PAM Actuators Applications in Robotics: Rapid Review

Dragana Oros, Marko Penčić, Maja Čavić, Marko Orošnjak, Dijana Čavić and Zhenli Lu

***Abstract*—The paper presents a review of Pneumatic Artificial Muscle (PAM) actuators with a focus on the muscle type, control and application. The rapid review covered journal articles, conference papers and book chapters from the SCOPUS database, and according to the PRISMA protocol. Careful forming of research questions, the initial search and further data analysis led to the selection of 21 papers. The most common use of PAM actuators is in humanoid and rehabilitation robots – the PAMs are usually either prototypes or are based on McKibben air muscles, and are usually controlled by way of proportional valves and microcontrollers.**

***Index Terms*— Pneumatic artificial muscles; PAM actuators; robotics; applications; design; control; rapid review.**

I. INTRODUCTION

Human recovery after serious physical injuries is often a long, difficult, painful and monotone process which requires complete commitment not only from the patient but from the physical therapist as well, for the therapy to be fully adequate, continuous and total. The patient's condition is rarely monitored through scientific means (ex. by using measuring instruments and devices that record the motions of the patient for comparison and range of motion analysis, as well as the number of repetitions during following sessions), and the patient's progress is assessed and estimated by the physical therapist. Hours-long sessions with patients with different issues can lead to fatigue and a decline in concentration of the physical therapist, which can in turn negatively affect the outcome of the therapy. A key issue is finding a way to motivate the patients to repeat their exercises as many times and as often as possible, since the success of their recovery is directly proportional to the time they spend doing the therapy exercises.

Today the use of assistive robots to support physical therapy is becoming more and more frequent. Usually, these are robotic devices that aid patients with movement actuation, or social-assistive robots that demonstrate exercises that the patient should then repeat as many times as possible. Aside from their primary function, these robots also have a motivational role, since they make physical therapy more interesting, especially for younger patients. Accordingly, these robots must be completely safe for humans, as well as their surroundings. It should be noted that high positioning accuracy and motion repeatability of the robot is not of particular importance in the realm of physical therapy, which allows the selection of different types of actuators, such as classic pneumatic and hydraulic actuators.

Within the previous few years, the development of Pneumatic Artificial Muscles which are light, flexible, made from cheap materials, and can achieve a high power-to-weight ratio have captured the attention of many researchers. By activating the PAM actuator, the PAM converts the applied force by way of air pressure into physical motion. The manufacturing of these muscles is not particularly complicated, and the use of soft materials makes them attractive to humans – essentially, PAM actuators are made to mimic the look and function of human muscles. This makes the development and design of PAM prototypes and their control systems an attractive endeavor. To ensure a proper feedback loop between the input and output, it is necessary to gather information about the position of the actuator, the force it generates, the changes in the air pressure in the lines and actuator, the bend in the pneumatic muscle etc., which implies the need for a number of different sensors.

Figure 1 shows the control system of a single pneumatic muscle. The type of the PAM (pleated, braided, netted) depends on the application, while the control system is usually the same for all PAM types, and consists of: (i) a source of pressurized air, (ii) a proportional control valve, (iii) a pneumatic muscle, (iv) a sensor, (v) a controller, (vi) a power source, (vii) pneumatic lines and (viii) control cables. The pressurized air is lead to port 1 of the normally closed control valve which prohibits the air from reaching the PAM. The proportional valve is controlled by way of pulse-width modu-

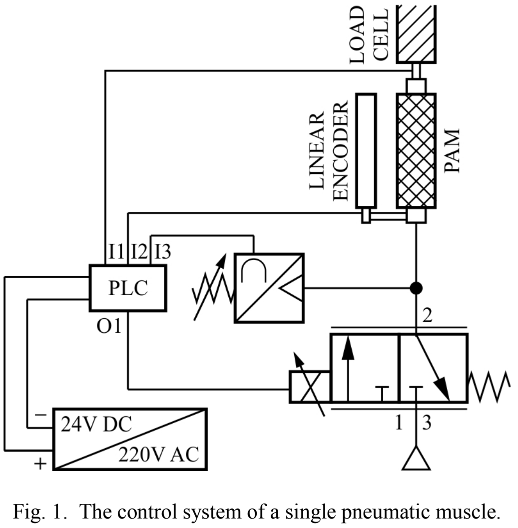

Fig. 1. The control system of a single pneumatic muscle.

