Human Movement Science 52 (2017) 191–196

Contents lists available at ScienceDirect

Human Movement Science

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

Full Length Article

Exploring phase dependent functional gait variability

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ARTICLE INFO

Article history:
Received 13 October 2016
Revised 4 February 2017
Accepted 12 February 2017
Available online 23 February 2017

Keywords:
Gait
Functional variability
Minimum toe clearance
Inertial sensor

ABSTRACT

Gait variability is frequently used to evaluate the sensorimotor system and elderly fallers compared to non-fallers exhibit an altered variability in gait parameters during unchanged conditions. While gait variability is often interpreted as movement error, it is also necessary to change the gait pattern in order to react to internal and external perturbations. This phenomenon has been described as functional variability and ensures the stability of gait motor control. The aim of the current study is to explore the functional variability in relation to the different phases of the gait cycle (phase-dependent gait variability).

Kinematics of the foot, shank and thigh were registered with inertial sensors (MTw2, Xsens Technologies B.V) in 25 older participants (70 ± 6 years) during normal overground walking. Phase-dependent variability was defined as the standard deviation of the Euclidean norm of the angular velocity data. To assess differences with respect to the variability of different body segments (foot, shank, and thigh), the statistical parametric mapping method was applied.

In normal walking, the variability of the time-continuous foot kinematics during parts of the swing phase was higher compared to the shank (9–14% of swing phase, $p < 0.000$) and to the thigh (3–43%, $p < 0.000$ and 92%, $p = 0.024$ of swing phase). Compared to the thigh, the shank kinematics was less variable at 62–64% ($p = 0.013$) of the swing phase. The magnitudes of the variability were comparable regarding all three body segments during mid swing. Furthermore, those magnitudes of variability were smallest during mid swing where the minimum toe clearance was identified.

In conclusion, we found signs of phase-dependent functional variability particularly in the swing phase of gait. In fact, we found reduced variability in the time-continuous foot kinematics in mid swing during normal walking where also the minimum toe clearance event occurs.

1. Introduction

Gait analyses are widely used to determine movement characteristics associated with orthopedic and neurologic disorders (Whittle, 1996) and elderly fallers compared to non-fallers exhibit an altered variability in gait parameters during unchanged conditions (Hamacher, Singh, Van Dieën, Heller, & Taylor, 2011). Sensorimotor control mechanisms during walk-

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http://dx.doi.org/10.1016/j.humov.2017.02.006
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ing can be validly assessed using the stride-to-stride variability of gait parameters. Extreme levels of gait variability seem to be indicators for pathologies with respect to the human sensorimotor system (Singh, Konig, Arampatzis, Heller, & Taylor, 2012).

However, movement variability can be caused by different sources: 1) by a noisy sensorimotor control system (variability interpreted as movement error), 2) by the adaption to situational constraints or 3) by mechanisms initiated to compensate for prior movement deviations (e.g. to compensate for earlier movement error) (Loosch, 1999). Since the sensorimotor system is intrinsically noisy (Davids, Glazier, Araújo, & Bartlett, 2003), movement variability during unchanged conditions is sometimes interpreted to be an error in the sensorimotor control of human motion (e.g. Hamacher, Hollander, & Zech, 2016). Yet, individual cyclic repetitive movement patterns (e.g. gait) are reproducible with some degree of precision. Despite of the movement variability, those movements are executed robustly and stably in healthy individuals even in situation with small perturbations (Riley & Turvey, 2002). Gait stability (e.g. local dynamic stability) is interpreted as the system's capacity to compensate or recover from small perturbations potentially arising from intrinsic (e.g. neuromuscular noise) or extrinsic sources (e.g. uneven ground) (Bruijn, Meijer, Beek, & Van Dieën, 2013). In order to compensate for perturbations, the sensorimotor system must adapt those perturbations which, again, results in movement variability (Muller, Tschiesche, & Blickhan, 2014).

