Design and Fabrication of PLA-Printed Wearable Exoskeleton with 7 DOF for Upper Limb Physiotherapy Training and Rehabilitation

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Abstract Most upper limb exoskeletons that have been presented in the literature are either intended for rehabilitation or for some type of industrial or Military work. However, there are a select few breakthroughs that offer both characteristics and aid with everyday life tasks. This study describes a wearable upper limb exoskeleton that can help people who have lost their ability to move and are undergoing rehabilitation. The exoskeleton arm has a maximum load lifting capacity of 50 kg and can lift that much weight with a 150-psi compressor pressure, which can help people with daily activities and provide mobility. In this study, a pneumatic exoskeleton arm with seven degrees of freedom (DOF) and flex sensors is used to control the extension and retraction of the arm using portable pneumatic pumps. This enables us to carry out the rehabilitation motion as exactly as possible and prevents us from adopting unfavourable postures while searching for the necessary answers. Promising findings were obtained through fabrication and testing that were done to validate our concept.

Keywords Exoskeleton · Pneumatic arm · Robotic arm · Rehabilitation · Assistive technology

1 Introduction

Since ancient times, human races have attempted to transcend human limitations by inventing a variety of aids, from crutches to future disability suits or defence mechanisms like knives, swords, or other contemporary fighting vehicles. In the

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pursuit of excellence, a state-of-the-art professional exoskeletons and orthoses are currently accessible and becoming more and more necessary to aid, facilitate, and speed up the training and recuperation of weak and wounded persons as robotic assistance and rehabilitative training have lately become more prevalent.

Robot is a mechanical device that can perform physical tasks. One of the types of robots which is very popular and simple is the robotic arm system. A mechanical system known as a robotic arm is utilised to lift, move, and manipulate the workpiece in order to lessen the workload placed on humans. A mobile machine made mostly of an outer framework worn by a human and driven by a system of levers, motors, hydraulics or pneumatics that aid's in limb movement is known as a robotic exoskeleton, also known as exoframe, powered armour or exosuit [1].

The number of handicapped persons has grown alarmingly during the past several decades. According to studies, the majority of handicapped persons are elderly. According to World Health Organization data, more than 20.5 million individuals worldwide experience a stroke or cardiovascular illness each year [2], Of these victims, 85% experience acute arm impairment following a stroke, and 40% experience chronic impairment or permanent disability [3]. Because of the deterioration of their physical and muscular power, elderly individuals, stroke patients, hemiplegic subjects, paralysed people, and those who have had spinal cord injuries all experience various types of locomotional handicaps. The major strategy for encouraging functional recovery in these patients is rehabilitation programmes. Exoskeleton robotic arms might greatly aid in the success of these initiatives because the prevalence of such instances is rising, and therapy is lengthy.

In many industrialised nations, including America, China, and India, musculoskeletal illnesses are the most prevalent ailments. These illnesses have a significant negative influence on the productivity of businesses as well as the quality of life for workers. In the logistics, construction, and medical rehabilitation sectors, there are 67%, 84%, and 75% workers with lumbar issues, respectively [4]. This issue has developed into a societal danger. There have been several methods put out to address this issue. The study of the lumbar exoskeleton is one of those that deserves attention. Statistics show that when users are wearing these, the lumbar spine's muscular activity might be decreased by as much as 30% [5]. Many colleges and research organisations are creating lighter and more potent lumbar exoskeletons to enhance its force-assisted performance.

Exoskeleton arms that are utilised in industry to carry big objects cannot be employed in daily life. It is difficult to reduce the size and weight of exoskeleton arms that are already on the commercial market. On how to enhance exoskeleton technology, there is ongoing discussion. By including a pneumatic cylinder as energiser, it is feasible to greatly minimise the muscle work required by a person. Many effective haptic interfaces have been developed recently as a result of advancements in processing power, control systems, and sensor and actuation technologies [6]. Despite the fact that there have been several high-performance hand controllers. The first exoskeleton arm and glove were created at ARTS Laboratory, [7] for the reconstruction of touch and impact feelings. The 7-DOF ungrounded ARTS arm, sometimes referred to as the PERCRO exoskeleton, is linked to the operator's torso and shoulder [8]. With his or her palm, the operator grips the gadget. Therefore, the gadget can only apply forces on the user's palm. Prosthetics for the lower limbs and upper limbs are becoming increasingly prevalent. Lower limbs devices like "Lokomat" and upper limbs devices like "PHANTOM, WAM, PUMA (MIME), MIT-MANUS" are utilised to demonstrate the therapeutic effectiveness of physical therapy for movement dysfunction arising due to neurological illnesses and stroke [5].