Dragana Oros, Marko Penčić, Maja Čavić, Marko Orošnjak and Dijana Čavić are with the Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia (e-mail: {spawn, mpencic, scomaja, orosnjak, dijana.cavic}@uns.ac.rs).

Zhenli Lu is with the School of Electrical Engineering and Automation, Changshu Institute of Technology, Hushan Road 99, 215500 Changshu, China (e-mail: zhenlilu@cslg.edu.cn)

lation (PWM) with a controller, and when activated, shifts the valve into an open position, allowing airflow to the PAM. This is how the pressure inside the actuator is regulated, and with it the force of the actuator as well. The controller receives information from the pressure sensor that measures the pressure in the line leading to the actuator, from the force sensor placed on the PAM and from the linear encoder that measures the position of the actuator. These measurements are then compared to their desired values and if there is deviation, a correction single is sent to the proportional valve.

The main goal of this paper is to determine the application, design and control of PAM actuators. The paper is structured as follows: the first section explains the motivation and goal of the research study; the second concerns the research strategy and its limitations; the third section explains why the chosen papers were selected and the results of the study are detailed in the fourth section; the final section covers the conclusion and possible directions for future research.

II. SEARCH STRATEGY

This study represents a systematic review of the available literature done using the Rapid Review (RR) method. This method allows the extraction and processing of search results in a way that enables both transparency and repeatability of the study. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was used as a methodology for conducting the RR. Accordingly, the following Research Questions (RQ) are formed:

RQ1: What are the applications of PAM actuators in the field of robotics?

RQ2: Which types of muscles, controls and sensors are most often used?

According to the posited RQs, the following search syntax is established:

(("Pneumatic Artificial Muscle" OR "PAM") AND ("Humanoid robot" OR "Social robot" OR "Assistive robot" OR "Service robot") AND ("Application" OR "Design" OR "Development")).

The search strategy consists of the following criteria. Since the SCOPUS database is the largest depository of „peer review" papers, it was selected to be searched using the designated strings. The search results were then filtered further using I/E (Inclusion/Exclusion) criteria. The inclusive criteria were: (i) the paper was published in the 2013-2023 period, (ii) the paper is in English, (iii) the paper was published in a journal, at a conference or as a section in a book (editor materials, short notes etc. were excluded). The exclusive criteria were: (i) the paper is unavailable for download, (ii) the paper does not cover the research questions or is just a software simulation of an existing system, and (iii) all papers have been reviewed in detail.

III. RAPID LITERATURE REVIEW

After conducting the analysis, it became evident that the reviewed papers can be categorized into two main groups: (i) PAM robots – most often these are assistive devices used as support in the rehabilitation of patients with gross motor skill issues, and (ii) PAM systems – design and control.

A. PAM Robots

The assistive robot BK-Gait with a total of 2 DOFs is shown in [1]. The robot has two pairs of artificial muscles located in the hip and knee area which are powered by four PAM actuators. The PAM actuators are controlled by regulating the air pressure via a proportional control valve. Sensors that detect the rotation angle of the joints and load cell sensors that determine pulling force of each muscle were used. To follow the robot's motion trajectory, the authors developed active disturbance rejection control (ADRC), and the control algorithm was coded using LabVIEW software. Experiment results show that the robot has potential for use in rehabilitation, but would first require a correction of the referent signal frequency, which is currently lower than the average human walking speed.

A flexible muscular-skeletal robotic neck, based on the biological principles found in the neck of giraffes, is shown in [2]. It consists of a skull and cervical vertebrae made using 3D printing technology. Between each two adjacent vertebrae is a viscoelastic disc, and along the neck are rubber ribbons that mimic the nuchal ligament. The neck moves by way of thin and flexible McKibben pneumatic muscles. Due to this, this neck can generate high forces, torques and speeds, can achieve a wide variety of movements, can absorb energy and adapt it's shape quite well. The authors tested the cooperation of the muscles with the goal of increasing the mechanical work of the robot, it's range of motion, the compensation of the force that gravity generates on the nuchal ligament and the adaptability of the poliarticulated muscle shape.

The development and realization of the Soft Robotic Hip Exosuit (SR-HExo) is shown in [3]. This robotic suit enables flexion and extension of the hip while walking, meant to be used during the rehabilitation of patients after an injury, hip surgery or spinal injury. SR-HExo consists of flat fabric pneumatic artificial muscles (ff-PAMs), oriented in the form of an "X", which contract due to changes in pressure. The digital control signal that activates the electromagnetic valve is sent by an Arduino UNO microcontroller by way of a MOSFET Driver Module. Two pressure sensors are used – one to measure the pressure after the compressor before the control valves, and one to measure the pressure in the line leading to the exosuit. The authors used a motion capture system and a surface electromyography sensor to follow the hip's range of motion and muscle activity when walking.

