Human-in-the-loop optimization of a multi-joint wearable robot for movement assistance

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Abstract: Soft, lightweight wearable robots can assist individuals with a lower limb weakness. However, it its challenging to identify control parameters that optimize the robotic assistance for a specific user and task. In this context, "Human-in-the-loop" techniques have been suggested to automate this optimization process. Here, we show that the assistance from the Myosuit, a multi-joint wearable robot, can be optimized using a Covariance-Matrix Adaptation Evolution Strategy. The optimization resulted in a reduction of a participant's energy expenditure that was nearly twice as large (18 % vs. 9.6 %) than when using hand-selected parameters, thereby motivating future work with patients.

I. Introduction

Wearable robots have been developed as training tools for rehabilitation following stroke[1], spinal cord injury [2], or as assistive devices for users with spinal cord injury[3]. Some of these devices, typically powerful, rigid exoskeletons, were designed to substitute the function of users who are completely paralyzed. Here, only the robotic controller drives the movement of the human-robot system.

More recently, soft, lightweight wearable robots have been proposed for users with some residual leg motor function [4, 5]. These devices allow – and require – active contributions from the users. In this case, the robotic controller needs to account for voluntary input from the user and adapt the robotic assistance accordingly. However, this adaptation process is often challenging. Different users will generally require different assistance, depending on their specific pathology, rehabilitation progress and environmental factors.

So far, this challenge has been addressed by extensive and repeated manual tuning of the robotic assistance by clinical or technical experts. This approach is time-consuming, heavily dependent on the skill of the expert, and will often not converge towards an optimal solution in finite time.

As an alternative, "human-in-the-loop" (HIL) techniques have been suggested to automatically optimize the robotic assistance from a wearable robot for the individual user and task at hand[6, 7]. In brief, physiological data is used to drive a model that estimates the human energy expenditure during movements. Based on the estimated energy expenditure as a cost function, an optimization algorithm selects robotic control parameters that are more likely to reduce human energy expenditure and applies these to the wearable robot (see Figure 1). This process is repeated in an iterative fashion until a pre-defined termination criterion is fulfilled.

The robotic devices for which HIL techniques were demonstrated so far targeted the reduction of energy expenditure of unimpaired users. Here, assistance is provided to a single joint. Wearable robots for impaired users that require more support due to a lower limb weakness must typically assist at least hip and knee extension against gravity to prevent collapse [5]. In this paper, we investigate if HIL techniques can also be used to optimize the assistance for such a multi-joint wearable robot with respect to energy expenditure. Thereby, we work towards eventually applying the HIL concept on patients.

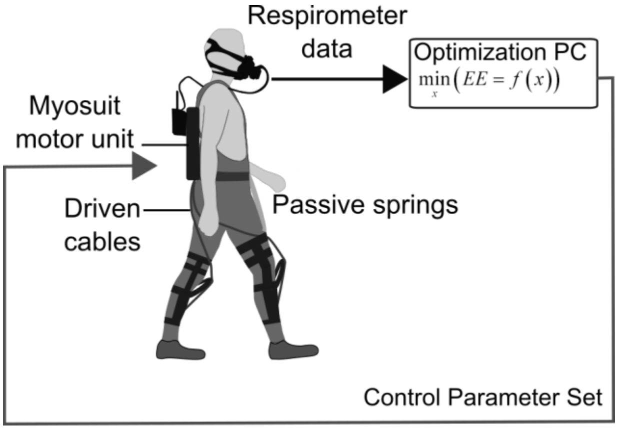

Figure 1: Respirometer data is used to drive the optimization of robotic control parameters which are then iteratively tested on the human in the loop. Energy expenditure is approximated from the respiratory data as cost function.

II. Material and methods

II.I. Participant

A single unimpaired male (25 yrs, 181 cm, 71 kg) participated in this pilot test.

