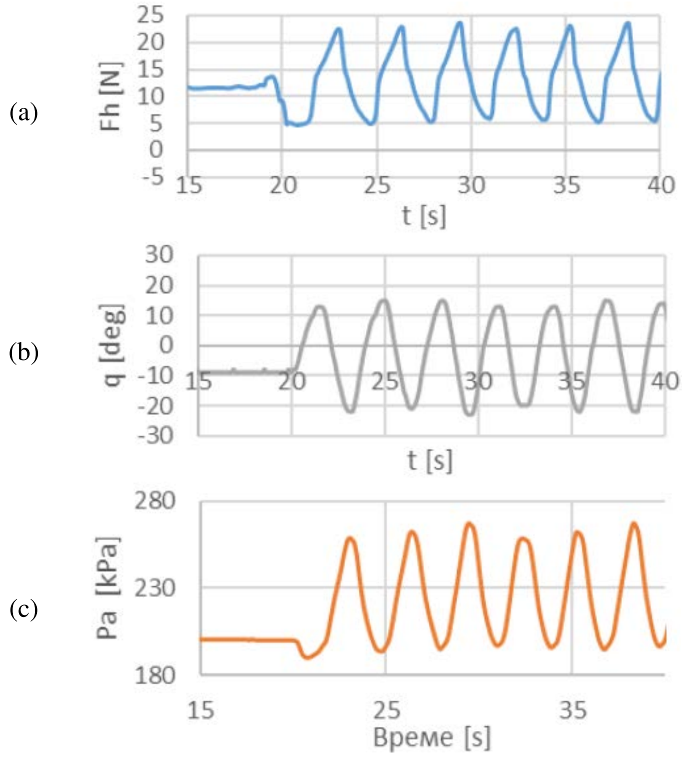


Fig. 7. (a) End-effector interaction forces at supply pressure $p_a = 200$ kPa; $p_b = p_{\text{atm}}$; (b) End-effector rotation at supply pressure $p_a = 200$ kPa; $p_b = p_{\text{atm}}$; (c) Measuring pressure changes p_a in the chamber **a** at supply pressure $p_a = 200$ kPa and $p_b = p_{\text{atm}}$.

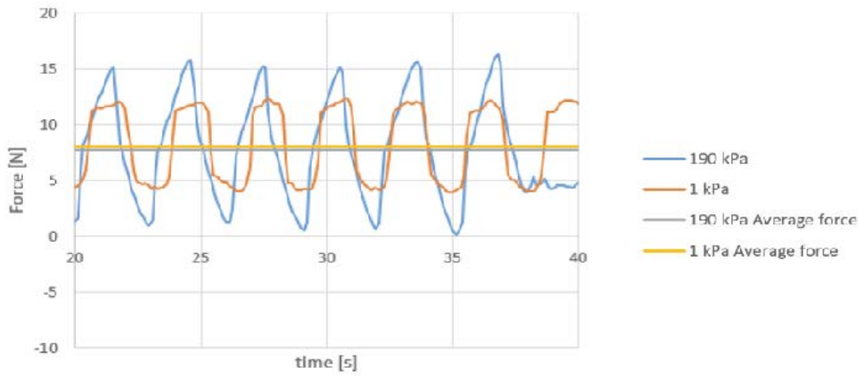


Fig. 8. Comparison of interaction forces of the exoskeleton arm driven by vacuum pressure or by high pressure, with similar average values.

3.3 EXPERIMENTS BY PNEUMATIC DRIVE WITH COMBINED PRESSURE

In order to increase the average force of the exoskeleton arm, without major decrease in transparency, the elastic compression resistance has to be minimized. For this to be achieved, a combination of vacuum and high pneumatic pressures actuation is proposed.

In this experiment the exoskeleton arm is actuated with $p_a = 150$ kPa in pressure chamber A, and $p_b = 1$ kPa (vacuum pressure) in pressure chamber B. The arm is harmonically driven by the patient, with rotational interactions taking place at $q_0 = \pm 20^\circ$ around the horizon line with a constant frequency and amplitude. The changing force of interaction at the End effector can be seen in Fig. 9(a). In Fig. 9(b) is shown the change of rotational angle, and in Fig. 9(c) is shown the change in pressure p_a in chamber A.

