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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.

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

Contents

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 in type tube V collagen. This results in a lower velocity of shortening and a change in the length-tension relation, which causes a reduction of force production (Narici et al., 2008). In addition, with age the tendon becomes thicker, hypoechogenic and more likely to tear (Yu et al., 2012). Orthopedic pathologies (e.g. arthritis) can lead to restricted mobility; arthritis correlates with a decrease in range of motion in joints (Badley et al., 1984; Hughes et al., 1994).

Deterioration of the nervous system

The sensory and motor systems are linked by the nervous system. The nervous system has the adaptive capacity to compensate for the deterioration of the sensor and motor systems by selecting a compensation strategy to maintain balance. However, this capacity deteriorates with age and disease (Horak et al., 1989). In the elderly, deficits in stimulus encoding, central processing and response initiation result in diminished transmission speed and a lower accuracy of sensory information and delayed muscle activation (Horak et al., 1989). Impaired blood pressure regulation, as demonstrated by hypertension and orthostatic hypotension, could result in a decrease of cerebral blood flow (Strandgaard and Paulson, 1995; Novak et al., 1998) and therefore increase the risk of hypoperfusion of the brain, resulting in brain damage and impaired neural control. As with age cognitive control seems to become of increasing importance for standing balance (Ward and Frackowiak, 2003; Heuninckx et al., 2005), balance will also be negatively influenced by deteriorating cognitive function (Shin et al., 2011; Suttanon et al., 2012; Taylor et al., 2013).

Compensation strategies to maintain standing balance

System deterioration may induce the selection of alternative compensation strategies. First, sensory reweighting implies that the nervous system will rely on more accurate as compared to less accurate and conflicting sensory information. The elderly are less capable of reweighting sensory information than young people (Teasdale et al., 1991; Hay et al., 1996). Furthermore, in balance control the elderly rely more on visual information than do the young (Faraldo-Garcia et al., 2012). As a consequence, the elderly are less able to compensate in situations where visual information is disturbed or excluded by the environment. Second, the elderly rely more heavily on the hip strategy, i.e. movement around the hip joint, to maintain standing balance compared to the young who rely more on the ankle strategy, i.e. pivot around the ankle joint during normal stance (Hsu et al., 2013). In response to more challenging conditions, e.g. altered sensory conditions in which vestibular or proprioceptive information is reduced, the young will change their balance strategy by relying more on the hip strategy (Turcato and Ramat, 2011). As elderly already rely more heavily on the hip strategy, they are less able to adapt to environmental changes. Third, co-contraction is a commonly used strategy in the elderly when other compensation strategies cannot be used efficiently (Benjuya et al., 2004). Co-contraction is energy-demanding and makes the body stiffer, reducing the range of motion. As a consequence, resilience to larger disturbances is reduced and stepping out strategies may be required to prevent falling (Rogers and Mille, 2003). Fourth, deterioration of underlying systems increases the attentional demands to maintain standing balance (Shumway-Cook and Woollacott, 2000). When attentional resources are limited, this could result in impaired standing balance or falls; if two tasks are performed simultaneously and require more attentional demands than the total capacity, the performance on either or both tasks deteriorates, depending on the difficulty of the tasks. One can compensate for the shortcoming of attention by task prioritization; one task is prioritized over another task to complete the most important task successfully (Woollacott and Shumway-Cook, 2002; Lacour et al., 2008).

CURRENT STANDING BALANCE ASSESSMENT

Clinical balance tests

Clinical balance tests are developed to assess physical performance, such as the Tinetti balance test (Tinetti, 1986), the functional reach test (Duncan et al., 1990), the BBS (Berg, 1989), the clinical balance test of sensory interaction and balance (CTSIB) (Shumway-Cook and Horak, 1986), the SPPB (Guralnik et al., 1994), the balance error scoring system (BESS) (Finnoff et al., 2009), the star excursion balance test (SEBT) (Gribble et al., 2012) and the Romberg's test (Rogers, 1980). As daily activities require balance and balance is hard to detect during these activities, in those tests the ability to maintain balance is dichotomously assessed and scored in specific standing and/or dynamic balance conditions, possibly combined with walking.

