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Advanced age brings a greater reliance on visual feedback to maintain balance during walking

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A B S T R A C T

We implemented a virtual reality system to quantify differences in the use of visual feedback to maintain balance during walking between healthy young ($n = 12$, mean age: 24 years) and healthy old ($n = 11$, 71 years) adults. Subjects walked on a treadmill while watching a speed-matched, virtual hallway with and without mediolateral visual perturbations. A motion capture system tracked center of mass (CoM) motion and foot kinematics. Spectral analysis, detrended fluctuation analysis, and local divergence exponents quantified old and young adults' dynamic response to visual perturbations. Old and young adults walked normally with comparable CoM spectral characteristics, lateral step placement temporal persistence, and local divergence exponents. Perturbed visual flow induced significantly larger changes in mediolateral CoM motion in old vs. young adults. Moreover, visual perturbations disrupted the control of lateral step placement and compromised local dynamic stability more significantly in old than young adults. Advanced age induces a greater reliance on visual feedback to maintain balance during waking, an effect that may compensate for degradations in somatosensation. Our findings are relevant to

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the early diagnosis of sensory-induced balance impairments and also point to the potential use of virtual reality to evaluate sensory rehabilitation and balance training programs for old adults.

1. Introduction

Lateral step placement is an important control variable in the maintenance of balance during walking (Bauby & Kuo, 2000; Donelan, Shipman, Kram, & Kuo, 2004). In contrast to step placement in the direction of movement, which benefits from some passive stability, lateral step placement is more highly dependent upon the integration of reliable visual, vestibular, and somatosensory feedback (Bauby & Kuo, 2000; Collins & Kuo, 2013; Donelan et al., 2004; O'Connor & Kuo, 2009; O'Connor, Xu, & Kuo, 2012). It is well recognized that the quality of sensory information declines considerably with advanced age (Patel, Magnusson, Kristinsdottir, & Fransson, 2009). These changes are functionally exacerbated by longer reflex latencies and slower maximum rates of muscle force development in old adults (Dorfman & Bosley, 1979; Thelen, Schultz, Alexander, & Ashton-Miller, 1996). Ultimately, age-related sensorimotor decline may compromise old adults' effective use of lateral step placement to maintain balance during walking, thereby increasing their risk of falling. Indeed, one third of old adults (i.e., 65+ years) fall annually and most of these falls occur during locomotion (Berg, Alessio, Mills, & Tong, 1997; Niino, Tsuzuku, Ando, & Shimokata, 2000; Tinetti, Speechley, & Ginter, 1988).

Evidence from the postural control literature may provide indirect insight into how old adults differ from young adults in their use of sensory feedback to maintain balance during walking. For example, using a unique combination of visual and somatosensory perturbations, Eikema, Hatzitaki, Konstantakos, and Papaxanthis (2013) found that advanced age brought an increased sensitivity to visual feedback coupled with a reduced sensitivity to tendon vibration. A common interpretation of these findings is that a decline in somatosensory feedback with age brings a greater reliance on visual feedback for postural control (Bugnariu & Fung, 2007; Eikema et al., 2013; Jeka, Allison, & Kiemel, 2010; Sundermier, Woollacott, Jensen, & Moore, 1996; Yeh, Cluff, & Balasubramaniam, 2014). In addition, Yeh et al. (2014) found that visual reliance in old adults was direction-dependent, with greater sensitivity to visual perturbations in the mediolateral control of posture. The well documented age-related increase in visual reliance suggests that there may also be a unique role of visual feedback in old adults' control of lateral step placement and balance during walking.

Removing or disrupting visual feedback impairs the control of lateral step placement during walking in young adults (Bauby & Kuo, 2000; McAndrew, Dingwell, & Wilken, 2010; O'Connor & Kuo, 2009; O'Connor et al., 2012). For example, compared to normal walking, Bauby and Kuo (2000) found that step width variability disproportionately increased when young adults walked with their eyes closed. More recently, O'Connor and Kuo (2009) and O'Connor et al. (2012) have used virtual reality to reveal that the control of lateral step placement in young adults is compromised more by mediolateral than anterior-posterior visual perturbations. If old adults rely more on visual feedback than young adults to maintain balance during walking, we would anticipate more pronounced effects of visual perturbations on their control of lateral step placement.

Dynamic analysis of center of mass (CoM) motion and step placement can provide insights into the sensorimotor control of balance during walking. For example, spectral analysis can quantify one's dynamic response to visual perturbations (Loughlin & Redfern, 2001), and the temporal dynamics of CoM motion can delineate old adults at risk of falls (Latt, Menz, Fung, & Lord, 2009). In addition, the emergence of lateral step placement as a balance control variable during walking suggests a high probability for step-to-step dependence. Detrended fluctuation analysis (DFA) quantifies step-to-step correlations and is commonly used to study walking in healthy adults and those with neurological impairment (Dingwell & Cusumano, 2010; Hausdorff et al., 1997). Finally, local dynamic stability quantified via maximum divergence exponents is strongly associated with falls risk in old adults