DIGITAL FLUID POWER FOR EXOSKELETON ACTUATION – GUIDELINES, OPPORTUNITIES, CHALLENGES

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ABSTRACT

Exoskeleton technology is currently getting a strong momentum by increasing academic and industrial R&D work, by the foundation of new enterprises, and by rising sales numbers. More and more rumours are circulating about hydraulic actuation. Hydraulics companies are exploring the business opportunities as a basis to decide on investments in the development of appropriate hydraulic actuation technologies. This paper starts with some insight into the state of the art of exoskeletons and actuation technologies. General requirements are discussed first. More specific ones are studied by the simulation of a knee joint actuator for two specific motions, a squat and fast walking. Finally, the concept of a digital hydraulic cylinder and its control by a hydraulic binary counter for a knee joint is presented. It is assessed by these two motions and some design aspects are discussed.

KEYWORDS: Exoskeleton, hydraulic drives, digital hydraulics, digital cylinder, hydraulic binary counter.

1 WEARABLE ROBOTICS

1.1 Definition and purpose

Exoskeltons form a subset of wearable robotics devices. These are defined in [1] as "*technology that extends, complements, substitutes or enhances human function and capability or empowers or replaces (a part of) the human limb where it is worn*".

Such exoskeletons are defined here as devices which are worn outside of human limbs either to enhance power, force, durability, or load carrying capacity of a person (empowering exoskeletons) or to regain lost or weak limb functionality (orthotic robots). Not considered here is prosthesis, a third type of wearable robotic functionality, which is replacing lost limbs. A complete wearable robot has some structural elements interconnected by mechanical joints and connected to the body, some active or passive elements creating support for the human motion, and functions to recognize the movement intention of the human. Even though this paper is devoted to hydraulic exoskeleton actuation, a proper consideration of the other sub-systems is necessary, since only a system with matched components can provide the expected performance.

Fig. 1: Lower limb exoskeletons: left: Hyundai to provide walking aid; right: Ekso Bionics a full locomotor for a paretic person.

Fig. 2: Left: XOS 2 Full body exoskeleton for military use by Sarcos/Raytheon; right: Lockheed Fortis for worker support; a passive system.

The areas of use of exoskeletons are quite different. It ranges from therapeutic tasks for individual joints, e.g. to assist recovery after implanting an artificial knee joint, over assistance to part of a worker's limbs in specific working conditions to a full locomotor system for enabling walking of a paraplegic or for extending the operation range and durability of an action force.

1.2 Topicality

There are some hints that the market for exoskeletons will increase substantially in the next years. A press release by WinterGreen Research [2] gives a growth expectation from $16.5 million in 2014 and $36.5 million in 2015 (all for medical exoskeletons) to $2.1 billion by 2021. Costello [3] argues that "*Exoskeletons and wearable robotics are where drones were 5 years ago, on the cusp of commercialisation. They are almost ready to explode on the market in many varied applications from medical rehabilitation to solidly deployable industrial manufacturing exoskeletons*." He states the same market growth numbers as [2] and lists several challenges concerning control, materials, and battery life and that tests of Lockheed Martin's 'Hulc' - a lower limb exoskeleton for military use (see [4]) - quickly showed that it actually tired wearers faster than walking unaided. Furthermore, it was a commercial failure because the control system used was linear and slow, whereas human movement is more complex. NDTV [5] speaks of 80 million disabled people in China, many of them unable to walk, and estimates the global market for walk-assisting exoskeleton robots to exceed $1.8 billion by 2020.

1.3 General requirements relevant for actuation systems

Wearing comfort is essential for a broad acceptance of exoskeleton technology for all types of use. The examples in Fig. 1 and Fig. 2 show a considerable size and weight of the exoskeletons which is conflicting with most wearers' expectations on high compactness, in particular, a low distal space. Normal human movability should not be restricted.

Efficiency of the drive systems is mainly a matter of wearing comfort (size and weight of batteries or other energy sources and the corresponding prime mover, if required) and operating time and range. Energy cost is secondary.

Exoskeleton weight and inertia costs extra force and power and may alter the natural motion of the human. Therefore, light weight and compact design are key requirements on all components, of course, also on actuators and the power supply system. There is a progressive effect of light-weight design breaches. A heavy component requires more force to be actuated, stronger structural elements to provide support, and larger power supply units to provide the additional power demand. In turn, the corresponding sub-systems become larger and heavier and exponentiate the weight effect. In [6] acceptable weights are seen in the ranges of portable consumer electronic devices for the hand, or of a backpack for the spine or hip.

A major aspect is to emulate the natural human motion and to protect the human locomotion system, i.e. the limbs and the muscles against overload and injury. Human walking, for instance, has a strong passive portion. Ankle, knee and hip actuation interact. The shank motion, for instance, is the result of gravitational and muscular forces and the knee joint motion [7]. Power is transferred from the ankle joint to other body segments [8]. Control of the many muscles seems to follow certain patterns which are developed when learning to walk. The free swing of the shank, for instance, should be facilitated by releasing the knee joint actuator in that phase. Back-drivability of the actuation system is a minimum requirement, but is probably insufficient if the actuator has high inertia as is the case for electric drives combined with a high gear ratio mechanical transmission.

1.4 The symbiotic mechatronics paradigm for exoskeleton actuation

A further aspect is to which extent the actuation system can support other functions, like the support (structure) function, the control or even detecting the wearer's intention, in order to optimize the system performance. In best case the sub-systems of the exoskeleton and the human body parts form a symbiotic mechatronic system.

Symbiotic Mechatronics is a new design paradigm developed by the Linz Center of Mechatronics (LCM) and is the name of an Austrian COMET K2 Center which will be run by LCM in 2018-2021. It was developed in the process of identifying the role and proper nature of future mechatronic systems which more and more will be parts of a cyber physical system. In [9] symbiosis in this context is defined as

"an association yielding mutual benefits for the involved agents; it is related to the central hypothesis that exactly this mutual benefit can be created for mechatronic systems and for the entities they are interacting with."

Proper control, for instance, is key for such a symbiosis. It requires the sound understanding of the human motion as mentioned in the last paragraph for realizing that symbiosis. Human motion control seems to differ strongly from conventional engineering control. In [10] it is shown to be accomplished by "*a small set of basic temporal components or activation patterns, shared by several different muscles and reflecting global kinematic and kinetic goals.*" In a symbiotic setting the actuation system has to be such that it matches this principle and benefits from it. Benefits for the actuation system are, for instance, lower weight, higher compactness, less energy consumption, ease of adaptation to different types of motion, joints, and wearers' body data.

Therefore, exoskeleton development is foremost a system design task. However, an exoskeleton which works in a satisfactory manner requires also specially designed sub-systems which fulfil the high technological demands. Thus the tight cooperation of system designers with top notch experts in the relevant engineering fields, like robotics, drive technology, control, light weight design, sensor technology, and medicine is necessary.

1.5 State of the art of exoskeleton actuation

In a literature survey done by a group at the author's university on exoskeleton research in summer 2016 from more than one thousand papers only 63 were dealing with hydraulic drives, however 151 with electro-mechanical drives. This reflects the situation concerning the prevalence and perception of appropriateness of modern drive technologies. Robots, the big brother of exoskeletons, are dominated by electrical drives, at least industrial robots. Mobile robots like humanoids or quadrupeds use hydraulic drives to a substantial extent, as is the case of most of Boston Dynamics robots [11] or the quadruped of the Italian Institute of Technology (iit) [12], for instance.

Hydraulic actuation was quite prominent in the beginnings of exoskeleton development. University of California at Berkeley did so for its lower extremity exoskeleton entitled BLEEX [13] to [15], shown in Fig. 3, as well as XOS 2 of Sarcos [16], shown in Fig. 2, both for augmenting the performance of humans. Fig. 3 shows also the hydraulic concept of BLEEX. This and XOS 2 use resistance control by servo valves as also

Boston Dynamics and iit do for their mobile robotic systems. The main argument for hydraulic drives is the low peripheral mass which is crucial to achieve the required dynamic properties and is enabled by the high force density of hydraulic actuators. This advantage is thwarted by the bad efficiency of resistance control which rules out the use of electrical batteries as energy source and brings in combustion engines to exploit the high energy of fuels.

