Analysis of a predictive forward simulator of human gaits

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***Abstract*— Although predictive forward gait simulators have existed for a little while, only few sensitivity studies have been proposed. We present a study analysing precision, accuracy, stability and sensitivity of such simulator. We studied a gait simulator based on the trajectory mimicking method proposed by Lee et al. [1]. We assessed the effect of motion variation on the resulting gait simulation using the sensitivity analysis method proposed by Saltelli et al. [2]. Our method supports the use of this simulator for prediction.**

I. INTRODUCTION

In recent years, predictive gait simulators met some successfull applications. Lee et al. [1] showed that muscle contraction patterns and post-operation gaits can be predicted. Falisse et al. [3] can predict transitions between walking and running, the effects of some muscles weaknesses, and the effects of wearing an orthosis. To our konwledge, only Falisse et al. [3] studied the sensitivity of their framework, and only to foot shape variation. We propose a method to analyze the sensitivity of such simulator to many parameters. We illustrate our method on a simulator proposed by Lee et al. [1].

The simulator proposed by Lee et al. trains a neural network (NN) to produce stable walking simulations using target position for proportional-derivative (PD) controllers (trajectory mimicking) and a second NN computes muscle activations (muscle coordination). This preliminary study focuses on the effect of wearing a knee brace without modeling muscles. Without loss of generality, it allows us to simplify the model and the framework by removing the muscle coordination part which makes the framework faster and allows us to perform a large number of simulations for our sensitivity study.

II. MATERIAL AND METHODS

After training our controler to replicate a reference gait motion, a quasi-random low-discrepancy sequence is used to generate sets of motions variations for the forward simulator. Measures are performed on the resulting simulations in order to analyze the predictive capability of the simulator. Input variations and measures are detailed in section II-B.

This research is supported by the ANR agency under grant number ANR-16-CE92-0042. The authors would like to acknowledge the Labor für Biomechanik und Biomaterialien at the Medizinische Hochschule Hannover for their collaboration.

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A. Model and simulation

The model used in our simulator is based on the full body *gait2392* OpenSim model [4] where arms and muscles have been removed for computational performances.

The reference motion has been obtained through a commun pipeline : motion capture with Plug-In Gait marker-set then scaling and inverse kinematics using OpenSim. The stability of the simulator have been improved by smoothing every joint angle trajectory with a two-way 10Hz Butterworth filter, then the angular trajectories have been cyclified. The resulting motion is used to train the trajectory mimicking controler with a reward function based on the tracking of the angular trajectories, the end-effector positions and the cost of transportation.

B. Inputs and measures

For each trained NN, many simulations are done thanks to input variations.

Inputs. The variation over $\phi \in [0, 1]$, the normalized starting time in the gait cycle, is used to avoid ill-conditionned simulations. Two inputs have been chosen to simulate the effect of wearing a knee-brace : the limitation of the range of motion of the right knee (RK) and the distortion of the reference angular trajectory of the right knee. The distortion is made using variations of the four extremum control points ($D1$, $D2$, $D3$, $D4$) of the spline approximating the right knee trajectory.

Measures. We chose commonly used measures in biomechanical studies [5] and introduced additional measures that are relevant to our case study (see Table II). We used spatio-temporal measures but also mean, minimum and maximum of angular trajectories during various phases of the gait cycle. We do not compare directly joint trajectories in order to get more quantitative outcomes. For each simulation the measures have been automaticaly computed.

C. Analysis

In this work, we use the data from one healthy subject (M, 26). The gait with the best 'cycle' was studied.

Precision. First, we tested the precision of the training as the learning process is stochastic. 18 training sessions were done and we measured P^i for each measure as:

$$P^i = \sigma(\overline{M^i_{simu}(\phi)})_{NN_j} \text{ wit+h } 0 < j < 17$$

where $\overline{M^i_{simu}(\phi)}$ is the mean of each measure i over the variation of the normalized starting time ϕ in the gait cycle.

Accuracy. In order to assess the accuracy of the simulator, we computed A^i for each measure, for a selected NN:

$$A^i = |M^i_{ref} - \overline{M^i_{simu}(\phi)}|$$

where the M^i_{ref} is the value measured on the reference motion.

We ran simulations for 80.000 sets of input values. These sets were generated using a Sobol sequence of 6 inputs with 10.000 samples. The sequence and the number of samples have been choosen to be optimal to compute the sensibility indices according to Saltelli et al. [2]. The measures from theses simulations are used for sensitivity and stability analysis.

