A computational framework to explore optimality in human movement

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***Abstract*—Predictive model-based simulations of system dynamics are powerful tools to explore optimality criteria underlying human movement (e.g. walking). This field of research is raising interest from the biomechanics and robotics communities, as predictive approaches can provide new insights in many areas, such as in the design and control of robotic assistive devices.**

***Index Terms*—predictive, human gait, optimal control, multi-objective optimization**

I. INTRODUCTION

Predictive musculoskeletal simulations have recently begun to show their potential as synthesis tools to predict movement ex-novo (i.e. independently from experimental motion data), thus giving insights into the neuro-motor control principles that regulate human movements. In this context, optimal control techniques have been used to identify optimality criteria underlying human movement, both in healthy [1] and pathological subjects [2], [3]. If the musculoskeletal model is combined with a model of an assistive device such as an active prosthesis or a robotic exoskeleton, predictive simulations can help to test, calibrate, and optimally/ergonomically design the device itself [4], [5]. Even though the potential of these techniques is quite clear, the available works and the proposed strategies are not mature yet, and the identification of the optimality criteria related to human tasks is still an open research question. Discovering such criteria would have important implications for robotics, as the design and control of robots and robotic devices reflect our understanding of human motor control. To date, results obtained from predictive musculoskeletal simulations are questionable for various reasons: (i) the musculoskeletal model is often not sufficiently accurate, (ii) many state-of-the-art predictive simulations have been defined as single-objective optimization problems, with the cost function chosen a priori, and (iii) rigorous multiobjective optimization (MOO) strategies have not been employed yet.

In this work we propose hierarchical optimization as a systematic method to solve model-based predictive problems of human walking in a rigorous MOO fashion.

II. HIERARCHICAL OPTIMIZATION

We set out to formulate predictive simulations of human walking as a *two-level hierarchical optimization*: while the lower level solves the MOO optimal control problem (OCP) of gait, the upper level identifies the (optimal weights of the) objectives in the MOO OCP by smartly exploring the Pareto front. The goal is to find the set of optimal weights that minimize the error between simulation results and experimental data of human walking (Fig. 1). Numerical simulations were performed using the computational framework developed in [6] using MATLAB and CasADi.

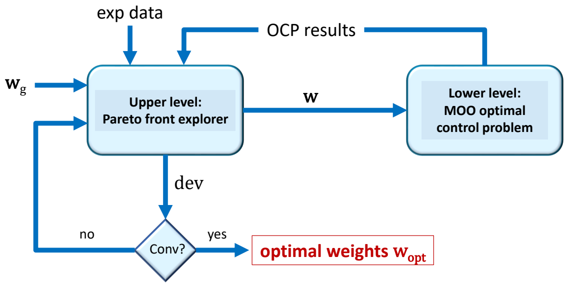

Fig. 1. Hierarchical optimization for the predictive problem of walking: the lower level solves the MOO OCP, while the upper level, starting from an initial guess ($\mathbf{w}_{\text{g}}$), systematically identifies optimal weights ($\mathbf{w}_{\text{opt}}$) of objective functions such that the deviation index (dev) between experimental data (exp data) and simulation results (OCP results) is minimized.

A. The lower level: multiobjective optimal control problem

The musculoskeletal model on which predictive simulations are based is the OpenSim model implemented in [6]. The goal of the lower level was to find, given a set of weights, such states $\mathbf{x}$ (e.g., joint angle trajectories) and controls $\mathbf{u}$ (e.g., muscle activations) that minimize a vector of weighted normalized cost functionals $\tilde{\mathbf{J}}(\mathbf{x},\mathbf{u})$. Equation (1) shows the objective functionals tested in this study: (i) $||\tilde{\mathbf{a}}_m||_{100}$ (soft max of muscle activations, representative of muscle fatigue), (ii) $||\tilde{\mathbf{a}}_{\text{arms}}||_2$ (arm activations), (iii) $||\dot{\tilde{\mathbf{a}}}_m||_2$ (time-derivative of muscle activations for smoothness), and (iv) $||\tilde{\dot{\mathbf{E}}}_m||_2$ (metabolic energy rate). In (1), d is the distance traveled by the pelvis, while T is half a gait cycle (symmetry hypothesis). The MOO problem was tackled through the weighted Chebyshev method (2). In (2), F denotes the feasible region determined by the problem's constraints.

$$\tilde{\mathbf{J}}(\mathbf{x},\mathbf{u}) =$$

$$\frac{1}{d}\int_0^T \left(w_1||\tilde{\mathbf{a}}_m||_{100}^{100}, w_2||\tilde{\mathbf{a}}_{\text{arms}}||_2^2, w_3||\dot{\tilde{\mathbf{a}}}_m||_2^2, w_4||\dot{\tilde{\mathbf{E}}}_m||_2^2\right) \text{dt} \tag{1}$$

$$\min_{\mathbf{x},\mathbf{u}\in F} \max \tilde{\mathbf{J}}(\mathbf{x},\mathbf{u}) \tag{2}$$