Hydraulic actuation concepts discussed in [17, 18] employ displacement control principles which have lower losses but are dynamically less performant than resistance control. The system described in [17] uses a variable speed electrical motor in combination with a constant displacement pump for the actuation of ankle prosthesis, the ELBOT lower limb exoskeleton [18], instead, an interesting switching concept in combination with displacement control. Thus, it can be classified as a digital hydraulic concept: according to the classification of Linjama [19] it is on-off type. In [20-22] switched inertance type hydraulic control in form of a hydraulic buck converter of the iit HyQ mobile robot is investigated. A moderate efficiency advantage over resistance control is outweighed by actuator softness due to the hydraulic accumulator needed to reduce pulsation effects due to switching and by the high mass of the converter block. The buck converter's performance suffered from its oversize for the particular application which reduced its energy saving potentials considerably. The major concern is the little chance seen to reduce the weight of the required fast switching valves and of the hydraulic block.

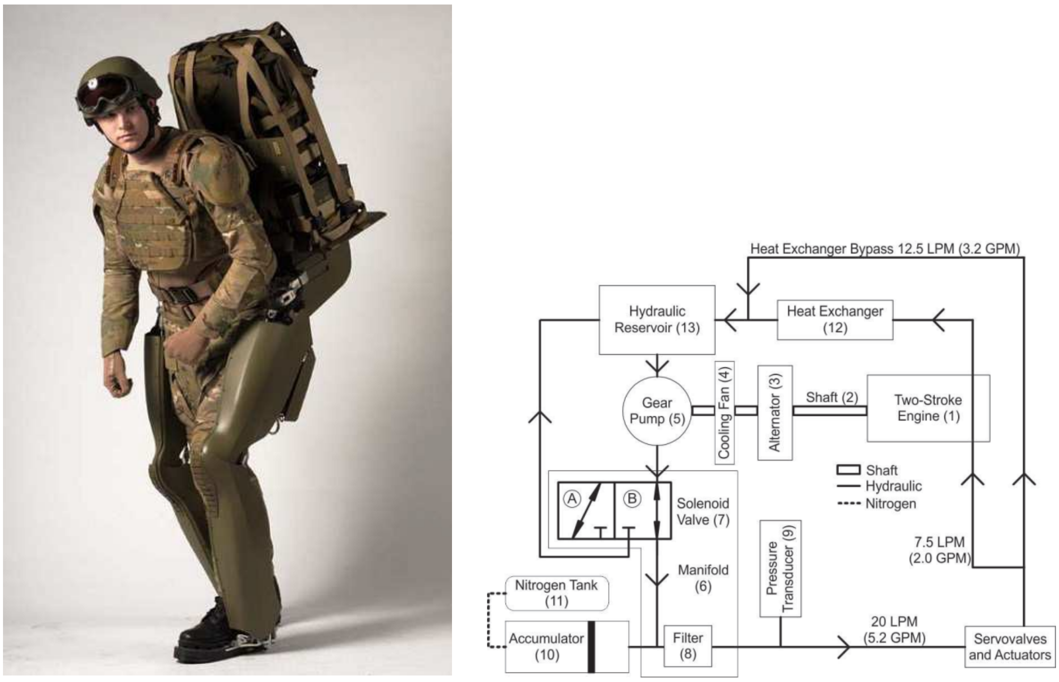

Fig. 3: Berkeley's lower limb exoskeleton BLEEX and its hydraulic actuation concept.

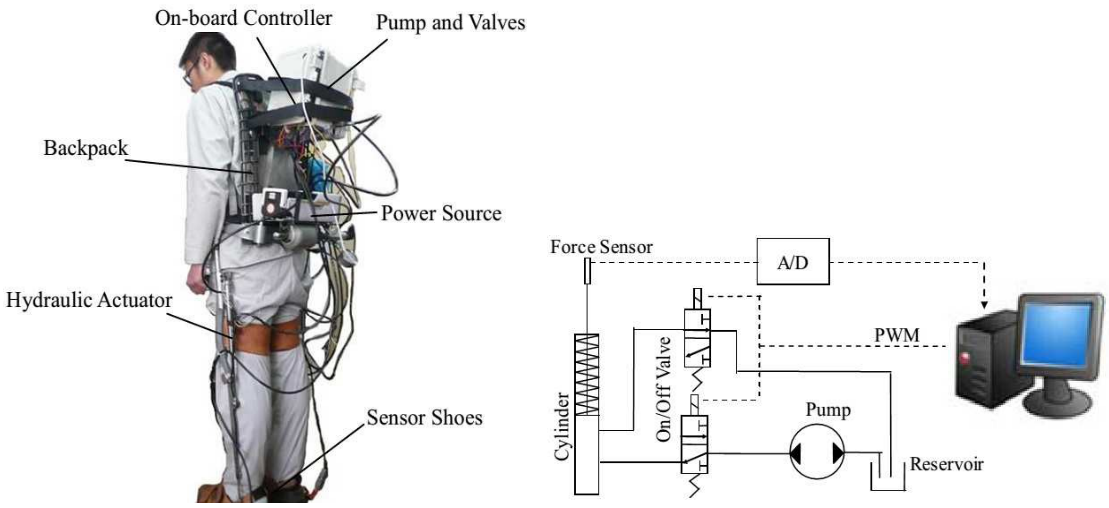

Fig. 4: Berkeley's The ELEBOT lower limb exoskeleton and the hydraulic actuation concept.

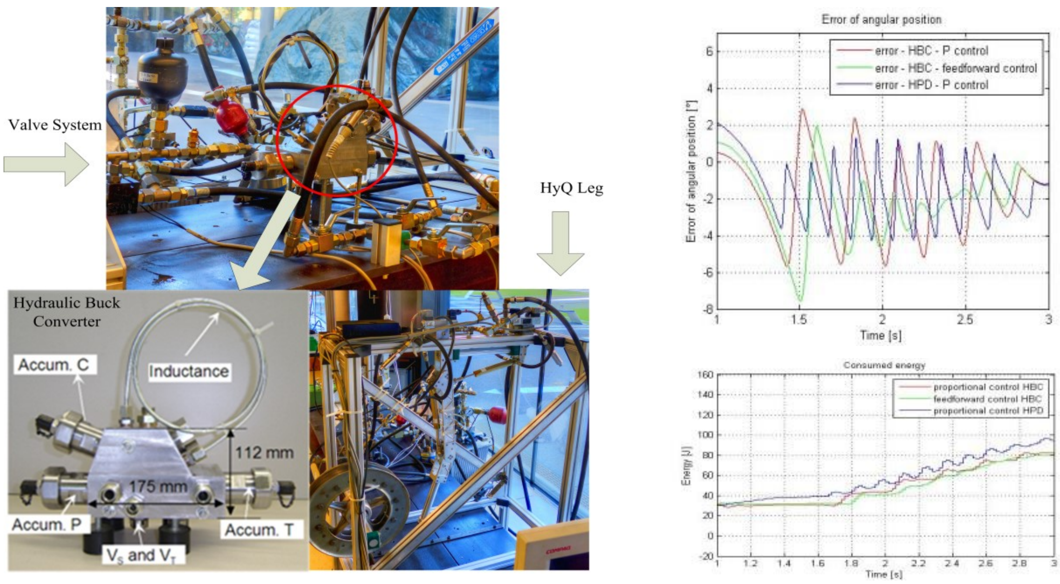

Fig. 5: Test rig and results of a hydraulic buck converter for driving a quadruped joint [22].

Electrical motors need some gear to transfer the rotary movement to the exoskeleton joint to overcome some distance, e.g. by cables, and to adjust the motor characteristic to the working characteristic of the exoskeleton. In [23] electrical drives are assessed as follows:"*Electric actuators are limited by their need for transmission elements to convert their high-speed, low-torque output to the low speeds and high torques needed to drive orthoses. These transmission elements may negatively affect the back-driveability, efficiency, safety, size, mass, noise, cost and complexity of electric actuators*." Furthermore, due to the relatively fast movements of the legs during locomotion, gear ratios cannot be made too large which limits the torque assistance of electric actuators according to [24]. An impressive development is ANY drive, developed be ETH Zurich. It weighs 1 kilogramme, has a nominal and peak power of 240 and 720 watts, a programmable controller and is manufactured and sold by the company ANYbotics.

