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A Comparison of Critical Time Interval Between Young and Old Subjects

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Abstract. Earlier research showed that human quiet upright stance posture is intermittently controlled through both open and closed loop control mechanisms. Critical time interval (CTI), the duration describing the time interval between the intermittent control signals is essential to understand the switch frequency of between the open and closed loop control. Yet the value of CTI, in particular the differences between young and older adults remain insufficiently investigated and thus un-clarified. In this research, intermittent critical time interval (ICTI) method was proposed to evaluate the differences of CTI between young and older adults. Consistent to conventional CTI method, it was found that young adults have larger CTI than older adults. The results from the ICTI method have smaller variation and better consistency across participants compared to the conventional CTI method. It is suggested that the higher frequency of intermittent control signals among older adults could be an indicator of lack of confidence or capacity in maintaining quiet upright stance.

Keywords: Critical time interval · Quiet upright stance postural control · Aging

1 Introduction

Human postural control is critical for maintaining balance of posture, which is subjected to risks of falling due to gravity and other internal/external perturbations. Multiple factors contribute to postural control mainly including neuromuscular, vision, proprioception, and vestibular systems. All these factors are integrated together forming a control system including actuator and feedback and feed forward control signals (Zhang et al. 2016; Zhang et al. 2014; Lockhart and Ting 2007; Maurer et al. 2006; Peterka 2002). It was proposed that instead of continuously activating ankle and trunk muscles, these muscle groups only contract intermittently under both open and closed loop control for maintaining the postural stability (Asai et al. 2009; Collins and De Luca 1993; Gawthrop et al. 2011; Loram et al. 2011; Nomura et al. 2013; Suzuki et al. 2012). The time interval between the intermittent postural control signal bursting events, which is also the time taken shifting from open to closed loop control is defined as critical time interval (CTI) (Collins et al. 1995; Collins and De Luca 1993).

Though not thoroughly investigated, the impacts of aging on postural control, in particular the critical time interval of the intermittent postural controller have been

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studied by previous research. It was demonstrated that the open loop control time interval was 300–600 ms longer for older adults (Collins et al. 1995). Additionally, older adults have increased postural correction activities in the mediolateral plane with prolonged open loop control time interval (Mitchell et al. 1995). More specifically, the ankle muscle response latency was found 15–20 ms longer among older adults during balance recovery process (Mackey and Robinovitch 2006).

However, existing CTI quantification methods have produced conflicting results and not well clarified. While conventional CTI method yielded the results at a rather wide range of 0.33–1.67 s (Collins and De Luca 1993), yet a smaller range of critical time interval approximately 1.0 s, was demonstrated by other studies (Doyle et al. 2008; Peterka 2000). Meanwhile though some research demonstrated a CTI about 1.3–1.6 s (Chiari et al. 2000; Newell et al. 1997), a much smaller approximately 0.5 s critical time interval has been identified by another study (Vieira et al. 2009). The lack of consensus for the critical time interval thus demands more research for investigating it. Hence, a further evaluation of the critical time interval differences between young and older adults is needed.

The objective of the study is thus to propose a new critical time interval (CTI) quantification method to quantify the differences of CTI between young and older adults. It is expected that the new CTI method can more consistently and accurately identify the effects of aging on the intermittent postural controller. The results of the study could also be useful for providing insights for postural control modeling studies.

2 Methods

2.1 Experimental Setup

32 participants, age and gender balanced, were recruited in this study. The details of the study is also given in the noted publication (Lin et al. 2008). All participants gave informed consent as approved by the Virginia Tech Institutional Review Board, and had no self-reported injuries, illness, musculoskeletal disorders, or falls in the year prior to the experiment. Participants were instructed to stand (without shoes) as still as possible on the force platform (AMTI OR6-7-1000, Massachusetts, USA) for three trials, with their feet together, arms by their sides, head upright, and eyes closed. Each trial lasted 75 s with at least one minute rest time interval from the next standing trial. The tri-axial ground reaction forces and moments from the force platform were sampled at 100 Hz. Raw signals were low-pass filtered (Butterworth, 5 Hz cut-off frequency, 4th order, zero lag), transformed to obtain center of pressure (COP) time series, and the first 10 s and the last 5 s were removed, resulting in 60 s COP data for use.

2.2 Critical Time Interval Methods

Conventional Critical Time Interval Method. The conventional critical time interval identification method demonstrated that the first minimum of the second order derivate of the diffusion coefficients corresponds to the CTI (Collins and De Luca 1993; Stamp

1997). The diffusion coefficients and its second order derivate are shown in Fig. 1. In Fig. 1 (bottom), it is evident that the second order derivate of the diffusion coefficients decreases starting from 0 s and reaches its first local minimum at around 1.0 s. Consistently, the time is also approximately equal to the time as the postural control switches from open-loop to closed-loop control, which is also the CTI (Fig. 1-top). As such, heuristically, the time window of the first local minimum of the second order derivate of the diffusion coefficients is determined as the critical time interval.

