Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Stepping boundary of external force-controlled perturbations of varying durations: Comparison of experimental data and model simulations

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A R T I C L E I N F O

Article history:
Accepted 3 May 2018
Available online xxxx

Keywords:
Protective step
Fall
Balance
Perturbation
Model

A B S T R A C T

This study investigated the stepping boundary – the force that can be resisted without stepping – for force-controlled perturbations of different durations. Twenty-two healthy young adults (19–37 years old) were instructed to try not to step in response to 86 different force/time combinations of forward waist-pulls. The forces at which 50% of subjects stepped (F_{50}) were identified for each tested perturbation durations. Results showed that F_{50} decreased hyperbolically when the perturbation's duration increased and converged toward a constant value (about 10% BW) for longer perturbations (over 1500 ms). The effect of perturbation duration was critical for the shortest perturbations (less than 1 s).

In parallel, a simple function was proposed to estimate this stepping boundary. Considering the dynamics of a linear inverted pendulum + foot model and simple balance recovery reactions, we could express the maximum pulling force that can be withstood without stepping as a simple function of the perturbation duration. When used with values of the main model parameters determined experimentally, this function replicated adequately the experimental results.

This study demonstrates for the first time that perturbation duration has a major influence on the outcomes of compliant perturbations such as force-controlled pulls. The stepping boundary corresponds to a constant perturbation force-duration product and is largely explained by only two parameters: the reaction time and the displacement of the center of pressure within the functional base of support. Future work should investigate pathological populations and additional parameters characterizing the perturbation time-profile such as the time derivative of the perturbation.

1. Introduction

The neural control of human standing is concerned with keeping the body mass balanced above a base of support (BoS) provided by stationary feet. From a functional perspective, the feet-in-place responses provide only a weak capacity to restore balance when threatened by internal or external disturbances. Stepping or grabbing responses to instability reconfigure the BoS and provide a much more efficient solution to preserve balance and stop falling (Maki and McIlroy, 1997). These automatic change-in-support reactions play a more important functional role in maintaining equilibrium than feet-in-place responses. Contrary to traditional view, they are not just strategies of last resort but are often initiated before balance approaches instability, particularly for older people (Mille et al., 2003; Pai et al., 2000).

Balance and stepping research has often applied perturbations to the body that directly constrain the mechanical state of the body and thus that constrain subjects' responses. Examples are: (i) tether-release experiments (Carbonneau and Smeesters, 2014; Hsiao-Wecksler and Robinovitch, 2007; Thelen et al., 1997) where the initial lean angle and a null velocity are imposed, (ii) position-velocity controlled waist-pull experiments (Mille et al., 2003; Rogers et al., 2001) in which the pelvis is shifted forward at a specified amplitude and velocity whatever the subject's responses, or

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https://doi.org/10.1016/j.jbiomech.2018.05.010
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(iii) position-velocity controlled support surface translation (Maki and McIlroy, 1997; Pai et al., 2000) where the feet are moved relative to the center of mass (CoM) at specified amplitude and velocity. The common feature of these perturbations is that the body displacement imposed by the perturbation does not change according to the subject's response. These perturbations place a subject in a given perturbed state mechanically defined by the position and velocity of his CoM relative to the BoS. From this state, stepping boundaries (whether a feet-in-place response can restore balance or a step is needed) are determined by neuromuscular characteristics of the subjects and the direction(s) of perturbation. However, other characteristics of the perturbations, i.e. how the mechanical state at the end of the perturbation is reached, do not influence the outcome of such perturbations (Moglo and Smeesters, 2005; Vallée et al., 2015).

Few studies focused on compliant perturbations (i.e. perturbation during which a subject's response modifies the body displacement induced by the perturbation such as force-controlled perturbations or long-lasting platform perturbation) despite them being more common in daily-life: a gust of wind, push by another person, public transportation decelerations, etc. For these more natural perturbations, the mechanical state of the person is the result of both the perturbation and the resistance (passive + person's responses) to the perturbation. As such, the time-profile of the perturbation, and in particular its duration, might greatly influence its outcomes. To our knowledge, relatively few studies have investigated stepping boundary with compliant perturbations and these have been limited to a single duration of perturbation (Sturnieks et al., 2012, 2013). There is thus a need to understand stepping reaction to compliant perturbation of various durations.

The present study investigated the stepping boundary during forward force-controlled (i.e. compliant) perturbation of varying durations delivered at waist level and confronted the experimental results with a simple biomechanical model that could predict when a subject had to step. We expected an inverse relationship between the force and the duration of the perturbation: the longer the duration, the smaller the force required to trigger a step.