Fig. 6: ANYbotics' ANYdrive; a compact powerful electro-mechanical actuation system for robotic applications also intended for use in exoskeletons.

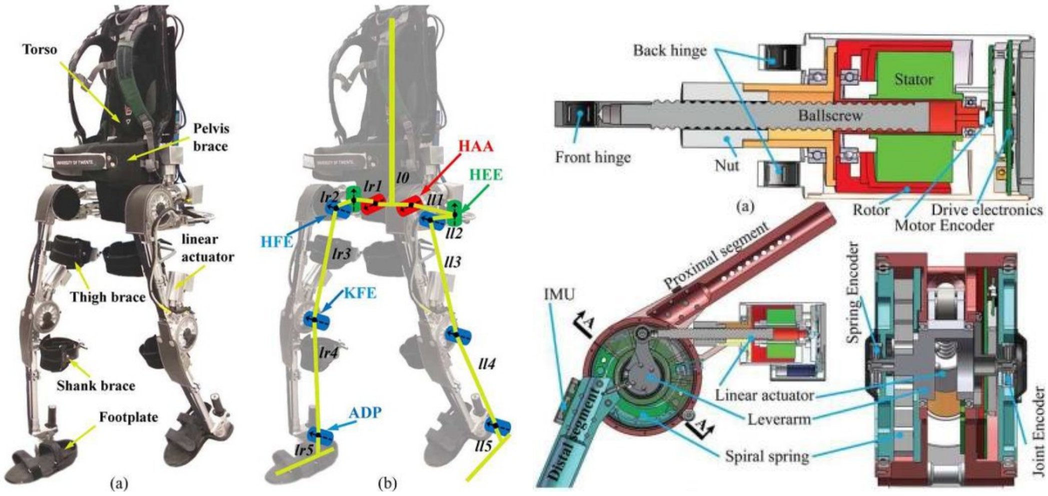

Fig. 7: Mindwalker is a lower limb exoskeleton with electric motor, ball screw gear and series elastic joints.

Mindwalker was developed by the University of Twente [25 - 27] and funded under the Seventh Framework Programme of European Commission. It consists of a permanent magnet brushless DC motor, a ball screw and a spring.

This section does not give a full report about all published type of exoskeleton actuators but only an insight into the state of the art. Several proposals for passive joints using spring and damper elements do exist and several groups – like the one developing Mindwalker – integrate passive parts into their active drive systems in order to obtain a favourable behaviour and compensate some weakness of the chosen drive.

1.6 Assessment of current drive technologies

In the eyes of the author currently no proven actuation technology exists which fulfils all major requirements for a broad use of exoskeletons. There is at least one conflict with the three most challenging criteria

- Low weight and high compactness
- Low energy consumption
- Symbiosis with the human motion system and the superior control level.

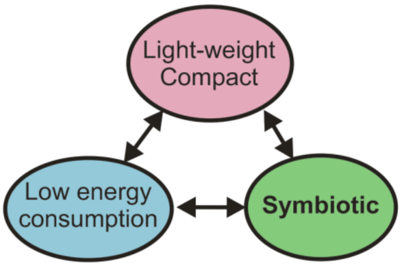

Fig. 8: The "trinity of requirements on exoskeleton actuation technology".

Actually, according to the state of art of actuation technologies the fulfilment of each of these criteria requires the other two to be fulfilled; they can be seen as a symbiotic triple or as the "trinity of requirements on exoskeleton actuation technology".

This offers the opportunity for new drive/actuation technologies, in particular to fluid power and digital fluid power, to fill this "technology vacuum". The present paper intends mainly to encourage digital fluid power community, academia and industry, to step into this area. If fluid power will be successful it could help to improve its image as a modern, competitive, and in some application areas superior technology.

2 DIGITAL FLUID POWER CONCEPTS

2.1 Quantitative mechanical requirements on the actuators

In this paper lower limb actuation is taken as reference for the assessment of different technologies. Fast gait and a swat are used as two motion patterns. During gait the knee joint typically does not deliver energy in the average and the joint torque has a peak when the foot touches ground with negative power and positive power flow phases. The extensive measurements [28] done on a special treadmill at Darmstadt University of Technology which are made available in the data base 'HUMOD' [29] are used to get required kinematic and force data. The knee joint is selected. All major criteria on exoskeleton drives can be assessed here. Results are given for a male test person from central Europe with the following data [29]: Age: 32 years, Height 179 cm, Weight 84.8 kg.

For the squat a plane multi-body model according to Fig. 9, comprising foot, shank, thigh, and body was used. The required torque was derived from the inverse of the model. Motion body data were taken from [29]. More details of this model and its simulation will be published in [30]. The results of the computed torque and power together with the knee angle ψ and its time derivative are shown in Fig. 11. The computed torques are in the range -100 .. $+100$ newton meter. The surprisingly high negative torques result form the acceleration in the phase when the knee is close to the stretched position. This motion is energy preserving. Since the model disregards any dissipative effect (which in reality occurs in the joints, muscles, and tendons, and by textile friction) no energy is consumed in the average. Individual cycles might have resulting drive energy, due to cycle variations. This can be best seen from the phase-plot of ψ, $\dot{\psi}$, M_{req} in Fig. 10. The squat is a rather smooth motion apart from the phases of motion reversal and has a low bandwidth, as can be seen from the spectrum in Fig. 11.

The fast walking was computed in a different fashion. A two body model comprising foot and shank was used. The coordinates of the knee joint, the foot and shank angles, and the ground reaction force and its action line were taken from the 'HUMOD' database. The inverse of the model delivers the required knee torque. The results are presented in the same fashion as for the squat in Fig. 10 (right plot) and Fig. 12. The evolution of ψ is basically the overlay of two oscillations, a smooth one with very small joint torques which constitutes the swing back of the shank, and a more dynamic one, when the foot contacts ground. These two oscillations correspond to the two ellipses in the phase plot, shown by the plan view of the spatial curve in Fig. 10 - right plot.

The maximum positive torque is higher, approximately 150 newton meter, the most negative torque is only −50 newton meter. The average energy to be delivered by the joint actuator is negative. Thus energy can be harvested at the knee in fast walking and transferred to the ankle joint, where energy has to be invested. The required torque bandwidth of the of the fast walking is approximately ten times higher than of the squat and is about 5 hertz.

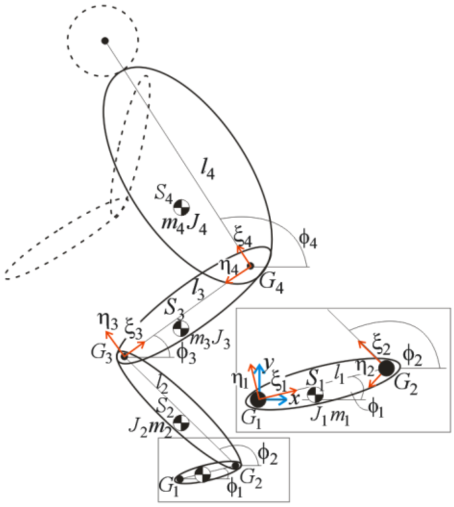

Fig. 9: Plain human body model: denomination of variables and parameters [30].

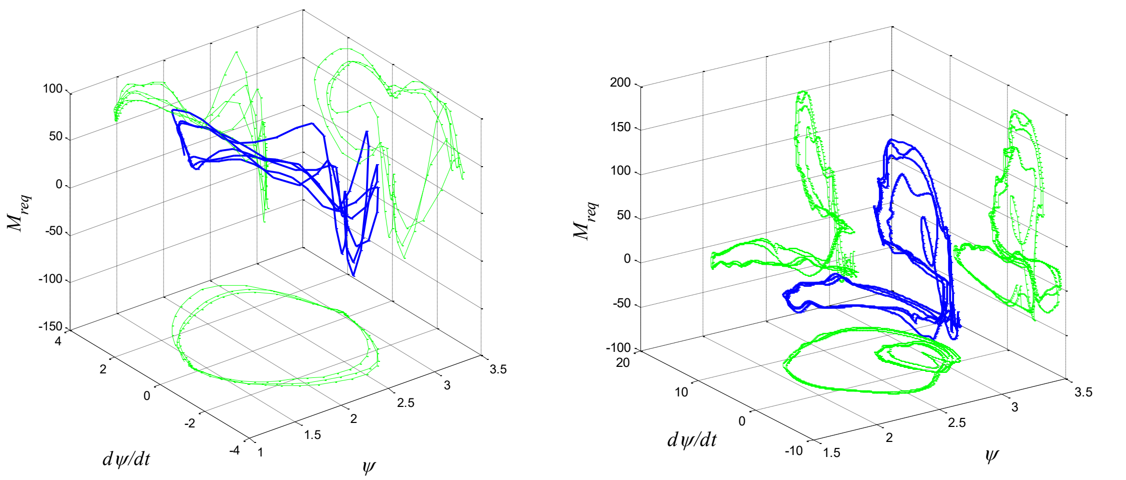

Fig. 10: Knee angle ψ, its time derivative $d\psi/dt$, and required torque M_{req} for squat (left) and fast walking (right). Results are the same as the time plots of and Fig. 12.