Clinical balance tests are practical in use because of their low cost, simple equipment and time efficiency. Furthermore, the tests have a good inter-rater and intra-rater reliability (Duncan et al., 1992; Whitney et al., 1998; Langley and Mackintosh, 2007; Bell et al., 2011; Freiberger et al., 2012; Gribble et al., 2013). Due to the dichotomous assessment of the ability to maintain standing balance, clinical balance tests only detect impaired balance when compensation strategies fail (Duncan et al., 1992; Pardasaney et al., 2012). Often, active people can maintain standing balance without any problem despite severe system deterioration due to an efficient compensation by selection of proper strategies (Pardasaney et al., 2012). This may hamper the use of clinical balance tests in active elderly people or at an early stage of deterioration (i.e. ceiling effect). In addition, clinical balance tests do not provide information about the underlying systems involved in maintaining standing balance and the compensation strategies used. Therefore, the underlying cause of impaired standing balance cannot be detected.

Posturography

Posturography is an alternative method to assess standing balance using a continuous scale (Visser et al., 2008). Static posturography comprises assessment of the center of mass (CoM) and/or center of pressure (CoP) movement during an unperturbed stance. CoM movement represents movement of the body, while CoP movement is a reflection of balance control to keep CoM within the base of support (Winter et al., 2003). CoM and CoP movement are interrelated but reflect different aspects of balance control, which shows the necessity to measure both entities simultaneously. CoM movement can be measured using inertial sensors (Aminian et al., 1999; Mayagoitia et al., 2002; Moe-Nilssen and Helbostad, 2002; Turcato and Ramat, 2011) or position tracking systems (Zabjek et al., 2008; Forsell and Halvorsen, 2009), which measure body segment displacement with respect to a local or global coordinate system. CoP movement can be measured using force plates (Rogind et al., 2003; Clark et al., 2010; Najafi et al., 2010) or in-shoe pressure assessment devices (Han et al., 1999; Donath et al., 2012) which measure ground reaction forces. Inertial sensors and in-shoe pressure assessment devices are less expensive and can be used outside the laboratory. Deterioration detection of a specific sensory system can be facilitated by manipulation of standing conditions, i.e. several foot positions (changes in base of support), with eyes open or eyes closed (elimination of vision), or on a firm or compliant surface (disturbance of proprioception) (Visser et al., 2008). The sensory orientation test (SOT) uses six sensory conditions in which the information of three main sensory systems is alternately eliminated or disturbed. Ratios between conditions give more insight into the quality of the underlying sensory systems (NeuroCom, 2012). In contrast to static posturography, dynamic posturography comprises CoM or CoP movement assessment during external disturbances applied by platform movement or disturbances applied to upper body parts.

Posturography is easily applicable, but a major disadvantage is the high intrasubject variability preventing individual assessment of standing balance (Visser et al., 2008). A main source of variability is the use of different compensation strategies depending on age, disease and test condition (Benvenuti et al., 1999; Helbostad et al., 2004; Lafond et al., 2004). The reliability depends on the population of interest, time of measurement and number of trials. To reach a good reliability, it is recommended to measure CoP and/or CoM movement more than once and during a time period of 90 s (Lafond et al., 2004; Ruhe et al., 2010), which is less feasible in clinical practice and in an elderly population. The results of posturography are also inherently difficult to interpret. Increased CoP or CoM movement is generally assumed to reflect a deterioration of balance control; this may however not be the case (Winter et al., 1990; Horak et al., 1997; Mancini and Horak, 2010). As the underlying systems are interrelated, selection of another compensation strategy could induce either increased or diminished CoP and/or CoM movement, in fact reflecting optimal balance control. Furthermore, changes in CoM and/or CoP movement can be multicausal, i.e. caused by deterioration of several underlying systems. In addition, CoP and/or CoM movement are influenced by training, such as ballet training. Ballet dancers show a better stability compared with untrained controls (Golomer et al., 1999; Hugel et al., 1999), but have an increased CoP and/or CoM movement in specific sensory conditions compared with untrained controls due to different use of sensory information (Perrin et al., 2002; Simmons, 2005). As a result, posturography cannot distinguish between the various underlying systems and the compensation strategies used and it therefore fails to reveal the details of the underlying pathophysiology of impaired standing balance (Mancini and Horak, 2010).

