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The validity of stability measures: A modelling approach

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ABSTRACT

Measures calculated from unperturbed walking patterns, such as variability measures and maximum Floquet multipliers, are often used to study the stability of walking. However, it is unknown if, and to what extent, these measures correlate to the probability of falling.

We studied whether in a simple model of human walking, i.e., a passive dynamic walker, the probability of falling could be predicted from maximum Floquet multipliers, kinematic state variability, and step time variability. We used an extended version of the basic passive dynamic walker with arced feet and a hip spring. The probability of falling was manipulated by varying the foot radius and hip spring stiffness, or varying these factors while co-varying the slope to keep step length constant.

The simulation data indicated that Floquet multipliers and kinematic state variability correlated inconsistently with probability of falling. Step time variability correlated well with probability of falling, but a more consistent correlation with the probability of falling was found by calculating the variability of the log transform of the step time. Our findings speak against the use of maximum Floquet multipliers and suggest instead that variability of critical variables may be a good predictor of the probability to fall.

1. Introduction

There is a steadily growing body of research focusing on falls and the stability of walking and standing in the elderly (Kang and Dingwell, 2008; Lockhart and Liu, 2008; Kang and Dingwell, 2009a, 2009b) and various patient groups (Dingwell et al., 2000, 2007; Moraiti et al., 2007; Fallah Yakhdani et al., 2010; Lamoth et al., 2010). In the quest for measures that may provide estimates of gait stability without physically perturbing the gait pattern, three measures have received considerable attention in the past two decades: maximum Lyapunov exponents (Rosenstein et al., 1993; Dingwell and Cusumano, 2000), maximum Floquet multipliers (Hurmuzlu and Basdogan, 1994; Hurmuzlu et al., 1996), and measures of gait variability (Maki, 1997; Hausdorff et al., 2001). For maximum Lyapunov exponents (Rosenstein et al., 1993; Dingwell and Cusumano, 2000), we have recently shown (1) that they can predict probability of falling in a mathematical model of walking (Bruijn et al., submitted for publication, 2010a, 2010b) and (2) that they can detect gait instabilities induced in young healthy subjects by galvanic vestibular stimulation during both treadmill (Van Schooten et al., 2011) and overground walking (Sloot et al., 2011). However, for maximum Floquet multipliers and variability measures, the existing evidence is less consistent.

Maximum Floquet multipliers (Hurmuzlu and Basdogan, 1994) (maxFm) have been used for almost two decades to quantify gait stability (Hurmuzlu et al., 1996; Granata and Lockhart, 2008; Kang and Dingwell, 2009a, 2009b). Nonetheless, it has been demonstrated that maxFm correlate inconsistently with the probability of falling in a passive dynamic walking model (Schwab and Wisse, 2001; Hobbelen and Wisse, 2007). Moreover, in recent studies, in which gait stability was reduced experimentally by having subjects walk on a compliant surface (Chang et al., 2010), or by application of galvanic vestibular stimulation (Van Schooten et al., 2011), the reduction in stability could not be demonstrated using maxFm. Yet, in another study in which mechanical perturbations were used, maximum Floquet multipliers did reflect reduced stability (McAndrew et al., 2011). Furthermore, maximum Floquet multipliers did distinguish between elderly with a history of falling and elderly without such a history (Granata and Lockhart, 2008), as well as between young and old subjects (Kang and Dingwell, 2008, 2009a, 2009b).

Methodological biases due to differences in gait speed and/or cadence between groups in the previous studies may have affected previous results. Alternatively, the discrepancy between

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