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A new method to assess passive and active ankle stiffness during quiet upright stance

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ABSTRACT

Both passive and active ankle torque contribute to postural stability during quiet upright stance, yet directly measuring their relative contributions is difficult. Here, a new method was developed to estimate passive and active ankle stiffness (ST) and damping (DA). In contrast to earlier approaches, the proposed method does not require external mechanical or sensory perturbations. Instead, the method is based on the assumption that upright stance is intermittently controlled, and that active ankle torque is in-phase coherent with ankle angular acceleration. Thus, identifying the local maxima of ankle angular accelerations facilitates the identification of time windows that include substantial active ankle torque. After identifying these local maxima and associated windows, estimates of passive and active ankle ST and DA were obtained using linear regression analyses. Consistent with earlier work, passive ankle torque was estimated to account for 94–97% of the total ankle torque, and to have linear relationships with ankle angle and angular velocity. Predicted values of passive and active ankle stiffness were also consistent with earlier reports. This new approach may be a useful tool to efficiently investigate passive and active joint stiffness during quiet upright stance.

1. Introduction

Control of balance during upright stance is achieved through corrective torques at multiple joints in the body (Cholewicki et al., 1997; Gribble and Hertel, 2004; Huryn et al., 2014; Kiemel et al., 2008; Schieppati et al., 2003; Vuillerme et al., 2002), and which are generated through intrinsic passive, reflexive, and active voluntary muscular contractions. Previous simulation modeling suggested that passive ankle torque alone might be insufficient to maintain upright stance (Morasso and Sanguineti, 2002). Because passive ankle torque is smaller than gravitational torque, the use of only passive ankle torque can further lead to substantial time delays in position/orientation control, thereby increasing instability and rendering the need for active control (Lakie et al., 2003). A number of studies have indeed confirmed the existence of active control torques during upright stance (Loram and Lakie, 2002a; Loram et al., 2005b; Peterka and Loughlin, 2004; Qu et al., 2007). Reflex activity also occurs, in response to tonic stretch or muscle lengthening during sway (Mirbagheri et al., 2000). However, this reflex activity remains difficult to measure, due to the low levels muscular activity present during quiet upright stance (Fitzpatrick, 2003). In fact, ankle reflex activities have not been detected for small perturbations during quiet upright stance (Loram and Lakie, 2002a).

Understanding the relative contributions of passive, active torques is of interest for movement stability, exercise, and rehabilitation (Kubo et al., 2015; Lamontagne et al., 2000). In practice, however, quantifying this contributions is challenging. Several previous studies have used sequential or random perturbations for measuring passive, active, and reflexive ankle stiffness (Galiana et al., 2005; Kearney et al., 1997; Kiemel et al., 2008; Roy et al., 2011), and using such perturbations can facilitate separation of the passive and active components from reflexive aspects of corrective ankle torque. However, ankle stiffness is dependent on muscular structure, operating states, and the magnitude of the external mechanical perturbation (Kearney et al., 1997; Latash and Zatsiorsky, 1993; Loram and Lakie, 2002a; Weiss et al., 1988). Active ankle stiffness measured using perturbations is larger than what has been obtained without using perturbations (i.e., during quiet upright stance scenarios). This difference has been attributed to the fact that during perturbations the active intrinsic and reflex pathways constitute a greater percentage of the total joint stiffness (Mirbagheri et al., 2000), and much larger muscular

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responses are elicited than in quiet upright stance conditions (Casadio et al., 2005; Loram et al., 2004). As such, an identification method that does not use perturbations may be more appropriate for estimating passive and active ankle stiffness during quiet upright stance.

The primary purpose of this work was thus to develop a method to estimate passive and active ankle stiffness during quiet upright stance without the use of external perturbations. Based on existing studies suggesting that quiet upright stance is controlled intermittently (Lakie et al., 2003; Loram et al., 2005b), and which involves intermittent "bursts" of active (muscular) control. In contrast to the intermittent generation of active joint torque, passive joint torque due to tissue stretch and/or deformation can be expected to be more continuous, and present at some level throughout sway motions. In turn, this intermittency in active control implies that distinct "zones" or time windows should exist, which involve either passive (P) or passive + active (P + A) control. Active zones only exist when intermittent muscle bursts of activation are present. In contrast, passive zones exist throughout a period of postural sway where no (or minimal) active muscle activity exists. In P zones, while some active ankle torque might be present, the magnitude is assumed small relative to that in the P + A zone. This latter assumption is supported by results from Loram and Lakie (2002b), which indicated that the soleus muscle contracts intermittently and that no major active muscle contractions could be detected between these intermittent episodes.

