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OPTIMAL CONTROL FORMULATION FOR THE GAIT WITH CRUTCHES

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SUMMARY

In spite of the large number of users, crutches have experienced few functional improvements over their long history. New designs and modifications have been proposed in the literature, such as the spring-loaded crutches, but the difficulty in quantifying their real benefits and determining appropriate parameters, have contributed to prevent their adoption. This manuscript describes an optimal control formulation which is suitable for generating predictive simulations of gait with crutches and can be used for preliminary investigations of the potential benefits of new designs and parameters. The approach is used to generate a predictive simulation of a complete crutch gait cycle with variable contact events and treatment of phase transitions.

INTRODUCTION

In spite of the large number of users around the world, crutches have undergone few functional modifications over their long history, with improvements almost exclusively limited to the use of new materials and to aesthetic aspects. Patients who would otherwise require wheelchairs can stand and walk with crutches, potentially benefiting from improved blood circulation, reduced bladder infections and better social inclusion [1]. On the other hand, some crutch gait styles require as much as 80% more energy expenditure than normal gait [2] and the large forces transmitted to the upper limbs can cause pain, discomfort, and conditions such as crutch palsy and thrombosis [3].

In order to mitigate the mentioned problems of the gait with crutches some functional modifications have been proposed, including the spring-loaded crutch, the rocker crutch and the prosthetic foot crutch [1]. Among these ideas, the spring-loaded crutch appears to be the most promising and has been experimentally investigated previously [4]. However, appropriate parameters for these new designs remain unknown, as for instance adequate stiffness values for spring-loaded crutches.

Predictive simulations of the gait with crutches using realistic models could potentially help in the determination of appropriate parameters, but such studies are scarce in the specialized literature, and limited to the investigation of a single phase of the gait cycle [5, 6]. This study proposes an optimal control formulation of the complete cycle of the gait with crutches. The proposed formulation is employed to generate a predictive simulation of the complete cycle of the swing-through gait style with crutches (Figure 1), using a

direct collocation approach and the optimal control package PROPT/SNOPT (tomdyn.com).

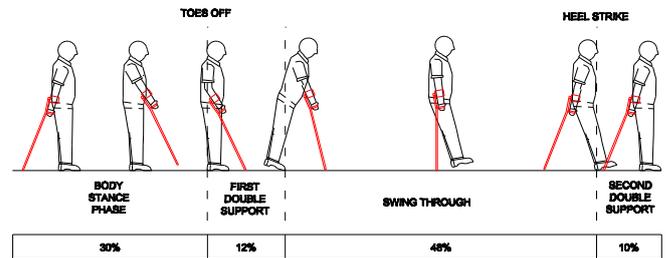


Figure 1: Complete gait cycle of the swing-through crutch gait style.

METHODS

In order to illustrate the approach, we adopt a 5 DoF model of the the swing-through crutch gait style for users of KAFO's (knee-ankle-foot orthoses), which fix the knee and ankle joints. The model is contained in the sagittal plane and is composed of three rigid body segments: 1) the arms and the crutches; 2) the trunk and the head; and 3) the lower limbs and the orthoses. The generalized coordinates adopted correspond to the angles of the segments with the vertical (positive in the counterclockwise direction), σ , φ , θ for segments 1, 2 and 3, respectively, as well as the horizontal and vertical coordinates, x and y , of the center of mass of segment 1. The anthropometric parameters, including mass, moment of inertia, length and position of the center of mass for each segment, are extracted from [8] and [9].

In this model, there is no active hip moment, representing the lack of hip muscle control in paraplegic subjects. Passive hip moment model is adopted from [7]. The only active control over the motion is through the shoulder joint moment. The contacts of the crutch tips and the feet with the floor are modeled by hinge joints, which are activated or deactivated along the gait cycle depending on the current gait phase ph , with $ph=1$ for the stance phase, $ph=2$ for the first double support phase, $ph=3$ for the swing phase, and $ph=4$ for the second double support phase, see (Figure 1). The equations of motion of the model are

$$M(q)\ddot{q} + k(q, \dot{q}) = k^e(q) + R\tau + C_{ph}^T \lambda_{ph}, \quad (1)$$

$$\text{with } C_{ph} = \frac{\partial c_{ph}}{\partial q^T} \quad \text{and} \quad c_{ph}(q) = 0 \quad \text{for } ph = 1..4, \quad (2)$$

where $q = [x; y; \sigma; \phi; \theta]$ is the vector of generalized coordinates, M is the 5×5 mass matrix, k is the vector of generalized Coriolis and centrifugal forces, k^e is the vector of generalized applied forces, not including the shoulder moment τ , λ_{ph} is the vector of Lagrange multipliers representing the active contact forces corresponding to the active constraints $c_{ph}(q) = 0$ in phase ph . The contact between the feet and the ground is modeled as a hinge joint.