The design of an anthropomorphic robotic hand with a total of 22 DOFs is shown in [4]. It first states the primary requirements: (i) the kinematic model of the robotic hand must mimic its human counterpart as closely as possible, (ii) each DOF must be articulated independently for easier control, and (ii) the realization and assembly must be as simple as possible. According to these requirements, each DOF is achieved by a pair of antagonistic PAMs, with Bowden cables being used as tendons. The advantage of these muscles and cables is their simple implementation, small space requirements and small mass. To control the pressure force of the hand parts, the authors used air bladder based pneumatic tactile sensors within the skin of the palm and fingertips, as well as additional sensors on the actuators.

A biologically inspired ankle-based soft active orthotic device meant to aid in dorsal flexion of the angle during walking is shown in [5]. The use of silicone-based PAM actuators supplies the angular assistant force to the ankle. This device has an integrated pneumatic and control system. The pneumatic system consists of a compressor, an airflow regulator and a proportional control valve meant to regulate the pressurized air coming to the command valve which controls the four PAMs, two for each leg. The control system consists of two mutually independent control units based on the use of Arduino-Uno R3 controllers. The first unit generates the PWM signal that controls the proportional valve, while the second receives the signals sent by the angle sensor, and based on that data, activates the command valves of the four PAMs. Experiment results have shown that this device can be used for walking stability and support of older people or people with muscle weakness.

The bionic design of a human-arm-like manipulator with 7 DOFs is shown in [6]. Each DOF is achieved with a pair of antagonistic PAMs which are mutually independent. To simplify the control and realization of the human-like motion, Bowden cables were used to actuate the PAMs, which are both flexible and reliable. The kinematic structure of the robot hand was configured according to a model of the human hand found in the KIT motion capture database.

The determination of the placement of PAM actuators for a Biomimetic Humanoid robot is shown in [7]. The model of the robot Gait 2392, adopted from the OpenSim software database for the purpose of this experiment, has a total of 23 DOFs. The robot is equipped with FESTO PAMs with diameters equaling 10, 20 and 40 mm, with the maximum theoretical force being directly proportional to the PAM diameters. The chosen PAM diameters match or exceed the maximum isometric force exhibited by human muscles, and the chosen lengths mimic the length of human muscles in each position. Using simulation software, the authors analyzed the length of the PAMs, the arm torque and isometric force of the PAMs for different joint configurations, according to the muscle placements. According to this data, the joint torques for each muscle on the model were determined.

An analysis of external constraints faced by a musculoskeletal humanoid robot with PAMs when conducting everyday human activities is shown in [8]. The experiment consisted of the robot being tasked with moving a lever handle to rotate it around a vertical axis in three positions to achieve a circular trajectory. The realization of this task implies that a complex system containing PAM actuators can have a simple control outline due to the physical constrains of the handle. Experiment results showed that the robot could indeed complete a full circular trajectory with only 3 positions of the handle, with the hand of the robot being fixed to the handle in the initial position to prevent loss of grip. The observed problems are related to the large tolerance in the individual movements for the periodic turning of the handle with the complicated optimization of the movements. The optimization issue worsens further with the exclusion of external constraints that are used to decrease the complexity of the dynamic system.

The development of a biologically inspired 7 DOFs robotic hand with rigid and soft robotic elements is shown in [9]. The shoulder, elbow and wrist each have 2 DOFs, while the gripper has 1 DOF, with all of the joints being actuated by McKibben PAM actuators. However, the authors modified the McKibben PAM with a mesh pipe enhanced with glass fibers with a layer of stretchy silicone adhered to the inside surface of the pipe. A three-position on/off and proportional valve is used to control the PAMs, while changes in the angular position of the joints was detected using a potentiometer. A PWM signal from an Arduino microcontroller was used to control the valve, while a microcontroller communicates with a PC by way of USB.

The application of multifilament PAMs in the motion of a head mounted on an artificial neck is shown in [10]. In the cervical spine region, the PAMs are organized into four groups. The first group enables head rotation, the second and third enable flexion and extension, respectably, and the fourth group of PAMs enables later flexion of the head. Experiment results show that this artificial neck configuration generates motion similar to that of a real human head, by activating different muscle groups. Each group of PAMs activates individually, with the pressure on each PAM changing within the range from 0 to 3 bar, thus allowing the PAMs to work together. The application of the same air pressure value on the PAM actuators of each muscle group allows this configuration to function without oscillations.

