Dynamic balance in persons with multiple sclerosis who have a falls history is altered compared to non-fallers and to healthy controls

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Abstract

Around 60% of persons with multiple sclerosis (MS) experience falls, however the dynamic balance differences between those who fall and those who don’t are not well understood. The purpose of this study is to identify distinct biomechanical features of dynamic balance during gait that are different between fallers with MS, non-fallers with MS, and healthy controls. 27 recurrent fallers with MS, 28 persons with MS with no falls history, and 27 healthy controls walked on a treadmill at their preferred speed for 3 min. The variability of trunk accelerations and the average and variability of minimum toe clearance, spatiotemporal parameters, and margin of stability were compared between groups. Fallers with MS exhibited a slower cautious gait compared to non-fallers and healthy controls, but had decreased anterior-posterior margin of stability and minimum toe clearance. Fallers walked with less locally stable and predictable trunk accelerations, and increased variability of step length, stride time, and both anterior-posterior and mediolateral margin of stability compared to non-fallers and healthy controls. The present work provides evidence that within a group of persons with MS, there are gait differences that are influenced by falls history. These differences indicate that in persons with MS who fall, the center of mass is poorly controlled through base of support placement and the foot is closer to the ground during swing phase relative to the non-fallers. These identified biomechanical differences could be used to evaluate dynamic balance in persons with MS and to help improve fall prevention strategies.

1. Introduction

Multiple sclerosis (MS) causes demyelination and axonal loss in the central nervous system resulting in a variety of sensorimotor impairments which negatively affect gait and balance (Noseworthy et al., 2000). Between 50 and 60% of persons with MS (PwMS) experience falls (Matsuda et al., 2011; Peterson et al., 2007), which often result in injuries requiring medical attention (Matsuda et al., 2011). Falls most commonly occur during functional mobility such as walking (Matsuda et al., 2011; Peterson et al., 2013). While fall occurrence is high in PwMS, up to 50–60% of individuals, not all PwMS fall. Fallers with MS may have made different gait adaptations (Kasser et al., 2011; Peebles et al., 2016; Sosnoff et al., 2011) or have different levels of motor control impairment (Moon et al., 2015; Socie et al., 2013) than non-fallers with MS.

PwMS walk with slower, shorter, and wider steps than healthy controls (Sosnoff et al., 2012). However, contradicting evidence exists relating these gait changes to fall risk since it was found that fallers walked slower than non-fallers but with similar step widths (Sosnoff et al., 2011), and that step width significantly contributed to fall risk but velocity did not (Kasser et al., 2011). This discrepancy may be due to traditional spatiotemporal measures (e.g. step length, width, and time) of gait being reflective of ‘fear of falling’ rather than ‘risk of falling’ (Maki, 1997). These spatiotemporal alterations are significantly correlated with fear of falling in PwMS (Kalron and Achiron, 2014). Spatiotemporal variability, however, reveals important features of sensorimotor impairment and has well documented success in prospectively identifying elderly fallers (Hausdorff et al., 2001; Maki, 1997). While evidence exists linking increased spatiotemporal variability to falls in PwMS (Moon et al., 2015; Socie et al., 2013), experimental design limitations hinder the generalizability of the results. Some studies have looked at gait variability only over a short distance (7.9 m) (Socie et al., 2013), which may lead to unreliable results (Riva et al., 2014), while others compared variability to a physiological fall risk...
assessment rather than actual fall occurrence (Moon et al., 2015). Although previous research has identified important features of dynamic balance which are altered during gait in PwMS relative to healthy controls (Huisenga et al., 2013; Sosnoff et al., 2012), it is unclear if these dynamic balance features are altered in fallers with MS.

Dynamic balance, or gait stability, has been quantified in many different ways (Bruijn et al., 2013). Nonlinear variability measures have been used to quantify the predictability and complexity of dynamic systems which is reflective of gait stability (Bruijn et al., 2013). For example, Lyapunov exponent is predictive of future falls in elderly individuals (Toebes et al., 2012). PwMS have altered nonlinear variability of both spatiotemporal parameters and trunk accelerations during gait (Huisenga et al., 2013; Kaipust et al., 2012). Gait stability may also be defined as the ability to maintain the extrapolated (velocity-adjusted) center of mass (CoM) within the base of support, with the distance between the two referred to as the margin of stability (MoS) (Hof et al., 2005). PwMS tend to increase MoS during gait, highlighting a cautious gait adaptation (Peebles et al., 2016). Increased MoS was positively correlated with self-reported number of falls in PwMS which indicates that the cautious gait adaptation may actually cause instability (Peebles et al., 2016). While average MoS across strides depicts overall gait strategy (walking slow or taking wide steps), stride-to-stride variability of MoS may be better suited for investigating dynamic balance as it reflects the consistency of step placement relative to CoM motion (McAndrew Young et al., 2012).