Stability. In the stability analysis, for each input, we searched for the upper and lower limits allowing 10 successfull gait cycles.

Sensibility. The main effect index (S_{main}) was used as the sensitivity index. There are various ways to compute this index and we used the one introduced by Saltelli et al. [2]. It can be viewed intuitively as the expected variance that would be left if all parameters but parameter k could be fixed and normalized by the global variance. We computed those values for an increasing number of samples to determine if they converge towards stable values.

III. RESULTS

Table I presents the results for the stability analysis and Table II presents the results for precision, accuracy and sensitivity. For the sensitivity, N means that for 9.000 to 10.000 samples the value of S_{main} is less than 1. If for 9.000 to 10.000 samples the value of S_{main} is greater than 1, the rank is displayed. U is used otherwise.

Parameter	Lower limit	Upper limit
RK	$53.5°$	$120°$
$D1$	$-60°$	$0°$
$D2$	$0°$	$38°$
$D3$	$-15°$	$12.9°$
$D4$	$0°$	$36.5°$

TABLE I

STABILITY STUDY : UPPER AND LOWER LIMITS FOR EACH PARAMETER

We observe $23°$ of ankle range of motion during a cycle. Also a precision of $12°$ for the minimum ankle DF in SW is an important variation. Likewise, double support is usualy less than 10%, so 5% of accuracy is rough. Sensitivity results may be interpret as follows: the relation between inputs variations and measures are not straight. For example, the distortion D1 modify the maximum right knee flexion in swing phase on the reference motion and this value is not the one with the highest main effect index for D1 variation.

The sensitivity experiment shows that the maximum right knee flexion in swing phase is not the most influenced measure during variation of D1, so the relation between parametres and measures are not straight forward.

IV. DISCUSSION AND CONCLUSION

As outlined above, this work is a preliminary study of a forward gait simulator where precision and accuracy of the trainning, stability and sensitivity of the simulation are observed regarding input variations. Precision and accuracy sucessfully highlight some weaknesses of the simulator. Furthermore, stability confirms that the framework is suitable for predictive simulation. As suspected, the relationship between the inputs and the measurements is complex. We expect that further researchs will highlight similar relations between inputs and measurements in clinical studies.

Measures	P	A	D1	D2	D3	D4
Walking velocity $m.s^{-1}$	0.04	0.03	9	N	N	N
Stride length m	0.04	0.04	N	N	N	N
Cadence $step.min^{-1}$	0.06	0.03	N	N	N	N
Stance (ST) time %	0.02 0.02	3.0 4.0	N N	N N	N N	N N
Double support %	0.02	5.0	U	U	U	U
Time to peak knee F s	0.04 0.05	0.02 0.01	1 10	3 N	3 N	6 11
Mean pelvis tilt	1.2	2.2	N	5	2	5
Max hip F in swing (SW)	3.0 3.4	6.7 9.0	N N	N N	N N	N N
Mean hip F in ST	2.2 2.0	2.5 0.48	U N	N N	6 N	3 N
Hip flexion (F) at initial contact (IC)	4.0 3.9	7.9 8.1	3 N	1 N	7 N	1 N
Max hip abuction in SW	2.3 2.7	2.0 0.12	6 4	N 6	N U	7 2
Max knee F in SW	2.3 3.3	3.5 3.0	7 5	4 7	9 4	N 4
Min knee F in SW	3.7 3.4	4.6 6.3	N N	N N	N N	N N
Max knee F in SS	4.5 2.8	8.0 12	N N	N N	N N	N N
Min knee F in SS	2.9 3.1	3.3 6.1	11 N	N 2	1 N	N 9
Max ankle dorsiflexion (DF) in ST	2.4 2.9	4.7 5.5	N N	N N	N N	N N
Min ankle DF in ST	3.7 4.2	12 14	12 N	N N	N N	N N
Max ankle DF in SW	2.2 2.7	3.0 3.3	2 N	N N	8 N	10 N
Min ankle DF in SW	4.1 4.7	12 14	8 N	N N	5 N	8 N

TABLE II

COLUMN P IS THE PRECISION, A IS THE ACCURACY, AND THE LAST 4 COLUMNS ARE FOR SENSITIVITY ORDERING. WHEN TWO VALUES ARE GIVEN, THE FIRST ONE REFERS TO THE LEFT SIDE AND SECOND ONE TO THE RIGHT SIDE.

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