The development of a robot with a single leg and integrated distributive force sensors in the foot is shown in [11]. To supply the leg with motion, 2 PAMs integrated within the robot's thigh were used to generate an antagonistic force that further generates torque in the hip joint. Aside from the actuators, the control system contains a proportional control valve for flow regulation that receives signals from development board NI myRIO. Two encoders were placed on the hip and knee to detect changes in their angular positions, which enables a feedback loop. Force sensing linear potentiometer (FSLP) sensors built into the foot detect external signals. The robot recognizes characteristics of the surface it is on and adjusts its stance and stability accordingly.

The control of a PAM-actuated robotic hand based on a Reinforcement Learning (RL) algorithm is shown in [12]. Shadow Dexterous Hand is an advanced robotic hand that consists of a passive forearm along and around which PAMs are placed, and a hand with a kinematic structure that enables human-like movement. The experiment focused on the control of a single finger with 4 DOFs. A pressure sensor is placed upon the fingertip. To actuate the n DOFs of the finger, the authors used McKibben PAM actuators which are especially suited for human interaction safety-wise, due to their flexibility. The PAM actuators are controlled by a discreet control valve.

The design and control of a PAM-actuated musculoskeletal two-legged robot is shown in [13]. The robot lacks an upper-body and consists of two identical legs that have 3 DOFs each. The muscles of the robot are actuated by 18 McKibben PAMs controlled by small, fast 5/3 on/off electromagnetic valves. A microcontroller controls the valves and receives information from the angle sensor. The authors created a control scheme in accordance with the robot model and verified it with experiments. The results imply that the robot moves slowly due to the small diameter of the pneumatic lines, and the low flow of the control valve. Further, the motion of the robot is limited by the length of the line running from the compressor to the robot.

A biologically inspired robotic hand with five fingers and 17 DOFs is shown in [14]. The hand is actuated by McKibben PAM actuators that activate at a low pressure (2 bar). The authors developed a controller called Yuragi to manipulate the middle finger of the hand. This finger has 3 DOFs and 4 PAM actuators. The Yuragi controller can be used for different tasks, such as grasping and pinching, or other, more complex tasks. The experiment is based on the communication between the computer and the controller which sends signals to the pressure regulators, which then further direct the airflow through the control valves to the PAMs. During all this, a camera follows the position of the fingertip and sends the signal to the Yuragi controller.

B. PAM Systems: Design and Control

A prototype of a multi-connection PAM (MPAM) actuator is shown in [15]. Six narrow muscle fibers similar to McKibben PAMs are organized in two rows and three columns. This placement results in a larger contact surface of the fixed end and a smaller total volume, which increases the flexibility of the muscles. To achieve MPAM, the muscle fibers are formed in a type 3 and 5 Y configuration. The muscle fibers are directly activated by a proportional pressure valve controlled by a microcontroller. A displacement sensor for monitoring muscle movements, a tension sensor for monitoring the muscle strain and a pressure sensor were used. The signals from the sensors are forwarded to the microcontroller to establish a feedback loop. The MPAM system has potential applications in the development of wearable power assist suits.

A one-dimensional two-way pneumatic flexible bending joint is shown in [16]. To make the robot arm safer to use – one way to do this is to increase the flexibility of the structure, the authors suggested a one-dimensional two-way joint based on PAM technology. The system consists of a compressor, service unit, a proportional pressure valve, a directional solenoid valve, a PAM actuator, a gyroscope, a programmable logic controller (PLC), a 3D capture system and a control computer. This kind of pneumatic muscle was the base of the design and realization of a one-dimensional two-way flexible bending joint. This joint is both flexible and compact.

Sliding mode control based on a nonlinear disturbance observer (SMCBNDO) for better PAM performance monitoring is shown in [17]. For the needs of this experiment, the authors developed a three-part PAM actuator – McKibben type, controlled by a proportional regulation valve. To detect the actuator position, a laser sensor was used, while the load was measured with a load cell. NI cDAK-9178 controller supplies the output signals and controls the proportional valve, but also receives input signals from the sensors. The suggested model provides an insight into the dynamics of the PAM and has the ability to predict muscle motions. This model and method have potential applications in rehabilitation systems with PAM actuation.

