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REVIEW

IMPAIRED STANDING BALANCE: THE CLINICAL NEED FOR CLOSING THE LOOP

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Abstract—Impaired balance may limit mobility and daily activities, and plays a key role in the elderly falling. Maintaining balance requires a concerted action of the sensory, nervous and motor systems, whereby cause and effect mutually affect each other within a closed loop. Aforementioned systems and their connecting pathways are prone to chronological age and disease-related deterioration. System redundancy allows for compensation strategies, e.g. sensory reweighting, to maintain standing balance in spite of the deterioration of underlying systems. Once those strategies fail, impaired balance and possible falls may occur. Targeted interventions to prevent falling require knowledge of the quality of the underlying systems and the compensation strategies used. As current clinical balance tests only measure the ability to maintain standing balance and cannot distinguish between cause and effect in a closed loop, there is a clear clinical need for new techniques to assess standing balance. A way to disentangle cause-and-effect relations to identify primary defects and compensation strategies is based on the application of external disturbances and system identification techniques, applicable in clinical practice. This paper outlines the multiple deteriorations of the underlying systems that may be involved in standing balance, which have to be detected early to prevent impaired standing balance. An overview of clinically used balance tests shows that early detection of impaired standing balance and identification of causal mechanisms is difficult with current tests, thereby hindering the development of well-timed and target-oriented interventions as described next. Finally, a new approach to assess standing balance and to detect the underlying deteriorations is proposed. © 2014 IBRO. Published by Elsevier Ltd. All rights reserved.

Key words: balance control, elderly persons, standing balance, system identification.

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INTRODUCTION

Impaired standing balance, defined as having difficulties maintaining an upright position in daily life activities, is a common problem among the elderly (Jonsson et al., 2004; Lin and Bhattacharyya, 2012) and has a significant impact on the health and quality of life (Lin and Bhattacharyya, 2012). Impaired standing balance plays a key role in falls (Rubenstein, 2006) and is a strong risk factor for falls (Muir et al., 2010); one third of

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Abbreviations: BSS, Berg balance scale; CoM, center of mass; CoP, center of pressure; FRF, frequency response function; SPPB, short physical performance battery.

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elderly persons aged 65 or older falls at least once a year (Tinetti and Ginter, 1988; O'Loughlin et al., 1993; Luukinen et al., 1994; Stalenhoef et al., 1999; Chu et al., 2005). Ten percent of falls among community-dwelling elderly persons result in serious injuries, such as hip fractures (1–2%), other fractures (3–5%) or head injuries (5%) (NVKG, 2004). A quarter of the deaths in home situations are the result of falls (CBS, 2013). Furthermore, falls are related to psychosocial factors such as fear of falling and social isolation. (Tinetti et al., 1994; Vellas et al., 1997); the resulting restricted mobility may further deteriorate standing balance (Vellas et al., 1997; Allison et al., 2013). Therefore, falls have a profound socioeconomic impact (Hartholt et al., 2012). To prevent falling, targeted interventions improving standing balance are needed which requires knowledge of the underlying cause of impaired standing balance at an early stage.

The ability to maintain balance requires appropriate interaction of several key systems, i.e. the motor (muscles), nervous and sensory systems, connected via efferent and afferent signal pathways resulting in a closed loop in which cause and effect are interrelated. Aforementioned systems deteriorate with advanced age (Horak et al., 1989; Manchester et al., 1989; Sturnieks et al., 2008) and as a result of specific diseases and medication use (Konrad et al., 1999). System redundancy allows for compensation strategies to maintain balance and so it is only when those strategies fail, e.g. in cases of severe system deterioration, multiple system deterioration and/or environmental disturbances exceeding system resilience, that impaired balance and finally falling may occur. Impaired balance may thus go unnoticed until an advanced stage.

Current clinical balance tests, such as the Berg balance scale (BSS) and the short physical performance battery (SPPB), include an assessment of the ability to maintain standing balance during challenging standing conditions (Whitney et al., 1998; Langley and Mackintosh, 2007) by narrowing the base of support or closing the eyes. However, identification of cause-and-effect relations, primary deterioration and compensation strategies, and ultimately the quality of the underlying systems requires new technical approaches such as closed loop system identification techniques. This allows for early failure detection, so that there are no missed opportunities for targeted interventions and disease management.

The present paper outlines the clinical need for proper balance assessment, describes the available balance tests and proceeds to describe promising control engineering-based solutions and their applicability for clinical practice.

DETERIORATION OF STANDING BALANCE

Advanced age in combination with (multi) morbidity and the use of medication will result in a variety of deterioration patterns in the underlying systems involved in maintaining standing balance, which subsequently results in a widely heterogeneous pathophysiology of impaired standing balance among the elderly (Horak et al., 1989). Changes in the sensory systems lead to conflicting and inaccurate sensory information about body position. Motor system changes comprise low muscle mass and strength, preventing correction for balance deviations in a proper and efficient way. Changes in the nervous system result in abnormal scaling and timing of corrective responses to internal disturbances, which include sensor and motor noise due to deterioration of the underlying systems, and external disturbances, which are caused by the environment, for example a slip or a push (Horak et al., 1989). Due to system redundancy it is possible to compensate for those changes by selecting proper strategies to maintain balance.

Deterioration of the sensory systems

With advanced age, sensory systems deteriorate. Impaired proprioception is apparent from reduced vibration sense by the cutaneous receptors (Dorfman and Bosley, 1979) or reduced joint position sense by the muscle spindles and the golgi tendon organs (Gilman, 2002), due to axonal degeneration and decrease in the number and density of nerve fibers (Dorfman and Bosley, 1979). Reduced joint position sense can also be due to degenerating chrondrocytes in the cartilage surface of joints caused by degenerative joint disease (Skinner et al., 1984). Age-related diseases, such as diabetes, also result in impaired proprioception (Arnold et al., 2013). Visual impairment at an advanced age comprises a decline in visual acuity, contrast sensitivity, glare sensitivity, dark adaptation, accommodation and depth perception (Horak et al., 1989; Sturnieks et al., 2008). Cataract and macular degeneration mainly affect central vision, whereas chronic glaucoma reduces peripheral vision (Eichenbaum, 2012). Vestibular impairment at an advanced age results from a reduced number of vestibular hair cells, Scarpa's ganglion cells and nerve fibers (Horak et al., 1989; Woollacott, 1993; Sturnieks et al., 2008; Barin and Dodson, 2011). Nerve conduction speed in afferent and efferent pathways slows down due to a decrease in the number of neurons, loss of myelination and other neural changes (Sturnieks et al., 2008; Barin and Dodson, 2011).

Deterioration of the motor system

With advanced age, muscle mass decreases, which can result in low muscle mass, i.e. sarcopenia (Morley, 2008). Furthermore, muscle strength, the rate of force production and muscle power declines with age (Thom et al., 2007; Narici and Maffulli, 2010) due to age-related alterations in muscle architecture (Narici et al., 2003), muscle control (Campbell et al., 1973; Dalton et al., 2008), activation dynamics (Payne and Delbono, 2004; Short et al., 2005; Gannon et al., 2009) and muscle fiber typing (Vandervoort, 2002). Tendon stiffness decreases with age due to an increase of non-reducible collagen cross-linking, a reduction in collagen fibril crimp angle, an increase in elastin content, a reduction of extracellular water content and an increase