Because active zones involve bursts of muscle activity, one approach is to measure such activity directly (e.g., using electromyography or ultrasound). Here, an alternative method was used to identify the P + A zones. Based on our earlier results using a sliding mode control model (Zhang, 2013), which modeled human quiet upright stance as single inverted pendulum under the control of intermittent controller, we found that active ankle torque (T_a) is strongly in-phase coherent with ankle angular acceleration ($\ddot{\theta}_{ankle}$); a representative sample is shown in Fig. 1. Thus, local maxima of active ankle torque – associated with muscle activity – are coincident with local maxima of $\ddot{\theta}_{ankle}$. By identifying local maxima in the absolute values of $\ddot{\theta}_{ankle}$, the temporal centers of P + A zones can be identified, and these zones should range (temporally) on both sides of the local maxima.

Inspired by this evidence, a new algorithm was developed to separate the intermittent passive and active components of active ankle torque and thereby to quantify passive and active ankle stiffness and damping. Because the method is relatively straightforward (e.g. does not involve external perturbations), it may have future utility for application in clinical settings for calculation of passive and active ankle stiffness and damping.

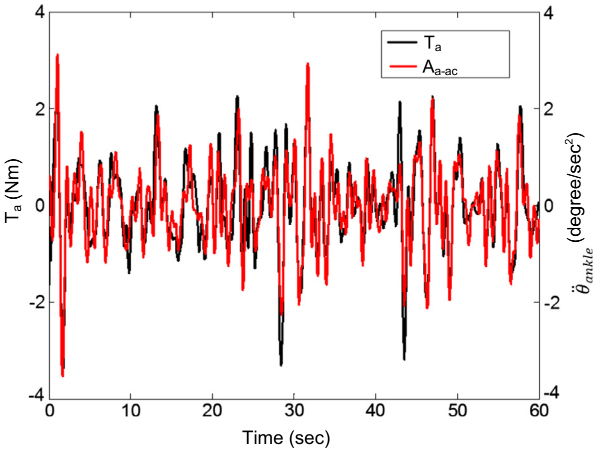

Fig. 1. A sample of model-estimated active ankle torque (T_a) and measured ankle angular acceleration ($\ddot{\theta}_{ankle}$).

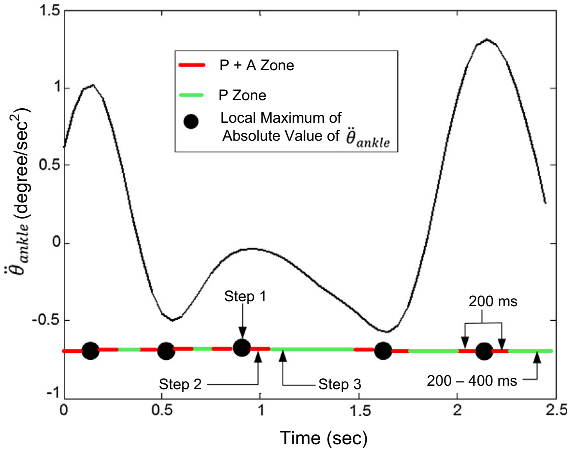

Fig. 2. Steps used to determine the local maxima, passive (P) zones, and passive + active (P + A) zones. The P + A zone size is fixed in size (200 ms), yet the P zone sizes vary. Step 1: Identify the local maxima of absolute values of ankle angular acceleration ($\ddot{\theta}_{ankle}$); Step 2: Determine the locations of P + A zones; Step 3: Determine the locations of P zones.

2. Methods

2.1. Experimental kinetics and kinematics

The experimental data used here were obtained from a previous study (Lin et al., 2009), in which three trials of quiet upright stance were completed by 32 participants (16 males and 16 females), aged 18–65 years. Participants were instructed to stand on a force platform (AMTI OR6-7-1000, Watertown, MA, USA) for a total of 75 s with their eyes closed and feet together. Ground reaction forces were obtained from the force platform (at 100 Hz). Joint positions were estimated using 18 spherical reflective markers attached over bony landmarks. Marker locations were sampled (at 20 Hz) using a 6-camera motion capture system (Vicon 460, Lake Forest, CA, USA).

Time series of external (experimental) ankle torques, in the sagittal plane, were calculated based on downsampled (to 20 Hz) ground reaction forces (Masani et al., 2003), and averaged across the right and left sides. Bilateral means of ankle, trunk, and neck joint angles, in the sagittal plane, were derived from surface markers locations (Black et al., 2007; Zhang et al., 2014). Specifically, the configuration of each of these three segments was determined from the respective proximal and distal joints, and bilateral segments were averaged. For each segment, orientation in the sagittal plane relative to the vertical was obtained, and finite difference methods used to derive angular velocity and angular acceleration. These kinetic and kinematic time series were subsequently used to fit regression models to predict passive and active ankle torque using regression models that are described below.

2.2. Passive and active zones and ankle torques

As discussed above, quiet upright stance appears controlled intermittently with intermittent "bursts" of active (muscular) control, and distinct "zones" or time windows should exist that contain either passive (P) or passive + active (P + A) control. Here, three steps were used to determine, in each trial, the temporal location and size of the P + A zones (Fig. 2). First, the center points of each P + A zone were identified using local maxima of absolute