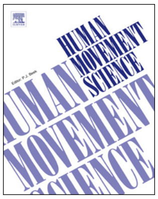
Human Movement Science 62 (2018) 67–80

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov



Healthy aging does not impair lower extremity motor flexibility while walking across an uneven surface

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ARTICLE INFO

Keywords:
Irregular surface
Uncontrolled manifold
Motor redundancy
Elderly
Gait
Code:R

ABSTRACT

It is crucial to understand age-related degenerative processes that affect dynamic postural control and ultimately increase the risk of falling for older adults. Mediolateral stability during gait, which requires active control of foot placement, may be particularly diminished with age. Using the uncontrolled manifold-analysis (UCM), we aimed to quantify the effect of age and uneven surfaces on the ability to rely on motor equivalent control to stabilize the mediolateral trajectory of the swing limb during gait. The UCM analysis tests the extent to which all available degrees of freedom (DoF) that contribute to a task-relevant performance variable co-vary so as to stabilize, i.e., reduce the variance of, that performance variable. Within the UCM analysis, variability is partitioned into two components: "good" variance that has no effect on the performance variable, and "bad" variance, that results in a variable performance. A synergy index quantifies the relative amount of "good" variance compared to "bad" variance. Thirteen healthy younger (mean age 23 years) and 11 healthy older adults (mean age 73 years) walked across an even lab floor and a more challenging uneven surface. The UCM analysis was performed using lower extremity segment angles as the DoF that contribute to the mediolateral trajectory of the swing limb. We found that both, young and older adults were able to exploit motor flexibility to stabilize the foot trajectory regardless of walking condition, resulting in similar synergy indices. However, to counteract the age-related increase in performance destabilizing variability on the uneven surface, older adults increased "good" variability to similar degree. We conclude that increasing variability is not a sign of decreased motor control but rather an intentional strategy of the neuromuscular system to compensate for possible age-related declines in strength and balance. There is great potential to improve fall prevention programs by introducing tasks that promote, rather than limit, exploration of motor solutions to strengthen appropriate synergies.

1. Introduction

Nearly half of all community-dwelling older adults above 65 years of age may fall annually (Delbaere, Close, Brodaty, Sachdev, & Lord, 2010). The majority of falls in community-dwelling older adults (Berg, Alessio, Mills, & Tong, 1997), as well as in long-term care residents (Robinovitch et al., 2013) tend to occur during locomotion, especially when gait is challenged as by walking on sloped, slippery or uneven surfaces. Mechanically stable locomotion requires continuous adaption and response to internally and externally

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https://doi.org/10.1016/j.humov.2018.09.008
Received 19 March 2018; Received in revised form 16 July 2018; Accepted 15 September 2018

generated perturbations through feedforward and feedback mechanisms (Kuo, 2002). Whereas passive dynamics of the lower extremities suffice to counteract small perturbations in the anterior/posterior direction during locomotion, active control by the central nervous system (CNS) is needed to respond to mediolateral perturbations (Kuo, 2002). This control is generally realized through accurate mediolateral (ML) positioning of the swing-foot relative to the center of mass (CoM) (Bruijn & van Dieën, 2018). In particular, recent evidence points to a specific neuromechanical strategy to stabilize gait whereby activity in the swing limb hip muscles predicts foot placement, and whereby this muscle activity can be predicted by mechanical states of the stance limb and pelvis as sensed through hip proprioceptors (Hof & Duysens, 2013; Rankin, Buffo, & Dean, 2014; Roden-Reynolds, Walker, Wasserman, & Dean, 2015); perturbations to the CoM that affect these mechanical states results in appropriate alteration in foot placement to maintain stability (Hof & Duysens, 2013; Rankin et al., 2014). Age-related changes that affect this neuromechanical strategy and in turn MLplacement of the swing-foot may increase the risk of falls by older adults (Arvin et al., 2016; Lord, Rogers, Howland, & Fitzpatrick, 1999).

Multiple neuromuscular factors that contribute to ML foot placement may degenerate with age. For example, older adults demonstrate unsteady force output (Manini & Clark, 2012) and degraded accuracy of sensory information, which (Shaffer & Harrison, 2007) contribute to age-related increased neuromotor noise and associated motor variability (Christou, 2011b; Enoka et al., 2003; Kang & Dingwell, 2009; Shaffer & Harrison, 2007). With regard to ML placement of the foot, increased step width variability (SWV), a measure of precision in ML foot placement, has been related to decreased active control of foot placement and to an increased risk of falling (Brach, Berlin, VanSwearingen, Newman, & Studenski, 2005). Nonetheless, if an individual is able to compensate for high SWV (i.e. high motor noise), particularly when additional challenges of locomotion are introduced, then the high variability alone may not be problematic. However, descriptive statistics such as SWV provide no indication of the extent to which the system is able to compensate for motor noise (Greve, Hortobàgyi, & Bongers, 2015; Greve, Hortobágyi, & Bongers, 2017) nor about the role of foot placement in stabilization of gait. More sophisticated analyses, including the uncontrolled manifold (UCM) analysis may these limitations of SWV.