INTERVENTIONS TO IMPROVE STANDING BALANCE

Individually targeted multifactorial intervention, including individual risk assessment, is shown to be the most effective with a significant and beneficial effect on the rate of falling (Gillespie et al., 2012). However, due to the lack of clinical tests that can make a distinction between underlying causes of impaired standing balance, nowadays general fall prevention interventions are used, comprising exercising, environmental modification, medication optimization, education, or a combination. To reduce the risk of falling, exercising seems to be the best to use in the elderly (Chang et al., 2004; Sherrington et al., 2011; Gillespie et al., 2012). Exercising, either balance, resistance or cognitive-motor training (Granacher et al., 2011a,b; Pichierri et al., 2011) could also be prescribed to improve standing balance in the elderly in particular (Howe et al., 2011).

For traditional balance training there are hardly any scientific guidelines regarding contents, optimal duration and intensity. The American College of Sports Medicine (ACSM) recommends exercises that include (1) standing conditions with increasing difficulty caused by gradually reducing the base of support (e.g. semi-tandem stance, tandem stance and one-leg stance); (2) dynamic movements that disturb the CoM (e.g. tandem walk, circle turns); (3) stressing muscle groups involved in standing balance (e.g. heel stands, toe stands); and (4) reducing sensory input (e.g. standing with eyes closed) (Chodzko-Zajko et al., 2009). Perturbation-based balance training concentrates on compensation strategies to recover from unexpected disturbances using exercises matching real life conditions (Maki et al., 2008). Multitask balance training focuses on balance control during dual task activities, as instability increases when shared attention is needed (Granacher et al., 2010). Perturbation-based and multitask balance training are shown to be more effective than traditional balance training (Granacher et al., 2011a,b). However, a drawback of all aforementioned training types is the lack of a clear dose–response relationship and the unknown effects on the underlying systems and the compensation strategies used (Granacher et al., 2012).

Resistance training is used to improve the motor system, i.e. muscle function. It comprises strength training (Fiatarone et al., 1990; Granacher et al., 2009) and power training (Fielding et al., 2002; Reid et al., 2008) to increase muscle strength and velocity of force production respectively. High-intensity strength training appears to be more effective than low-intensity training. However, the effect on standing balance is less clear (Latham et al., 2004). Power training has been shown to be more effective in improving standing balance than strength training (Tschopp et al., 2011). Low-intensity power training seems to be better than high- or medium-intensity power training (Orr et al., 2008). However, the most effective intensity of resistance training is still under debate.

Cognitive-motor training focuses on the attentional demands needed to perform standing balance conditions. Three types of cognitive or cognitive-motor trainings are proposed. First, cognitive rehabilitation intervention has as goal to maximize the cognitive functioning and/or to reduce the risk of cognitive decline, e.g. by mental imagery training on standing balance. Second, cognitive-motor interventions are interventions combining cognitive tasks with physical tasks, e.g. balancing with a current mental task like memorizing words. Third, computerized interventions use biofeedback or virtual reality to improve standing balance. In the first case, feedback is given on the balance task, e.g. by visual feedback about the CoP movement. In the second case, environments are created in which subjects interact with images and virtual objects in a virtual environment, such as computer games. Previous research showed that cognitive and cognitive-motor training are effective to improve standing balance. However, more research is needed to get more evidence on the effectiveness of cognitive or cognitive-motor training (Pichierri et al., 2011).

Despite the generally positive effect of balance training, resistance training and cognitive-motor training on standing balance, it remains unclear which intervention (i.e. content, duration and intensity) can best be prescribed to improve standing balance in any specific case. This requires identification of the underlying cause and primary deterioration in impaired standing balance and the proper compensation strategy to be trained to improve standing balance. This is not possible with the current clinical assessment tools, preventing goal directed and time efficient therapy.

A NEW METHOD TO IDENTIFY THE UNDERLYING CAUSE OF IMPAIRED STANDING BALANCE

As with current clinical balance tests and posturography it is difficult to identify and to distinguish the primary deterioration of the various underlying systems and the used compensation strategies which are needed to prescribe targeted interventions, there is a clear clinical need for novel techniques to assess standing balance.

