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Comparison of human experimental trajectories and simulations during gait

I. Maroger, O. Stasse, and B. Watier

LAAS-CNRS, Université de Toulouse, CNRS, UPS,
Toulouse, France

1. Introduction

The French national project COBOT aims to generate a cooperation between a human and a humanoid robot in order to lift and carry a table. To fluidly perform such interaction, a model of gait is needed to mimic human trajectories. Thus, we investigate which trajectories are spontaneously chosen by humans during locomotion with a given initial and final positions. The trajectories of the Body Center Of Mass (BCOM) were then generated thanks to two models: one based on parametric curves called clothoids and the other using Optimal Control (OC). These models have been chosen because previous researches already shown their closeness to human locomotion. Indeed, it has been demonstrated that clothoid arcs give good approximations of human trajectories during gait (Arechavaleta et al. 2008). These trajectories are also well fitted by an OC model established by Mombaur et al. (2010). In order to compare the trajectories generated with these models to human trajectories, an original experimental setup was made in the context of this study.

This work is meant to be implemented in the walking pattern generator of a humanoid TALOS to improve its interaction with a human being by planning its real-time behaviour during gait.

2. Methods

2.1. Trajectory generation

The models presented below generate smooth BCOM trajectories (i.e., without taking into account lateral oscillations induced by the steps) during gait. $(x(t), y(t))$ is the instantaneous position of the BCOM in the horizontal plane, $\theta(t)$ the pelvis orientation,

$v_{forw}(t)$ and $v_{orth}(t)$ the forward and sideward (called orthogonal) velocities relatively to the pelvis.

Clothoid model Clothoid curves are defined by this system of ordinary differential equations:

$$\begin{cases} \dot{x}(t) = \cos(\theta(t)) \\ \dot{y}(t) = \sin(\theta(t)) \\ \dot{\theta}(t) = \kappa_0 + \kappa_1 t \end{cases}$$

with the initial condition $x(0) = x_0$, $y(0) = y_0$ and $\theta(0) = \theta_0$. κ_0 and κ_1 are called the initial curvature the sharpness of the curve respectively. To generate clothoid curves between a starting position and a goal position with a given orientations a fitting method has been established by Bertolazzi and Fregio (2015).

OC model An OC model to describe human BCOM trajectories during gait was first proposed by Mombaur et al. (2010). For this study, we adapt the cost function to use a Differential Dynamic Programming (DDP) solver from the open-source Crocoddyl library (Mastalli et al. 2020). Thus, we solved the following OC problem:

$$\begin{cases} \min \int_0^T \phi(X(t), U(t)) dt \\ \phi(X, U) = \alpha_0 + \alpha_1 u_1^2 + \alpha_2 u_2^2 + \alpha_3 u_3^2 + \alpha_4 \psi^2 \\ + \alpha_5 \Delta_{yx}^2 + \alpha_5 \Delta_y^2 + \alpha_6 \Delta_\theta^2 \end{cases}$$

with $X = (x, y, \theta, v_{forw}, v_{orth}, \dot{\theta})$ the state vector, $U = (u_1 = \dot{v}_{forw}, u_2 = \dot{v}_{orth}, u_3 = \ddot{\theta})$ the control vector, $\psi(X, U) = \tan^{-1} \frac{y_f - y}{x_f - x} - \theta$, $\Delta_X = (X_f - X)$, $(\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6) = (1, 1.2, 1.7, 0.7, 5.2, 5, 8)$. The five first weights correspond to those chosen by Mombaur et al. (2010), the other two have been heuristically found to end at the desired goal position.

2.2. Trajectory measurements

Subjects Two males and eight females, without any pathologic disorders altering gait, volunteered for this study. Their ages, heights and weights ranged from 18 to 26 years (average 23.3), from 1.68 to 1.84 m (average 1.77) and from 58 to 105 kg (average 73.9) respectively. They were informed of the experimental procedure and gave their writing consent before the experiment.

Experimental protocol The subjects had to walk from 10 different starting positions with 4 different orientations to a goal position in front of a table as

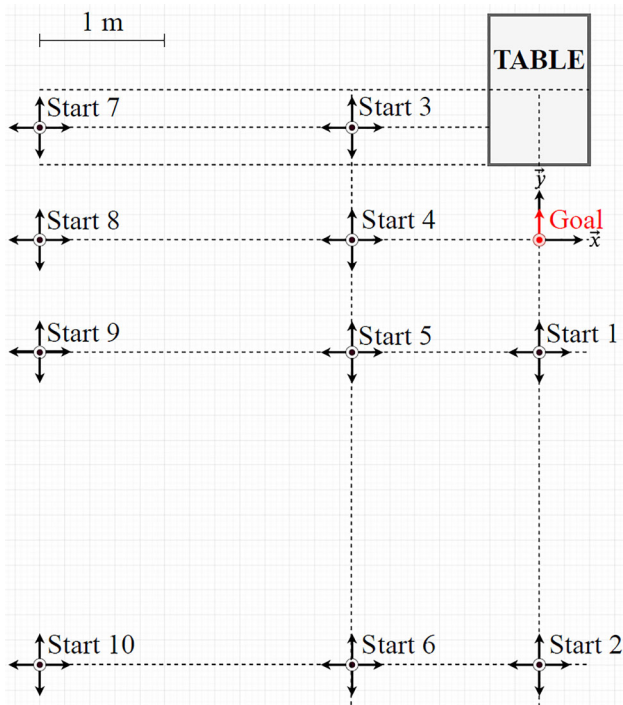


Figure 1. Forty starting and goal positions.

represented in Figure 1. They performed 3 trials on each starting position for each orientation. Thus, 120 trajectories were measured and at least one trial per each participant was analysed. The starting positions were chosen to be representative of common locomotion paths within a range of 0.6 to 5.5 m from the goal.