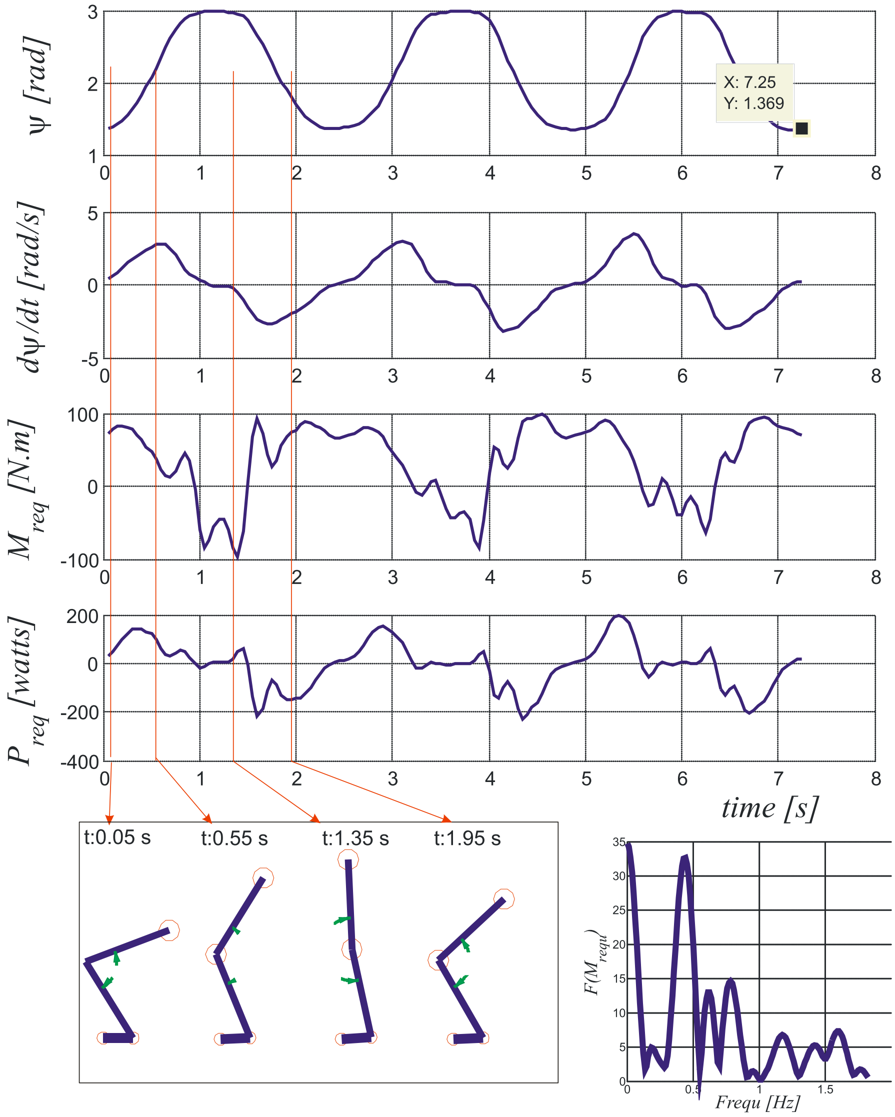

Fig. 11: Squat motion: knee angle ψ and angular speed $d\psi/dt$, required joint torque and power; lower left picture shows leg configuration at different times; bent arrows indicate the actual knee joint torque; lower right picture gives the amplitude-spectrum of the required torque.

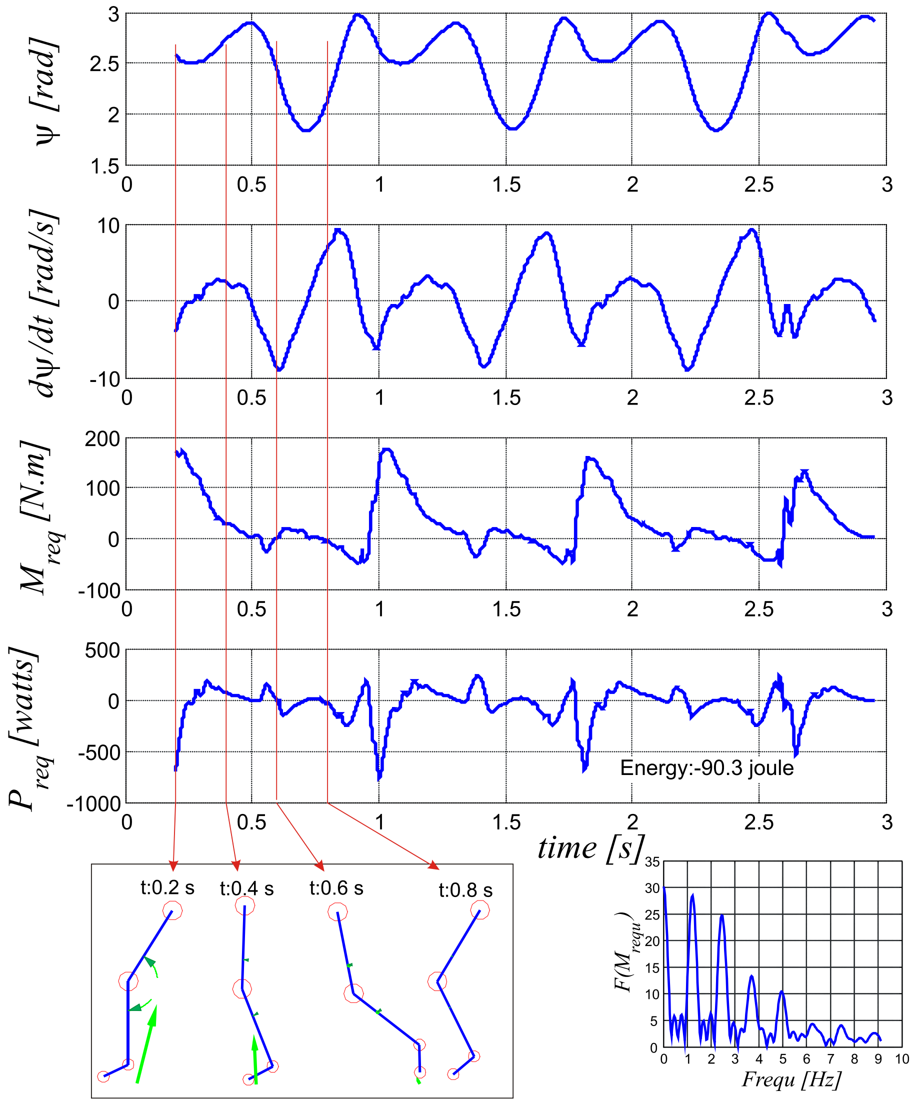

Fig. 12: Fast walking (2 m/s): knee angle *ψ* and angular speed *dψ/dt*, required joint torque and power; lower picture shows leg configuration at different times; bent arrows indicate the actual knee joint torque; straight arrow shows the ground reaction force; lower right picture give the amplitude-spectrum of the required torque.

2.2 System considerations

Actually, for a rigorous classification and assessment of digital fluid power concepts all varieties of sub-systems needed for the complete actuation system, from the energy source to the actuator and, if present, to the mechanical gear need to be taken into account in all meaningful combinations. This is not done here. Instead, some concepts and theoretical investigations are presented, which the author thinks to have a chance of becoming very competitive solutions.

