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Comparison of closed-loop system identification techniques to quantify multi-joint human balance control

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ABSTRACT

The incidence of impaired balance control and falls increases with age and disease and has a significant impact on daily life. Detection of early-stage balance impairments is difficult as many intertwined mechanisms contribute to balance control. Current clinical balance tests are unable to quantify these underlying mechanisms, and it is therefore difficult to provide targeted interventions to prevent falling. System identification techniques in combination with external disturbances may provide a way to detect impairments of the underlying mechanisms. This is especially challenging when studying multi-joint coordination, i.e. the contribution of both the ankles and hips to balance control.

With model simulations we compared various existing non-parametric and parametric system identification techniques in combination with external disturbances and evaluated their performance. All methods are considered multi-segmental (both the ankles and the hips contribute to maintaining balance) closed-loop balance control. Validation of the techniques was based on the prediction of time series and frequency domain data. Parametric system identification could not be applied in a straightforward manner in human balance control due to assumed model structure and biological noise in the system. Although the time series were estimated reliably, the dynamics in the frequency domain were not correctly estimated. Non-parametric system identification techniques did estimate the underlying dynamics of balance control reliably in both time and frequency domain. The choice of the external disturbance signal is a trade-off between frequency resolution and measurement time and thus depends on the specific research question and the studied population.

With this overview of the applicability as well as the (dis)advantages of the various system identification techniques, we can work toward the application of system identification techniques in a clinical setting.

1. Introduction

Maintaining a stable upright posture is a complex task. The body is inherently unstable due to the gravitational pull, and it would fall without stabilizing control. The central nervous system (CNS) stabilizes the body by integrating sensory feedback signals to determine the appropriate response, which is sent to the muscles and results in corrective joint torques to keep the body upright (Peterka, 2003). How the stabilizing mechanism of the CNS regulates balance can be investigated by estimating the dynamics of the so-called neuromuscular controller that outputs corrective joint torques as a response to body sway (Engelhart et al., 2014).

With aging or due to disease, sensory systems or the neuromuscular controller can deteriorate and as a result, balance control problems can arise (Pasma et al., 2014). For example, the elderly often have difficulties maintaining balance during daily life activities, and this impaired balance is a strong risk factor for falls (Rubenstein, 2006; Muir, Berg, Chesworth, Klar, & Speechley, 2010). About 28–35% of people aged over 65, fall each year and this incidence increases with age (WHO, 2007). To determine who is at risk of falling, clinicians use clinical balance tests (e.g. Berg Balance Scale (Berg, Wood-Dauphinee, Williams, & Gayton, 1989)) and posturography measures (e.g., sensory organization test (Cohen, Heaton, Congdon, & Jenkins, 1996)). These tests assess the ability to maintain standing balance and the quality of balance by measuring body sway. However, these tests do not determine the contribution and quality of the underlying mechanisms (Engelhart et al. 2014; Pasma et al., 2014). In addition, it is currently not

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possible to determine who has an increased risk of falling in the next year (Ganz, Bao, Shekelle, & Rubenstein, 2007; Laessoe, Hoeck, Simonsen, Sinkjaer, & Voigt, 2007; Visser, Carpenter, van der Kooij, & Bloem, 2008). Therefore, it is difficult to provide targeted interventions to decrease fall incidence. In other words, there is a clear (clinical) need to be able to (a) identify people with an increased fall risk, (b) evaluate targeted interventions, and (c) improve our overall understanding of the pathophysiology of balance-control impairments (Visser et al., 2008; Kingma et al., 2011; Sibley, Straus, Inness, Salbach, & Jaglal, 2013).

Estimation of the neuromuscular controller dynamics is difficult, as in a closed-loop feedback system (such as balance control) it is hard to disentangle cause and effect. That is, without externally applied disturbances, it is difficult to determine if, for example, changes in muscle activity result in changes in muscle force that will affect body sway, or that the opposite is true, i.e. changes in body sway are detected by sensors and transmitted to the nervous system that excites the muscle groups reflected in changes in the muscles' electromyography (EMG). Furthermore, standing balance is regulated around the ankles and hips, and multi-joint coordination must be achieved. Movements of one segment influence movements of the other segment (Horak & Nashner, 1986; Park, Horak, & Kuo, 2004), resulting in additional interactions.

