Artificial Muscles with the Possibility of Application in Medical Practice

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Introduction

Movement reproduction and control in medical practice is an important technological and engineering task. Recently, the development of artificial muscles (AMs), which are in demand in many fields of medicine, has been in focus of medical professionals and engineers. The research in this direction include concerns creating artificial heart muscle patches and sphincter cuffs for different body parts (urethra, anal canal, and lower esophagus). The AMs are widely used as executive mechanisms (actuators) in prostheses, exoskeletons, implanted drug delivery tools, etc. Medical engineers face the problem of designing light, biocompatible, and reliable AMs, which would be safe for humans and characterized by the low power consumption and acceptable operating temperature. In view of the aforesaid, the properties of various materials, including polymers and nanocomposites, promising for fabricating AMs have been studied. One of the fundamental properties of such materials is their high biocompatibility. It is proposed to use mainly electroactive polymers and nanocomposites containing carbon nanotubes (CNTs). The latter deserve much attention, since they are characterized by the combination of the high strength, flexibility, elasticity, and electrical conductivity.

Here, we made a brief literature review of the current state of research and development in the field of AM drives and prototypes and discuss prospects of their application in medical practice.

Artificial Muscles

A. Pneumatic artificial muscles

The McKibben mechanical drive operates by pumping a fluid or gas under pressure into a chamber bounded by a rigid braid [1]. A new-type McKibben muscle uses paraffin as an expandable material, which is heated to a temperature of 95°C. This type of muscles has certain advantages over the liquid type, but is not compact, hard to control, has a high operating temperature, and, thus, inapplicable in medicine.

A pneumatic artificial muscle (PAM) drive offers great potential for prosthetics, since it is characterized by the high power density ($P_m \geq 4$ kW/kg) and exhibit other properties of natural human muscles [2]. A PAM prosthesis provides a torque sufficient for the knee joint in performing the high-energy human motor functions (fast walking, climbing stairs, etc.) and imitating normal gait parameters [3].

The trigger mechanism for a hydraulic artificial muscle (HAM) is similar to that of a PAM, but the HAM has several advantages, e.g., ductility, low weight, easy maintenance, and low cost [4]. The PAMs and HAMs are designed as drives for robotics and various engineering products. Sometimes, they can be used for external strengthening of human limb movement, but are not intended for invasive use as artificial human muscles.

B. Electroactive polymers

Electroactive polymers (EAPs) have some characteristics similar to those of natural muscles. In particular, they are driven by electric pulses [5]. Usually, the EAP materials are divided into two main groups: electronic (activated by the electrostatic field) and ionic (activated by ion transport). The group-I EAPs are high-voltage (≥ 1 kV), develop a low power ($P_m \leq 0.1$ kW/kg), and exhibit the high efficiency (CE $\geq$ 90%). The group-II EAPs are considered to be low-voltage (≤ 5 V) and have high power and low efficiency (CE $\leq$ 20%).

Obviously, the group-I EAP materials are inapplicable for use in artificial muscles (prosthesis and implants) because of the high-voltage breakdown danger. The EAPs contained in ionic polymer composites and metals are promising for creating various medical products, including electroactive AMs, distributed biomimetic nanoactuators, nanoconverters, nanorobots, and nanosensors. They are characterized by the combination of high load force and low electric voltage (1–3 V) [6]. Ion EAPs is, in fact, functional materials for the development of AMs. Their low-voltage power supply ensures the high safety; the polymer surface electrodes made of noble metals (Au, Pd, Pt, etc.) provide the acceptable biocompatibility and make these materials suitable for use in invasive medical implants. For example, the ionic EAP-based AM is designed to fabricate artificial sphincters of the lower esophagus, anal canal, urinary canal urethra, and heart muscle patches [7]. The EAPs based on the elastic ionic polymers and electrodes are immersed in an electrolyte and all parts are encapsulated in an elastic hermetic. Such a system represents an AM prototype and, depending on its characteristics (mechanical, power, and others), can be used in medical practice [8]. However, this direction is still at the stage of intense research and a practical AM prototype for medical applications has not been fabricated yet.