That, however, is based on some assumption on the selection of some of the mentioned technologies: As energy source a battery is selected and not some fuels in combination with some combustion engine, as studied for exoskeleton use in [31, 32]. Availability of a light-weight and compact high power energy source which can be efficiently be transformed into hydraulic power, is key. A technology which can do that at least one order of magnitude better than a battery and, in addition, is not conflicting with other basic requirements, like safety, noise, or pollution, releases the hydraulic system from the efficiency requirement. Since such an alternative source at a sufficient technological readiness level is not available now, a battery is chosen.

In that case at least one electric motor and one pump are required. Depending on the concept, larger numbers of pumps or motors might be used.

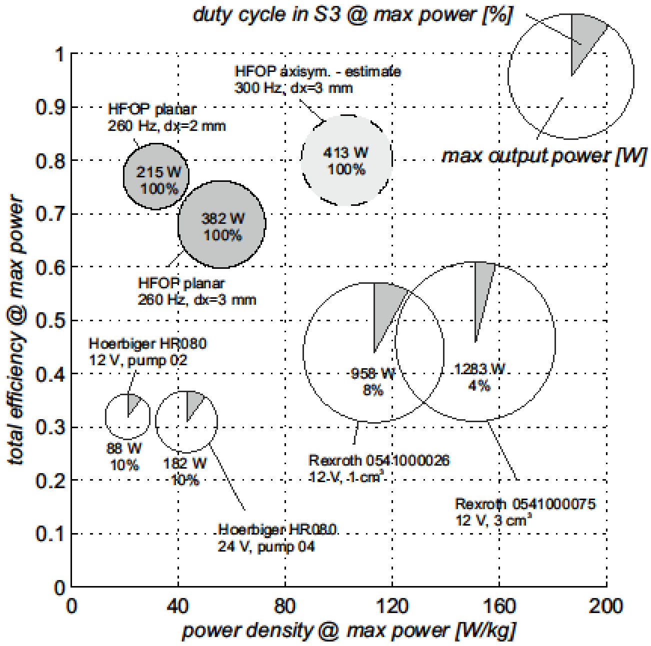

Fig. 13: Efficiencies and power densities of pump motor combinations in the factional horsepower range.

One extreme concept is using one speed variable electric motor and a constant displacement pump per actuator. Each of these motor-pump units must be able to provide the peak power of the driven joint. They could be placed close to the body to avoid high peripheral masses and to use hoses and pipes for power transmission. Of course, this is no digital concept but in the light of the success of speed variable electric motors – hydraulic pump drives in industry an obvious solution concept.

For the fast walking's peak power of approximately 750 watts (see Fig. 12) and a nominal power of only 162 watts a powerful motor weighs about one kilogram, e.g. a maxon motor EC4 pole with the product number 397800 weighs 0.86 kg without power electronics and cables and can drive a permanent power of 440 watts (4350 min^{-1}, 0.961 newton meter) and has a peak torque doubling the nominal torque. The peak power of two knee joints is not significantly higher, as can be concluded from Fig. 12, since the second leg takes that peak power when the first needs no power. Thus, one electric motor could drive both knees if a hydraulic actuation system can do the control of the individual joints.

2.2.1 Pumps

A hydraulic pump is a must. Taking the 750 watts at a pressure of 200 bars as reference, a flow rate of 2.25 liters per minute are required. With a speed of 4350 min^{-1} the specific displacement would be roughly 0.5 cm^3 per turn. Conventional fractional horse power pumps have a low efficiency and only a few products are available today [33]. Best pump efficiencies at the optimum operation point seem to be in the range of 50% to 60%. As a trend, higher rated power improves efficiencies. Also the weight advantage of low power pumps over electrical drives is less pronounced than of higher power pumps. From catalogue data of pumps or power supply units in the mentioned power range one can estimate that 0.4 kilogram to 1 kilogram is a realistic estimate if also the hydraulic block is taken into account.

Therefore, to keep total weight low, an exoskeleton drive system which can work with only one electric motor and one pump for several joints has a certain advantage, provided the control concept is not adding more losses and weight.

2.2.2 Valves

Also small hydraulic valves' weight characteristics scale badly with lower valve nominal flow rate. This relates mainly to the magnetic actuator with its coil and iron parts. One of the smallest fast switching valves seems to be the micro-valve package of IHA – Tampere University of Technology. According to [35] that 4 x 32 valve package weighs approx.. 9 kg, has a response time smaller than 3 milliseconds and a flow rate of 49 l/min at 35 bar pressure loss. This package features a very parallel design which allows a linear scaling of its size with respect to the required performance. The flow rate per metering edge is specified to 0.5 liters per minute at 5 bars pressure loss. Thus for the specified maximum flow rate of 2.25 l/min approximately 5 valves are needed, if 5 bars are accepted for the maximum flow rate case. In total this makes 10 valves and a weight of 0.7 kg. A Parker GS03 2/2 way valve has 1 l/min at 5 bar pressure loss and weighs 0.14 kg. To meet the 2.25 l/min in total 6 valves for both directions are needed which means 0.84 kg of weight. If such masses have to be placed at the joints no weight advantage over the best electromechanical devices can be gained. The next largest valve with a nominal flow rate of 9 l/min has the same weight, thus, only two valves are needed with only 0.28 kg in total. However, that valve has a response time of 40 milliseconds instead of 10 of the smaller valve. The Moog valve 024 Series Servo Valve has a mass of only 0.092 grams but consumes a pilot stage flow of 0.3 l/min which consumes a permanent hydraulic power of 100 watts if supplied with 200 bar of system pressure.

IHA - digital valve package (4x32 valves)

Parker GS02 -. 2/2 switching valve

Moog E024 series servo valve

Fig. 14: Three compact valves

These component data show that weight, compactness and low losses are very tough criteria and are hardly fulfilled by the currently available technologies.

2.3 A digital cylinder concept for a knee joint drive

2.3.1 Squat Motion

This is a fist study of the author's group on hydraulic exoskeleton actuation. A digital cylinder concept, as proposed by Linjama [36], is used. The realization of a squat motion, as described in Section 2.1 and Fig. 11, respectively, is taken as a first test case.

The details of this investigation will be published in [30]. Here only the concept, a sketch of the basic design and the results are reported.

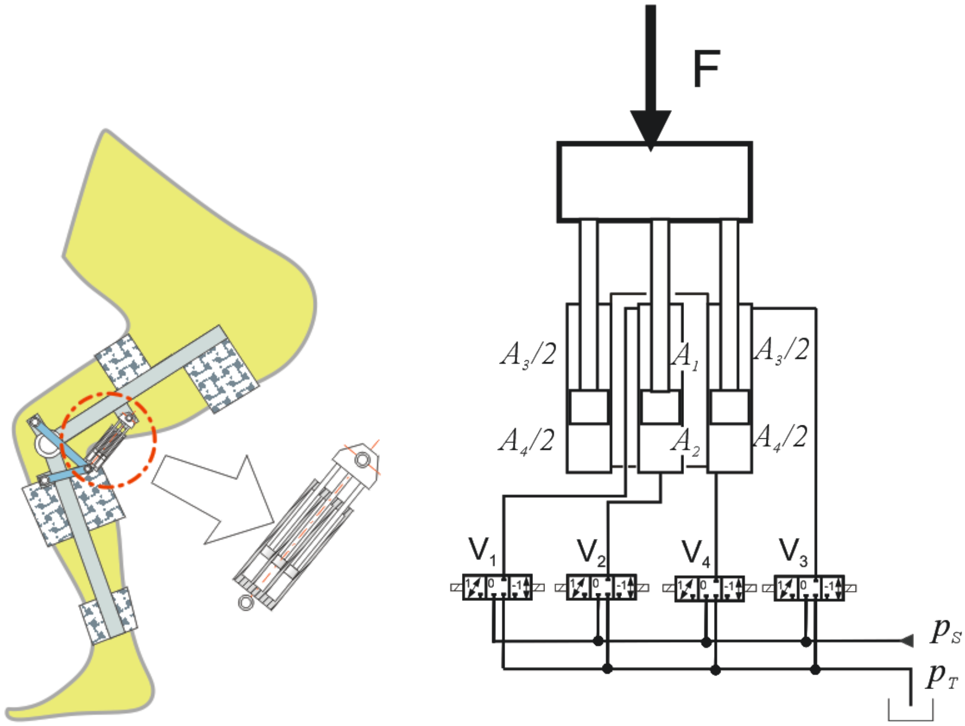

Fig. 15: A four chamber digital cylinder drive for a knee exoskeleton [30].

