Control optimization of digital hydraulic drive for knee exoskeleton

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Summary. A successful knee exoskeleton device must follow the periodic motion of the gait cycle in an energy efficient manner. This work investigates an optimal control strategy that can allow the periodic behavior of such a device with minimum error while also consuming minimum energy. Using a multi-objective optimization technique, a trade-off between the periodicity error and energy consumption is demonstrated. From the pareto front, an optimal control variable set is determined which allows an acceptable periodic behavior of the knee exoskeleton with negligible energy consumption.

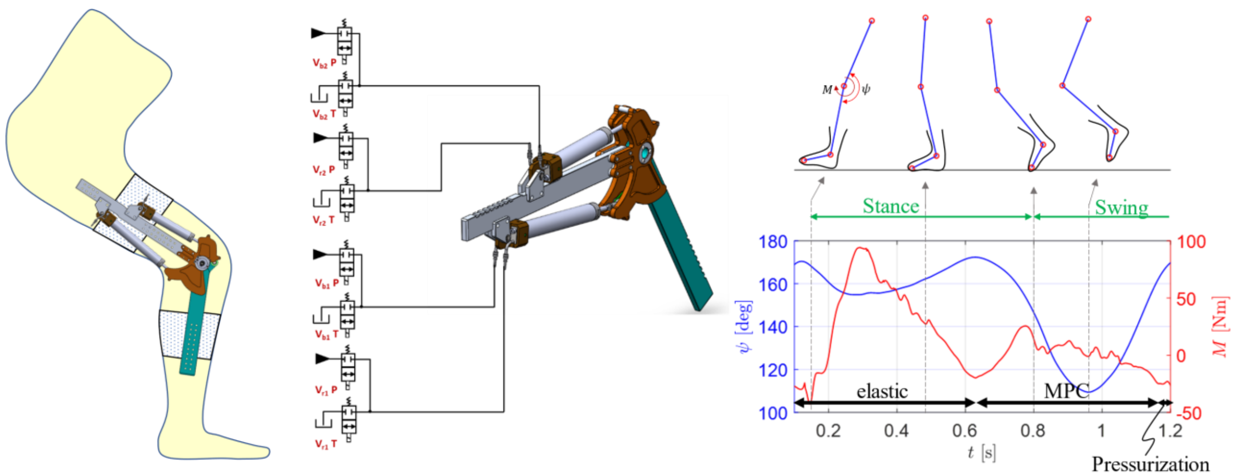
Introduction

Exoskeletons are wearable devices that provide additional strength to the wearer's limbs. These devices are commonly used in physical rehabilitation to assist in the recovery of a limb's motion and strength. Furthermore, they are used by factory workers, military personnel, and firefighters for carrying heavy equipment over long distances. Most of these devices currently use electromechanical drives for motion actuation. However, in recent years, hydraulically driven exoskeleton devices have gained interest among the researchers [1–3] due to their capabilities of high force density, easy energy recuperation, motion locking, and damping. The advent of digital hydraulic technology in the last decade has strengthened the case for hydraulically driven exoskeleton devices due the added advantages of high energy efficiency, power density, precision, and robustness.

Inspired by these benefits, the authors have recently developed a novel design of digital hydraulically driven knee exoskeleton [4]. A novel control strategy is also proposed in an upcoming work [5]. However, a key challenge with this exoskeleton device is its motion repeatability over multiple gait cycles. The device should track the desired knee motion in the same periodic manner as observed in typical gait cycles. Furthermore, to keep the power source light, the device should consume as little energy per gait cycle as possible. In this work, a control optimization study is conducted to determine the optimal sets of control variables that can allow the desired periodic behavior of the knee exoskeleton device with minimal energy consumption.

Knee exoskeleton design and control strategies

Figure 1 shows the knee exoskeleton design, its hydraulic drive, and the control strategies in different phases of the gait cycle. The comprehensive details are present in [4,5]. In brief, the exoskeleton device is actuated by two hydraulic cylinders. The hydraulic chambers of each of the cylinders are connected to the pressure source and tank via 2/2-way valves. The motion control is achieved via three different control strategies during different phases of the gait cycle. In the stance phase, where an inverse relation between the knee angle and knee torque exists, an elastic control is employed, which allows the hydraulic chambers to act as elastic elements. Next, a simplified form of the model predictive control (MPC) strategy is used to ensure proper tracking of the knee motion. Finally, a pressurization control strategy is employed for a brief period where hydraulic chambers are pressurized to the appropriate levels needed for the next gait cycle.



(a) (b) (c)

Figure 1: (a) Knee exoskeleton design, (b) hydraulic system, (c) phases in the gait cycle and control strategies used.

Control optimization study

The numerical simulations of the knee exoskeleton device show that the duration of each of the aforementioned control strategies and the time step involved in MPC significantly influence the accuracy of the periodic behavior of the device motion over multiple gait cycles as well as the energy consumed per cycle. Thus, in the optimization study, the duration of the elastic control phase, the duration of the pressurization phase, and the time step in MPC algorithm are considered as the optimization variables.

