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Possible recovery or unavoidable fall? A model to predict the one step balance recovery threshold and its stepping characteristics

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ABSTRACT

In order to prevent fall related injuries and their consequences, one needs to be able to predict the outcome of a given balance perturbation: a possible Balance Recovery (BR) or an unavoidable fall? Given that results from the existing experimental studies are difficult to compare and to generalize, we propose to address this question with a numerical tool. Built on existing concepts from the biomechanics and robotics literature, it includes the optimal use of BR reactions and particularly the possibility to perform a recovery step. It allows estimating 1) the possibility to recover a steady balance from a given initial state or perturbation using at most one recovery step; 2) the set of recovery steps leading to a BR. Using standard sets of parameters for young and elderly population, we assessed this model's predictions against experimental data from the literature in the anterior direction. Two classical representations of the human body (inverted pendulum (IP) vs. linear inverted pendulum (LIP)) were also compared. The results showed that the model correctly predicted the possibility to recover using a single protective step (1-Step BR threshold) and the characteristics (step length and time) of the protective step for both the young and the elderly. This tool has a real potential in the field of fall prevention to detect risky situation. It could also be used to get insights into the neuromuscular mechanisms involved in the BR process.

1. Introduction

A fall is a common event that everyone can encounter throughout their life. Consequences can be extremely severe such as hip fracture, upper limb injuries or traumatic brain injuries especially for frail people such as the elderly. The average cost of one fall injury is about 1049$ in the US with 28–35% of people over 65 years falling each year (World Health Organization, 2008). These figures highlight the necessity for better fall prevention.

In this context, BR thresholds are an important variable to predict the perturbations that may lead to a fall. They can also be used to identify different BR performances between population groups or to better understand the neuromuscular mechanisms involved in the BR process. Note that in this study we define a BR by the action to restore a steady standing state, i.e. the Center of Mass (CoM) above the Base of Support (BoS) with a null velocity.

BR thresholds have been experimentally assessed for different population groups, using various kinds of perturbations (tether-release, pull force, slip) and different instructions about the way to recover (Bariatinsky, 2013; Carbonneau and Smeesters, 2014; Cyr and Smeesters, 2009; Do et al., 1999; Hsiao-Wecksler and Robinovitch, 2007; King et al., 2005; Madigan and Lloyd, 2005; Mille et al., 2003; Wojcik et al., 1999). In particular Cyr and Smeesters (2007) showed that the BR threshold obtained when only one recovery step is allowed (1-Step BR threshold) is a good approximation of the maximal state or external perturbation that can be handled without falling.

Although interesting, these experimental data are very specific (i.e. perturbation, population and instruction dependent) and cannot be easily compared between studies. They are also hardly generalizable and their use to predict the outcome of a non-tested condition is limited. Moreover, they did not allow a complete identification of the role and influence of the different physiological parameters involved in the BR process. Consequently, a numerical model that can estimate the 1-Step BR thresholds for various populations, perturbations and instructions, is a necessary complement to these experimental observations.

One of the main difficulties in obtaining such a model is the necessity to include the automatic postural responses and the

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voluntary reactions to the balance disturbances. Some studies explicitly include a regulation of BR actions based on the system state and/or perceived perturbation (Atkeson and Stephens, 2007; Peterka, 2002; Van der Kooij et al., 1999, Aftab et al., 2012). However, the control of BR reactions tends to limit these models usability (close-loop controller requirement, additional parameter adjustments, etc.). A pragmatic alternative to estimating only the BR thresholds is to consider only the most efficient BR reactions. Based on this idea the possibility to avoid a fall using a fixed support strategy, i.e. without performing a recovery step, was first assessed by Pai and Patton (1997). They represented the human body by an Inverted Pendulum (IP) and the recovery actions by the development of a maximal eccentric ankle joint torque. This approach was further simplified by Hof et al. (2005) and Pratt et al. (2006) who used a Linear Inverted Pendulum (LIP), i.e. a pendulum that travels at a constant height (Kajita and Tani, 1991), and replaced the eccentric ankle joint torque by the displacement of the Center of Pressure (CoP) within the Base of Support (BoS). The possibility to avoid a fall can be estimated from the current state of the Center of Mass (CoM) and expressed as the inclusion of a specific point, named eXtrapolated Center of Mass (XCoM) or Capture Point (CP) (the first denomination will be used in this study), within the BoS. Hof et al. (2005) showed the validity of the pendulum linearization by comparing their results to those of Pai and Patton (1997). Pratt et al. (2006) also included an additional BR mechanism (the angular momentum control due to the rotation of body segments) by adding a flywheel (FW) centered at the CoM. Eventually further works included recovery steps. Wu et al. (2007) complemented the model from Pai and Patton (1997) to include a single step which duration is driven by the system's geometry and Koolen et al. (2012) extended the works from Pratt et al. (2006) to include multiple steps with a constant length and duration.