The digital cylinder is hydraulically composed of two mechanically synchronized dual stroke cylinders. The four chambers have areas $[A_1, A_2, A_3, A_4] = [0.12, 0.24, 0.48, 0.96]$. cm^2. With four 3/3 way valves 16 force levels in equal steps in the range [-1200 .– +2400] . newton can be created when a system pressure of 200 bar is used. The larger of theses two cylinders is realized as two identical cylinders which are placed on both sides of the smaller cylinder to annihilate the torques of all three cylinders at the hinge points (see Fig. 15). Furthermore, the three cylinders are identical and the serial arrangement gives a slim design such that actuator protrusion – a central criterion of wearing comfort - is small. A four bar linkage mechanism is applied to transfer the linear actuator motion to joint rotation in a favorable way. Its geometry has been optimized for adjusting the actuator with the load characteristics. The resulting gear ratio as function of the knee angle ψ is shown in Fig. 16.

A simple control concept was employed. For each sampling period a certain actuator force level (out of the 16 possible steps) was selected. These periods T_{period} were kept constant for a certain simulation run. Only one degree of freedom, the thigh angle ϕ_3, was left from the four body model according to Fig. 9 for integration. All other positions and their first and second time derivatives were taken from the database HUMOD, as described in Section 2.1. The force step was computed as the one closest to the force derived from an inverse dynamical model at the midpoint of the sampling period. The results for a sampling period of 0.1 seconds are given in Fig. 1.

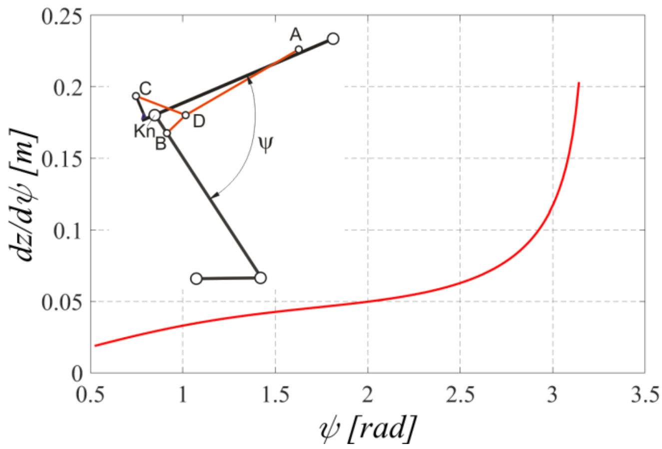

Fig. 16: Gear ratio *dz/dψ* of the four bar linkage mechanism; *z* is the cylinder extension.

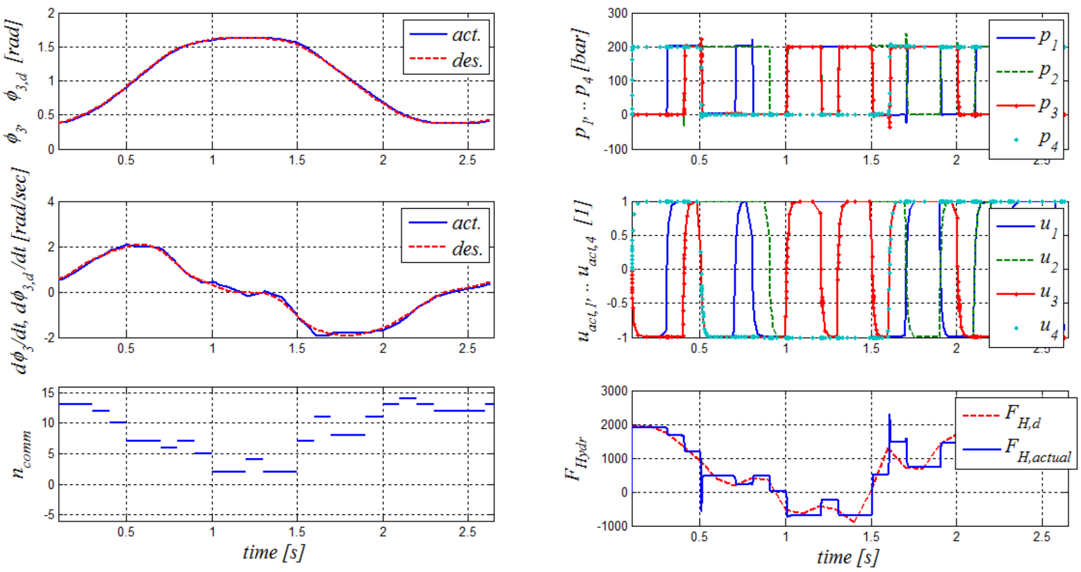

Fig. 17: Result of a simulation run for one full squat, sampling time T_{period}: 0.1 s.

The desired motion of the thigh angle ϕ_3 is met quite well despite the simple control concept. The actual hydraulic force which is the result of all cylinder pressures follows in steps the required force of the desired motion. Fig. 18 gives the flow rates to all four cylinder chambers and the oil volumes taken from the pressure (V_P) and submitted to the tank line (V_T). Since a constant pressure is assumed V_P is proportional to the energy consumed. The results show the good efficiency and the recuperation ability of that concept. Here, only compression and valve losses occur, since friction in the cylinders or in the mechanical joints was neglected. In this simple model the actuator consumes only 8.8 joule whereby squat lifting phase takes 91 joule. The control concept fails for this case if a sampling period of 0.2 seconds is used. Higher sampling rates lead to a better following of the desired motion but increase the compression losses. Of course, variable sampling periods could improve the control.

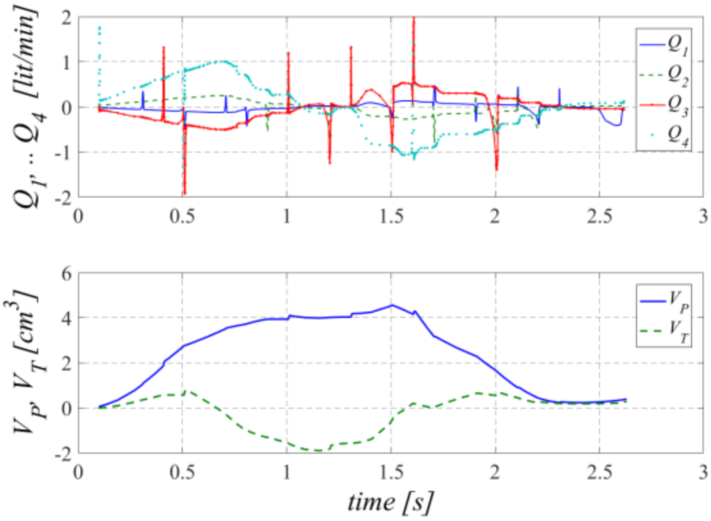

Fig. 18: Flow rates Q_i and consumed oil volume from pressure line (V_P) and tank line (V_T).

2.3.2 Fast Walking

Fast walking requires a higher actuator bandwidth. This can be concluded from the power peaks and torque gradients and spectrum in Fig. 12 . Basically, the same drive as for the squat is used, only the cylinder forces were increased to +2750 N and −1375 N.

Since the simple controller for the squat did not give satisfactory results for fast walking the controller was modified to a real model predictive controller with a one step control horizon and a two step prediction horizon. The model for finding the optimal controller output, i.e. the force level, used only the equations of motion and assumed a perfect cylinder force according to the selected force level. Thus, pressure build-up in the cylinder chambers and pressure losses in the valves were disregarded. However, in the simulation model for studying the full system these effects were taken into account. Also the sampling frequency had to be increased.

Results are shown in Fig. 19 and Fig. 20 for a sampling frequency of 20 hertz. The oil volume taken from the pressure line (V_P) is close to zero. The negative energy consumption of the knee joint for this type of motion as shown in Fig. 12 is consumed mainly by the compression losses in the hydraulic system. A larger sampling time leads to reduction of these losses but to a worse tracing of the desired motion as the results for a frequency of 13.3 hertz show in Fig. 21.