Due to the different explanatory approaches, the term "functional variability" has not been consistently used in the literature. Frequently, it is referred to as the adaptability to varying situational constraints in order to achieve a consistent performance (Barris, Farrow, & Davids, 2013, 2014). Bootsma and van Wieringen (1990) provided a more general definition. They propose the term "compensatory variability" in the cases where the variability in an execution variable (relevant variable that does not directly reflect the primary result parameters but does influence those) is compensated by the variability of another execution variable in order to achieve a stable result parameter (Bootsma & van Wieringen, 1990).

Our definition of functional variability is an enhanced version of the definition of Barris et al. (2014). We define functional variability as the variability which is not simply movement error but which evolves 1) due to adaptions to situational constraints or 2) due to the compensation for deviations in different movement parameters (points 2 and 3 according to Loosch, 1999). As an approach to identify functional movement variability, we will use the Bootsmas et al. (Bootsma & van Wieringen, 1990) definition: In cases where the functional variability exists, the variability of the task-relevant result parameter is rather small when comparing it to the variability of the execution variables (Müller & Loosch, 1999; Winter, 1984).

The occurrence of functional variability has already been investigated in e.g. acyclic sports techniques as for instance, in trained athletes performing sprint starts (Bradshaw, Maulder, & Keogh, 2007) and athletic pistol shooting (Scholz, Schöner, & Latash, 2000). It also has been reported that (functional) movement variability increases with enlarged expertise in handball players regarding their throw movements (Schorer, Baker, Fath, & Jaitner, 2007). However, another study did not find an altered variability with increasing expertise in the basketball free-throw (Button, MacLeod, Sanders, & Coleman, 2003). Furthermore, Koenig, Tamres, and Mann (1994) reported that in golfers the variability of the ground reaction force increased during the back swing and during parts of the downswing but it was particularly reduced during the impact phase (Koenig et al., 1994) indicating phase dependent functional variability.

While most studies focused on acyclic sports techniques, there are only few that analyzed functional variability in gait. Winter (1984) analyzed force moment variability in the sagittal plane of the lower extremity. The sum of the force moment variances of each joint was higher than the support moment which indicates that there was a 'cancellation of joint moments'. This was interpreted as a 'fine motor tuning' to 'correct minor deviations' (Winter, 1984, p. 60) and can, thus, be described as functional variability. However, this work only analyzed averaged and non-phase-dependent force moment variability of the lower extremities. Other studies analyzed gait variability and the adaptability of human locomotion by looking at time-discrete parameters (mostly variability of stride time, stride length, speed and minimum toe clearance) (Bohnsack-McLagan, Cusumano, & Dingwell, 2016). One reason why functional variability was rarely examined in cyclic movements might be the fact that the task-relevant result parameters are not that obvious. However, since functional variability is required to form a stable system (stable gait pattern), analyzing the role of functional variability in gait is important to understand gait variability which is also frequently assessed with respect to pathological gait. Thus, the aim of the current study was to explore whether phase-dependent functional variability can be verified in human gait.

To analyze functional variability, the task-relevant parameter must be analyzed. For human walking, it was supposed that the minimum toe-ground distance (minimum toe clearance) might be a task-relevant parameter during swing phase (Hamacher, Hamacher, Herold, & Schega, 2016; Hamacher, Hamacher, & Schega, 2014a). Obviously, our task-relevant parameter is indirectly affected by the kinematics of shank and thigh. Analogues to the approach of Winter (1984), Müller and Loosch (1999) and Bootsma and van Wieringen (1990), functional variability manifests as a relatively low variability of the task-relevant parameter (foot kinematics during minimum toe clearance) compared to the variability of parameters in the execution space (kinematics of shank and thigh). Thus, if there is either no increase or even a decrease in the variability of the foot compared to the shank or thigh kinematics, we consider this as a sign of functional variability.

Due to the above mentioned facts, we hypothesized that during minimum toe clearance the variability of the foot kinematics is lower or equal compared to the variability of the kinematics of shank or thigh.

Another focus of gait control is on the stabilization of the body, and especially the pelvis during the stance phase (Perry, 2010). Regarding the stance phase, the current study also explores the time-continuous variability of the lower extremities. Since an altered gait variability is associated with increased fall risk (Hamacher et al., 2011), functional variability is relevant in older adults and we, thus, will test the hypotheses in elderly.