Simulation-based optimization approach for explicit forward gait prediction

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ABSTRACT

Accurate and specific predictive numerical simulation of the human gait can help in many clinical routines. Predictive methods often track modifications applied to a reference motion but that usually do not take into account the characteristics and the stability of the predicted motion. We propose an approach that includes a cost function, computed on the predicted motion, which optimization preserves these concerns. Experimental studies on subjects with different walking patterns confirmed that our method preserves the characteristics of the gait.

KEYWORDS

Human gait simulation, Reinforcement learning, Knee brace, Explicit forward simulation, CMA-ES

1 INTRODUCTION

Computer aided predictive simulation allows the testing of a variety of gait scenarios on a numerical representation of the human. With improvements on accuracy and patient specificity such simulation can nowadays be used in clinical procedure. This study aims at predicting gaits with emphasis on the conservation of a patient specificity. We make the distinction between patient specificities related to its musculoskeletal model and specificities due to others factors (e.g. footwear, pain, chronic disease). Currently, there are two ways to make such predictions: the implicit approach and the explicit approach. In the implicit approach, the dynamics of the system is turned into a system of algebraic equations where states and control signals are the unknowns. While the forward explicit approach uses an adaptive system to produce the control signals, and than the system dynamics is integrated. Methods based on implicit approaches can achieve predictions with a good accuracy and in a limited amount of time, but they are not suited for interactive simulation [Falisse et al. 2019]. Most forward explicit methods obtain predictive motions from the tracking of a modified reference motion [Lee et al. 2019]. We propose a different approach for the search of the modifications. Our method uses an optimization of a cost function that includes the evaluation of the simulated motion. Because running such optimization-based simulation takes time we reduced the search space. This reduction is achieved with the use of an optimal parametric representation of the reference motion and with gait analysis knowledge.

2 METHOD

Forward simulation

Our forward predictive simulator uses a skeletal model placed inside a physics-based virtual environment and actuated by an adaptive system. This adaptive system generates appropriate control signals to maintain balance, to produce a motion similar to a reference motion and to ensure additional tasks such as minimizing the cost of transportation. At each time step, hypothetical servo-motors placed at each degree of freedom of the model receive signals from the adaptive system. Once the signals are converted into angular moments, the system dynamics is resolved by the physics engine.

Our adaptive system is based on a neural network and stable proportional derivative controllers (SPDC) for each degree of freedom of the virtual character. The input of each SPDC is the sum of an open-loop angular target and an adaptive correction. The open-loop angular target is evaluated from the kinematics of one reference gait cycle. The adaptive correction is computed by the neural network from the current pose of the character and the current percent of gait cycle denoted as ϕ.

The neural network is trained to maintain balance using a data-driven approach. Our goal is to learn a control policy that produces motions that resemble the reference kinematics. The cost function is composed of a weighted combination of terms computed from the difference between the current and the reference model's state. An additional term aggregates the sum of the angular moments.

We hypothesis that training the neural network on more than one reference kinematics will make it more robust to variations on the reference input, and therefore will allow for prediction. We first processed the raw kinematics data by rotating the motion to have every mean heading of each motion clip in one direction and setting $\phi = 0$ on the first right foot contact. This way the neural network will not be specialized for a particular walking direction and timing.

We use two sets of eight kinematics reference data. In the first set, the initial condition denoted as $C0$, a subject walked normally at a self selected speed. In the second set, the altered condition denoted as $C1$, a subject walked also at a self selected speed but was wearing a restrictive brace on the right knee, thus imposing a stiff-knee gait. The restriction was set to 20 degrees of flexion.

Gait predictions

Once the neural network is trained, the reference kinematics data can be modified to obtain new motions. Predictive motions are thus found by searching sets for modifications that produce valid simulations. The quality of the predictive simulations is measured with an objective function composed of a weighted combination of two terms. The first term measures the relevance of the produced motion by penalizing simulations for which the character falls and collisions occur between the legs. The second term depends on the targeted pathology and for our example, the stiff-knee gait pathology, it penalizes the knee flexion.