Exoskeletons, unlike the Sarcos design, which would lighten the load for troops and other people who carry large packs and equipment [9]. According to recent research, even though the weight carried by the wearer's back was significantly smaller, the person carrying the load nevertheless used 10% more oxygen than normal because of the extra effort needed to make up for the gait disturbance. There is one obstacle, nevertheless, that every creator or researcher of exoskeletons says must be cleared first: the price. Each powered exoskeleton costs between $75,000 and $130,000 [10]. The price does not include servicing or maintenance. If we add the initial cost to its upkeep and service, the total comes to $205,000 [11], which is astronomically costly.

Since wearable exoskeletons are so expensive, posing challenges and competitors are a losing proposition. Exoskeleton manufacturing is coming to an end because of its high cost. Exoskeleton development may be considerably accelerated with more funds and resources. The investors aren't keen on getting involved in a market where powered exoskeletons seldom goes beyond few hundred units a year. A profit hasn't been made in years, too. Without making improvements to the product, the annual number of exoskeleton units sold cannot be increased, and the cycle continues. The use of exoskeleton arms is also declining as a result of other well-established sectors, such as wheelchairs.

There are two types of haptic display devices: grounded and ungrounded. A stiff base is attached to a grounded haptic device, which transmits response forces to the ground. Only the operator's body is connected to an ungrounded haptic device, which applies response forces to the user where it is linked. Rehabilitation robots may generally be divided into three categories: (1) supporting structures for posture, (2) rehabilitation approaches, (3) robots to support or take the place of bodily functions [12]. Posture support mechanism is done with the help of a back support robotic exoskeleton as the body posture is controlled by the spinal cord. Rehabilitation mechanism robots help as a support system for a semi functional part which needs a push to regain the muscle strength completely. Lastly, the robots which replace a body function consists of a prosthetic assisted with a robot connected with neurons for the brain to send the signals to the prosthetic. In this work, the focus has been put on a robot assisted exoskeleton for rehabilitation purpose. Based on hand control assist system, developed using electronic and mechanical arrangement controlled by a microcontroller, the exoskeleton/prosthetic prototype is sufficiently powered by a pack of 48 V battery and weighs around 12 kg [11]. Knowledge of rebuilding exoskeletons has been systematically established, and majority of them are intended to empower paraplegic clients to leave the wheelchair and walk upstanding with the help of the gadget. Some of the efforts have been scrutinised critically in Table 1.

Table 1 Work performed by peer groups in related exohands

DOF									
	SHOULDER	6	3	3	4	7	4	1	1
	ELBOW	1	1	1	3				
	WRIST	2	3	3	-				
Research group		Tsai et al. [13]	Jiafan et al. [14]	Wen et al.[15]	Moubarak et al. [16]	Garrec [17]	Ruoyin et al. [18]	Lara et al. [19]	Ngai [20]
Technology		Gear drives—dc motor	Crank-Slider mechanism and Links—Pneumatic actuators	Gear drives—dc motor	Gear drives—dc motor Brushless	Ball Screw and cables—motor	Cables—actuators	Shape memory alloy	Gear system—stepper motor
Control method		Electromyography	Force and position sensors	-	Force controlling with position feedback	Indigenious system		Force Controlling	Two push-button sensors—switch based
Special feature		Avoid going through the ill-postured configurations	Produce the vivid feeling in addition to the soft control interface	Controller guarantees the asymptotic stability, for this class of robotic manipulators	Relatively lightweight with a high ratio of DOF/weight	Allows true joint torque control without force sensor	Can accommodate variety of hand sizes to some extent	Compact and portable	Motion was assumed to be axial, but forearm was resisting the axial rotation of
Application		Rehabilitation	Teleoperation	Assistance	Rehabilitation	Assistance	Rehabilitation	Assistance	Assistance

Few Applications of exoskeletons are as follows:

Automotive industries—It provides the workers with ease of ability to walk and stand on their own, decreases the fatigue level and also prevents injury for the workers who have a prolonged use of the same muscle every day for hours.

Logistics Department—Logistics workers use their lower and upper muscles for the lifting of the goods, and thus, this exoskeleton arm can lower their risk of injury.

Construction—Construction industry has a large number of workers who work on daily basis and are very much prone to disabilities and injuries faced by them at work.