Balance control: a closed loop

The underlying systems involved in balance control interact within a closed loop (Fig. 1). When the body is disturbed by internal and/or external disturbances, it has to react to these disturbances. Changes in body position are perceived by the three main sensory systems: central and peripheral (Paulus et al., 1984; Bardy et al., 1999) vision, proprioception and the vestibular system (Johansson et al., 1988). This sensory information is combined and integrated by the nervous system with a specific time delay. Subsequent motor system action in the form of corrective, stabilizing joint torques is generated. This changes body position, which is again perceived by the sensory systems. Thus, in daily life cause and effect are interrelated in a continuous process (Fig. 1) within a closed loop (Morasso and Schieppati, 1999).

Externally applied disturbances and closed loop system identification techniques

One way to “break open” the loop of balance control and disentangle cause-and-effect relations is to apply precise external disturbances and record how the system reacts. The relation between the disturbances and the response can be described in the frequency domain by a frequency response function (FRF); per applied disturbance frequency the amplitude ratio and time delay between input and output is described. FRFs can be compared between or within subjects to identify changes in the balance control across different disturbance conditions. An additional step is to translate those FRFs to parameters, which makes it possible to describe the underlying systems involved in balance control. The experimental FRFs are compared with a model of the balance control describing the underlying systems mathematically. Using optimization methods, the parameters are estimated, so that they will represent the experimental data the best. The estimated parameters give a physiological meaning to the FRFs (van der Kooij et al., 2005).

Identifying deterioration in the nervous system and changes in strategies requires mechanical disturbances. Measuring separately the generated activity of each leg (i.e. the CoP movement) and the CoM movement, makes it possible to identify the contribution of each leg to the stabilization of standing balance (van Asseldonk et al., 2006). By applying mechanical disturbances at ankle and hip level, the inter-segmental stabilizing mechanisms which represent the contribution of the ankle and hip strategy to the control of standing balance can be identified. Furthermore, the movements of the two joints influence each other. This coupling between the joints can be expressed by relating the joint torques to the joint angles (Boonstra et al., 2013).

Quantifying the contribution of the sensory systems requires disturbances of a specific sensory system, e.g. visual scene movement disturbing vision or ankle rotations disturbing proprioception. The contribution of each sensory system in maintaining standing balance can subsequently be expressed by a weighting factor