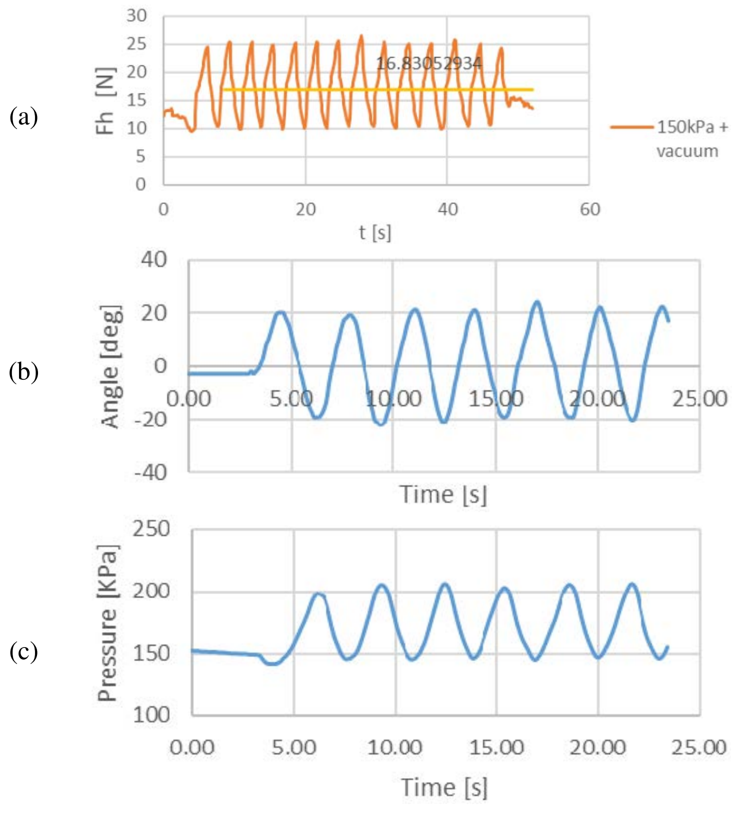


Fig. 9. (a) End-effector interaction forces at supply pressure $p_b = 1$ kPa; $p_a = 150$ kPa; (b) Measuring rotational changes at supply pressure $p_b = 1$ kPa and $p_a = 150$ kPa; (c) Measuring pressure changes p_a in the chamber A at supply pressure, $p_a = 150$ kPa.

When supplying a combination of air pressures in the rotary pneumatic actuator, the experiment, shows that the force of interaction has changed to around 15 N (from 10 N to 25 N averaged at 16.8 N), as the pressure in the chamber varies from 140 to 204 kPa.

The next experiment is performed in order to evaluate the influence of the pressure increase in chamber A with a combination of vacuum pressure in chamber B. In this experiment the exoskeleton arm is actuated with $p_b = 1$ kPa (vacuum pressure) in pressure chamber B, and a varying pressure of $p_a = p_{\text{atm}}$ to 250 kPa in chamber A. The pressure is slowly being increased with a pressure regulator while performing continuous harmonic rotations of $q_0 = \pm 20°$ around the horizon line. The change in interaction force and pressure can be seen in Figs. 10(a) and 10(b).

From these graphs, it can be clearly seen that with identical rotational deviations, the increase of pressure in chamber **a**, creates an increase in the amplitude of the interaction force and compression force.