The purpose of this study is to identify distinct features of dynamic balance that are different between PwMS who have a history of falls, PwMS with no history of falls, and healthy controls. Previous research has focused only on comparing spatiotemporal parameters between fallers and non-fallers with MS (Kasser et al., 2011; Socie et al., 2013; Sosnoff et al., 2011). The present study utilizes measures of dynamic balance which reflect CoM motion and control, both important for maintaining balance (Hof et al., 2005), and swing foot motion and control, related to trip risk (Byju et al., 2016). Our first hypothesis is that compared to non-fallers and healthy controls, fallers will have a more cautious gait strategy as demonstrated by increased MoS and increased minimum toe clearance (MTC). Previous work has found that fallers with MS walk slower than non-fallers (Sosnoff et al., 2011), that slow walking increases MoS (Peebles et al., 2016), and that elderly fallers had a higher MTC than non-fallers (Karmakar et al., 2013). Elderly fallers are also known to have increased variability of spatiotemporal parameters (Maki, 1997), trunk accelerations (Toebes et al., 2012), and MTC (Karmakar et al., 2013). Therefore, our second hypothesis is that compared to non-fallers and healthy controls, fallers will have increased variability of MoS, MTC, spatiotemporal parameters, and trunk accelerations.

2. Methods

2.1. Participants

Twenty-seven healthy controls (HC) and fifty-five PwMS were enrolled in the present study (Table 1). The University of Kansas Medical Center Human Research Committee approved this study and all participants gave informed written consent. HC were free of any known neurological or musculoskeletal pathologies or disorders that would have an adverse effect on the participant’s balance or gait. All subjects with MS were between the ages of 21–60, had relapsing-remitting MS, had mild-to-moderate disease severity with an EDSS score less than 5.5, and normal or corrected to normal vision. Each PwMS completed the timed 25-foot walk and berg balance scale to assess clinical walking and balance dysfunction and lower limb spasticity was quantified with the modified Ashworth scale. The self-reported number of falls in the six months prior to data collection was recorded for PwMS and HC, with falling defined as “an event which results in a person coming to rest unintentionally on the ground or lower level” (Tinetti et al., 1988). Non-fallers (NF) were classified as PwMS who did not experience a fall in the previous 6 months (n = 28) and fallers (FA) were classified as PwMS with 2 or more falls in the previous 6 months (n = 27), as PwMS who fall more than once are more likely to fall due to intrinsic disease specific factors (Kasser et al., 2011). Demographics were compared between groups using paired t-tests (Table 1).

2.2. Data collection

All subjects walked on a treadmill for 3 min. Subjects were instructed to walk naturally, at their comfortable self-selected pace without holding onto the treadmill side rails. Treadmill speed was slowly increased from zero until the subject reported they were at a comfortable pace. Subjects wore their own tennis shoes and no other type of shoes were allowed. Kinematic data was collected at 60 Hz (Motion Analysis, Santa Rosa, CA, USA) using retroreflective markers placed bilaterally on the anterior and posterior superior iliac spine, heel, lateral malleolus, top of the second metatarsal phalangeal joint, and lateral metatarsal phalangeal. A wireless inertial sensor (Opal, APDM, Portland, OR, USA) placed on the trunk, over the midline of the sternum, inferior to the manubrium and superior to the xiphoid process was used to measure acceleration at 128 Hz.

2.3. Data analysis

2.3.1. Foot motion

Step length and step width were defined as the anterior-posterior (AP) and mediolateral (ML) distance between contralateral heel markers at each left and right heel strike. Stride time was defined as the time between two ipsilateral heel strikes. Spatiotemporal variability was determined using coefficient of variation, which represents the standard deviation normalized by the mean (Sosnoff et al., 2012). MTC was defined as the vertical distance from the toe marker to the treadmill, at the local minimum during mid-swing phase (Santhiranayagam et al., 2015). Occasionally, swing phases occurred which resulted in no true local minimum, and MTC was recorded as the toe height at the average percent of swing phase for other MTC (Santhiranayagam et al., 2015). Participants who exhibited somewhat of a shuffle gait, visually determined as abnormal swing phases, were excluded for the statistical analysis of MTC only (1 NF; 8 FA). Variability of MTC was determined using the time series standard deviation (Karmakar et al., 2013).

2.3.2. Trunk acceleration

Linear accelerations were measured in the AP, ML, and vertical (VT) axis, and analyzed independently. Root mean square transforms (RMS) were used to describe the dispersion of each signal (Craig et al., 2016; Huisenga et al., 2013). Temporal structure of trunk accelerations was assessed with Lyapunov exponents (LyE) and sample entropy (SaEn). Raw acceleration time series were down-sampled to 60 Hz and truncated to the middle 60 strides (Kao et al., 2014). Sixty strides is an appropriate number to reliably quantify nonlinear variability measures used in the present study (Riva et al., 2014). Delay-embedded state spaces were reconstructed independently in each axis. Embedding dimensions were found using the global false nearest neighbor algorithm, and time delays were found using the average mutual information algorithm (van Schooten et al., 2013), and the median of every subject resulted in an embedding dimension of 7 for each axis, and time
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