System identification techniques in combination with specifically designed external disturbances provide a way to disentangle cause and effect in balance control and identify the dynamics of the neuromuscular controller. Therefore, our group (Van der Kooij, van Asseldonk, & van der Helm, 2005, 2007; Van Asseldonk et al., 2006; Boonstra, van Vugt, van der Kooij, & Bloem, 2014b; Engelhart et al., 2014; Pasma et al., 2014) and other groups (Johansson, Magnusson, a, & Karlberg, 2001; Peterka, 2002; Kim, Horak, Carlson-Kuhta, & Park, 2009, 2012; Jeka, Allison, & Kiemel, 2010; Mergner, 2010; Goodworth & Peterka, 2012) have developed and evaluated novel quantitative balance-control assessment methods based on system identification techniques to better understand the balance-control system, with the ultimate goal to improve clinical decision making. As the balance control system is dynamic (i.e., its response is described as a function of time), system identification techniques can be used to determine the underlying structures of the system by unraveling cause-and-effect relations in multi-joint coordination. The field of system identification is very broad, with many approaches and various techniques and methods. It is far from trivial to compare the methods reported in literature, as there are always differences in experimental design and the results are presented in different ways. If meaningful interpretation and comparisons are to be derived from balance-control experiments in different labs, there is a clear need for standardized protocols (Visser et al., 2008).

In this paper we compare different multivariable system identification techniques to estimate the neuromuscular controller dynamics with model simulations (as applied in literature), to evaluate the effects of various disturbance types and analysis methods. The advantage of model simulations is that all methods were validated based on one system from which all dynamics are known. We focused on methods that approached the human balance-control system as a double-inverted pendulum, pivoting at the ankles and hips in the anterior–posterior direction. This is contrary to many other methods that have approached the balance-control system as an inverted pendulum, with only an ankle joint. Our approach was chosen because recent studies have shown that differences between e.g. Parkinson's disease patients and the elderly (Boonstra, Schouten, van Vugt, Bloem, & van der Kooij, 2014a) and between the elderly and young (Accornero, Capozza, Rinalduzzi, & Manfredi, 1997; Hsu, Chou, & Woollacott, 2013) were the most pronounced in multi-segmental balance-control coordination.

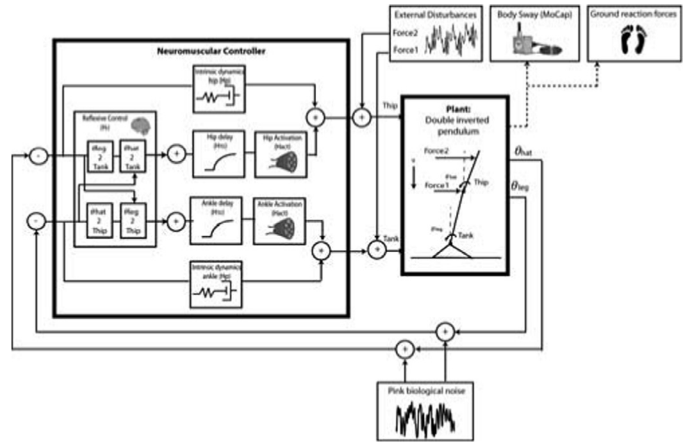

Fig. 1. Simple representation of the human balance control system. The human body is represented by a double-inverted pendulum, with a leg and a hat-arms-trunk (hat) segment. The neuromuscular controller generates corrective joint torques (T_{ank},T_{hip}) to regulate balance over time, by intrinsic dynamics (H_p) together with time-delayed (H_{TD}) reflexive activation (H_r, H_{act}) of muscles. For system identification purposes the body is disturbed by two external force disturbances at the hip and shoulder level, and body sway and ground reaction forces are measured.

Here, we give an overview of the applicability and (dis)advantages of various system identification techniques, which will aid toward the use of standardized measurement protocols to assess balance control with system identification techniques in a clinical setting.

2. Materials and methods

This section describes the general goal of system identification in human balance control, i.e. estimating the dynamics of the neuromuscular controller. By simulating a two-segmental balance-control model that contains the dynamics of the underlying physiology, various system identification techniques were presented, validated, and compared.

2.1. Modeling of human balance control

Fig. 1 shows a model of human balance control, in which the underlying physiology is described by various underlying mechanisms. When only considering anterior–posterior movement, the body dynamics can be regarded as a double-inverted pendulum, consisting of two segments; the lumped legs and the head-arms-trunk (hat) segment pivot around the ankle and hip joint respectively. Internal disturbances (biological noise in muscles, sensory organs, and the nervous system) and external disturbances (pushes and pulls on the human body and the pull of gravity) drive the system away from equilibrium. Maintaining standing balance is controlled by a feedback, i.e. a closed-loop system. The sensory systems (visual, vestibular, and proprioceptive) give information about the body position and velocity relative to the environment. These signals are processed and integrated by the CNS and fed back (with a neural transport delay) to the muscles. Corrective joint torques result from the activation of muscles (reflexive dynamics), together with intrinsic properties of the muscle-skeletal system (intrinsic dynamics). The entire neuromuscular controller describes how balance is regulated and is the system of interest in this study. This neuromuscular controller has separate feedback paths for the leg and hat segment and is therefore a multiple-input-multiple-output (MIMO) system.