Comparative analysis of exoskeletal actuators
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Abstract: Since the beginning of the development of exoskeletons in the early 1960s there was a constant need for improving their actuators technology. Requirements for high power and torque for the lower body and very high precision for the hand motion, while maintaining the flexibility of biological muscles, are still not fully satisfied. The problem lies not just in the lack of appropriate actuator technology, but also in the inability to meet their energy needs. This paper contributes to this problem, first by describing the most commonly used technologies and then by presenting simulation results for lower limb exoskeleton motion. In addition the energy requirements of the modeled devices and their control possibilities along with their usage in various parts of the exoskeleton construction are analyzed.

Keywords: exoskeleton, artificial muscle, actuator, energy source, modeling

1. Introduction

Currently, exoskeletons are one of the most advanced branches of mechatronics. The essence of these systems is generally to support the processes of human movement through the use of technologically advanced equipment and technology, particularly in the field of prosthetics. These devices are powered by a set of sensors – typically used in electromyography, or electromyography – and actuators that lead to the construction of devices, in which the essence of movement is consistent with the will of the user, without the need for additional peripheral devices – for example, a joystick [23].

The first research on exoskeletons date back to the beginning of 60s in the last century. The aim of the pilot project, undertaken by the Department of Defense of The United States of America, was to create an armor that increases the strength of the user. The main barriers in the development of this concept were the technological limitations of power systems (too heavy and inefficient), sensors, structures, and actuators. However, the study of pneumatic artificial muscle (PAM), which started in the 60’s [5] and the subsequent development of this technology (e.g. the solution presented by the Japanese company Bridgestone) gave further development of exoskeletons. The emergence of modern and far more efficient electric motors (e.g. brushless stepping motors) additionally contributed to the development of exoskeletons.

The primary factors associated with the emergence of these disadvantages include high power consumption resulting from the need to obtain a high torque drive during movement of the limb, and consequently – also high energy requirements for applied actuators and control systems. Presented in [6] studies of the mechanics of the limbs movement show, that during human walk peak torque at the knee is 0.34 ±0.15 Nm/kgm for women and 0.32 ±0.15 Nm/kgm in the case of men. This means that, e.g., for a man weighing 80 kg and 180 cm tall, peak torque at the knee during normal walk is 45 Nm.

These arguments show that the energy requirements for exoskeletons should be considered as fully significant, current and not quite properly recognized. For this reason, in this article the essence of the energy requirements of the actuating device adapted for use in structures of exoskeletons responsible for assisting movement of the knee was presented. The article focuses on a comparison of the two main technologies for exoskeleton limb actuators – DC brushless motors and pneumatic artificial muscles. The first part describes the actuators based on electric motors, McKibben muscles as well, as shape memory materials and dielectric elastomers. Secondly the models and the results of numerical simulation are given. Finally, given at the end are the key conclusions and predictions resulting from the use of the examined technology in building exoskeletons.

2. Actuator technologies

2.1. Electric drives

DC motors are currently the group of most commonly used actuators in robotics. However, as drives in the structure of exoskeletons, servomotors propulsion systems with permanent magnet are used [11–14]. There are two types of motors: synchronous AC motors and brushless DC motors. Permanent magnet motors in relation to other devices are characterized by a number of beneficial properties and characteristics that are particularly important in robotics. The most important among them include a favorable torque to weight ratio, high overload capacity and the ability to develop high torque when the motor shaft is stationary.

2.2. McKibben artificial muscles

Artificial McKibben muscles are an example of technology simulating real action of the elements of mechanics of living organisms that move using limbs. These devices, being powered by a specific medium (liquid or gas – but also latest conducted research focuses on chemically activated pneumatic muscles [24]) mimic the processes of contraction and relaxation of muscles, causing the formation of the corresponding axial stresses. Their main advantage is high power to weight ratio and power to volume ratio – accordingly 1 W/kg and 1 W/cm² [17]. These values are five times higher than...
This kind of assumption is justified because, during normal man – by analogy – a model of the pendulum was used. In order to simulate the movement of the lower limb of the human body, a model of the pendulum is utilized. For this reason, the relevant part of the pendulum can be regarded as typical physical pendulum, on which the driving force is applied which is produced by the control device that includes a counteracting resistant force $F_r$ (fig. 1).