The UCM analysis tests the extent to which all available DoF that contribute to performance (i.e., elemental variables) co-vary so as to keep a performance variable that is relevant to the task relatively invariant and stable (Latash, Scholz, & Schöner, 2007). It was developed as means to deal with the problem of motor redundancy, i.e., that there exist more motor components or degrees of freedom (DoFs) involved in the production of actions than are required by the constraints of the action (Bernshteĭn, 1967). Within the UCM analysis, variability in the elemental variables is partitioned into two variance components (VC): one termed "good" variance that has no effect on the performance variable, and one termed "bad variance" that results in a variable performance. If the former exceeds the latter ("good" > "bad") then there exists a synergy, or multi-DoF covariation, to stabilize performance (Martin, Foulonneau, Turki, & Ihadjadene, 2013). Accordingly, a set of elemental variables may show high variability without affecting performance. In fact, exploitation of redundant DoFs is actually a necessary means for stabilizing motor perform and for appropriately reacting to perturbations and challenging circumstances (Latash, 2000, 2012). For example, while younger and older adults increase motor variability in response to increasing task demands during reaching tasks, they appear to do so in such a way that does not lead to movement errors (Greve et al., 2017; Greve, Zijlstra, Hortobágyi, & Bongers, 2013); i.e., by channeling the increased variance into "good" variability. We will conceptually define this strategy as exploiting motor flexibility, which is not synonymous with "good" variance, as information regarding "bad" variance is required to ascertain whether the strategy was employed. As eloquently described by Tuitert et al. (2017), motor flexibility can be thought of as the "deployment of a range of different solutions to solve a given motor problem. Imagine, a system is challenged by perturbations and variability is channeled into "good" variance to counteract an increase in "bad" variance; i.e., holding a glass of water without spilling by facilitating multiple motor solutions, when tripping. The ratio between the two variance components may remain the same; however, this strategy indicates flexible motor behavior to maintain a relatively invariant and stable performance variable, i.e., not spilling water" (Tuitert et al., 2017). Thus, motor flexibility may, in part, reflect a specific strategy of the CNS to compensate for age-related neuromuscular degeneration (2013; Greve et al., 2015).

UCM analysis may be useful to provide information regarding the extent to which inter-limb coordination involved in neuromechanical stabilization of gait relies on motor flexibility. As Krishnan, Rosenblatt, Latash, and Grabiner (2013) pointed out, the swing-foot can be viewed as an end-effector of the open kinematic chain of the lower limbs and is therefore dependent on coordination of multiple redundant DoFs. Using the UCM analysis, the authors found that older adults had significantly greater total variance in elemental variable space, but that they partitioned relatively similar amounts of this increased variance into the two VC. Thus, to counter greater "bad" variance, older adults appear to exploit motor flexibility, walking with significantly greater "good" variance compared to the younger adults. It is unclear whether similar strategies are used during more challenging daily locomotor activities, which may present greater fall risk (e.g., traversing surfaces of varying compliance and evenness). Physical challenges, such as those presented by walking on uneven surfaces, not only alter lower limb kinematics in young adults (Gates, Wilken, Scott, Sinitski, & Dingwell, 2012; Voloshina, Kuo, Daley, & Ferris, 2013), but influence lower limb kinematics of older adults even more (Marigold & Patla, 2008; Thies, Richardson, Demott, & Ashton-Miller, 2005). Thus, walking on uneven surfaces may also influence kinematic synergies that stabilize the ML trajectory of the swing limb. There is a need to investigate how healthy aging affects coordination of lower limb joints while walking on challenging surfaces.

The purpose of the study was to quantify age- and surface-related effects on UCM-derived kinematic synergies related to the ML trajectory of the swing limb during gait. First we hypothesized a main effect of VC; regardless of age, during both even and uneven surface-walking "good" variance would be larger than "bad" variance indicating the presence of a kinematic synergy. Second, we hypothesized a main effect of *surface*; regardless of age, the synergy index would be greater on the uneven surface. Third, we hypothesized a *surface x age* interaction; on the even surface the synergy index would be similar for younger and older adults