Large and small warehouses—In warehouses, the main function will be of transportation of the goods, and thus, it has a high application rate.

Prosthetics—It will be a boon for the prosthetics industry to afford an effective and ergonomic exoskeleton.

Rehabilitation—The majority of rehabilitation robots fall into the category of rehabilitation exoskeletons, which are wearable and can regulate entire joint motion during training.

Physical Therapy—Use of flex sensors can also make it very easy for a single person to have a rehabilitation session of his own.

All major industries—Currently being widely used by major businesses in the logistics, automotive, aerospace, and construction industries.

2 Exoskeleton—Rehabilitation Purpose

It may be summed up based on the examination of pertinent material that was done that—The exoskeleton arm can be used in medical rehabilitation and can be used as prosthetics Exoskeletons are used in industries for assistance lifting and can lighten the load on the worker. The exoskeleton arm can be utilised for prosthetics and medical rehabilitation. Although the exoskeleton arm may be controlled by a variety of cutting-edge technologies, including electromyography and brain wave methods, the pneumatic system is the most secure, affordable, and adaptable power source and offers sufficient strength for lifting weights.

The suggested design comprises a low-cost, ergonomic tool that lifts various loads for accident-prone logistics workers, individuals with disabilities, and others with no physical strain or with little effort actuated by suitable sensors installed capable of measuring the user's action. Prototype which shall be a wearable powered exoskeleton is based on hand control assist system, which is controlled by signals from the user. This whole three major stages.

(i) Design of a working and effective robotic exoskeleton with 7 DOF
(ii) Analysis of design for failure

(iii) Fabrication of designed robotic exoskeleton to assist in upper extremities.

A. **Design**

Exoskeletons may be used for a broad range of activities, but their application is limited by their high cost. Any industry, including industrial operations, medical technology, and military might, will find considerable value for such an economical solution. The design proposed is based on average built human being as given in Table 2.

The anatomical ranges and related exoskeleton range are shown in Table 3 as biomechanical models can be employed for the prototype's design and control in robotic rehabilitation to make the human–robot interaction mechanism simpler.

Table 4 shows range of motion (ROM) for mechanical joints used in exoskeleton inspired by date from Table 2 and Table 3 also establishing against activities of daily living (AOL).

There are four distinct elements that make up the exoskeleton unit.

(a) Structure
(b) Power supply
(c) Control system and
(d) Electronic firmware.

Table 2 Statistical data of average human dimensions [3, 4, 21]

	Minimum	Medium	Maximum
Age (years)	22	30	Above 30
Weight (kg)	60	67	Above 70
Height (cm)	160	170	185

Table 3 Anatomical range versus exoskeleton range [1, 20, 22, 23]

Motions required	Anatomical range	Exoskeleton range
Elbow and forearm		
Supination	80°–90°	90°
Pronation	80°–90°	80°
Extension	0°–5°	0°
Flexion	140°–145°	140°
Shoulder joint		
Internal rotation	80°–90°	90°
External rotation	60°–90°	90°
Flexion	170°–180°	170°
Extension	30°–60°	50°
Abduction	170°–180°	170°
Adduction	0°–50°	0°

Table 4 Mechanical joint range of motion [17]

Joint	Motion	ADL ROM (deg)	EXO ROM (deg)
Shoulder	Fle-Ext	110	140
	Int-Ext Rot	135	145
Sternoclavicular	Ele-Dep	35	30
Elbow	Fle-Ext	150	155
	SupPron	90	90

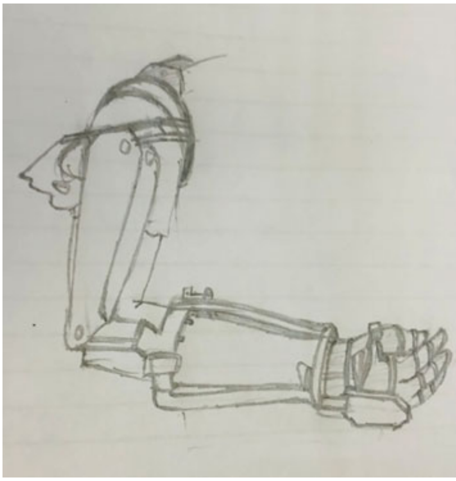


Fig. 1 Prototype model sketch showing three major parts

The whole structure of arm as shown in Fig. 1 is divided into three stages, i.e. forearm, elbow and shoulder, and the mechanical design consists of the following parts:

