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The altered vestibular-evoked myogenic and whole-body postural responses in old men during standing

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ABSTRACT

Age-related decrements within the sensorimotor system may lead to alterations and impairments in postural control, but a link to a vestibular mechanism is unclear. The purpose of the present study was to determine whether vestibular control of standing balance is altered with adult aging. Eight old (~77 years) and eight young (~26 years) men stood without aids on a commercially available force plate with their head turned to the right, arms relaxed at their sides and eyes closed while receiving stochastic vestibular stimuli (0–25 Hz, root mean square amplitude = 0.85 mA). Surface electromyography signals were sampled from the left soleus, medial gastrocnemius and tibialis anterior. Whole-body balance, as measured by the anteroposterior forces and muscle responses, was quantified using frequency (coherence and gain functions) and time (cumulant density function) domain correlations with the vestibular stimuli. Old men exhibited a compressed frequency response of the vestibular reflex with a greater relative gain at lower frequencies for the plantar flexors and anteroposterior forces than young. In the time domain, the peak amplitude of the short latency response was 45–64% lower for the plantar flexors and anteroposterior forces ($p \leq 0.05$) in the old than young, but not for the tibialis anterior ($p = 0.21$). The old men had a 190% and 31% larger medium latency response for only the tibialis anterior and anteroposterior forces, respectively, than young ($p \leq 0.01$). A strong correlation between the tibialis anterior and the force response was also detected ($r = 0.80$, $p < 0.01$). In conclusion, net vestibular-evoked muscle responses led to smaller short and larger medium latency peak amplitudes in anteroposterior forces for the old. The present results likely resulted from a compressed and lower operational frequency range of the vestibular reflexes and the activation of additional muscles (tibialis anterior) to maintain standing balance.

1. Introduction

Maintaining standing balance is a critical component of tasks of daily living that is often compromised with healthy adult aging (Shaffer and Harrison, 2007; Ishiyama, 2009). For example, old adults are more unstable (Abrahamová and Hlavacka, 2008; Baudry et al., 2012; Kouzaki and Masani, 2012) and require greater corticospinal activity to stand (Baudry et al., 2014) than younger adults. As a result, old adults exhibit increased plantar flexor activation and greater co-activation of the antagonistic dorsiflexors (Baudry et al., 2012, 2014; Benjuya et al., 2004; Laughton et al., 2003) than young, which may stem from age-related alterations in the vestibular, proprioceptive and visual systems (Lord and Menz, 2000; Lord et al., 1991; Shaffer and Harrison, 2007). Vestibular impairment may be a critical factor for imbalance and falls (Pothula et al., 2004) since hair cell loss and degeneration of vestibular afferent pathways are both consequences of natural adult aging (Ishiyama, 2009). The involvement of the somatosensory and visual systems in elderly balance deterioration is well-documented (Abrahamová and Hlavacka, 2008; Lord and Menz, 2000; Sundermier et al., 1996), but the involvement of the vestibular system with age-related balance impairments has been evaluated only through the exclusion of other sensory systems. For example, the contribution of the vestibular control of balance is often speculated based on postural tests of sway with altered visual (e.g., blindfolded) and proprioceptive cues (e.g., standing on foam). Thus, the effect of adult aging on the vestibular control of balance is still not well-understood.

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Galvanic vestibular stimulation (GVS) and stochastic vestibular stimulation (SVS) are valuable tools for investigating the role of vestibular information in the control of standing balance (Britton et al., 1993; Dakin et al., 2007; Fitzpatrick and Day, 2004). Low amplitude currents applied over the mastoids modulate the firing rate of the underlying vestibular afferents (Goldberg et al., 1984) and produce compensatory myogenic responses and whole-body movements to maintain upright posture (Dakin et al., 2007; Day et al., 1997; Fitzpatrick et al., 1994; Luu et al., 2012). In the lower limb, muscle responses exhibit a biphasic pattern consisting of two distinct peaks of short (~60 ms) and medium (~110 ms) latencies (Britton et al., 1993; Fitzpatrick et al., 1994; Lee Son et al., 2008; Nashner and Wolfson, 1974; Welgampola and Colebatch, 2002). Details of the physiological mechanisms have yet to be determined, but reports have suggested that the short and medium latency components may originate from different sources (Britton et al., 1993; Cathers et al., 2005; Dakin et al., 2007, 2010; Mian et al., 2010; Welgampola and Colebatch, 2002). Welgampola and Colebatch (2002) reported that the peak amplitude of the short latency response was smaller in old adults, but the medium latency response was similar when compared with young controls. However, that study focused solely on a single muscle group, the soleus, using traditional GVS. It is unknown whether the observed age-related alterations observed for the soleus are indicative of altered vestibular responses at the whole-body level during the maintenance of upright balance. Measuring forces applied to the whole-body would offer valuable information regarding the net result of all muscles involved in the vestibular postural response (Mian and Day, 2009; Pastor et al., 1993).