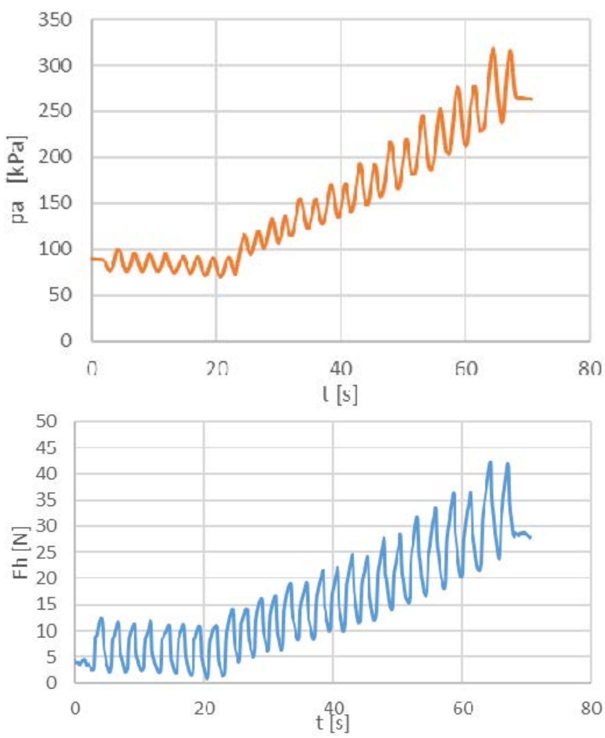


Fig. 10. (a) Measuring pressure in chamber A slowly being increased with a pressure regulator; (b) Measuring changes in the interaction forces when the pressure increase in chamber A with a combination of vacuum pressure in chamber B.

The next experiment was performed in order to compare the deviations between the forces of interaction of two systems with equal average forces, but powered with high pressure and combination between vacuum and high pressure. The actuator chamber A is supplied with $p_a = 238$ kPa and chamber B is opened to atmospheric pressure $p_b = p_{\text{atm}}$. The arm is harmonically driven by the patient, with rotational interactions taking place at $q_0 = \pm 20^\circ$ around the horizon line with a constant frequency and amplitude, the force of interaction is shown in Fig. 11. Additionally, in Fig. 11 is also shown a second system, where chamber A is powered by $p_a = 150$ kPa, and chamber B is powered by $p_b = 1$ kPa (vacuum pressure).

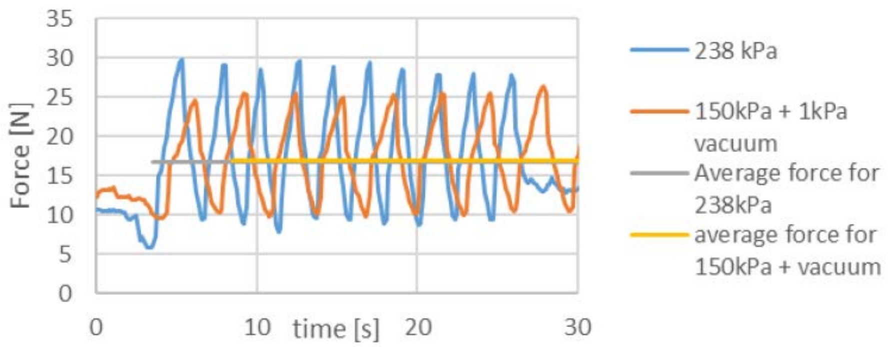


Fig. 11. Comparison of interaction forces of the exoskeleton arm driven by high pressure $p_a = 238$ kPa, $p_b = p_{\text{atm}}$ or by combination of high pressure, with vacuum pressure ($p_a = 150$ kPa; $p_b = 1$ kPa).

From the results shown in Fig. 11, a difference in deflections is clearly visible, demonstrating greater forces when feeding only with higher pneumatic pressure. The average force of the first system where $p_a = 238$ kPa is 16.7 N and 16.8 N when $p_a = 150$ kPa and $p_b = 1$ kPa. Although the average force of interaction is the same, the amplitude of unwanted deviations in the first system is greater than the second.

For comparison of the interaction force change for the three cases of experiments the results are summarized in Fig. 12. There are cases of vacuum pressure power ($p_a = p_{\text{atm}}$, $p_b = 1$ kPa), high pressure power ($p_a = 200$ kPa and $p_b = p_{\text{atm}}$) and combined activated pressure ($p_a = 150$ kPa, $p_b = 1$ kPa). The average force of the vacuum pressure is smallest and not enough to freely lift the upper limb, however it also has smallest deviations in amplitude. The average forces of the high pressure and combined pressures is similar and big enough to move the upper limb, however the combined pressures show a better smaller deviation in the amplitude.

