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Analysis of human leg joints compliance in different walking scenarios with an optimal control approach ⋆

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Abstract: Compliance at joint level in human locomotion has played a central role in many studies. In particular joints in the lower body were mainly considered in order to create mechanisms able to reproduce human-like gaits such as prostheses, exoskeletons or walking robots. In a previous study, we have used an 11 DOF 2D human model to carry out the analysis of compliance in the leg joints during level ground walking, by introducing torsional springs with variable stiffness in the leg joints and dampers in the ankle joints. In this paper we have significantly extended this study to different walking scenarios, such as slope and stair walking, in addition to level ground walking. In the dynamic model, two degrees of freedom have been added to the trunk in order to better reproduce the flexibility of the human trunk, resulting in a 13 DOF 2D human model. In addition, biarticular springs as coupling between hip and knee joints have been introduced. Optimal control is applied to identify the stiffness profiles, the rest positions of the springs and the value of the damper at the ankle that best reproduce measured human joint trajectories in these walking scenarios.

Keywords: Human walking, periodic gait, joint stiffness identification, optimal control

1. INTRODUCTION

Researchers over several research fields such as biomechanics and robotics have been interested in the investigation of human locomotion. Their main objective is to create new devices that are able to help people with mobility challenges to walk or improve human walking capabilities. Such as orthoses, prostheses or exoskeletons in Haight et al. (2015); Grimmer et al. (2014); Zoss et al. (2006), or to build walking robots, such as humanoid robots in Huang et al. (2014).

A factor of human locomotion that has been the core interest of these studies is compliance, which has been demonstrated to be fundamental in walking motions (Geyer et al., 2006) by means of simple spring mass models. In particular, compliance at joint level plays a central role as per Latash and Zatsiorsky (1993). Researchers have focused on lower body joints carrying out analysis on dynamic hip, knee and ankle joint stiffness both in walking in Shamaei et al. (2013b,c,a) and running in Günther and Blickhan (2002). In some studies biarticular muscles were also included as coupling between these joints such as in Iida et al. (2008) and Mombaur (2014).

Humans in daily life walk in many different environments, the most common ones are level ground, up and down slopes of different inclinations, stairs of different sizes and different type of rough terrains. So in order to better understand locomotion it is necessary to analyze walking in all these different scenarios. However despite the large amount of literature on stiffness at joint level, most of them are focused on level ground walking, with a much smaller amount of works on other walking scenarios. In biomechanics there is some work on the analysis of kinematics and kinetics of slope walking as Franz et al. (2012); Silder et al. (2012) and stair climbing as Andriacchi et al. (1980); Amirudin et al. (2014), but there is a lack of studies focused on joint stiffness.

In robotics, the main objective of these studies is to gather fundamental information to develop compliant actuators, which are believed to be able to recreate more human-like and human-friendly motions in robots. Many types of these actuators were developed, some of which have elastic elements with fixed stiffness and others with variable stiffness. A comprehensive review can be found in Vanderborght et al. (2013). Among the existing actuators, there are some that have already been used in humanoid robots, such as the Series Elastic Actuators (SEA) used in CoMan (Colasanto et al. (2012)) and M2V2 (Pratt and Krupp (2008)), tendon driven actuators in Roboray (Kim et al. (2012)) and pneumatic artificial muscles in Lucy (Verrelst et al. (2005)).

The objective of this paper is to analyze the variation of stiffness at joint level during walking in three walking scenarios, namely level ground, slope and stair walking, and to evaluate the possible differences due to these scenarios. In contrast to many other studies, we are not interested to find a stiffness that produces just some

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walking motions, but to precisely identify the stiffness profiles that produce certain measured gaits.

The approach we follow is summarized as in Fig. 1. Joint angles are computed from motion capture data and then fitted to a two-dimensional (2D) human model, which is a simplified model with the essential human joints restricted in the sagittal plane. This model has a total of 14 segments and 16 degrees of freedom (DOF), including the floating base. In addition to this model, torsional springs with variable stiffness are introduced in the hip, knee and ankle joints. Biarticular springs with variable stiffness are also introduced as coupling between the hip and knee joint, and a damper is included in the ankle joints to avoid oscillations. The variable stiffnesses are the control inputs of the optimal control problem for the lower body joints, while for the upper body the control inputs are torques. A least squares fit is carried out to fit the dynamic walking model to the measured data to identify the stiffness profiles.