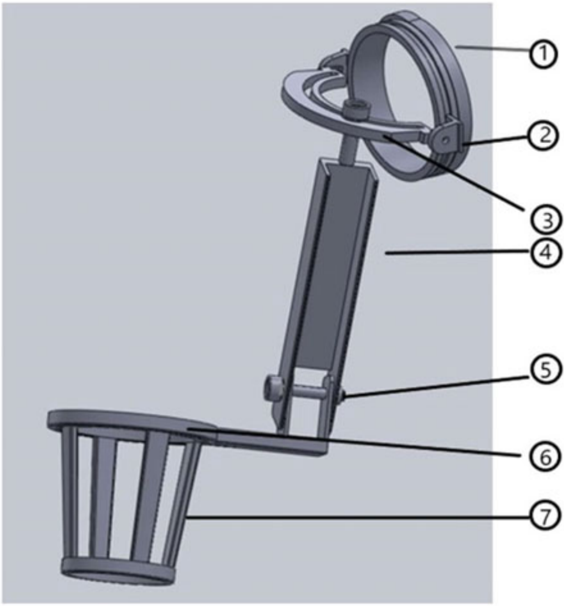
This arm majorly consists of mechanical links joined together and working in tandem by activation of actuators.

(a) Mechanical links—Links are modelled as a network of rigid links and an ideal pair, called kinematic chains to manage forces and movements.
(b) Joints—A mechanical joint used to connect one or more mechanical parts to another yet allow the relative movement to a certain degree of freedom and limit movement in one or more direction.
(c) Pneumatic actuators—A pneumatic actuator consisting of a piston, cylinders and valves or connections can turn energy into linear or rotating mechanical movements.

Exoskeleton arm modelled on software is shown in Fig. 2.

1. Shoulder cover (200 mm diameter)
2. Slider
3. Abduction movement plate

Fig. 2 Arm design



4. Elbow support (330 mm length)
5. Connecting bolt (7 mm diameter)
6. Ball bearing (200 mm diameter)
7. Lower arm case

Wearable battery pack is modified rechargeable power source that powers the primary actuators in addition to the microprocessor. The actuators are made up of pneumatic and motor systems. They both attempt to support the exoskeleton arm in providing the desired torque increase.

Control of robotic exoskeleton arm with a transmitting device or wireless controller can be done by just sending a signal via a transmitting device or wireless controller for the required movement of arm or hand, and once the signal is transmitted, signal is processed by arduino and executed on either hand via pneumatic cylinders or the hand via servo motors [24]. This paper is based on hand control assist system, developed using electronic and mechanical arrangement controlled by a microcontroller.

Sensor interface circuitry majorly makes up the exoskeleton. Rechargeable batteries cascaded to power it along with a voltage regulator are used. Together, they feed the microcontroller with a steady DC supply. Flex sensors, which the user wears to identify his motions and operate the arm, are mounted on the forearm. Any bending of the user's hand is detected by the flex sensor glove, which then has an impact on the exoskeleton structure in a comparable way. For instance, the user can activate the exoskeleton arm to automatically lift an object just by keeping it in place without hitting any buttons (or any other indication) [22].

The exoskeleton arm enables the transmission of external load to the stronger part of the body through precisely positioned links in joints. The robotic exoskeleton arm in this paper is controlled by hand a transmitting device which can be any Bluetooth transmitter device. It is hypothesised that the lumbar spine is a hard, non-deformable body since its distortion during movement is so little. The mechanical design would be made of aluminium [25, 26] so that it goes not only light weight but also have much strength. The amount of muscular effort needed by a person can be greatly reduced by adding a pneumatic cylinder to the system. Then main thing in designing a prosthetics model is its control. Flex sensor would be connected to the body of the operator. A microcontroller would get signal from the flex sensor and would actuate the motors accordingly [4, 7]. Components used as shown in Fig. 3 with a brief description are:

- **Microcontroller**—Widely used open-source microcontroller board used is Arduino Uno. The Arduino Uno is a microcontroller board based on the ATmega328. External power supply that is other than USB, can be of AC or DC supply with the adaptor or a battery. This adapter will be linked to the board power jack by plugging it into a 2.1 mm centre-positive plug. The circuit board might be capable to operate up to 6–20 V when connected to an external supply. But if the supply is below 7 V the 5 V pin may not function properly, and the board may get unstable and if the supply is more than 12 V the board may get overheated and damaged. The safe and prescribed range should be between 7 and 12 V.