The equations of motion in the form of Eqs. (1-2) allow for a straightforward treatment of phase transitions and formulation of the optimal control problem. The transitions between phases $ph=1$ and $ph=2$, corresponding to the contact of the crutch tips with the ground in the end of the stance phase, and between phases $ph=3$ and $ph=4$, corresponding to the collision of the feet with the ground in the end of the swing phase, are treated as perfectly inelastic collisions [10].

The optimal control problem consists of searching for the time series of the states, $q(t)$ and $\dot{q}(t)$, the shoulder moment $\tau(t)$, and the Lagrangian multipliers vector $\lambda_{ph}(t)$ for phases $ph = 1..4$, as well as for the two step lengths, L_1 and L_2 , and the time duration T_{ph} for all phases, $ph=1..4$, that minimize a cost function J , and that are subject to constraints given by Eqs. (1-2) and additional constraints, ensuring continuity between adjacent phases and periodicity. The cost function adopted in this study is a measure of shoulder effort per unit of distance travelled, as

$$J = \frac{1}{L_1 + L_2} \int_0^{\sum T_{ph}} \tau^2 dt. \quad (3)$$

The additional constraints ensure that there is continuity of generalized coordinates between adjacent phases as well as continuity of generalized velocities in phase transitions without collisions. For phase transitions characterized by collisions, collision treatment as in [10] guarantees appropriate relationships between generalized velocities at the end of the preceding phase and at the beginning of the subsequent one. In addition, constraints on the Lagrange multipliers that guarantee fulfillment of unilateral contact constraints along each phase of the cycle can be enforced.

RESULTS AND DISCUSSION

The optimal control problem formulated in the previous section is solved using a direct collocation approach [11] and the PROPT optimal control solver (tomdyn.com). In this example, both double support phases do not occur as the collision treatment determines direct transition between the stance phase and the swing phase and vice-versa (Figure 2).

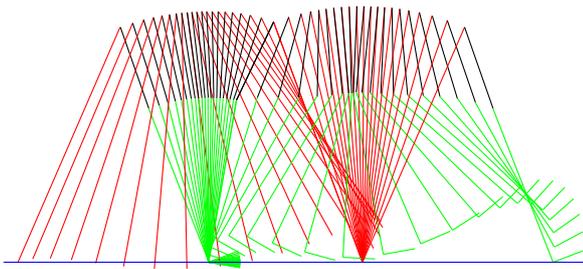


Figure 2: Stick figures of the simulated crutch gait cycle, showing trunk (black), legs (green) and crutches (red).

The optimal trajectories according to the cost function in Eq. (3), are shown in (Figure 3). The optimal, predicted stride length, L_1+L_2 , is 2.01m and the total cycle duration is 2.04s, resulting in an optimal gait speed of 0.99 m/s, which is consistent with values for the swing-through style reported in the literature [4], although the stride length and cycle duration predicted here are both larger than the reported in the literature. The jumps in the generalized velocities in the transitions between phases (Figure 3) are consistent with the treatment of the corresponding collision events.

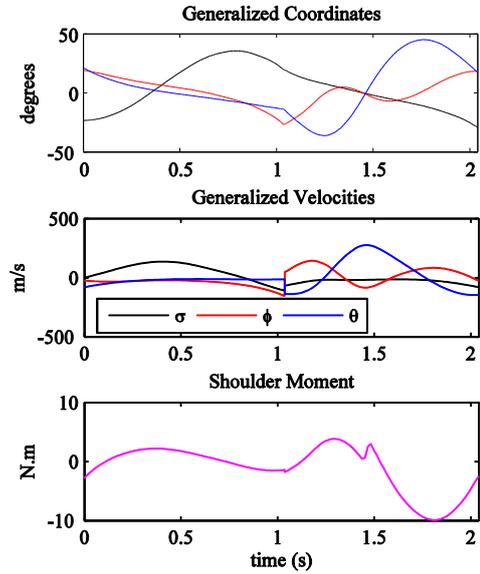


Figure 3: Results for the simulated crutch gait cycle.

CONCLUSIONS

This study introduces an optimal control formulation suitable for simulating the gait with crutches using direct collocation, which can be extended to other gait styles characterized by variable contact events. The approach is implemented using optimal control software and predicts reasonable crutch gait patterns with low computational cost.

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