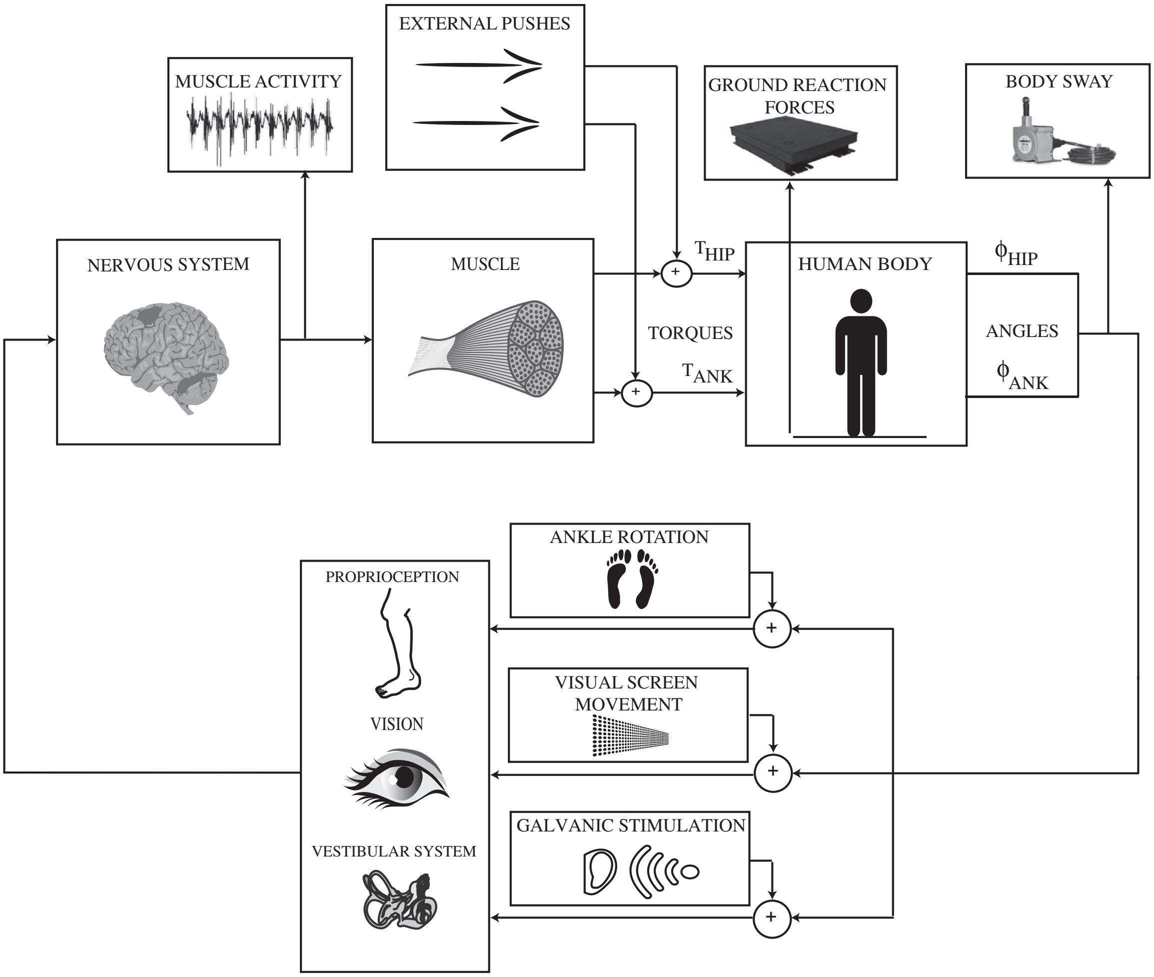

Fig. 1. Balance control is represented as a closed loop. The position of the human body is perceived by the sensory systems (i.e. proprioceptive, visual and vestibular system). The sensory information is sent to the central nervous system. Here, the information is combined and a command is sent to the muscles (i.e. the motor system), which will contract and change the body position. Using external disturbances the balance control can be disturbed at different places in the loop (e.g. by external pushes, ankle rotations, visual scene movement or galvanic stimulation) and the reaction to the disturbances can be established in different places by measuring muscle activity, ground reaction forces (i.e. center of pressure movement) and body sway (i.e. center of mass movement).

(Peterka, 2002). A distinction can be made in the contribution of the proprioceptive information of the left and the right leg to detect asymmetries (Pasma et al., 2012). Sensory *re*weighting strategies can be assessed by increasing sensory disturbance amplitudes (Peterka, 2002) as this scales down the contribution of a sensory system, and thus lowers its weighting factor. The quality of the sensory systems can be determined by estimating the noise level (van der Kooij and Peterka, 2011).

Applying precise external disturbances makes it possible to identify the quality of each underlying system. Simultaneous disturbances of different sensory systems allow for assessment of sensory reweighting and together with mechanical disturbances aimed at different joints, hip and ankle strategies can be identified. The use of random multisine disturbances consisting of specific frequencies prevents anticipation and allows for assessment of the bandwidth of system quality. As the goal is to identify balance control and not to identify its limits, sub maximal amplitudes which the participant can withstand, are used to disturb the system.

Clinical relevance

The use of externally applied disturbances and closed loop system identification techniques makes it possible to detect a deterioration in the underlying systems and the compensation strategies used by elderly persons with impaired standing balance. Using this knowledge a physician can diagnose the underlying and primary cause of impaired standing balance, which makes it possible to prescribe targeted interventions. This method may also be applicable to detect deterioration of balance control at an early stage in elderly persons without impaired standing balance, i.e. who do not show deterioration of balance control using current clinical balance tests. Furthermore, the described method is time and cost effective since it allows for simultaneous application of several external disturbances with different frequency contents. The external disturbances are sub maximal, which makes the method safe for the patient. However, before this method can be clinically applied, further research has to investigate sensitivity and specificity of the method to identify impaired standing balance and risk of falling in the population of interest. As such, prototypes are currently implemented and evaluated in clinical practice.

CONCLUSION

There is a clinical need for new techniques to assess standing balance that can detect the underlying cause and primary deterioration in impaired standing balance at an early stage. Externally applied disturbances in combination with closed loop system identification techniques may fill the void, which makes it possible to intervene in impaired standing balance, at an early stage, with targeted interventions.

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