Better safe than sorry: stochastic optimal control of gait predicts larger foot clearance

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Summary

Predictive simulations aim to explain human walking by minimizing some energy-related objective. These optimizations assume a deterministic environment and perfect control, while in reality the environment and the human control will be uncertain. This might explain why some of these predictions are unrealistic.

We hypothesize that humans prefer a reliable gait over a more energy efficient, but riskier gait. To study this, we have developed a stochastic trajectory optimization approach that finds optimal controls over several noisy episodes to study the effect of noise in movement planning, especially gait. This method was applied to a torque-controlled model of human gait. Our method shows that foot clearance is higher in the stochastic model than in the deterministic model.

Introduction

Predictive simulations of human movement, such as walking, do not always predict realistic gait cycles when minimizing muscular effort [1]. These simulations are solved in a deterministic environment and ignore all noise. Recent studies suggest that humans prefer safe strategies rather than theoretically optimal ones, and take uncertainty into account when planning their movements (e.g. [2]). Thus, predictive simulations of human movement might be improved when solved on a stochastic dynamic model.

Recently, we developed a method to solve trajectory optimization problems in a stochastic environment. This approach was first applied to a pendulum swing-up problem and to show that co-contraction of muscles can be optimal in a stochastic environment [3]. In the current study, this approach was applied to find predictive simulations of gait. It was hypothesized that in a stochastic environment, foot clearance will be larger during the swing phase than in a deterministic environment.

Methods

Predictive simulations of gait were found using a sagittal plane model with 9 degrees of freedom [1]. Ground contact was modeled using contact points at the heel and toe of the foot. The model was operated by six torques in the hip, knee, and ankle joints using a combination of open loop and closed loop control. A trajectory optimization problem was formulated over 10 gait cycles to find controller parameters that minimize the tracking error and the squared torque, similar to [4]. A periodicity constraint was added between the first and final gait cycle under the assumption of left-right symmetry.

Noise was added to the control torque to model the stochasticity of human control. The standard deviation of the noise was varied between 0 Nm (deterministic environment) and 100 Nm. The noise was piecewise constant white noise, sampled at a rate of 0.037 s. The trajectory optimization problem was solved using direct collocation and a backward Euler discretization [1] with 30 nodes per half gait cycle.

To study the foot clearance, the clearance of the heel and toe during the swing phase will be compared. It is expected that the clearance of the foot will increase in the stochastic model to avoid tripping or foot dragging, which would increase the control cost.

Results

Figure 1 shows the foot clearance at the heel and toe. A more detailed graphs of the final part of the swing phase is given in the smaller graphs. These graphs show that in this phase the foot clearance increases when the noise has a larger amplitude.

Table 1 shows the minimum foot clearance of the toe and the heel during the phase that is plotted in the detailed graphs. The clearances of both heel and toe are around 8 mm larger at the highest noise level.

Discussion

Figure 1 and Table 1 show a clear trend towards increased foot clearance with increasing control noise. This confirms our hypothesis. In a stochastic environment, a more reliable solution is optimal, but a riskier solution, with lower foot clearance, is optimal in a deterministic environment.

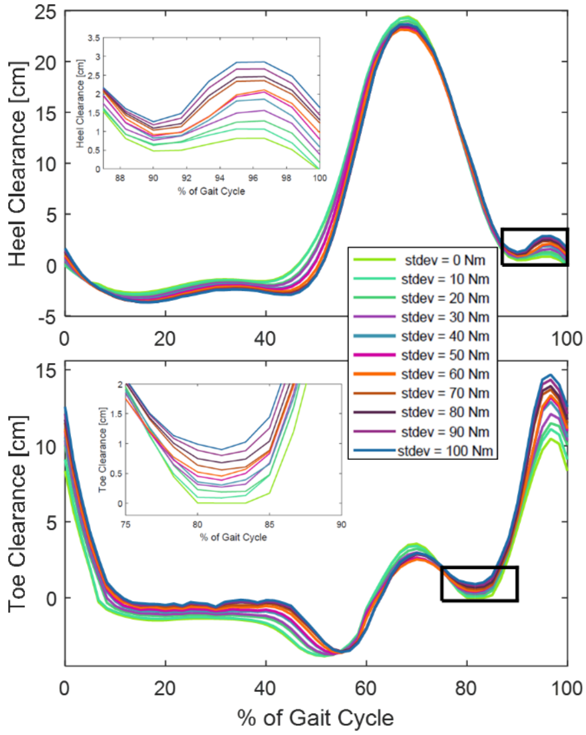

Figure 1: Foot clearance of the heel and toe. The figures on the top left zoom in on the part in the black square.

Occasionally, contradicting results were seen (e.g. the heel clearance at 10 Nm vs. 20 Nm). This might be an artifact of the noise, which was sampled only for 10 gait cycles. To avoid this, the number of gait cycles should be increased. It is expected that a larger number of gait cycles is required to correctly estimate the effect of the noise, since a convergence analysis on a problem with one degree of freedom showed that at least 30 episodes were required for that problem [3], and this problem has more degrees of freedom.

However, even with the small number of gait cycles, it was already possible to confirm our hypothesis. It is expected that the effect of the noise on the foot clearance will be larger when the optimization is solved over a larger number of gait cycles, since then the optimal solution will have a smaller chance to take advantage of the noise.

Using 10 gait cycles yields an optimization problem with 7000 optimization variables. This problem was solved in approximately four hours on a standard laptop computer. A larger number of gait cycles will increase the required solution time. Therefore, parallel computing will be employed for the convergence analysis to determine how many gait cycles are required to correctly estimate the effect of the noise in this problem.

Table 1: Minimal foot clearance of the heel and toe during the swing phase using different standard deviations.

Standard Deviation [Nm]	Toe Clearance [mm]	Heel Clearance [mm]
0	0.01	4.76
10	0.89	6.56
20	1.89	6.26
30	2.72	7.63
40	3.05	8.21
50	3.86	8.72
60	4.54	9.14
70	5.58	10.3
80	6.79	10.9
90	8.01	11.7
100	8.98	12.6

Another advantage of the solution method is that, besides the optimal trajectory, an optimal feedback controller is found. When a predictive simulation is solved in a deterministic environment, only an optimal trajectory is found. The controller is found separately, for example by linearizing around the trajectory. However, the controller would not be able to handle larger perturbations since it does not account for balance control. To solve this, a foot placement controller could be included in the trajectory optimization method used in this study.

References

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