2. Method

2.1. Experimental data

2.1.1. Subjects

Participants were twenty-two adults (5F, 17 M) aged 19–37 (mean 25.5 SD 4.13) years with mean height 174.3 cm (SD 7.14) and weight 69.9 kg (SD 10.2). Exclusion criteria were significant neurological (e.g. stroke, Parkinson's disease, neuropathy), musculoskeletal (e.g. joint replacement, leg or back pain), medical or balance disorders (e.g. cardiac, metabolic, respiratory, depression, surgery within 6 months) that could limit a person's movements. All participants gave written informed consent prior to the study, which was approved by the Institutional Review Board of the Institute of Movement Sciences, Aix-Marseille University and conducted in line with the principles of the Declaration of Helsinki.

2.1.2. Protocol

Subjects stood on a force platform (OR6-6, AMTI, MA) that recorded the forces under the feet from which the position of the center of pressure (CoP) was calculated. They adopted a natural and comfortable foot position that was traced onto the floor to replicate initial position between trials. The perturbation force was delivered by a computer-controlled synchronous servomotor (AKM52M, Kollmorgen, VA) that pulled through a lightweight non-elastic Kevlar line to a firmly fitting belt around the subject's waist at upper pelvis level (Fig. 1A). A load cell (MLP100, Transducer Techniques, CA) coupled the cable to the belt to monitor the perturbation force. A baseline tension of 8 N kept the cable taught.

Body movements were recorded by a video motion analysis system (CodaMotion, Charnwood Dynamics, UK) with markers on the heels and over the C7 and S1 spinous processes. A real-time acquisition system (ADwin-Pro, Jäger, Germany) running at 10 kHz used customized software (Docometre) to control the force perturbations and acquire synchronous data. Force plate and load cell data were sampled at 1000 Hz and the video motion data at 100 Hz.

The test protocol began with 4 practice trials before commencing 86 different force-time combinations (15 forces between 40 and 180 N, and 9 durations between 150 and 3000 ms: Fig. 1B) in random order. Each trial lasted 5–7 s. Subjects were instructed to "*try not to step*" in response to the perturbations. Arm and other segmental movements were not constrained. The pull came at unexpected time (1–5 s) after a "*ready*" signal. The perturbation profile was a simple step reaching the target force and held for a prescribed time before release (Fig. 1A). The perturbation stopped prematurely only if the subject completed two steps (i.e. stepped off the force plate). If a step was not initiated, the subject could lean back to the initial position for the next trial. If they stepped, they repositioned to the set foot placement.

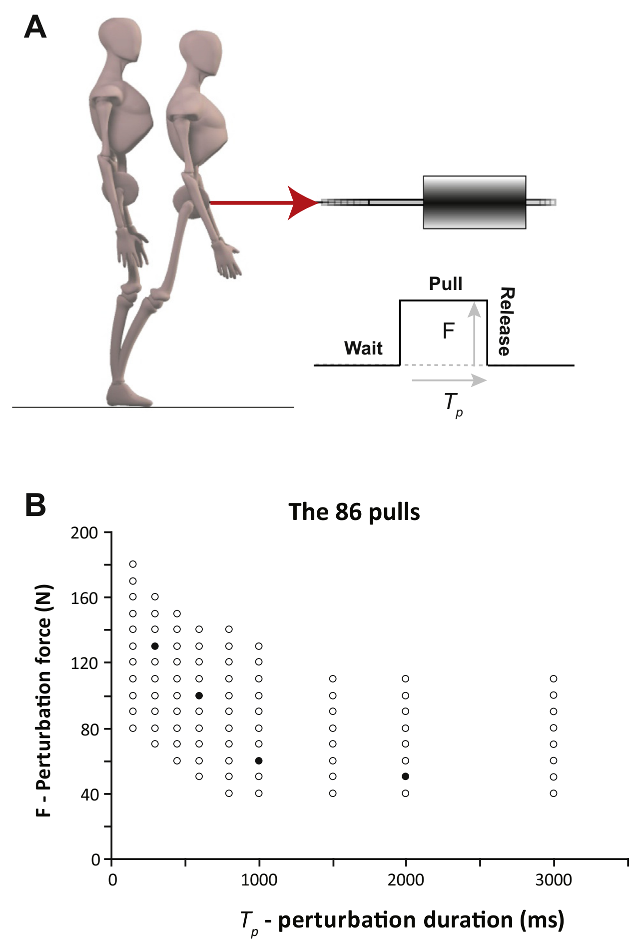

Fig. 1. *Experimental setup and protocol.* **A**: A rotary motor pulled subject forward by a flexible cable attached around his waist. The pulls started at an unexpected time and proceeded at test force (F) for a specific time (T_p) after which the cable tension was released and subject could lean back if a step had not already been initiated. **B**: Eighty-six pulls of different force (F) and duration (T_p) were delivered. Perturbations were presented in a random order different for each subject. Subjects started with 4 training trials (filled circles) to familiarize them with the perturbation.

Please cite this article in press as: Robert, T., et al. Stepping boundary of external force-controlled perturbations of varying durations: Comparison of experimental data and model simulations. J. Biomech. (2018), https://doi.org/10.1016/j.jbiomech.2018.05.010