![Fig. 1. The forces acting on the exoskeleton in the lower leg section along with its dimensions](image)

Equation (1) contains a mathematical description of the dynamics of the leg, as was applied in model

$$\dot{\theta} = \tau - c_1 \dot{\theta} - c_2 \text{sgn}(\theta)$$

where: $I$ is the inertia torque, $\tau$ – driving torque, $c_1$ – air resistance coefficient, $c_2$ – dry friction coefficient, $\theta$ – angle of inclination.

### 3. Dielectric elastomer artificial muscles

It should be noted that research of the possibility to use materials of varying shape concern not only SMA but also the dielectric elastomers. Preliminary results in this field show that the developed with the use of elastomers muscles are indeed efficient, but a small amount of change of length and a non-linear value of the contraction force do not yet allow their use as actuators in the major joints of the limbs. But one has to keep in mind that both the dielectric elastomers, as well as SMA materials, are a relatively young technology, and so further discoveries and implemented technical solutions will reduce the disadvantages of these materials that occur today, particularly in relation to their use as materials for artificial muscles.

### 4. Modeling and simulation of human leg swing phase

#### 4.1. Leg swing model

In order to simulate the movement of the lower limb of man – by analogy – a model of the pendulum was used. This kind of assumption is justified because, during normal walk, the swing movement of the lower leg is like a pendulum, and in addition, for most of this phase, the dynamics of the relevant portion of the limb is similar to the dynamics of the pendulum [8]. For this reason, the relevant part of the exoskeleton can be regarded as typical physical pendulum, on which the driving torque $\tau$ is applied which is produced by the control device that includes a counteracting resistant force $F_r$ (fig. 1).

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$$\dot{\theta} = \tau - c_1 \dot{\theta} - c_2 \text{sgn}(\theta)$$

where: $I$ is the inertia torque, $\tau$ – driving torque, $c_1$ – air resistance coefficient, $c_2$ – dry friction coefficient, $\theta$ – angle of inclination.

### 4.2. Actuator models

In the studied mechanical model, to produce the drivotorque that supports the strength of human muscles, a brushless DC motor with permanent magnets (PMSM) was used. Because of the high dynamic of the permanent magnet servomotor operation, the mechanical components in the presented model were assumed to be rigid.

To control the motor, the field-oriented method was used [19]. This control strategy is based on the orientation of the stator current vector relative to the rotor flux, which results in forcing the values of the stator current vector component in the axes $d$ and $q$ and the achievement of an independent control of the electromagnetic torque and stator flux. The presumed motor performance in the first zone regulations is the result of adopting a zero value of the stator’s current component. Thus, forcing the value of the current component is in the $d$ axis it is possible to control the electromagnetic torque of the motor. Furthermore, using in the control system an additional feedback loop from the angle of the motor shaft position, gives the possibility of a quick and accurate adjustment of the angle position of the exoskeleton representing the “shank”. Selection of the PI controller parameters in the control system of the motor shaft angle position is carried out by a computer simulation.
Because of the many models of this type of motor with such control systems, this study used a ready model contained in the libraries of MATLAB/Simulink software. Fig. 2 shows a schematic diagram of the exoskeleton’s lower limb actuated by a servomotor. Together with the motor a mechanical transmission was used.

\[
dW_m = dW_ext \Rightarrow p_i dV = F dL
\]  
(3)

where: \( p_i = p - p_{atm} \) is the relative pressure equal to the difference between the absolute internal gas pressure \( p \) and atmospheric pressure \( p_{atm} \).

Absolute internal gas pressure \( p \) in the case of antagonistic muscles is equal to \( p_0 \pm \Delta p \), where \( p_0 \) is the initial internal pressure.

It follows that the function of pressure and muscle contraction determining its axial tension force is

\[
F = \frac{p_i}{\sin^2(\alpha_i)} (3(1-k_e)\cos^2(\alpha_i) - 1)
\]  
(4)

Symbol \( e \) is the aforementioned muscle contraction grade equal to \((l_0 - l_1)/l_0\), \( r_0 \) is the muscle initial radius and \( a_0 \) is the initial braid interweave angle. Factor \( k \) compensates for the impact of deformation of the muscle at its ends, and for the purposes of this model has a value of 1.25 [10]. Hence the final formula for the force momentum in the ankle block, resulting from the mutually opposing muscle movement, takes the form [10]

\[
\begin{align*}
\tau &= (p_i - p_0) \cdot (K_i + K_i' \cdot \theta^2) - (-p_i + p_0) \cdot K_i \cdot \theta \\
K_i &= \frac{\pi \cdot r_0^2 R}{\sin^2(\alpha_i)} (3(1-k_e)\cos^2(\alpha_i) - 1) \\
K_i' &= \frac{6\pi \cdot r_0^2 R^2}{9g(\alpha_0) \cdot l_0} (1 - k_e)
\end{align*}
\]  
(5)

where \( e \) is the initial muscle contraction grade.