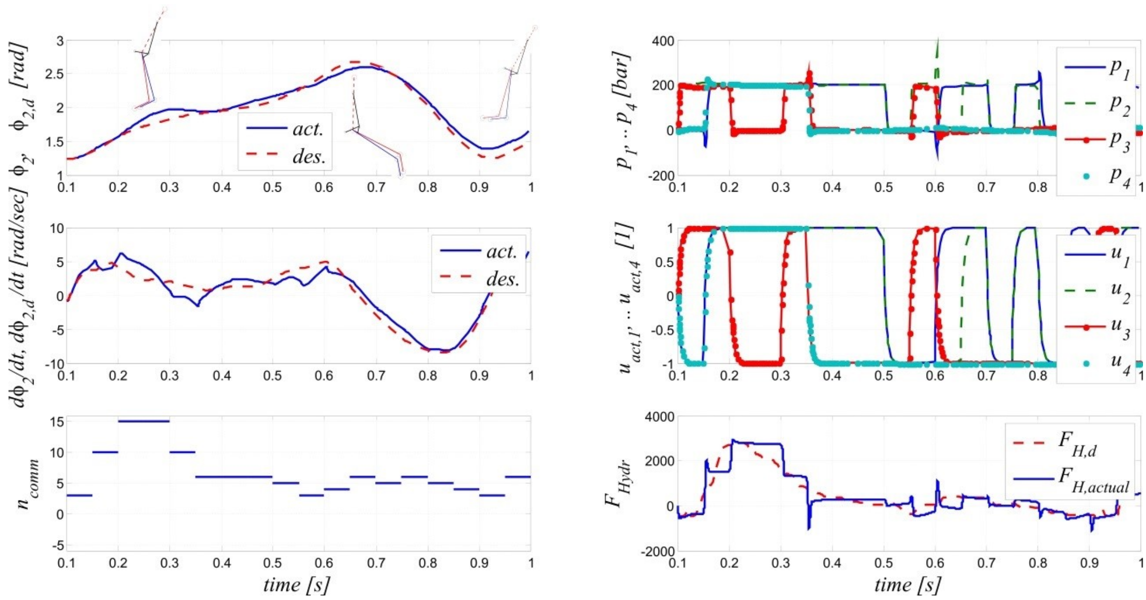

Fig. 19: Result of a simulation run for one full fast walking step, sampling time T_{period}: 0.05 s.

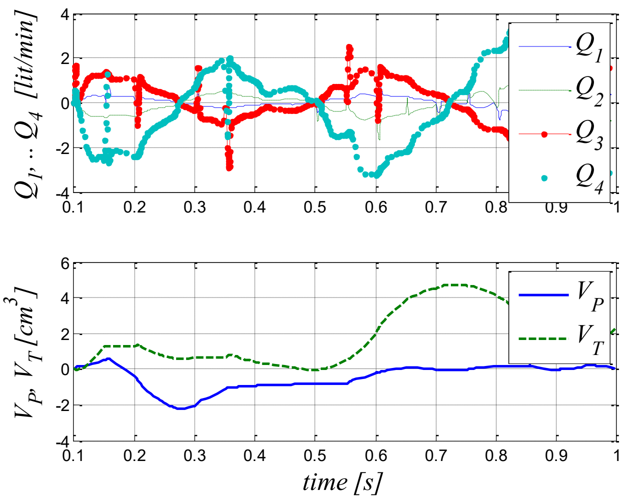

Fig. 20: Flow rates Q_i and consumed oil volume from pressure line (V_P) and tank line (V_T).

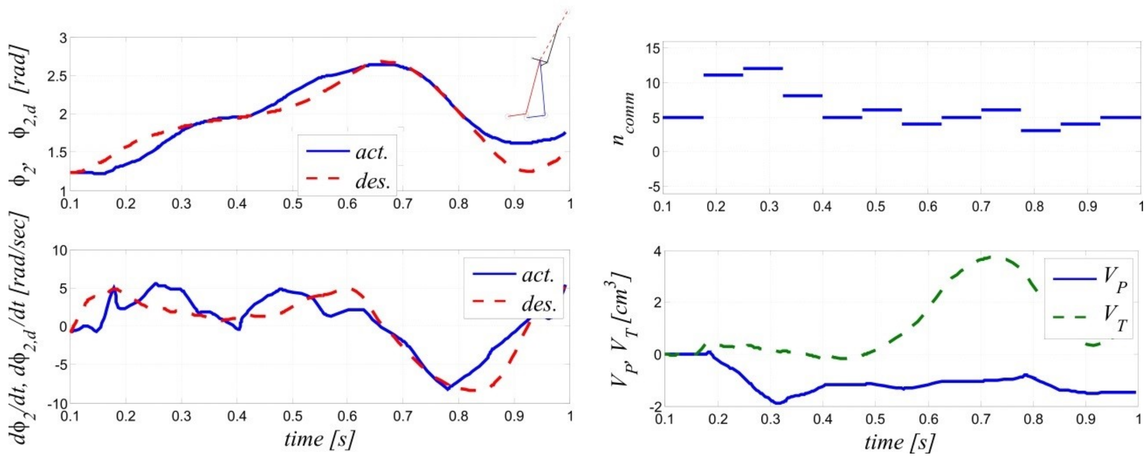

Fig. 21: Result of a simulation run for one full fast walking step, sampling time T_{period}: 0.075 s.

2.4 Design aspects

Low weight and a compact design are the essential challenges in the embodiment of the concept. Fig. 15 shows a cylinder design which might be realistic concerning the cylinder function but is missing the four valves shown in the schematic on the right hand side. According to the comments on valve technology in Section 2.2.2 a substantial extra weight and size would be added to the cylinder, if these valves are placed close to the cylinder.

2.4.1 Control by a binary hydraulic counter

In [37] a linear hydraulic amplifier was presented which employs a binary counter as essential element. It transfers the integral of an input flow rate – in other words an input flow volume – into a discrete value represented by the switching status of hydraulic valves. This concept can be exploited for the control of the digital cylinder also. Its main advantage over electrically actuated valves are the weight and space savings. A schematic of the concept is shown in Fig. 22. The input is a flow rate Q_x. It generates a pressure p_x in a pilot line. That pressure rises quickly as long as no valve switches from its initial state $u_i=-1$ to its on state $u_i=+1$. The hysteresis in the valve pilot pressure response to a displacement of its spool or poppet leads to a drop in pressure, which is essential for the binary counting properties. The pressure levels $p_{i,l}$ and $p_{i,u}$ are different for each valve; see Fig. 22. If the binary next valve switches, e.g. valve V_2, it lowers p_x to a pressure (e.g. $p_{2,l}$) below the lower threshold (e.g., $p_{1,l}$) of the one order lower valve, e.g. V_1. This makes this valve switching back to initial state (e.g., $u_1=-1$). In this way the state change of the four valves (V_1 to V_4) corresponds to the next integer of the input flow volume V_x if the fluid displacement due to switching of valve V_i is proportional to the series 2^{i-1}.

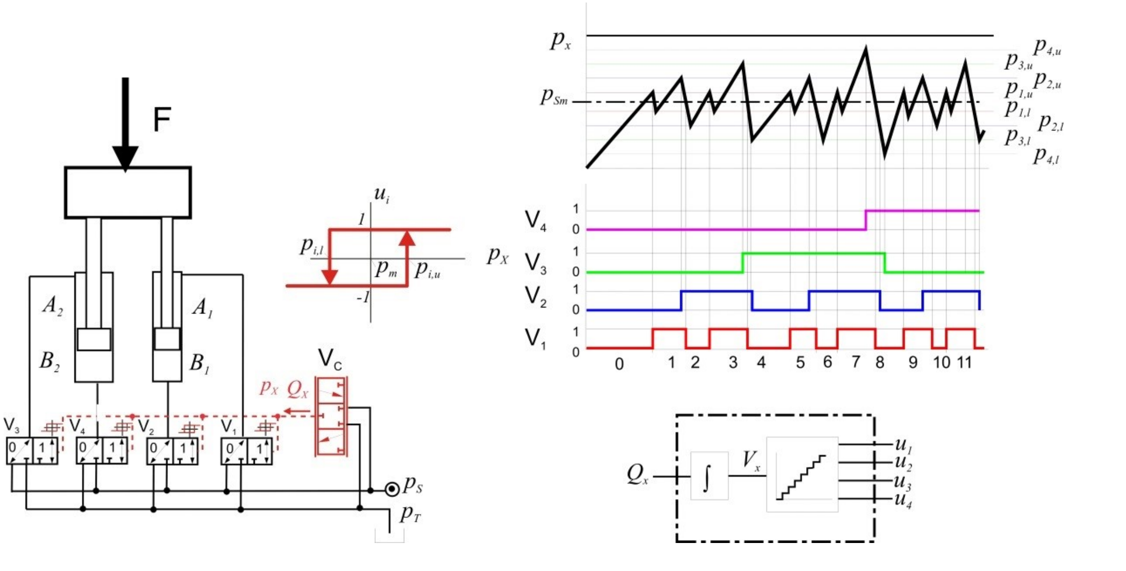

Fig. 22: Principle of the hydraulic integrating binary counter for the control of a digital cylinder drive.

