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Optimal Push Recovery for Periodic Walking Motions

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Abstract: We study how humans performing periodic walking motions react to strong perturbations that are applied in form of pushes from behind. We propose a computational method that allows to generate optimal recovery motions based on a dynamic multi-body model of the human walking process. The assumption is that humans in such a situation would aim to pursue the walking motions while at the same time limiting the effort for the motion. For a given position and velocity in the middle of a periodic walking motion and a given pushing force profile, magnitude and contact point we determine the motion of the human model that minimizes a combined criterion joint torques and a deviation from periodicity. The recovery horizon considered in the multiphase optimal control problem is one step. The optimal control problem is solved using a direct boundary value problem approach based on multiple shooting. We present resulting optimal recovery motions for pushing forces between 150 N and 600 N which all look realistic. The proposed method has potential applications in the computation of push recovery motions for humanoid robots or for elderly humans with physical assistive devices, in each case applied to the respective model.

Keywords: optimal control, periodic walking motion, push recovery, human motion, multi-body system dynamics.

1. INTRODUCTION

The ability to cope with large perturbations or pushes is important for humans to allow them to walk and interact in a variety of situations in the real world. Humans learn to walk from early childhood on, and after first unstable attempts and frequent falls, they usually manage to walk stably under different conditions and also to cope with large perturbations without falling. Pushes received while standing can either be compensated by counteracting movements of the arms or the entire upper body or, in the case of stronger pushes, result in one or more steps. If humans are pushed while walking, they typically try to recover while maintaining the overall walking motion as long as possible, i.e. the recovery does not aim towards any static resting posture but towards the periodic limit cycle of the original walking motion. Only for very large pushes, and when also the use of all parts of the upper body for stabilizing is not sufficient, pushes result in static postures or, in the ultimate case, in falling.

Gaining a fundamental understanding of the mechanisms of push recovery is important in the field of humanoid robotics. Robots cannot react to perturbations without being given explicit strategies on how to detect, classify and compensate disturbances. Such an understanding is also crucial for the control of technical devices assisting persons with mobility problems, e.g elderly persons or patients with prostheses. The study of human push recovery therefore is an important aspect of the KoroiBot project, Koroibot (2016a), which aims to improve walking capabilities of humanoid robots in different terrains by developing better motion generation and control methods. Pushes have been extensively studied in experiments and included in the KoroiBot data base, Koroibot (2016b); Mandery et al. (2015), and different novel methods for coping with pushes are being developed, such as the method presented in this paper.

The present study is based on the general assumption that human motions, as many processes in nature, are always optimal or close to optimal in some sense, Alexander (1984). We therefore propose to approach the problem of generating push recovery motions by means of mathematical optimization, or, more specifically, optimal control. The high complexity of the human body makes it difficult to analyze human motions. The human body has many degrees of freedom that allow relative motions of all segments of the body, and the system is highly redundant for performing many motion tasks. It can be modeled as a dynamic multi-body system with rigid segments, which is driven by torques at all internal degrees of freedom, resulting overall in an underactuated system.

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Formulating a walking motion with or without push for such a system results in a hybrid dynamics problem, i.e. it contains multiple continuous motion phases with different equations of motions as well as instantaneous phases describing discontinuities, e.g. in the velocities at the impact of a foot on the ground. This physical model has to be considered as underlying constraints of the optimal control problem. In this study we are using a model of human walking with 14 segments in the sagittal plane, resulting in 32 state variables and 13 control variables. We consider the types of pushes during periodic walking in which the aim is to maintain a motion close to the periodic one. We therefore formulate an objective function of the optimal control problem that aims to minimize the gap to periodicity after one step of the motion. We add a second term that minimizes a weighted sum of joint torques squared resulting in a reduction of efforts over all joints which has proven to be a suitable criterion for many types of motions, Schultz and Mombaur (2010); Koschorreck and Mombaur (2009); Felis and Mombaur (2013); Felis (2015). The push is added as a given function of time in the right hand side of the dynamics. Initial conditions for the step, i.e. just before the onset of the push, are fixed to the conditions of the periodic motion at this very moment. The duration of phases as well as the resulting step length (and all other positions and velocities) are free to be determined by the optimization. We study the result of this optimal control problem for pushes defined by a polynomial of order four with a duration of 0.1 seconds and a maximal amplitude which varies between 150N and 600N.