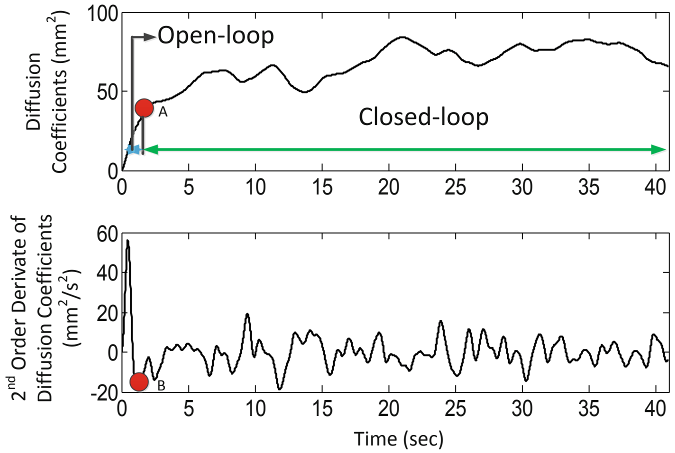

Fig. 1. Diffusion coefficients (top) and the second order derivate of the diffusion coefficients (bottom). Point A represents the distinction of open-loop control from closed-loop control. Point B is the first local minimum of the second order derivate of the diffusion coefficients.

More specifically, as shown in Fig. 1 (top), the critical time interval should be correspondent to the time interval when the increase rate of diffusion coefficient has slowly reached its minimum. It means that CTI should be approximately correspondent to the minimum of the changing rate. Mathematically, the second order derivate diffusion coefficients characterize the changing rate of the diffusion coefficients. Collins and De Luca 1993 proposed that the CTI is equal to the fist minimum of the second order derivate of the diffusion coefficients data. Likely based on a trial-and-error approach, they determined that the first local minimum of 2.5 s of the second order derivate of the diffusion coefficients data can yield the most confident CTI.

Intermittent Critical Time Interval Method. Upright stance is controlled intermittently. The intermittent control switches from open-loop to closed-loop can occur under the situation when the stability of the posture is threatened. More specifically, the intermittent contraction of the tibialis anterior muscle is evident when body sways away from the equilibrium positions during upright stance (Di Giulio et al. 2009). It was also suggested that the switching point is associated with local maximum (such as a local spike) of the posture (Bottaro et al. 2005). As such, identification of the local maxima can reveal the time intervals between the bursts of the intermittent postural control signals. For this aim, the Wavelet modulus maximum method was applied, because it is known able to extract the local maxima or singularities from a signal (Mallat and Hwang 1992).

Wavelet modulus maximum method searched the local region and identified local maxima from the wavelet power spectrum within a certain time and across a range of frequency band (Mallat and Hwang 1992). A representative output of the Wavelet modulus maximum is shown in Fig. 2. In Fig. 2, it is evident that the local maxima of the COP signal were extracted through the modulus maximum (MM). It also appears that MM is vertically aligned along the x-axis with the time interval between them approximately uniform. At a specific time, across the frequency of 0.5–1.1 Hz known associated with human quiet upright stance postural control (Singh et al. 2012; Thurner et al. 2000), MMs form a vertical line, namely Wavelet Modulus Maximum Line (MML). Since the MML represents the switching point between open-loop and closed-loop control, the time interval between the MMLs is equal to the CTI. The presence of MML is intermittent, as such the CTI is also named as intermittent CTI (ICTI) in distinction from the conventional CTI method.

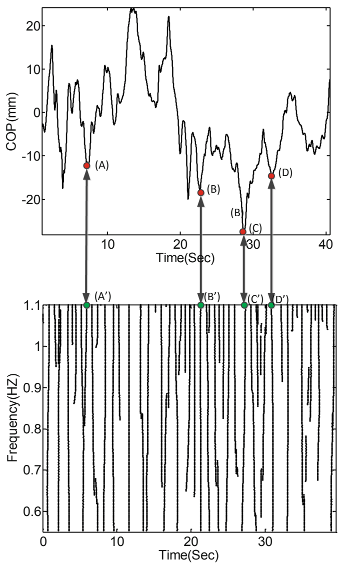

Fig. 2. Center of Pressure (COP, top) and Wavelet modulus maximum (Bottom). A, B, C, D represent the local maximum of the center of pressure. A', B', C', D' represent the Wavelet modulus maximum, which can corresponds to the positions of local maximum of the COP.