Vestibular reflexes induced via SVS are represented in the lower limb musculature over a bandwidth of 0–20 Hz (Dakin et al., 2007; Forbes et al., 2013), which corresponds to the dynamic range of the vestibular system (Armand and Minor, 2002; Huterer and Cullen, 2002). With healthy adult aging, whole muscle contractile properties are slower (Dalton et al., 2009, 2014), motor unit firing rates are lower (Dalton et al., 2009, 2010; Rubinstein and Kamen, 2005) and inherent motor neuron properties are altered (Kalmar et al., 2009; Piotrkiewicz et al., 2007), but these age-related declines cannot be generalized to all muscles and their constitutive motor neurons (Dalton et al., 2008, 2009; Deschenes et al., 2010; Ishihara et al., 1987; Moran et al., 2005). Further, high-frequency sound and vibrotactile detection thresholds are increased with adult aging (Wells et al., 2003; Willott, 1984). These results suggest a shift towards slower and lower physiological frequencies in the motor and various sensory systems with adult aging. It is reasonable to postulate that the operational frequency range of the vestibulo-motor system would also shift towards a lower compressed bandwidth in old when compared with young adults. Furthermore, disparate age-related alterations within the neuromuscular system combined with increased muscle activity during quiet standing may alter the representation of the vestibular reflex in the various muscles. Hence, the summation of these responses may reflect an altered vestibular control of balance at the whole-body level in old men compared with young.

The purpose here was to evaluate the effect of adult aging on how an isolated vestibular error signal is transmitted to the muscles controlling the ankle and the corresponding summation of these reflexes at the whole-body level using frequency (coherence and gain) and time (cumulant density) approaches. We hypothesized that the frequency bandwidth over which vestibular reflexes are represented at the muscle and whole-body levels would compress and shift towards lower operating frequencies. Although the vestibulo-myogenic response represents a summation of a broad bandwidth of frequencies in young adults (Dakin et al., 2011), it seems that the short latency response is shaped primarily by higher frequencies (>10 Hz); whereas the medium latency likely reflects lower frequencies (Dakin et al., 2007, 2010). Consequently, we hypothesized the short latency vestibular response would be smaller in the old men; whereas the later response (medium latency) would be maintained or larger for the old men than the young.

2. Materials and methods

2.1. Participants

Eight old (aged: 76.5 ± 6.3 years; mass: 78.5 ± 12.6 kg; height: 173.8 ± 5.1 cm) and eight young (aged: 26.3 ± 3.6 years; mass: 82.1 ± 13.9 kg; height: 179.9 ± 7.4 cm) healthy men with no known history of neurological diseases or injuries volunteered for the study. Participants were given written and oral details of the experiment and granted written and oral informed consent prior to participation. All procedures conformed to the standards of the Declaration of Helsinki and were approved by the local university's research ethics board.

2.2. Vestibular stimuli

A continuous randomly varying current, in both amplitude and frequency, was applied binaurally to the mastoid processes in a bipolar configuration. The SVS signal essentially is filtered white noise that is scaled to a desired peak to peak amplitude (Dakin et al., 2007). SVS allows for the characterization of whole-body postural and muscle responses in both the frequency and time domains (Dakin et al., 2007; Mian et al., 2010; Reynolds, 2010). Carbon rubber electrodes (9 cm^2), coated in Spectra 360 electrode gel (Parker Laboratories, Fairfield, USA), were positioned over the mastoid processes with Durapore tape (3M Canada, London, Canada) and an elastic headband. Vestibular stimuli were generated on a PC computer using Spike2 software (Cambridge Electronics Design, Cambridge, UK) and sent to an isolated bipolar constant current stimulator (input range: ±10 V, output range: ±10 mA; DS5, Digitimer Ltd., Welwyn Garden City, UK) via an analog output of a Power 1401 (Cambridge Electronics Design, Cambridge, UK). Once the SVS signal was generated, each subject was exposed to the same waveform for every trial to ensure that frequency bands were identical among subjects. To ensure a significant vestibular reflex (Dakin et al., 2010, 2011), the SVS signals were delivered using a 0–25 Hz bandwidth with a peak to peak amplitude of ±1.5 mA (RMS = 0.85 mA) for three 60-s trials. Stochastic vestibular stimuli containing similar RMS amplitudes and frequency bandwidth have been shown to evoke a postural reflex (Dakin et al., 2007; Forbes et al., 2013; Luu et al., 2012). Adequate rest (approximately 1 min) was given between exposures to prevent fatigue.

2.3. Experimental set-up

Participants stood upright with their medial malleoli ~10 cm apart on a force plate (Model 9287a, Kistler Instrument Corp., Amherst, USA). Participants stood relaxed while blindfolded and kept their arms at their sides and head rotated to the right, 90° (Fig. 1A). A laser pointer was secured above the left ear and oriented to Reid's plane, which passes bilaterally through the inferior orbital margin and the external acoustic meatus. The head was tilted ~18° upward from the horizontal. Because of the well-documented relationship between head yaw angle and the direction of the vestibular-evoked postural response and the orientation of the GVS vector that results from the presumed stimulation of all vestibular afferents (Cathers et al., 2005; Day and Fitzpatrick, 2005; Lund and Broberg, 1983; Mian and Day, 2009; Pastor et al., 1993), the postural response to the electrical vestibular stimulation was aligned primarily with the anteroposterior (AP) rotations about the ankles. This set-up maximized the vestibular-evoked reflex in line with the action of the ankle plantar flexors and dorsiflexors. Thus, for the purposes of this study we only tested time and frequency correlations with the SVS