Inverse modeling of nonlinear artificial muscle using polynomial parameterization and particle swarm optimization is shown in [18]. This modeling approach was suggested to compensate the nonlinearity that appears during PAM actuation. The system consists of a PAM, a laser motion sensor, a pressure sensor, a load measuring sensor, an accelerometer, weights, a digital regulator, an air compressor, and a controller for data collection and analysis. Based on the model parameters and systemic identification of the activation pressure, an experiment was conducted on the vertical load system with single a PAM. This PAM is a prototype based on a McKibben muscle which consists of a rubber pipe, a twisted mesh and a copper ring. Inverse PAM modeling is useful in the development of control systems in the fields of rehabilitation and humanoid robotics.

Human-mimetic soft robot joint for shock absorption through joint dislocation is shown in [19]. In accordance with the structure of the human elbow, a 1 DOF manipulator was developed. To assess joint dislocation, an experiment was conducted with dynamic and quasistatic impact on the 1 DOF joint. Also, the authors suggested a 2 DOFs human-mimetic soft robot which is able to realize four basic motions of the human arm by using PAM actuators that allow dislocation. It should be noted that the PAMs were developed based on the McKibben muscle type. A LabVIEW controller controls the PAM actuator by way of four proportional pressure valves, while a load cell was used to measure the PAM reaction force.

Printable PAMs for anatomy-based humanoid robots are shown in [20]. By applying 3D printing technology, the authors made a number of PAMs with different morphologies, lengths, widths and angles. Experiment results showed that the 3D PAM can mimic the characteristics of the human pennate muscle. Contraction elements and tendons can also be printed. Unlike classic PAMs, however, these muscles can only work with low pressure, which limits their application. According to the anatomy of the human hand, a prototype of a musculoskeletal hand with 3D printed PAM actuation is suggested.

An empirical model of the dynamic behavior of a PAM actuator is shown in [21]. The suggested model simulates the dynamics of a PAM actuator with the goal of increasing application efficiency and control realization. A linear variable differential transformer was used to measure the muscle position, while the force was measured with a load cell. Flow and pressure sensors were placed between the valve unit and the PAM. Data from the sensors was sent to a computer by was of a data acquisition card. The experiment was based on a valve unit with two parallel 2/2 electro controlled monostable valves, a flow valve and a PAM actuator. To move the PAM into different positions and with varying force, a hydraulic cylinder controlled by a 4/3 valve was used, with the piston being directly connected to the PAM.

IV. RESULTS AND DISCUSSION

Figure 2 shows the analyzed papers published in journals, conference proceedings and book chapters in the previous 10 years. Both journal articles and conference papers have a high and equal number of representatives – a total of 18 papers, with most of them published within the last 6 years, with book chapters offering only 3.

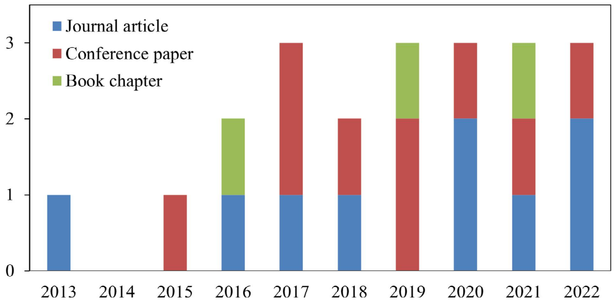

Fig. 2. The number of analyzed papers published in journals, conference proceedings and book chapters according to the year of publication.

Table I summarizes the results of the search and shows the PAM types, control systems, sensors and applications of PAM actuators. According to the results, most authors developed PAMs to solve specific problems, which led to different muscle configurations, as well as the use of different materials such as rubber with silicone on the inside surface and metal mesh elements on the outside. On the other hand, a smaller number of authors used McKibben and FESTO commercially available muscles. To control the PAMs, most authors used proportional and/or directional valves combined with microcontrollers. Some authors used LabVIEW software to create a simulation instead of a physical experiment. As for the sensors, the following was shown: for angle detection, angle sensors placed in the robot joints or gyroscopes were used; for displacement measurement, linear potentiometers, encoders, motion capture cameras and laser sensors were used; to measure force magnitude, load cells and tactile sensors were used; to measure pressure and pressurized air flow both analog and digital sensors were used.

Figure 3 shows the applications of PAM actuators and their development. At first, they were used for humanoid robot segment actuation – such as an arm or a leg, or they were developed as prototypes without a specific application in mind (N/A). However, within the last few years, PAM actuators are being used more often in the fields of rehabilitation and humanoid robotics equally, with some application in the development of power assist suits.