C. Other artificial muscle materials

The most accessible and simplest is a drive in which nylon and polyethylene fibers woven in a certain way (in spiral springs) contract in length and expand in diameter upon heating. Such drives are controlled using the Joule heat induced by the current transmitted through a conductive coating on the filament surface. The attained drive parameters are a volume energy density of 840 kJ/m^3, an energy density per unit mass of E_m ~ 530 J/kg, and a power per unit mass of P_m ~ 1.0 kW/kg [9]. These values are at a level of the human heart muscle parameters, i.e., P_m ~ 0.33 kW/kg. The inexpensive AMs are fabricated from highly oriented nylon threads [10, 11]. A twisted nylon bundle can lift a load exceeding tenfold the load lifted by a human muscle of the same length. An artificial finger has been demonstrated. However, drives of this type are not suitable for use in AMs for invasive prosthetics in a human body because of their strong overheating.

The high performances are typical of niobium nanofibers; specifically, their conductivity is ~$3 \cdot 10^6$ S/m, the tensile strength is up to ~ 1 GPa, and the Young's modulus is 20 GPa.

The twisted nanofiber yarn impregnated with a paraffin wax is strained upon heating and can work as a drive [12]. During the transmission of electric current, the wax melts, expands, and unwinds; the yarn drive does a torsion work. Numerous actuators based on heating and cooling of intermetallic materials employ the shape memory effect. They develop the high powers (P_m ~ 4 kW/kg) and are widely used in robotics [13]. However, despite the very high specific powers developed by the shape memory alloys, their elastic strain limit is 4% [14], while the value for the human muscle tissue is about 20%.

The available AM prototypes cannot simultaneously perform complex deformations (bending, contraction, extension, etc.) attributable to natural muscles. Recently, it has been established that a single-layered lattice microstructure of onion epidermal cells in applied electric voltages of 50–1000 V can simultaneously participate in complex deformations [15, 23]. Currently, this research direction is at the initial stage and its future prospects are still obscure.

D. Carbon nanotube-based artificial muscles

The unique mechanical and electrical properties of CNTs make them excellent candidates for application in AMs for medicine.

The CNT airgel, sometimes referred to as frozen smoke is an ultralow-density solid material [16]. Nanotubes in the airgel layers are arranged parallel and form a sort of framing. In high voltages (1–5 kV), the layers are expanded at a straining rate of $3.7 \cdot 10^4$ %/s, which exceeds many times the known values. The advantages of this material are an energy density per unit mass of E_m ~ 30 J/kg and an attainable strain stress reduced to the material density of ~ 15 $kPa \cdot m^3/kg$. In addition, they have a very wide operating temperature range (80–1900 K) and can develop a force that exceeds that developed by natural muscles with the same cross section by a factor of 30. Undoubtedly, the main mechanical, energy, and temperature parameters of the investigated CNT layers are acceptable for creating AMs, but, to use them in practice, it is necessary to solve the problems concerning the high power-supply voltage, encapsulation, and insufficient safety level and biocompatibility.

The biological polymer chitosan (nanocomposite) films saturated with single-walled CNTs (SWCNTs) exhibit a strain of ≤ 5 V under the action of a voltage pulse [17]. The electrothermal generation of mechanical movements, simplicity of controlling, and biocompatibility make these nanomaterials promising for application in AMs. The complication of a nanomaterial composition aimed at increasing its specific conductivity will help significantly reduce an existing SWCNT concentration of 25 wt.% and, consequently, further enhance the safety and biocompatibility of the proposed AMs. Test drives from multi-walled CNTs (MWCNTs) and niobium nanowires were fabricated [18]. The muscular structure matrix used is made of a heat-sensitive paraffin wax. As metal fillers, tungsten or NiTi alloy nanowires are used, which induce the Joule heating of the matrix. The proposed drives have the higher mechanical characteristics as compared with nylon filament-based actuators, but their drawback is the high operating temperature.