These later developments are conceptually very interesting and already used in robotics. However they still suffer from limitations. Firstly they lack validation against human data. Moreover there is no step length/duration regulation although it is known to play a critical role in the BR process (Hsiao-Wecksler and Robinovitch, 2007; Owings et al., 2001; Thelen et al., 1997). Lastly the CoM evolution before the recovery step landing – IP (Wu et al., 2007) vs. LIP (Koolen et al., 2012) – still needs to be clarified (Aftab et al., 2010; Li et al., 2014).

Consequently, the objective of this study is to propose a simple numerical tool that predicts if a balance perturbation (external perturbation or initial unbalanced state) can be recovered using a single recovery step. It is based on the previous developments and aims to overcome their current limitations: it includes step length/duration adjustment and can thus be used to estimate the characteristics of the most efficient recovery step (i.e. the shortest and fastest step); two different hypotheses about CoM's evolution are considered and evaluated; two sets of parameters are proposed to represent the BR characteristics in the anterior direction of young and elderly healthy subjects and are used to assess model performances against human data from the literature.

2. Method

2.1. Experimental data

In this study we chose to reuse experimental data from the literature. Three different relevant studies are selected as they provide sufficient information about 1-Step BR experiments for both young and elderly subjects (e.g. thresholds, step length, step timings) but also as they used different types of perturbation or BR instructions. Hsiao-Wecksler and Robinovitch (2007) determined the 1-Step BR threshold in tether released experiments for different constraints on the recovery step length: limited at 15%, 25% and 35% of subject body height or unconstrained. BR reactions are supposed to be at their maximal performances. The study from Thelen et al. (1997) also used tether release experiments. They imposed a recovery in one step but did not put constraints on the step length. They tested different release angles, up to the 1-Step BR threshold. BR reactions before the maximal release angle are thus considered sub-maximal. Moglo and Smeesters (2006) used several type of postural perturbations (tether release, tether release + waist pull and waist pull during walk) in order to establish the threshold line, in the plane of CoM's angular position and velocity at the onset of the reaction, that discriminated states that can be recovered in one step from those ones which cannot.

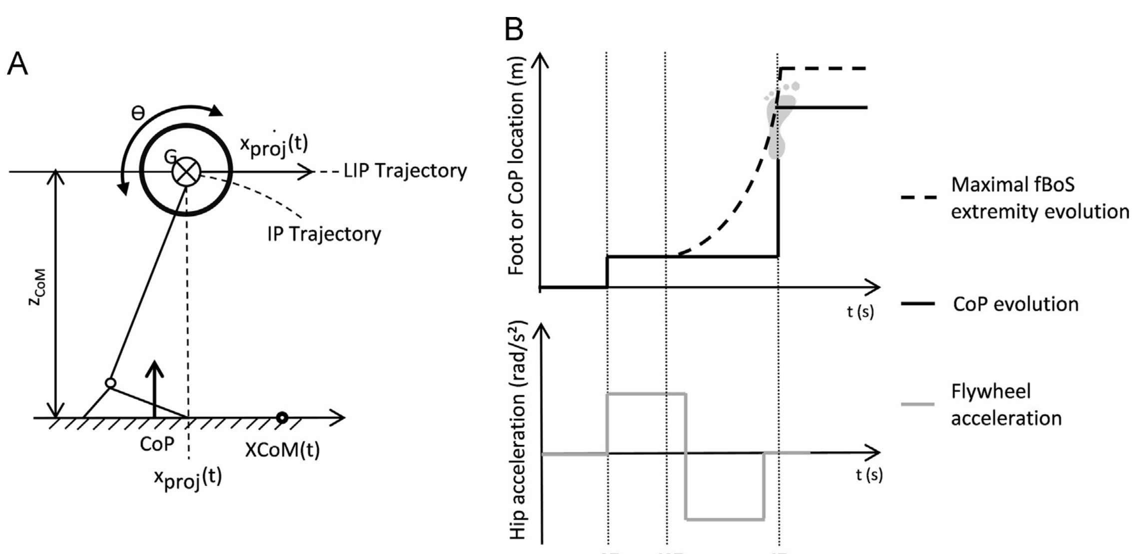

Fig. 1. (A) Representation of the IP and LIP model used in this study. (B) Maximal use of the three recovery strategies. No strategies are used from 0 to Reaction Time (RT). Ankle strategy, represented by the CoP evolution (black line), is launched at RT with a shift toward the fBoS extremity. Hip strategy is also launched at RT with the beginning of the bang–bang flywheel acceleration profile (gray line). The swing phase of a recovery step starts after an additional delay (Step Preparation Time, SPT). The furthest location of this recovery step is defined by a polynomial expression (see in the text) and represented as the black dashed line. Step Time (ST) corresponds to the recovery step landing. At this instant (gray footprint), the CoP is instantaneously shifted toward the new edge of the fBoS.