B. *The upper level: Pareto front explorer*

The upper level was formulated as a single-objective constrained optimization problem (3) aimed at finding the set of optimal weights $\mathbf{w}_{\text{opt}} = [w_1, w_2, w_3, w_4]$ that minimize the deviation between results obtained from the lower level and experimental data of human walking extracted from [6]. As shown in (4), the deviation index dev is given by the contributions from joint angle trajectories dev_{ja}, ground reaction forces dev_{grf}, and joint torque trajectories dev_{tq}.

$$\min_{\mathbf{w}\in[\mathbf{0},\mathbf{1}]} \text{dev}(\mathbf{w}) \text{ s.t. } \sum_{i=0}^{m} w_i = 1 \tag{3}$$

$$\text{dev}(\mathbf{w}) = \text{dev}_{\text{ja}}(\mathbf{w}) + \text{dev}_{\text{grf}}(\mathbf{w}) + \text{dev}_{\text{tq}}(\mathbf{w}) \tag{4}$$

As an example, Equation (5) shows the kinematic deviation index. N_{ja} is the number of joint angles considered, $\tilde{\mathbf{ja}}_{\text{exp}}^{\text{M}}$ and $\tilde{\mathbf{ja}}_{\text{sim}}$ are the normalized experimental (mean values) and simulated joint angle trajectories, respectively, and $\tilde{\mathbf{ja}}_{\text{exp}}^{\text{SD}}$ are the standard deviations of experimental data.

$$\text{dev}_{\text{ja}}(\mathbf{w}) = \frac{1}{N_{ja}} \frac{\text{rms}\left(\tilde{\mathbf{ja}}_{\text{exp}}^{\text{M}} - \tilde{\mathbf{ja}}_{\text{sim}}\right)}{\text{rms}\left(\tilde{\mathbf{ja}}_{\text{exp}}^{\text{SD}}\right)} \tag{5}$$

The optimization problem described in (3) was solved by the MATLAB's *pattern search* algorithm, parallelized over the available processors.

III. RESULTS AND DISCUSSION

In Fig. 2, predicted kinematic results (only in the sagittal plane for brevity) are plotted against experimental data. Fig. 3 shows predicted results in terms of muscle activations for the gluteus medialis and gastrocnemius medialis, and of the vertical ground reaction force. Please refer to the supplementary video file for the animated results.

Despite evident differences, predicted joint angles clearly follow the trend of experimental data, as well as muscle activations and the vertical ground reaction force, meaning that the devised framework is promising and the objective vector tested in this work is able to guide the model towards a physiological gait.

IV. CONCLUSIONS

A systematic method to solve the predictive problem of human walking in a multiobjective fashion has been defined. Hierarchical optimization allowed a more rigorous exploration of the Pareto front, thus avoiding trial-and-error approaches to identify optimal weights, while adopting the weighted Chebyshev method ensures that also solutions belonging to nonconvex regions of the Pareto front can be obtained. Only preliminary results have been shown, and more numerical experiments are in progress to draw better-informed conclusions about optimality principles underlying human walking. Future research can be devoted to implement the model of an assistive device to explore the potential for novel control strategies.

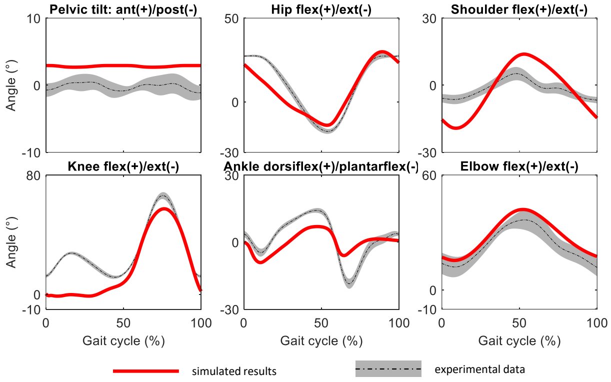

Fig. 2. Predicted joint angle trajectories are plotted against experimental data (mean±1SD).

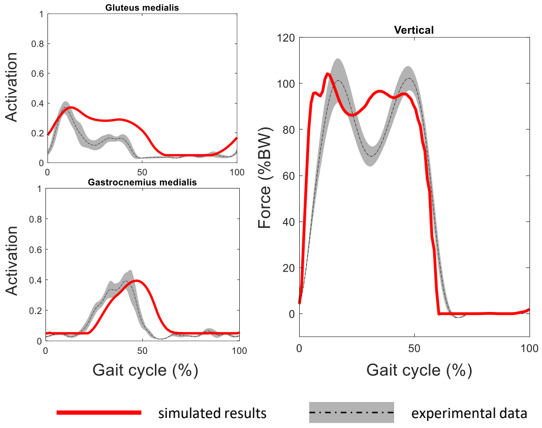

Fig. 3. Predicted muscle activations and vertical ground reaction force are plotted against corresponding experimental data (mean±1SD).

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