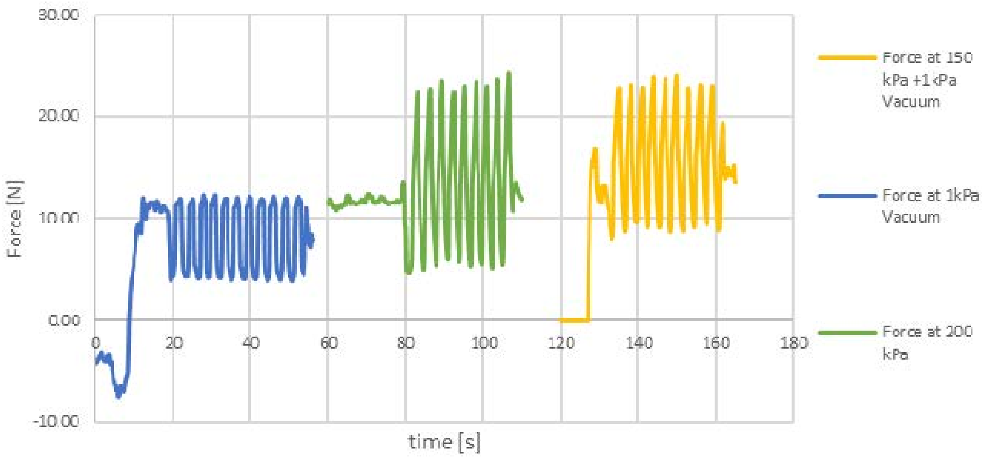


Fig. 12. Comparison of interaction forces of exoskeleton actuated with vacuum, high pressure and combination of both.

4 Discussion

In the work, experiments were carried out through a harmonious movement imposed by the patient in one joint of the exoskeleton. The interaction force in the end effector has been evaluated for cases of pneumatic actuator with pressure lower than atmospheric pressure (vacuum pressure), actuator with pressure higher than atmospheric pressure (positive pressure) and with combined pressure in both chambers of the actuator.

When the pneumatic actuator uses vacuum pressure, the force of interaction is with small deviations from the equilibrium position. These changes are the result of a number of other factors outside of pneumatics, such as inertial forces, friction in the joints, change in gravitational force, etc. The disadvantage of this approach is the limitation of the maximum value of the drive force determined by atmospheric pressure.

When the pneumatic actuator uses positive pressure, the compressed gas creates an elastic resistance force that is greater at higher pressures. The resulting deviations from the equilibrium position result in higher values of the interaction force, mainly due to the increased pressure and increased stiffness of the compressed gas. The advantage here is the theoretically unlimited magnitude of the driving force.

Positive pressure leads to intolerance to the patient, but to greater efficiency in performing power operations guided by the exoskeleton. The vacuum pressure drive reduces the stiffness of the gas and results in high transparency and patient safety. However, low stiffness is associated with low efficiency when performing exoskeleton-led operations.

The combined supply of the pneumatic actuator with vacuum pressure in one chamber and positive pressure in the other combines the requirements of transparency and safety on the one hand with the requirements of efficiency. Thus, with the appropriate choice of pressure sizes in both chambers, both the desired size of the driving force and the limited value of the force deviations can be achieved. The impact of supply pressure on the performance and safety of the pneumatic exoskeleton is summarized in Table 1.

Table 1. Influence of input pressure on the performance and safety of a pneumatic exoskeleton

Input pressures	Positives	Negatives
Vacuum pressure	Low interaction forces highest transparency	Smaller output forces Lower efficiency
Positive pressure	Higher output forces Theoretically unlimited increase of force Higher efficiency	Increasing the pressure increases the compression forces acting like a nonlinear spring, reducing transparency
Combined pressures	Sufficient output forces With good transparency	More complex system requiring a compressor and vacuum pump

5 Conclusion

In this work, an upper limb exoskeleton for rehabilitation and training has been examined. In the work, a suitable solution for the exoskeleton was sought, which provides productivity on the one hand and transparency and natural safety on the other. A rotary pneumatic actuator is used in the work, for which the drive under vacuum with the positive pressure drive is evaluated.

To evaluate transparency, the interaction force between the patient and the exoskeleton in passive mode is investigated, since this force represents the initial response of the exoskeleton, which can then be changed by active mode. The force of interaction is evaluated in cases of pneumatic actuation with pressure higher than atmospheric pressure, vacuum pressure actuation and combined pressure actuation.

The subject of the authors' future work is the development and experimentation of a rotary pneumatic actuator with a lightweight design, which allows combined drive by feeding one chamber of the rotary pneumatic actuator with vacuum pressure and supplying the other chamber with positive pressure.

The results of this work can be used for design of rehabilitation devices that are directed towards treatment and assisted therapy of patients with reduced muscle activity.

ACKNOWLEDGEMENTS

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