Topic: IOC-inspired reinforcement learning of walking with neuromusculoskeletal model

Gait simulations based on (neuro)musculoskeletal models are used to study the control of human movement. Since movement control involves a complex interplay between the central nervous system (CNS) and the musculoskeletal system, these simulations can further help to understand the interaction between these two in changing environmental or physical conditions [1].

Previous studies have shown that human walking can be generated based on a reflex-based controller, however, the control architecture was prescribed [7]. Deep Reinforcement learning (RL) can learn a controller without pre-defining its structure, which has the potential to provide additional insights into movement control and add to identify control schemes for prosthesis or exoskeletons [8].

Deep RL has already been successfully applied for the generation of natural walking motion [1, 3, 6]. In RL, the agent learns a policy that maximizes the reward that it gets from the environment. However, finding a suitable reward function that leads to physiologically plausible movement remains challenging [3]. In most existing work, cost function compositions (i.e., the relative weighting of the cost terms) are manually or heuristically tuned based on the researcher's domain knowledge, which is cumbersome. [5]. Often additional experiment data is required [2, 4]. Schuhmacher et al have found an algorithm that works very well on different models (2D and 3D) (https://arxiv.org/pdf/2309.02976), but hyperparameter tuning of reward terms was necessary such that resulting movement matched experimental data, which was time-consuming as well. What is lacking is a fast and objective approach of designing a physiologically plausible reward function that generalizes across environments and conditions.

It is generally assumed that natural walking emerges as an outcome of optimization processes by the central nervous system (CNS) [5]. The exact objectives of the CNS during movement are an ongoing research topic, which is addressed by inverse optimal control (IOC). In a bi-level optimization approach, the weightings of different cost function terms are optimized such that the simulated movement matches the corresponding experimental data as closely as possible [6]. Potential cost function terms include effort minimization, stability increase, or avoidance of passive ligament torques [1, 5]. The importance of different cost function terms varies between persons and walking speeds. Recently, Gambietz et al., have successfully applied IOC to identify objective weights for walking at arbitrary speeds and cadences and walking with or without inclination. While IOC can give insights into potential optimization criteria of the CNS, it cannot contribute to our understanding of how movement is controlled, since the underlying simulations are open-loop. However, we believe that the results from IOC can be transferred to RL to help design a suitable and physiological reward function, which we investigate in this work.

In this work, we propose an approach based on IOC to generate human walking using a neuromusculoskeletal model and deep RL. Specifically, we investigate whether incorporating IOC-derived objective terms and weightings, as identified in Gambietz et al., into the RL reward function, using Schuhmacher's RL algorithm, can achieve realistic walking behavior at the desired speed and cadence. If successful, this would represent an objective and biologically plausible method for designing reward functions without the need for extensive hyperparameter tuning. Should the IOC terms alone prove insufficient, our investigation will further explore what additional terms may be necessary. Additionally, we aim to compare the effectiveness of our proposed method at different walking speeds and inclinations against the baseline algorithm by Schuhmacher. Finally, we will apply our method to models with varying degrees of freedom (DOFs) to assess whether the approach generalizes to more complex models than the one used to compute the IOC terms.

To achieve these goals, the proposed work consists of the following parts:

- Literature research on IOC and reinforcement learning with musculoskeletal models.
- Replication of the results from Schuhmacher et al using their controller and models
- Identification of relevant IOC- reward terms and implementation into the RL reward function.

- Evaluation of the resulting kinematics compared to the baseline model
- Application of the method to different conditions (different speeds, inclination) and evaluation
- Application of the method to different musculoskeletal models (2D and 3D with varying numbers of muscles and DOFs) and evaluation

The thesis must contain a detailed description of all developed and used algorithms as well as a profound result evaluation and discussion. The implemented code has to be documented and provided. An extended research on literature, existing patents and related work in the corresponding areas has to be performed.

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