The first optimization objective is to minimize the difference between the values of the state variables of the system at the beginning ($t = t_0$) and at the end of two gait cycles ($t = t_e$). The state variables are the knee angle (ψ), knee angle derivative ($\dot{\psi}$), and pressures in the four hydraulic chambers of the cylinders (p_i). Thus, the objective function is

$$\text{Minimize: } \epsilon = w_1 e_\psi + w_2 e_{\dot{\psi}} + w_3 \sum e_{p_i} \quad (1)$$

where, $e_\psi = |\psi_{t_0} - \psi_{t_e}|$, $e_{\dot{\psi}} = |\dot{\psi}_{t_0} - \dot{\psi}_{t_e}|$, $e_{p_i} = |p_{i,t_0} - p_{i,t_e}|$, and w_i are appropriately chosen weights.

The second objective is to minimize the energy consumed over two gait cycles. The energy consumption is determined as $E = V_p p_S$, where, V_p is the amount of fluid volume delivered by the pressure source and p_S is its pressure level.

This multi-objective optimization problem is solved using NSGA-II algorithm. The initial design space is populated with 1000 designs and the optimization algorithm is executed for 50 generations.

Results and discussion

Figure 2(a) shows the results obtained from the optimization study where the approximate pareto front is shown in red. Computational expensiveness limits the number of optimization generations and thus, the accuracy of the pareto front. Nevertheless, a trade-off between the periodicity error (ϵ) and the energy consumption (E) is observed. The negative energy consumption observed in the pareto front is the result of two factors. Firstly, the natural knee motion is inherently an energy delivering system over a complete gait cycle [6]. Secondly, several control variable sets save energy by supplying lower amount of high pressure fluid to the actuators. However, as observed in the figure, most of such sets exhibit high periodicity error.

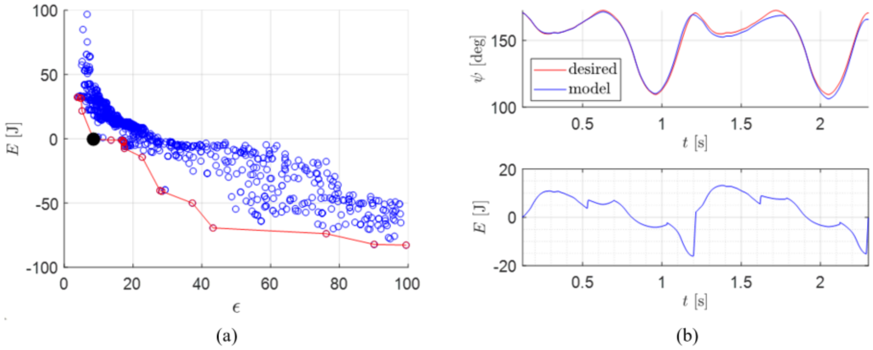


Figure 2: (a) Results from the optimization study with the pareto front shown in red, (b) Knee angle and energy consumption for a pareto optimal variable set (indicated as large black dot in Figure (a))

Figure 2(b) shows the simulation results obtained using a pareto optimal variable set (highlighted in large black dot in Figure 2(a)) for two gait cycles. The knee angle is tracked with reasonable accuracy and the energy consumption at the end of the gait cycle is almost zero. However, it is important to note that the losses due to internal friction were not considered in the energy calculation.

Conclusions

An investigation of the optimal control strategy for hydraulically driven knee exoskeleton is presented in this work. A multi-objective optimization study is conducted aimed at minimizing the error in the periodic behavior of the exoskeleton motion and the energy consumption per gait cycle. A trade-off between the two objectives is observed and using a pareto optimal variable set, it shown that a periodic behavior (with acceptable accuracy) could be achieved with theoretically zero energy consumption.

References

[1] A.B. Zoss, H. Kazerooni, A. Chu, Biomechanical design of the Berkeley Lower Extremity Exoskeleton (BLEEX), IEEE/ASME Transactions on Mechatronics. 11 (2006) 128–138. https://doi.org/10.1109/TMECH.2006.871087.

[2] W. Huo, S. Mohammed, J.C. Moreno, Y. Amirat, Lower Limb Wearable Robots for Assistance and Rehabilitation: A State of the Art, IEEE Systems Journal. 10 (2016) 1068–1081. https://doi.org/10.1109/JSYST.2014.2351491.

[3] H. Cao, Z. Ling, J. Zhu, Y. Wang, W. Wang, Design frame of a leg exoskeleton for load-carrying augmentation, in: 2009 IEEE International Conference on Robotics and Biomimetics, ROBIO 2009, IEEE, Guilin, China, 2009: pp. 426–431. https://doi.org/10.1109/ROBIO.2009.5420684.

[4] R. Rituraj, R. Scheidl, A novel design concept of digital hydraulic drive for knee exoskeleton, in: Proceedings of the ASME /BATH 2021 Symposium on Fluid Power and Motion Control FPMC2021, Online, 2021.

[5] R. Rituraj, R. Scheidl, Investigation of an optimal design and control of digital hydraulic drive for knee exoskeleton, in: The 13th International Fluid Power Conference, 13. IFK, Aachen, Germany, 2022.

[6] R. Scheidl, Digital Fluid Power for Exoskeleton Actuation - Guidelines, Opportunities, Challenges, in: The Ninth Workshop on Digital Fluid Power, Aalborg, Denmark, 2017.