The first term of objective function heavily penalizes simulations which fall or collide before 15 gait cycles. Correct evaluation of the second term is ensured by using an average of the measures over the last 10 gait cycles. So each simulation takes about $1s$ to execute (20 times faster than real-time). It was important to use a method that converge with a minimum number of evaluation and without the need to evaluate gradients because the problem is discontinuous. We chose the Covariance Matrix Adaptation Evolution Strategies (CMA-ES) method for the optimization process [Hansen 2016].

With the discrete representation of the motions, there is more than 1000 parameters to optimize. CMA-ES shows best performance with less than 100 parameters so two strategies were used to reduce the search space. First, we compute a parametric approximation of each trajectory of the kinematics data, allowing us to model a full trajectory from few control points only. Then, knowledge from gait analysis of the targeted pathology is used to identify a subset of the trajectories to include in the optimization.

Optimal parametric representation

The objective is to find an optimal parametric representation of each trajectory with a fixed number of parameters, while maintaining the C^2 continuity. The optimum placement of the 8 control points was computed as a weighted combination of terms relative to similarity, relative control points placement and weight distribution.

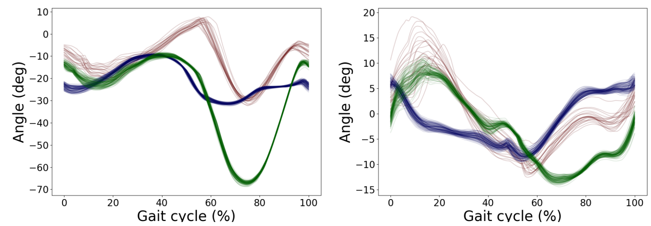
The similarity term is computed as the sum of normalized square residuals between the original data and the NURBS evaluation, for each frame of the original trajectories. The other terms are respectively computed as the minimum distance between two consecutive control points, the mean value of the weights, and the minimum of the weights. We use the CMA-ES method for the optimization as the problem presents discontinuities.

3 RESULTS

Optimal trajectories representation. Our optimal parametric representation gives almost identical trajectories for all reference kinematics. The worst observed error at any time was 8.365×10^{-04} degrees for the hip rotation and the mean error for all joints was 2.770×10^{-04} degrees.

Effect of multiple gait training. When the neural network is trained on one kinematics reference data of the $C0$ set, it is not able to produce stable motions for the seven others reference data of the same set. On the other hand, if the training is performed using the eight reference data from the set, the trained neural network is able to produce stable motions for all of them.

Prediction of stiff-knee gaits. We use the neural network trained with the complete set of $C0$ gaits. Using the optimal parametric representations we still have 208 parameters to optimize. With knowledge from literature [Lewek et al. 2012] and gait analysis of $C0$ and $C1$ we chose to select the following trajectories to reduce the search space to 44 parameters : pelvic obliquity, pelvis height, lumbar bending, hip abduction (left and right legs) and knee flexion (right leg). The target maximum right knee flexion was set to the value observed in the $C1$ condition.



(a) Right knee extension **(b) Left hip abduction**

Figure 1: Joint kinematics during the 13^{th} gait cycle. Green curves are $C0$, blue curves are $C1$ and red curves are predictions.

The optimization successfully found a set of modifications that match the constraints. To assess the advantage of the simulation-based optimization we analyze the result with 100 simulations generated with various starting ϕ. The starting ϕ were randomly selected with maximum variation of 2% from the one used during optimization process. We observe that the constraint on the right knee is satisfied for all the 23 successful predictions, but a hyperextension is observed at right toes off (Fig. 1a). On other trajectories, such as the left hip abduction (Fig. 1b), we observe that the pattern becomes similar to the one observed in the $C1$ condition even if it was not set as an objective.

4 CONCLUSION

We propose a method for predictive simulation of human gaits based on the optimization of an objective function including the evaluation of the simulated motion. Simulation are obtained from modifications of reference kinematics data. A reduction of the search space is used to compensate for the computational cost of the simulations. This reduction is achieved with an optimal parametric representation of the kinematics data and with the exclusion of trajectories. Knowledge about the simulated pathology is used to select the trajectories. Using the proposed method, we were able to produce stable predictions for a stiff-knee gait with significant severity.

Future works will involve improvements of the simulator to make it more robust to changes and therefore capable of a wider range of prediction. We will also work on the search algorithm to obtain predictions that best preserve a patient's walking pattern.

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