Diagram of the developed system is shown in fig. 4.
3.3. Simulation results

All presented results were based on MATLAB/Simulink software. Their aim was to study the swinging motion of the shank part of an exoskeleton, driven by two main types of actuators: a DC brushless motor and pneumatic artificial muscles. The dimensions of the limb segment were taken from the literature [12]: length – 50 cm, weight – 6.5 kg. These values take into account both the mass of the structure and the mass of a limb of a human 180 cm tall and 80 kg in weight.

Artificial muscles were modeled with a length of 30 cm, initial radius of 1 cm and initial braid angle equal to 23°. The initial pressure supplied to both muscles was 3 bar. Moreover, the leg angle control was based on a PID controller adjusted in such way, that the trajectory of the exoskeleton was close to the desired one, which involved bending and straightening the knee in a 4 seconds period (fig. 5).

Based on the obtained results (fig. 7), the total work done by the compressor supplying both muscles (for compression and decompression of gas) is equal to 75.84 J, including the efficiency of the compressor assumed as 0.8. For a two times shorter period of fluctuation, this value amounted to 78.25 J.

On the basis of formula (6), the force, achieved during compression and expansion of gas in the muscle in specific moments of time, was determined (fig. 7).

\[ P = p \cdot dV \] (6)

A congruent series of simulations were performed for a permanent magnet synchronous motor (for which

Fig. 5. The tilt angle of a PAM powered leg exoskeleton
Rys. 5. Kąt wychylenia egzoszkieletu kończyny dolnej poruszane- nego przez PAM

Fig. 6. Torque achieved during the leg fluctuations driven by a PAM
Rys. 6. Moment uzyskany podczas ruchu kończyny dolnej po- ruszanej przez PAM

Fig. 7. Actual power during the work of one PAM
Rys. 7. Moc rzeczywista działającego PAM

Fig. 8. Torque achieved during the leg fluctuations driven by the DC brushless motor
Rys. 8. Moment uzyskany podczas ruchu kończyny dolnej po- ruszanej bezszczotkowym silnikiem DC

Fig. 9. Actual power during the work of the DC brushless motor
Rys. 9. Moc rzeczywista działającego bezszczotkowego silnika DC
the gear ratio was 130). As a result, a similar to the PAM control quality was achieved. The mean values of torque and power (measured in the voltage inverter DC-link circuit) for an exoskeleton leg motion are shown in fig. 8 and fig. 9. System losses were taken into account during the simulation.

The peak torque resulting from the chart in fig. 8 is 3.05 Nm, while the energy consumed on this process by the motor was 594.7 J, representing a nearly 8 times higher value than the one achieved by the artificial muscles.

5. Conclusion

This paper shows the most popular actuator solutions for exoskeletons being under current development. However, it should be stressed that the shape memory alloy and dielectric elastomer materials, due to small force and displacement capabilities, are suitable mainly for use as actuators for joints which are not subjects of significant amount of force for long periods of time. Such applications may be suitable for systems driving, e.g., the wrist, metacarpal or hinge joints.

Presented examples of the electric motor drive and McKibben muscle are commonly used as actuators in the major arm and leg joints. In particular, achieved through high force momentum, they are suitable for driving the hip, knee and ankle, which are subjected to the highest, long-acting stress.

Taking into account the simplification of the calculations made for the PAM work, it can be said that their energy requirements during the specified motion are much smaller than for the electric motor drive with a converter. However, because of the current technology of mobile energy sources, which are not able to provide adequate power to move all elements of a construction of large size and considerable weight, it is insufficient for a long and stable operation of the exoskeleton structure. According to [1], currently the most popular types of batteries can supply power within the limits of 35–240 W/kg.

In summary, it is therefore considered that the future of exoskeletal actuators depends on the development of biomimetic technologies, such as presented pneumatic muscles or SMA based actuators. Although, it should be also noted that there exists control difficulties and – in the case of McKibben muscles – noise during operation along with the compressor alocating problem. However, the small energy requirements, significant safety of operation and large volume ratio of these technologies make them very interesting subjects to develop.

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Analiza porównawcza urządzeń wykonawczych w egzoszkieletach

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Słowa kluczowe: egzoszkielet, sztuczne mięśnie, urządzenia wykonawcze, źródło energii, modelowanie

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