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Mobile compressed gas supply for active orthoses and exo-skeletons

Abstract: In this study a basic principle for the gas supply of a pneumatic actuation for a mobile active knee joint orthosis is described. Instead of using a compressor or a bulky pressure reservoir, the system is supplied with pressurized gas directly from a thermodynamic process to reduce size and weight of the device. To achieve this goal a literature search was performed identifying chemical processes. These options were then analysed and evaluated considering the aspects energy density, safety, eco-friendliness, and technical feasibility of the construction. The expansion of liquified carbon dioxide with phase change achieves the best result due to its high level of safety and the simple technical feasibility of the system. However, CO₂ cools down considerably during the expansion, so heating up again to room temperature is necessary. Therefore, the technical construction includes a passive and an active heat exchanger.

Keywords: active orthoses, liquid carbon dioxide, pneumatic actuation

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1 Introduction

Most mobile active orthotic and prosthetic devices are supplied with electrical energy in order to provide the desired forces and torques. However, electrical energy has to be stored in batteries that still have unsatisfying energy density. This leads to the fact that the over-all systems either become rather heavy and bulky or provide insufficient endurance for comprehensive daily activity.

Pneumatic actuators have a favorable force-to-weight ratio. They can exert forces up to 400 times their weight, while normal DC-actuators can only exert around 16 times [1]. Therefore, pneumatic actuators could easily replace electrical actuators with gears and springs. Inherent to this approach is

the need of a supply of pressurized air – or gas in general. This has either to be carried in a pressure reservoir (max. energy density of pressurized air at 20 °C is 460 kJ/kg) or produced onboard using a compressor, which would have again to be powered by an electrical motor. While it is clearly possible to use a combustion engine, this is obviously of no practical use for most applications. Still, in a chemical way, energy can be stored with very high density. For comparison, the energy density of e.g. diesel fuel is 41900 kJ/kg – almost 90 times compared to pressurized air.

Thus, a system providing pressurized gas directly from a chemical or thermodynamic process would help to reduce size and weight of medical orthoses and make them useful in an every-day environment. The aim of this study was to investigate principles and methods to provide sufficient pressurized gas for a day full of activity.

2 Methods

To reach this goal, a system for the support of sit-to-stand movements for elderly people was excogitated and used to specify the energy needed [2]. Sit-to-stand movements and stair climbing were considered. For level walking the device should only compensate for internal friction and inertia.

Literature was then searched for all kinds of processes known in technical applications that provide pressurized gas for any purpose. After analyzing the identified options, a selection was made considering the aspects safety, toxicity of the reacting agents (educts) and reaction products, heat produced during the process, and practicability. After eliminating dangerous reactants and obviously impractical options from the list, the remainders were analyzed more thoroughly considering the features weight, energy density, and technical complexity.

3 Results

The envisioned active knee orthosis provides a torque of 30 Nm over an angle of up to 110°. Assuming a number of

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Table 1: Main specifications

item	stroke	max. torque / average torque	number of movements per day (12 hours)	one stroke volume	volume total
sit to stand	110°	30/5 Nm	60	61.43 ml	3.69 l
stair climbing	25°	12/2 Nm	50	6.49 ml	0.32 l
level walking	15°	0.8/0.8 Nm	2000	0.26 ml	0.52 l

60 sit-to-stand movements over 12 hours of daily activity 50 stairs to be climbed, and 2000 steps of level walking the volume of gas needed to drive the orthosis could be calculated. The length of the lever arm r is calculated from the maximum torque M and the force F with circle area of the piston A and pressure p .

$$r = \frac{M}{F} = \frac{M}{A \cdot p} \quad (1)$$

The distance Δx covered by the piston in the cylinder is determined by the following equation with angle φ :

$$\Delta x = 2 \cdot r \cdot \sin\left(\frac{\varphi}{2}\right) \quad (2)$$

From equations (1) and (2) follows the one stroke volume V :

$$V = A \cdot \Delta x = 2 \cdot \frac{M}{p} \cdot \sin\left(\frac{\varphi}{2}\right) \quad (3)$$

The resulting specifications are summed up in Table 1.

Seven different options have been identified (see Table 2). A first sorting has been done according to the features hypergolic properties, decomposition, spontaneous reaction, reaction after ignition, and simple decompression including phase change and heat transfer.