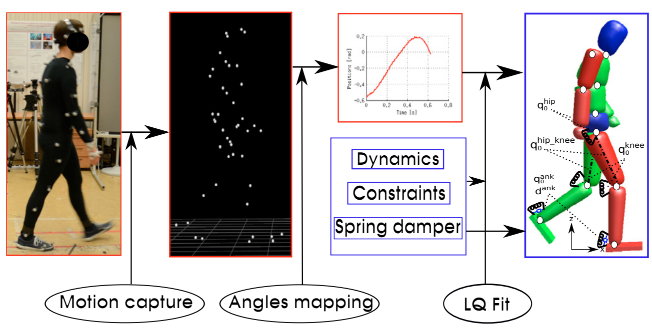

Fig. 1. Scheme summarizing our approach. Joint angles are retrieved from motion capture data, then fitted to the 2D human model via a least squares fit considering the dynamics, constraints and the spring damper system.

2. PROBLEM FORMULATION

2.1 Model description

The goal of this paper is to investigate the modulation of stiffness at joint level through the different walking phases in three walking scenarios: level ground, slope and regular stairs.

In a previous work (Hu et al., 2014) we addressed the same problem in level ground walking only on a preliminary set of data and a human model of 11 DOF in 2D. To have a more precise description of the human locomotion dynamics, we now add two more degrees of freedom in the trunk of the rigid multibody system to make the spine more flexible, resulting in a 13 DOF rigid body system with a total of 14 segments. As shown in Fig. 1, there are two segments for each leg, one per foot, two per arm, one per head and three for the trunk including pelvis. The floating base reference frame is located in the pelvis and allows 3 DOF in the sagittal plane, respectively two translations, along x and z directions and one rotation about the y axis. The axis pointing to the walking direction is x while the z axis is pointing up. Since we only consider planar motions, all internal joints represent 1 DOF joints with rotations about the y axis.

The total number of degrees of freedom of the model is $n_{dof} = 16$, taking into account also the floating base. This means that the actual actuated degrees of freedom is $n_{actuated} = 13$. The model is described with the generalized coordinates $q \in \mathbb{R}^{n_{dof}}$.

To achieve our goal of analyzing the stiffness modulation at joint level, torsional springs with variable stiffness are introduced in the hip, knee and ankle joints of the legs as shown in Fig. 1. Hip and knee joints are coupled by a biarticular muscle which is a spring with variable stiffness. In the ankle joints, dampers are introduced to avoid oscillations that might occur during the lift off of the foot from the ground. The variable stiffnesses of the springs are time varying and represent the free control inputs of the optimal control problem as explained in the following section 2.2. They are constrained to be always positive given that negative stiffness is unphysical. The rest positions of the springs and the value of the dampers at the ankles are also left free to the optimization to find the best values.

We consider a simple foot model, where only two contact points are taking into account, one on the toe and one on the heel and which allow to describe flat foot contact as well as heel only and toe only contact to describe the different walking phases.

In walking, in contrast to running, there is always at least one contact point with the ground, independently from the walking scenario. Assuming non-sliding contacts, the system dynamics taking into consideration contacts can be described as in Mombaur (2009):

$$\begin{bmatrix} H & G^T \\ G & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ -\lambda \end{bmatrix} = \begin{bmatrix} \tau - C \\ -\gamma \end{bmatrix} \tag{1}$$

Where H is the joint space inertia matrix, G is the Jacobian of the contact points, $\ddot{q}$ is the vector of joint accelerations, λ the vector of Lagrange multipliers. On the right hand side of the equation we have τ as the vector of torques, C as the vector of all nonlinear terms and γ the generalized acceleration independent part of the contact point accelerations, namely $\gamma = (\partial G/\partial q)\dot{q}$, which is sometimes also denoted as constraint Hessian. Each phase of the motion is described by its own set of differential equations of the above type (1).

When a point comes in contact with the ground, there is a sudden change in the generalized velocity $\dot{q}$ at the touchdown. The impact dynamics can be described as in Mombaur (2009):

$$\begin{bmatrix} H & G^T \\ G & 0 \end{bmatrix} \begin{bmatrix} \dot{q}^+ \\ -\Lambda \end{bmatrix} = \begin{bmatrix} H\dot{q}^- \\ v^+ \end{bmatrix} \tag{2}$$

In this formulation it is assumed that the collision is inelastic and instantaneous. In equation 2 $\dot{q}^+$ is the generalized velocity after the impact, Λ the impulses at each constraint, $\dot{q}^-$ the generalized velocity before the impact, and v^+ the desired velocity of contact points after the impact, the default value of which is 0. Obviously these hybrid system dynamics are non-differentiable in time. However, it is important to note that the states of the system at every instant are differentiable with respect to the changes in initial values (at $t = 0$) and in the right hand side (e.g. changes in the torques) since derivatives can also be computed over the impacts. The latter is the kind of