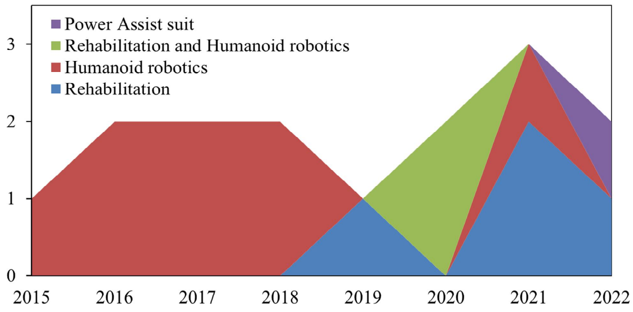

Fig. 3. The application of PAMs by field.

TABLE I
Review of Selected Papers: PAMs Types, Control, Sensors and Application

Paper	PAMs	Control	Sensors	Application
Trinh, *et al.* [1]	Prototype	Proportional valve, ADRC controller, PC	Load cell, Angle	Rehabilitation
Niikura, *et al.* [2]		N/A	N/A	N/A
Zhang, *et al.* [15]		Proportional valve, Microcontroller	Displacement, Tension, Pressure	Power assist suit
Wang, *et al.* [16]		PLC, Proportional valve, Directional valves, PC	Gyroscope, 3D capture system	Humanoid robotics
Thalman, *et al.* [3]		Directional valves, Arduino	Pressure, Motion capture system, Surface electromyography	Rehabilitation
Gong, *et al.* [4]		N/A	Tactile, Load cell	N/A
Mat Dzahir & Yamamoto [18]		LabVIEW, PC	Laser, Pressure, Load cell, Accelerometer	Rehabilitation and Humanoid robotics
Seo, *et al.* [19]		Proportional valves, LabVIEW, PC	Load cell	
Hu, *et al.* [5]		Proportional valves, Arduino	Angle	Rehabilitation
Gong, *et al.* [6]		N/A	N/A	N/A
Hitzmann, *et al.* [8]				Humanoid robotics
Garriga-Casanovas, *et al.* [10]				
Leu, *et al.* [11]		NI myRIO board, LabVIEW, PC	Force linear potentiometer, Encoders	
Niiyama, *et al.* [20]		N/A	N/A	
Vu, *et al.* [17]	McKibben	Proportional valve, NI cDAK-9178, LabVIEW, PC	Laser, Load cell	Rehabilitation
Ohta, *et al.* [9]		Directional valves, Proportional valve, Arduino	Potentiometer	Humanoid robotics
Cui, *et al.* [12]		Directional valves	Tactile	N/A
Zang, *et al.* [13]		Directional valves, Microcontroller	Angle	Humanoid robotics
Ide and Nishikawa [14]		Directional valves, PC,Yuragi controller	Camera	
Bolen and Hunt [7]	Festo	N/A	N/A	N/A
Wickramatunge and Leephakpreeda [21]		Directional valve, Data acquisition card, PC	Flow, Pressure, Load cell	

V. CONCLUSION AND FUTURE WORK

The paper shows the rapid review of the available literature on the topic of PAM actuators with a focus on the applications, muscle type and control systems, according to the SCOPUS database and PRIZMA protocol. After the initial search, 21 papers were selected and analyzed in detail. PAM actuators are very flexible, made from light, low-cost materials, simple to realize and can achieve high forces allowing a high power-to-weight ratio. However, the choice of actuator is based on the specific task it is meant to fulfill, which makes it difficult to adapt it for different applications, their response time is slow, the possible actuator contraction is small, the contraction force is difficult to change in case of different initial parameters, and the existence of compressors is mandatory which limits the mobility of the systems.

Most often, PAM prototypes are developed for to solve specific problems, so different muscle configurations and materials are used – commercially available McKibben and FESTO air muscles are used less often. PAMs are most often controlled using proportional and/or directional valves with microcontrollers, with a combination of different sensors for angle, displacement, force magnitude, pressure and air flow measurement. Finally, PAM actuators are most often used in humanoid and rehabilitation robotics, with a tendency toward applications in the development of power assist suits.

Future studies will encompass other types of actuators, such as Soft Pneumatic Actuators (SPA), BLDC and PMDC motors, step motors, Series Elastic Actuators (SEA) to ascertain key parameters for the choice of actuator, as well as their most common applications within the field of robotics.

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