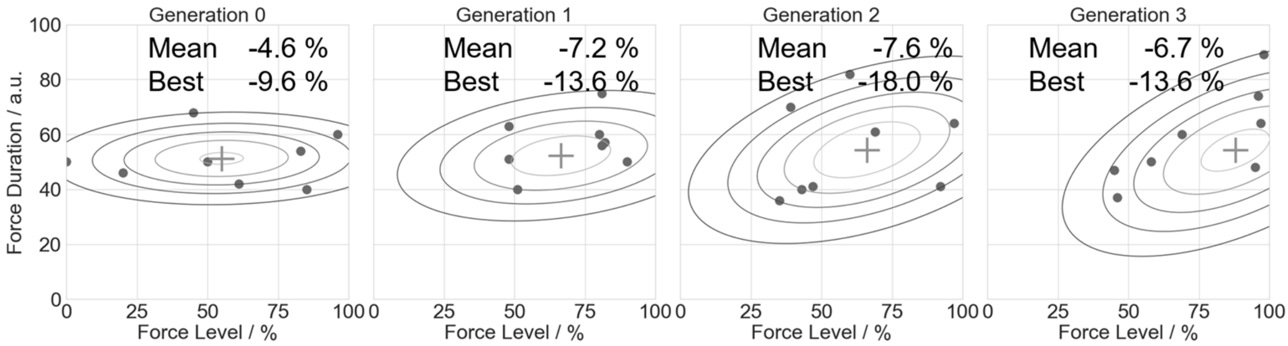

Figure 2: Evolution of the mean best control parameter estimate (cross), the tested conditions (dots) and underlying probability distribution (ellipses) of the Covariance-Matrix Adaptation Evolution Strategy algorithm from generation 0 to generation 3. A trend towards reduced mean energy expenditure within generations ("Mean") and better individual conditions ("Best") is observed.

II.II. Robotic hardware

The soft wearable robot used in this work (Myosuit Beta, MyoSwiss AG, Switzerland) is composed of three functional layers: (1) a textile garment layer, (2) a passive, spring-like "ligament layer", and (3) a "power layer". Together, the three layers allow the Myosuit to work like an external muscle and provide continuous assistance at the hip and knee joint when moving with and against gravity in activities of daily living. The assistance from the Myosuit can be adapted in terms of force magnitude and force (application) duration for each leg, resulting in a total of four independent parameters. This set was constrained to the subset of symmetric parameters for the left and right leg as we tested on an unimpaired user.

II.III. Optimization algorithm

Following previous work [6], a Covariance-Matrix Adaptation Evolution Strategy (CMA-ES) was used to optimize force magnitude and duration of the Myosuit. The parameters tested in the initial generation were hand-picked by the investigators.

II.IV. Experimental setup and protocol

During the experiment, the participant walked on a split-belt treadmill (V-Gait Dual Belt, Motekforce Link, The Netherlands) at 0.9 m/s and an incline of 10° while wearing the Myosuit. In each of the in total four optimization generations, the participant stood quietly for two minutes, then walked for four minutes without forces being applied from the Myosuit, and then experienced eight different assistance settings for two minutes each. Energy expenditure was approximated from respirometer data (K5, COSMED, Italy) using the Peronnet equation. A first-order model was fitted to the transient metabolic data of each individual assistance setting as basis for offline CMA-ES.

III. Results and discussion

From the initial generation 0 onwards, the mean best control parameter estimate shifted towards higher force magnitudes (see Figure 2). No similarly clear trend was found for the force duration. A trend towards reduced mean energy expenditure compared to the previous generations was observed over the course of optimization (gen. 0: -4.6 %, gen. 1: -7.2 %, gen. 2: -7.6 %, gen. 3: -6.7 %). Consistent with this trend, the largest individual reduction in energy expenditure of -18 % was recorded in generation 2, compared to only -9.6 % in the initial and -13.6 % in generation 1.

The results indicate that the optimization successfully identified parameter values that reduce the participant's energy expenditure while wearing a multi-joint wearable robot compared to an initial, hand-picked guess.

IV. Conclusions

Our findings suggest that HIL techniques can be transferred from single-joint wearable robots to multi-joint devices. Hence, these techniques bear promise to automate the individual adaptation of robotic assistance for users with a lower limb weakness. For this population, additional parameters (e.g. walking speed, gait safety) might be added to the optimization cost function to more accurately reflect user needs and preferences.

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