A nanocomposite consisting of a nanogel, which contains boric acid, hyaluronic acid, and MWCNT nanowire strands, was used for creating a drive [19]. A MWCNT strand immersed in the nanogel swells and execute a torsion motion due to the internal anion charge variation. Such a drive can be used for implementing torsion movements, is sensitive to glucose, and has the high potential for application in AMs. In addition, such an AM can work as a glucose sensor (in the range of (55–100)$\cdot 10^{-3}$ M), which automatically releases the medication when needed.

In a liquid electrolyte, the twisted CNT strands can generate rotational motion and length shortening. Owing to these properties, the novel materials are capable of lifting loads that are heavier than those lifted by a human skeletal muscle of the same size by a factor of 25 [20–22]. To control their operation, low voltages (≤ 5 V) can be used. With these materials, a rotational speed of 590 rpm and a maximum reversible rotation angle of 15000° were attained. The high developed power, fast response, and low supply voltage are positive indicators for creating AMs; however, it remains difficult to convert the rotational motion into other motion forms.

In an electrolyte consisting of KOH in a concentration of 1M, the SWCNTs coated with platinum nanoparticles ensure a desired deformation in low applied electrical voltages (≤ 1.5 V) and currents (≤ 0.08 A) [23]. The proposed principle of generating the mechanical deformation due to the charge redistribution in the electrolyte is promising for the development of AMs, including those for medical applications.

A new-type AM with artificial absorption of a solvent is highly efficient without changing the temperature [24]. Such AMs are driven by rubber swelling in a nonpolar solvent. The calculated CE value is ~16%, which is similar to an CE value of ~20% of the human muscle tissue [25].

Polyhydroxylated fullerene added to the sulfonated polyetherimide matrix increases the ionic conductivity and this effect can be further enhanced by coating nanotubes with platinum particles [26]. The obtained energy of $E_m \leq 10$ J/kg is lower than the energy $E_m \sim 40$ J/kg generated by a human skeletal muscle [25]. The developed power ($P_m \sim 0.1$ kW/kg) is also lower than a value of $P_m \sim 0.3$ kW/kg of the human heart muscle tissue.

The operational principles of AMs discussed in reviewed works [18–23, 26] are common and analogous to those of natural muscles. These are the redistribution of ions under the action of current pulses in an electrolyte, straining a CNT filament, and plate motion. Therefore, these research directions are promising for creating AMs for use in medicine.

Conclusions

The analysis of available literary data allowed us to draw the following conclusions:

- Artificial muscles operating on the basis of the flow dynamics laws (pneumatics and hydraulics [1–4]) can develop extremely high specific powers ($P_m \geq$ 4kW/kg) and are suitable for robotics and external prosthetics of human limbs. However, it is hard to use them as invasive implants because of their unacceptable energy supply and insufficient biocompatibility.
- The AMs made of electroactive ionic polymers ([1–8]) are characterized by a power of $P_m \sim 1.0$ kW/kg, an energy of $E_m \sim 530$ J/kg, and an efficiency of CE ≤ 20 %, which are analogous to the human muscle tissue parameters ($P_m \sim 0.33$ kW/kg, $E_m \sim 39$ J/kg, and CE ~ 20%). However, the structural components used (electrolytes, polymers, electrodes, etc.), high cost, and limited durability of the available AM prototypes do not meet the medical requirements.
- The actuators based on the laws of conversion of the electrical energy into mechanical one (nylon and polyethylene fibers [10,11], niobium nanofibres [12], and shape memory materials [13]) have operating temperatures of ≥ 60° C and, certainly, cannot be used in invasive medical implants.
- Carbon nanotubes and their layers immersed in an electrolyte deform in the course of the chemical reaction and generate mechanical movement [18–23, 25], analogously to mammal muscles. To date, the test parameters of an AM artificial muscle prototype are inferior to the natural muscles.

Thus, the intense research and development directed to improving the characteristics of drives based on ionic electroactive polymers and composite nanomaterials containing carbon nanotubes will make it possible to create invasive muscles for medical purposes. Solving the existing problems in this way is claimed by the modern state of medicine and, especially, the need for treating the heart diseases. Now, heart failure is a cause of about 10 million people die around the world and the creation of an artificial muscle as an auxiliary part instead of a damaged heart site will save numerous lives.

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