They can be adjusted for each valve by a proper spring force $F_{S,i}$ and area $A_{i,x}$. The design in Fig. 23 is only a principle sketch and not a mature detail design. The valves are very small; a typical appropriate spool diameter would be 3 ÷ 4 mm. A robust design requires thorough consideration of tolerances as well as ease of manufacturing and assembly. The required metering edge openings are in the range of 0.05 to 0.2 mm. A fairly modular design for the four valve stages is recommended; for instance, using the same spool diameter and staggering the valve openings according to the series [1, 1, 2, 4] such that the fluid displacement if a switching of stage i covers all lower stages displacements.

There are different options to realize such valves. One is sketched in Fig. 23.

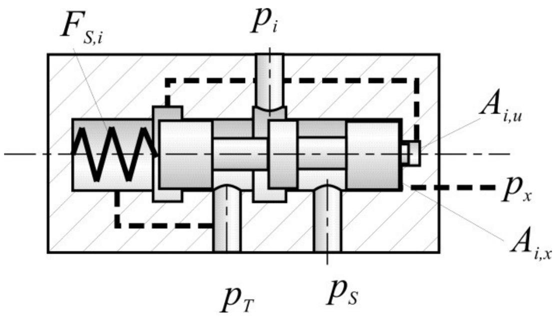

Fig. 23: Possible principle of a valve for realizing a binary counter.

If the spring force $F_{S,i}$ is constant, the switching pressures are

$$p_{i,u} = \frac{F_{S,i}}{A_{i,x}}; \quad p_{i,l} = \frac{F_{S,i}}{A}; \quad A = A_{i,u} + A_{i,x} . \tag{1}$$

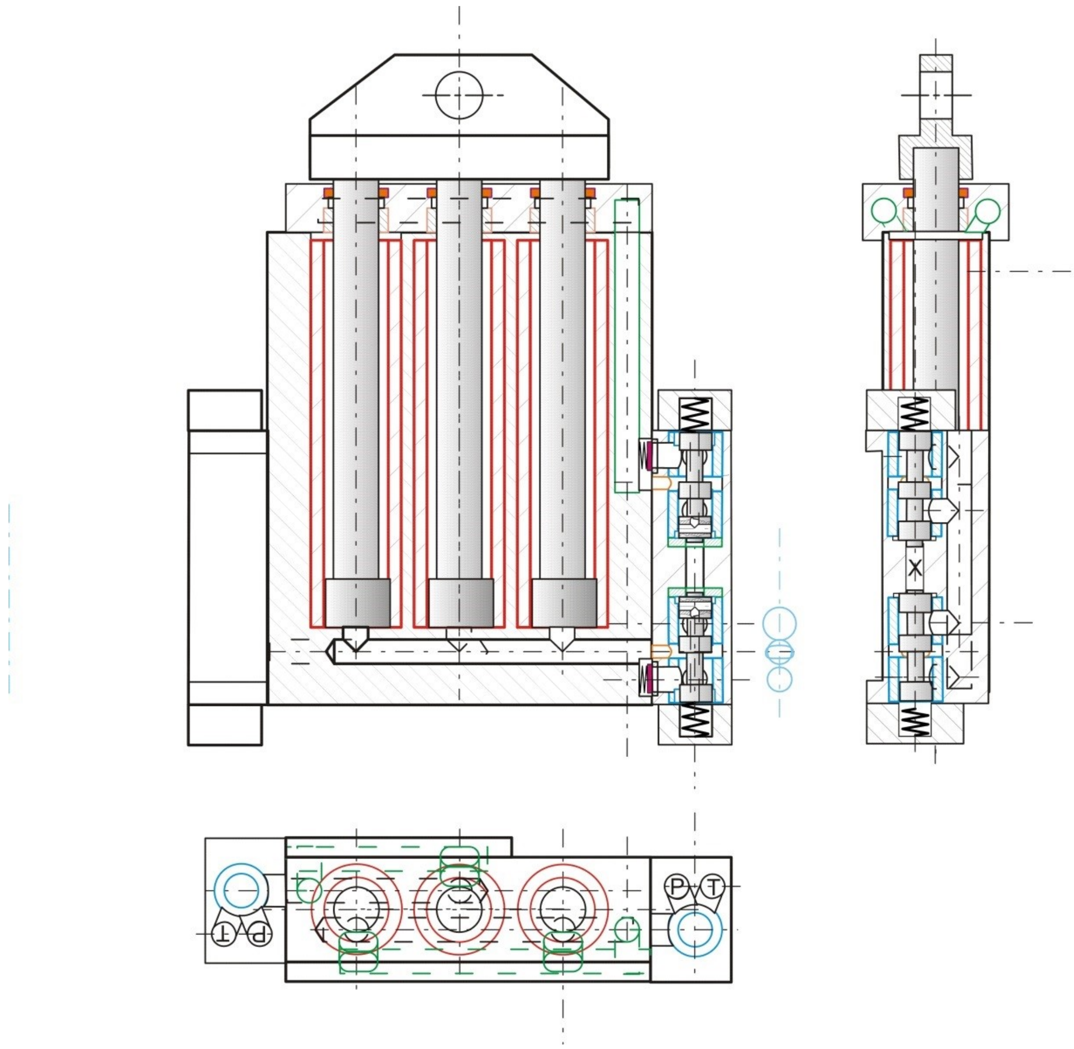

Fig. 24: Design study of a digital cylinder with four integrated valves for realizing a binary counter; the proportional valve to control the input to the binary counter (valve V_C according to Fig. 22) is missing.

A design study of such a valve system integrated into the cylinder block is given by Fig. 24. The piston diameters are approximately 8 mm, with which a force of 3000 newton could be generated with a system pressure of 200 bars. The cross section of the block is 16 mm x 65 mm. Sealing design is crucial; the design shown uses gap sealing and extra contacting seals for the piston rods. The shown system cannot shut off the valves. This might be accomplished by one extra valve per supply line. These valves could be realized as hydraulically piloted follow-up valves which are shut off, if p_X falls below $p_{4,l}$. The system weighs approximately 400 grams, if the block is manufactured in aluminum. May be, lower weight can be achieved if part of the block is made of high strength plastics into which cylinder jackets and pressurized channels guiding conduits made of steel are integrated.

3 CONCLUSION AND OUTLOOK

Actuation of exoskeletons is a very challenging area. Fluid power drives have a high potential, but require quite new concepts and components to provide the functionality and fulfil the tough constraints on weight and size. Furthermore, the actuation system has to form a symbiosis with the wearer's body and locomotion dynamics and control. Thus, the tight interaction of experts from robotics (or multibody dynamics), bio-engineering, actuation technologies, materials technology, and control is an absolute minimum condition to reach a performance which makes exoskeletons acceptable for a broader practical use. Good system design is crucial. In addition to that, new sensors or other principles to detect the motion intention of the wearer will be needed. Fast success to develop exoskeletons for a broader use is not very likely. But for special applications exoskeletons can be realized and will be used in the next years.

Fluid power is challenged to demonstrate its capabilities in this area. This paper addresses basically one digital hydraulic concept, which the author found most appropriate and having the highest chance to be successful. Hopefully, there will be other competing proposals and the engagement of fluid power companies in this area.

The digital cylinder with the binary counter control will be realized by a prototype in the coming months.

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