At specific time, MML method attempts to construct a vertical line from the discrete MM points across a range of frequency band. MML(f, t) was defined as a line consisting of the modulus maximum wavelet power spectrum points at time t across the frequency band from f_1 to f_2. This can be described by

$$MML(f,t) \stackrel{d}{=} \{MM(f,t), t = t_{\min}...t_{\max}, f = f_1..f_2\} \quad (1)$$

s.t.

$$|t_{\max} - t_{\min}| \leq 2\Delta t_{MML}$$

where f is 0.5–1.1 Hz and t is between 0–40.96 s; and $MML(f,t)$ is a modulus maximum line consisting of modulus maximum $MM(f,t)$. Specifically, for time t, the modulus maximum line is restricted within a line searching time interval of $2\Delta t_{MML}$, start from $t - \Delta t_{MML}$ and end at $t + \Delta t_{MML}$.

As illustrated in Fig. 3, at a specific time t, the search scanned each frequency in the 0.5–1.1 Hz band (starting at the higher end) and marked the positions of the modulus maxima in the region of $[t - \Delta t_{MML}, t + \Delta t_{MML}]$. Within this region, the mean across identified modulus maxima at a given frequency was treated as one data point that belonged to the modulus maximum line at time t. This scanning and identification process was repeated for all times t in a trial 0 to 40.96 s and yielded a set of MMLs. To exclude the too short MMLs, the final MMLs also need to satisfy the length ratio of MML, which is equal to the percentage of the data points on a MML versus the total of data points across 0.5–1.1 Hz frequency band at time t.

CTI is defined as the time interval between two consequent MMLs. More specifically, CTI is equal to the differences of two consequent MMLs. ICTI is equal to the mean of CTIs. The sensitivity of the ICTI to the local searching region Δt_{MML} and length ratio of MML is shown in Fig. 4. Among them, 60% of length ratio yielded average level of CTI. Further increase of tMML beyond 390 ms did not benefit to the significant decrease of CTI. As such, 60% of length ratio and 390 ms of tMML were used in this study.

3 Statistical Analysis

The differences of critical time interval between young and older adults were analyzed through repeated measures analysis of variance (ANOVA). In ANOVA model, age is an independent variable and three repeated trials of conventional CTI and ICTI per subject in both ML and AP directions are dependent variables. No substantial departures from parametric assumptions were evident, and significance was concluded when $P < 0.05$. Three repeated trials of COP intraclass correlation coefficients (ICCs) were used to determine the reliability of the ICTI, with $ICC < 0.4$ (poor reliability), $0.4 \leq ICC \leq 0.75$ (fair to good reliability), and $ICC > 0.75$ (excellent reliability) (Chiari et al. 2000).

4 Results

The results of critical time interval from both conventional CTI and ICTI methods indicated young adult CTI is significantly larger than that of older adults in both mediolateral (ML) (<0.0001) and anteroposterior (AP) (<0.0001) directions. The

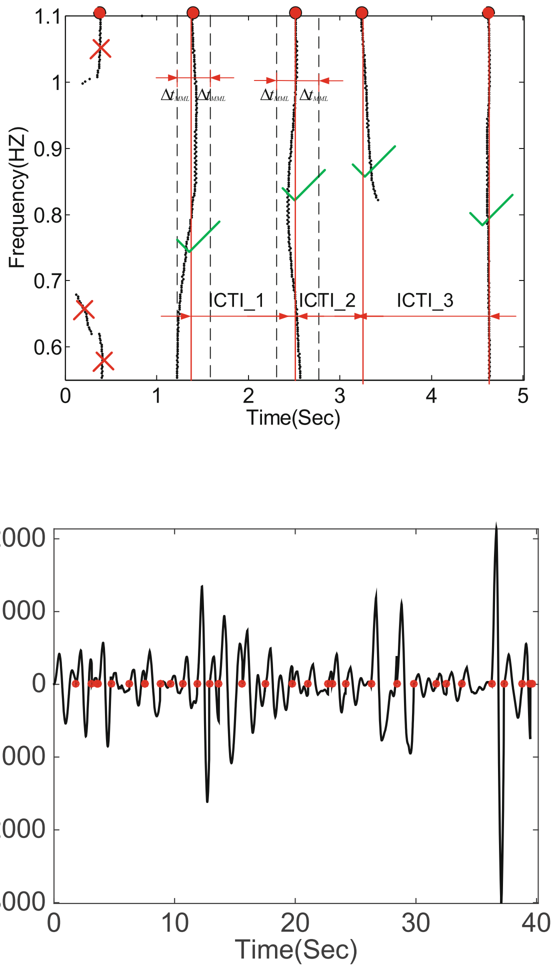

Fig. 3. Wavelet modulus maximum line (MML) identification process. Top: X represents the MMLs not able to meet the MML identification length ratio criterion. ∨ represents the qualified MML. CTI_1, CTI_2, and CTI_3 are the time intervals between MMLs. Δt_{MML} is the MML search interval. Bottom: An example of identified critical points.

results of the CTI and ICC for both young and older adults are summarized in the Table 1.