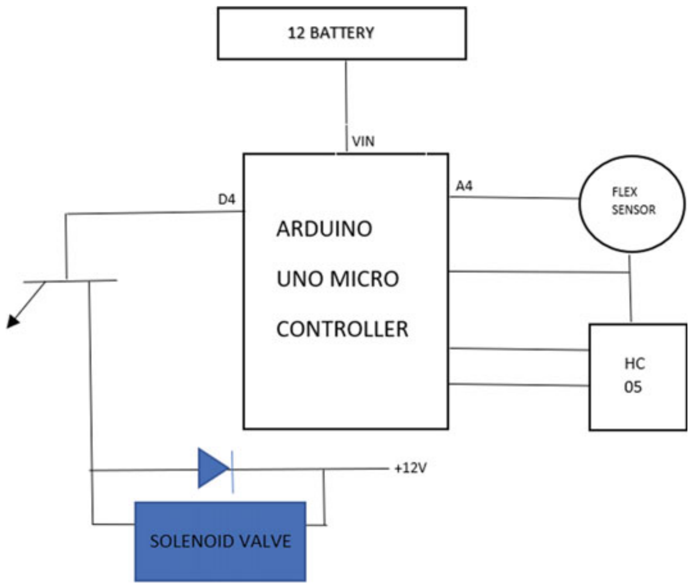


Fig. 3 Circuit diagram of the mechanism used

- **Flex sensor**—A flex sensor, sometimes known as a bend sensor, is a device with variable resistors that gauges how much something is bending or deflecting. Typically, the sensor is adhered to the surface, and the surface's bending changes the sensor element's resistance.
- **Compressor**—Air compressors are used to produce compressed air. A power tool that produces and transports compressed air is an air compressor. When air is compressed, it produces a powerful force that may be utilised to power a variety of equipment.
- **Solenoid Valves**—An electromechanical device that controls, regulates and keeps track of flow, pressure and other factors. A 5/3 double-solenoid valve is used made it feasible to accomplish intermediate postures and make distinct arm motions.
- **Pneumatic cylinders**—Mechanical devices that use the force of compressed gas to produce power in a responsive linear movement are sometimes referred to as "air cylinders".
- **Hc-05 Bluetooth modules**—A simple Bluetooth SPP (Serial Port Protocol) module called the HC-05 is made for setting up transparent wireless serial connections.

B. **Stress Analysis of every part**

This design has the capability to lift **50 kg** of weight from a single arm, and thus, the load taken for calculations is **50 * 9.8 = 500 N** (approx.). Stress analysis using ANSYS was found out to be well within the limits Fig. 4. Above these limits the PLA material can break as the individual part is constructed using the 3D printer with different parameters such as ink weight, strength-to-weight ratio.

C. **Fabrication**

The fabrication of the parts is done by using a 3D printer (CubeX, Fig. 5.), and the material [27] used was PLA which is very durable, light and strong. Free conversion software is included with every CubeX 3D printer. This programme layers slices of a 3D object so they may be printed on your device. Other characteristics and applications of CubeX software include interface that is simple to use and familiar movement, rotation and scaling of components on a virtual print bed. Part and toolpath viewer combined STL file verification built-in profiles for various materials and supports.

Few fabricated parts of exohand are shown in Fig. 6.

3 Results and Discussions

Push-button switches located at the wrist section are operated utilising flex sensors to control the arms. This sensor can help the old people as their muscle power is low, so the flex sensor is able to detect a small strain on forearm muscles during flexing or relaxing arm and functions easily with the help of the pneumatic.