Push recovery has been a very active field of research in recent years, in particular in the robotics community. Since the focus often is on short computation times, many studies are performed on simplified models of walking. A common model is the linear inverted pendulum (LIP) that is a very simplified representation of human and robot walking. Push recovery methods such as the calculation of capture points have already been developed with this kind of model. The capture point denotes the point where a system has to step in order to come to a complete stop, Pratt et al. (2006). Capture point calculations have also already been made for much more complex models. In Rebula et al. (2007) capture points for a three dimensional (3D) humanoid model with 12 degrees of freedom (DoF) were computed by learning the offsets to the capture points predicted by a LIP model. Often only pushes from standing position are analyzed taking the step length of the capture motion into account, Wu et al. (2007); Hsiao and Robinovitch (1999). The recovery strategies are categorized in levels such as 1) using ankle joints to apply torque to the ground, 2) using hips or arms to generate horizontal ground forces and 3) using knees and hips to squat or take a step, Stephens (2007). Some age-related studies on the frequency and severity of falls have been made by Hsiao and Robinovitch (2007); Semwal and Nandi (2014). Semwal also analyzed the differences between open and closed eye reaction on the perturbations. In Adiwahono (2011) disturbed walking motions have been analyzed. A 12 DoF model that can handle pushes from any direction is presented. Oliveira suggests in Oliveira et al. (2012) a modular organization of muscular activation during recovery of balance during gait.

The novelty of the approach presented in this paper is that it explicitly addresses large perturbations during periodic walking with the aim to go back to the limit cycle and not to stop to recover. It is the first optimization approach based on a whole-body model of human walking. While it may be too time consuming to preform this type of computations on-line in the robotics context, the trajectories can easily be pre-computed for different levels of pushes and executed according to the sense push signal, as we will discuss in Section 4.

The paper is organized as follows. In Section 2, we present the dynamic model of human walking including external pushes. Section 3 is dedicated to the formulation and solution of the optimal control problem to generate optimal recovery motions. In Section 4, we present extensive computational results for different pushes. In Section 5, we finally give some conclusions and perspectives of this research.

2. DYNAMIC MODEL

For our approach of the analysis of human push recovery motions a model of a human is needed. The movement is simulated by the definition of the dynamics of a multibody system. To be able to imitate a push, an approach to include external forces into the human model is presented.

2.1 Human Model

The model used in this paper is a planar multi-body system consisting of 14 segments connected by 13 joints that enable rotations around the y axis (i.e. in the sagittal plane). There are three segments for each leg, two for each arm, three for the trunk and one for the head. The joints give an approximation of the human ankles, knees, hips, elbows, shoulders and the neck. Two joints in the trunk give the opportunity to approximately mimic the motion of the human spine. The pelvis is a free floating body in the planar space, which allows for translation and rotation in sagittal plane. This results in a total of 16 degrees of freedom, or 32 state variables, consisting of all position and velocity variables. The motion is controlled by the torques in all 13 internal joints. Contacts with the floor are described by additional constraint equations resulting in equations of motion in the form of differential algebraic equations as described in detail in the next section. The model is based on the `HeiMan` model, Felis et al. (2015), a highly parametrized rigid model for humans. The parameters such as segment lengths, masses and inertia tensors are set based on human values from de Leva (1996).

2.2 Multi-body Dynamics

The dynamics of a human body can be approximated by a system of rigid bodies connected by rotational joints. The model used in this work is implemented in the rigid body dynamics library `RBDL`, Felis (2016). The dynamical behavior of the model can be described by the following differential equation of motion

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) = \boldsymbol{\tau}. \tag{1}$$

Pelvis position and orientation and the joint angles are defined by the vector $\mathbf{q} = (q^{(1)}, \ldots, q^{(n_q)})$, $q^{(i)} : \mathbb{R} \rightarrow \mathbb{R}$,