Data recording Fifteen infrared cameras (VICON, Oxford, United-Kingdom) sampling at 200 Hz collected the positions of passive markers placed on the body of the subjects. The 4 markers fixed on the pelvis were used to approximate the BCOM position (Gard et al. 2004) and to compute the orientation of the pelvis during gait.

Data analysis Kinematics data were filtered using a 4th order, zero phase-shift, low-pass Butterworth with a 10 Hz cut-off frequency.

2.3. Comparison

For each starting position and orientation, trajectories are generated with both models. Then, we normalize all the generated and measured trajectories from 1 to 100% with a step of 0.1. The mean measured trajectory for each 40 starting position is computed as follows: $X_m^i = \frac{1}{10} \sum_{j=1}^{10} X_j^i$ where $X_j^i = (x_j^i, y_j^i, \theta_j^i)$ with j stands for the j^{th} subject and $i \in [1, N]$ with $N = 1000$ for the i^{th} position along the BCOM trajectory.

To compare the experimental trajectories with the generated ones, the following average distances are

Table 1. Average linear distance according to θ_0 .

θ_0 (rad)	$-\pi/2$	0	$\pi/2$	π
d_{xy}^{Clothoid} (m)	0.812	0.336	0.208	1.063
d_{xy}^{OC} (m)	0.141	0.188	0.187	0.234

Table 2. Average linear distance according to the distance between the starting and the goal position.

$d_{\text{Start/Goal}}$ (m)	< 3	> 3
d_{xy}^{Clothoid} (m)	0.320	0.952
d_{xy}^{OC} (m)	0.175	0.234

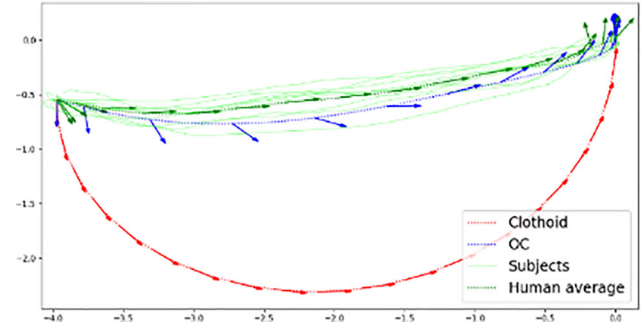


Figure 2. Comparison between the two models and measurements on 10 subjects from start 9 with $\theta_0 = \frac{\pi}{2}$.

defined:

$$\begin{cases} d_{xy} = \frac{1}{N} \sum_{i=1}^N \sqrt{(x_m^i - x_{gen}^i)^2 + (y_m^i - y_{gen}^i)^2} \\ d_{\theta} = \frac{1}{N} \sum_{i=1}^N \sqrt{(\theta_m^i - \theta_{gen}^i)^2} \end{cases}$$

x_m are the measurements and x_{gen} the generated data.

3. Results and discussion

3.1. Results on the positions

The results show that the trajectories computed with the OC model are closer to the measurements. Indeed, we obtain $d_{xy}^{\text{Clothoid}} = 0.605 \text{ m} \pm 0.628$ and $d_{xy}^{\text{OC}} = 0.188 \text{ m} \pm 0.104$. This gap is even wider depending on θ_0 and on the distance to the goal as Tab.1 and 2 shows respectively.

3.2. Results on the orientations

This study shows that the orientation of the pelvis during gait is mostly tangent to the velocity vector as in the clothoid model. Indeed, we get $d_{\theta}^{\text{Clothoid}} = 0.521 \text{ rad} \pm 0.279$ and $d_{\theta}^{\text{OC}} = 0.874 \text{ rad} \pm 0.530$. As observed on Figure 2, the orientation is overall tangent to the trajectory during the middle stage of the gait but not at the initial and final positions.

4. Conclusions

In this study, we show that an OC model adapted from Mombaur et al. (2010) better describes human BCOM trajectories during gait than a clothoid based model with an acceptable mean distance to the measurements for cobotic applications. However, regarding the orientation, the clothoid model is the most accurate: the orientation of the pelvis is tangent to the trajectory during a main part of the gait.

Ongoing works must optimize the weights α_i used in the OC cost function to confirm these results.

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KEYWORDS Human locomotion; modeling; clothoid; optimal control; human-robot interaction

 imaroger@laas.fr