5 Discussion

In this research, a new CTI quantification method namely ICTI was created to quantify the critical time interval. In contrast to previous results (Collins et al. 1995), which showed that older adults have larger CTI, ICTI method however demonstrated the

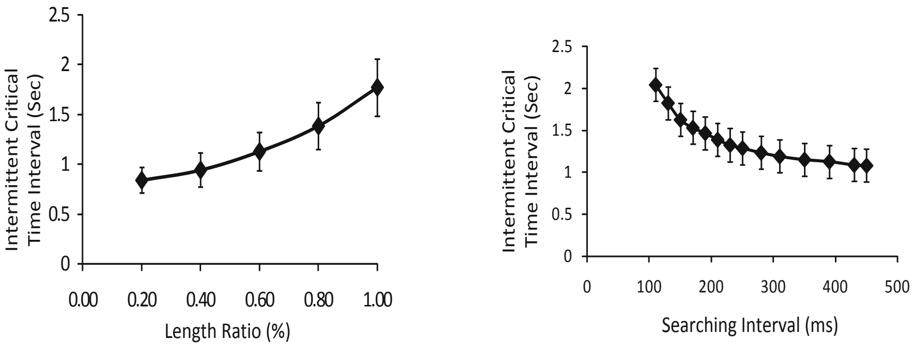

Fig. 4. The sensitivity of Wavelet modulus maximum line (MML) to length ratio (left) and searching interval (right).

Table 1. The results of critical time interval (CTI) and intraclass correlation coefficients (ICC) of young and older adults from both conventional CTI and ICTI methods

	Young Adults		Older Adults	
	ML	AP	ML	AP
Conventional Method (CTI)	CTI: 1.33 (0.38) s ICC: 0.27	CTI: 1.30 (0.41) s ICC: 0.58	CTI: 1.09 (0.38) s ICC: 0.16	CTI: 1.02 (0.39) s ICC: 0.06
New Method (ICTI)	CTI: 1.08 (0.19) s ICC: 0.53	CTI: 1.03 (0.14) s ICC: 0.65	CTI: 0.96 (0.17) s ICC: 0.67	CTI: 0.89 (0.12) s ICC: 0.70

opposite showing young adults have larger CTI than older adults. Consistent to ICTI results, conventional CTI method also showed that CTI is larger among young adults. The consistency indicates that older adults should have smaller CTI compared with young adults.

Though similar results yielded from both methods, the results from conventional CTI method have larger variation, which might explain the wide variation of CTI results obtained from conventional CTI methods in existing literatures. Conventional CTI method treated the first local minimum of the second order derivate of diffusion coefficients as its CTI making the method sensitive to noises embedded in the COP data. In distinction from the conventional CTI method, the ICTI method attempts to find the CTI in specific frequency range, 0.5–1.1 Hz. This frequency range is associated with postural control mechanisms and less likely containing high frequency noise (Singh et al. 2012).

The reduced critical time interval indicates increased frequency of postural control signal, which could be a result of lower extremity muscle weakness associated with aging frequently regarded as one major factor contributing to the compromised postural control among older adults (Daubney and Culham 1999; Pijnappels et al. 2008). Due to the lowered capacity of these postural control actuators, the lower extremity muscles need to adjust more frequently in order to maintain upright stance balance. Additionally, it is known that aging brain suffers from increased neuronal noises in the presence of structure, volumetric, and neurotransmitter changes (Bã et al. 2000; Boyke et al. 2008; Hedden and Gabrieli 2004; Raz et al. 2005). Thus it suspects that the aging brain might not able to generate appropriate postural control signals during quiet upright stance.

Compared to the conventional CTI method, the ICTI method is more reliable. Collins showed that the CTI ICC is between 0.04 and 0.62 (Collins and De Luca 1993). Similarly, ICCs from enhanced CTI method are in the range of 0.2–0.85 (Chiari et al. 2000). However, the ICTI method yielded the ICC all above 0.5 in both ML and AP directions and larger than conventional CTI method. Better reliability of the ICTI method may indicate the method is less likely affected by various postural control signal noises such as the neuromuscular, data collection, and environmental noises underlying the intermittent postural control signals.

Several drawbacks remain within this research. First, only limited frequency band 0.5–1.1 Hz was explored to identify CTI. Though this is a frequency band mostly likely associated with quiet upright stance postural control mechanisms, analysis of other frequency bands and its relationship with CTI could be useful. Second, the results demonstrated that older adults have smaller CTI, indicating the higher of postural control frequency, yet the specific underlying causes of this still remain to be identified.

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