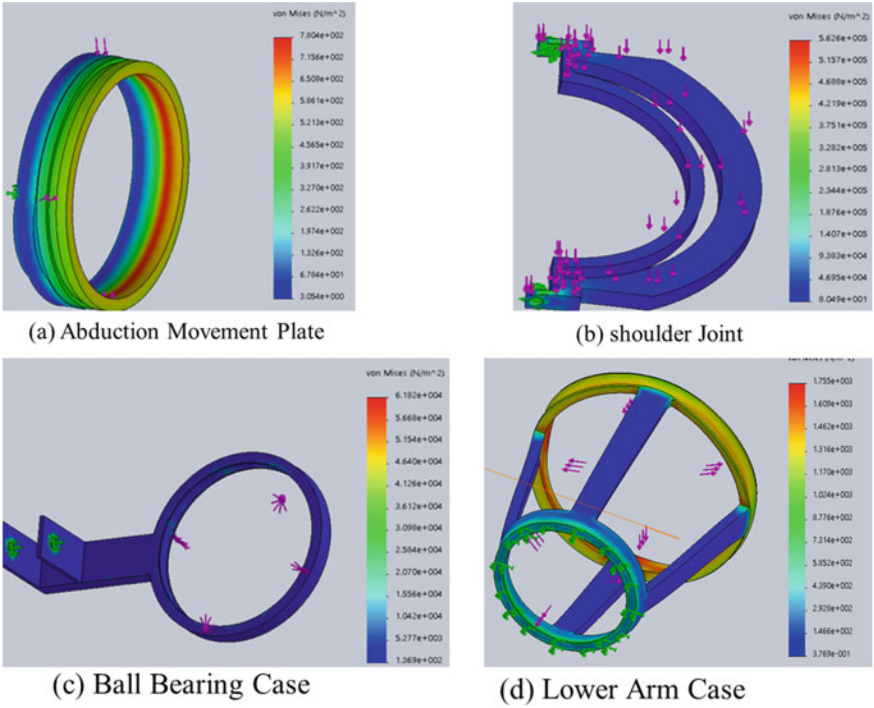


Fig. 4 **a** Abduction movement plate—maximum stress – 8.049 * 10^1, **b** shoulder joint—maximum stress – 7.804 * 10^2, **c** ball bearing case—maximum stress – 1.369 * 10^2, **d** lower arm case—maximum stress –1.755 * 10^3

After several trials, the exoskeleton proved to be capable of lifting 50 kg of weight with ease at a compressor pressure of 150 psi. It was able to achieve intermediate positions and distinct arm motions owing to 5/3 double-solenoid valves. Increasing the compressor pressure supplied can enhance the lifting capability. At extremely high compressor pressures, the movement becomes more challenging to regulate.

The design is very flexible for all types of users, and it allows a worker to move freely in a restricted free environment and also with the use of portable compressor it can be used for prosthetics and rehabilitation purpose. Selection of Aluminium series 7 material for the fabrication has brought light weight, high strength and easily workability. Exoskeleton evenly distributed the load throughout the upper body with almost no human effort requirement for load lifting.

Future extension of current work could be an exoskeleton for the lower body attached to the main body. The weight will be more easily transferred to the ground with the addition of the lower body to the upper body. Because of this, the user won't be able to feel the weight of their body or the burden they are carrying. Pneumatic systems might be employed in a similar design to help with leg mobility.

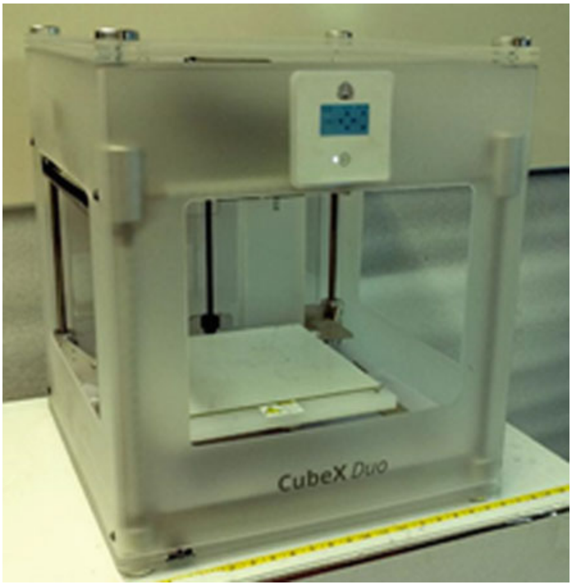


Fig. 5 CubeX duo 3D printer

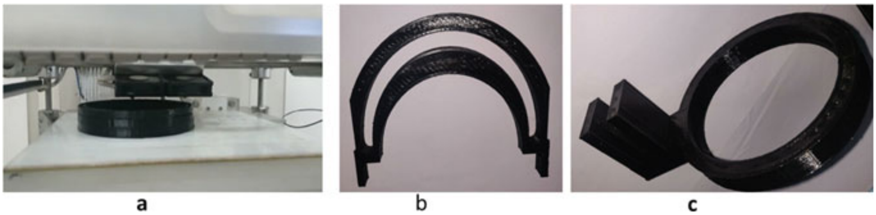


Fig. 6 **a** 3D printing of shoulder part of the exoskeleton, **b** 3D-printed sliding pair part, **c** 3D-printed forearm outer cage part

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