The rocket propellants like liquid oxygen ($O_{2[l]}$) and ethanol (C_2H_5OH) or hydrazine (N_2H_4) and dinitrogen

tetroxide (N_2O_4) have a high energy density. Nevertheless, the combustion of these rocket fuels produces extremely high reaction temperatures (see Table 2) and therefore cannot be realized.

After eliminating the toxic and impracticable options the remainders were analysed considering the main criteria energy density, safety, eco-friendliness, and technical feasibility. The topic safety is subdivided into health hazard, chemical hazard, and physical hazard. Effects of the substance on the human body (eyes, skin, respiration, carcinogenicity, etc.) are included in the aspect health hazard. The chemical hazard mainly refers to the chemical stability, which is inferred from the self-accelerating decomposition rate of each reacting agent. The extremely high and low temperatures after the chemical reaction are considered as physical hazard. The criterion technical feasibility of the construction comprises the number of components, the type of fuel transport, and the necessary heat supply.

The reactions are rated with points from 1 (barely sufficient) to 5 (ideal) in each category. Table 3 shows the results. Figure 1 compares the results of the evaluation of the chemical processes. The category health hazard corresponds to the average of the health hazard of educts and products.

Table 2: Identified options to provide pressurized gas through chemical or thermodynamic reactions. Chemical product marked with an asterisk are considered highly toxic.

No.	character	educts	products		energy density kJ/kg	density at 8 bar g/l	tempera- ture °C	endo- / exothermic	activation
			gas	by-product					
1	decomposition	H_2O_2	O_2, H_2O	-	543.4	1.34	1351.8	exothermic	catalytic
2	combustion	$O_{2[l]}$ C_2H_5OH	CO_2, H_2O	-	1979.8	0.36	7150.5	exothermic	ignition
3	combustion	$N_2H_4^*, N_2O_4$	N_2, H_2O	NO_2^*, NO^*	1763.2	0.41	4929.3	exothermic	hypergolic
4	thermal decomposition	$NaClO_3$	O_2	$NaCl$	144.2	2.28	1080.3	exothermic	heat transfer
5	thermal decomposition	$NaHCO_3$	CO_2	Na_2CO_3 H_2O	24.2	7.88	265.4	endothermic	heat transfer
6	dissolving	$NaHCO_3$ CH_3COOH	CO_2	CH_3COONa H_2O	37.9	8.93	201.7	endothermic	spontaneous
7	decompression with phase change	$CO_{2[l]}$	$CO_{2[g]}$		50.4	14.45	-14.9	endothermic	spontaneous

Table 3: Evaluation results of the chemical reactions

No.	reacting agents	energy density	health hazard		chemical hazard	physical hazard	eco-friendliness		technical feasibility of the construction	sum
			educts	products			educts	products		
1	H ₂ O ₂	5	2	5	2	1	4	5	4	28
4	NaClO ₃	4	4	4	4	1	1	5	3	27
5	NaHCO ₃	2	4	4	1	4	4	4	2	25
6	NaHCO ₃ CH ₃ COOH	1	2	4	1	4	4	4	2	22
7	CO ₂ [1]	2	5	5	5	4	5	5	4	35

The same applies to the category eco-friendliness.

Hydrogen peroxide achieves a good rating, especially in the categories energy density and technical feasibility. However, hydrogen peroxide (H₂O₂) is metastable and tends to

Figure 1: Results of the evaluation of the chemical reactions

decompose spontaneously releasing the stored energy at once, which can be dangerous if control is lost [3]. The rate of decomposition rises due to both contamination of the dissolution with metal oxides and with increasing temperature or concentration [4].

The reactions with sodium chlorate (NaClO₃) and natron (NaHCO₃) achieve only 2 or rather 3 points in the criteria of technical feasibility. This is due to the practicability of the chemical reaction. The educts are solid and therefore require a more complex fuel transport to the combustion chamber than liquid or gaseous substances. In addition, thermal energy must

be supplied in all reactions, especially in the decomposition of sodium chlorate. This only takes place at 478 °C [5]. In all three reactions, solid by-products are produced in addition to the required gas.

Liquid carbon dioxide has the lowest energy density of the assessed principles but performs best in safety, eco-friendliness, and feasibility. Its phase change during decompression allows a high energy density in kJ/l.

4 Discussion

It becomes clear that the majority of options would be able to provide sufficient gas volume at the desired pressures. For evaluation purposes, the reaction enthalpy was calculated neglecting any heating-up effects or heat losses. This seems to be appropriate for comparison but should be rendered more precisely for modelling and control of such processes.

Most of the reacting agents or the reactions products tend to be toxic in different ways. Reaction products like carbon dioxide or steam would be acceptable given a large enough room or indoor air exchange rate. Highly concentrated hydrogen peroxide exerts a cytotoxic effect on tissue. Nevertheless, H₂O₂ is only an educt and normally will not be released into the environment. Even more toxic is the by-product of the combustion of hydrazine and nitrogen tetroxide – nitrogen oxides. To avoid the poisoning of the environment, an exhaust aftertreatment would be necessary. Selective catalytic reduction could be utilised for this purpose. It is already applied in the exhaust aftertreatment of diesel engines. Nitrogen oxides are broken down into nitrogen and water by ammonia [6]. Nevertheless, this aftertreatment would drastically complicate the technical implementation of the device. Therefore, this reaction was not further investigated.

Figure 2: Principle of the technical implementation with liquid CO₂: liquid CO₂ is stored in a container, which is locked by the first valve. The gas is then expanded by a first expansion valve, heat is exchanged with the environment in the heat exchanger and the gas is then actively heated to the desired temperature. Finally, a directional control valve feeds the gas to the cylinder (from left to right).

Only a few reactions were examined more closely and finally evaluated. The best option, expanding and heating liquefied carbon dioxide to room temperature involves not only rather simple chemistry but also leads to a lightweight and technically simple system. Moreover, CO₂ is particularly convincing with regard to safety. Carbon dioxide is chemically stable, does not cause extremely high reaction temperatures and is not hazardous to human health as long as sufficient air exchange is ensured.

Compared to the other chemical reactions the phase change of liquid carbon dioxide performs best. However, CO₂ has the lowest energy density. It amounts only to around 50 kJ/kg. Nonetheless, the low energy density of CO₂ is sufficient to supply the pneumatic cylinder with the necessary pressure.

In comparison to compressed air, the energy density (in kJ/kg) of CO₂ is ten times lower. Still, utilizing CO₂ leads to a much lower initial volume (for 60 sit-to-stand movements only around 37 ml) than compressed air (for 60 sit-to-stand movements around 834 ml). Comparing the energy density in kJ/l of CO₂ and compressed air under the same conditions, the energy density of CO₂ is nearly eight times higher.

In the further course of this study therefore, a principle was developed for the technical implementation of the pneumatic actuator with CO₂ (Figure 2).

This would consist of a pressure reservoir containing 28.39 g of CO₂ (for 60 sit-to-stand movements), a safety valve, a control valve and a throttle valve included in a passive heat exchanger to heat up the fluid after expansion, an active heat exchanger to heat the fluid up to the desired temperature and pressure and the actual directional control valve to initiate the piston's movement. The heat flow will be controlled to achieve an energy-efficient gas production at any rate using as much environmental heat energy as possible while maintaining the pressure in the system.

Further work will comprise the modelling of the expansion and heating process including valve dynamics and fluid consumption in the cylinder and the mechanical design of a lightweight active knee orthotic system.

Author Statement

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References

- [1] P. D. T. Teufel and I. I. Rechenberg, "Modellierung und Regelung pneumatischer Muskeln," 2005.
- [2] M. Gross, P. Stevenson, S. Charette, G. Pyka, and R. Marcus, "Effect of muscle strength and movement speed on the biomechanics of rising from a chair in healthy elderly and young women," *Gait & posture*, vol. 8, no. 3, pp. 175-185, 1998.
- [3] G. P. Sutton and D. M. Ross, *Rocket propulsion elements : an introduction to the engineering of rockets*, 4. ed. ed. (A Wiley-Interscience publication). New York [u.a.]: Wiley, 1976.
- [4] J. Hartmann-Schreier, "Wasserstoffperoxid," ed: Georg Thieme Verlag, 2004.
- [5] C.-C. Rossow, K. Wolf, and P. Horst, *Handbuch der Luftfahrzeugtechnik*. Carl Hanser Verlag GmbH Co KG, 2014.
- [6] O. Kröcher, A. Tissler, and R. Althoff, "The State of the Art in Selective Catalytic Reduction of NO_x by Ammonia Using Metal-Exchanged Zeolite Catalysts AU - Brandenberger, Sandro," *Catalysis Reviews*, vol. 50, no. 4, pp. 492-531, 2008/12/01 2008.