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Uncontrolled manifold hypothesis: Organization of leg joint variance in humans while walking in a wide range of speeds

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A B S T R A C T

This study aimed at investigating the organization of joint angle variability during walking by using the uncontrolled manifold (UCM) theory. We tested two hypotheses: i. the coordinative mechanism underlying joint angle variance during the stance phase is compatible with a kinematic synergy that stabilizes the centre of mass (CoM) position; ii. the walking speed affects the variance components onto and orthogonal to the UCM.

Eight healthy subjects (26.0 ± 2.0 years old) steadily walked on a treadmill at five normalised speeds (from 0.62 ± 0.03 m/s to 1.15 ± 0.07 m/s). Joint angles and foot orientation, and components of the CoM position were, respectively, used as elemental variables and task performance for the UCM implementation. The effect of speed, time events, and variance components on the distribution of data variance in the space of joint angles was analyzed by the ANOVA test.

Results corroborated the hypothesis that the variance of elemental variables is structured in order to minimize the stride-to-stride variability of the CoM position, at all speeds. Noticeably, both variance components increase during the propulsive phase, albeit that parallel to the UCM was always grater than the orthogonal one. Accordingly, the observed kinematic synergy is supposed to contribute to accomplishing an efficient transition between two steps. Results also revealed that the walking speed does not affect the partitioning of elemental variables-related variance onto and orthogonal to the UCM. Accordingly, the organization of leg joint variance underlying the stabilization of CoM position remains almost unaltered across speeds.

1. Introduction

Human walking is a complex motor task involving the coordination of several redundant actuators and joints, thus allowing persons to properly tune gait patterns in accordance with the desired speed. Although walking can be achieved in steady conditions (i.e. at constant speed), gait patterns are always characterized by stride-to-stride fluctuations. This intrinsic and unavoidable variability has been, in part, ascribed to the motor redundancy, that is, an excess of degrees of freedom (DoF) that overcomes the number of variables required to unambiguously set a specific task-related performance (Black, Smith, Wu, & Ulrich, 2007; Dingwell & Cusumano, 2015; Dingwell, John, & Cusumano, 2010; Krishnan, Rosenblatt, Latash, & Grabiner, 2013; Papi, Rowe, & Pomeroy, 2015; Qu, 2012; Robert, Bennett, Russell, Zirker, & Abel, 2009; Rosenblatt, Hurt, Latash, & Grabiner, 2014;

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Srivastava, Kao, Reisman, Higginson, & Scholz, 2016; Toney & Chang, 2013, 2016; Verrel, Lovden, & Lindenberger, 2010). The *abundant* amount of DoFs hence represents an adaptable source of solutions that allows the Central Nervous System (CNS) to ensure stable behaviours against unpredictable and/or context-specific perturbations. This motor control strategy was termed *principle of abundance* (Gelfand & Latash, 1998; Latash, Scholz, Danion, & Schoner, 2001; Latash, Scholz, & Schoner, 2007).

The uncontrolled manifold (UCM) theory was developed (Scholz & Schoner, 1999; Scholz, Schoner, & Latash, 2000; Schoner, 1995), in accordance with the principle of abundance, to investigate the task-specific organization of motor variability underlying several motor tasks including human walking (Black et al., 2007; Krishnan et al., 2013; Papi et al., 2015; Qu, 2012; Robert et al., 2009; Rosenblatt et al., 2014; Srivastava et al., 2016; Toney & Chang, 2013, 2016). Specifically, the UCM approach aims at testing the hypothesis that the variance in the space of the DoFs (also named elemental variables) is mostly confined in a suitable subspace (the UCM) corresponding to all solutions that preserve the task performance. To test this hypothesis, the DoFs-related variance across trials is split in two components respectively projected onto and orthogonal to the UCM (see Section 2.3 for further details). When the former component is higher than is the latter one, the UCM hypothesis is accepted and the task performance is said to be stabilised by a synergy (Latash et al., 2001, 2007).

As far as human walking is concerned, several authors have already investigated the hypothesis that the stride-to-stride variability related to different sets of DoFs is exploited by the CNS to stabilize specific task performance (i.e. to preserve the task performance against potential perturbations) in healthy, aged and disabled subjects (Black et al., 2007; Dingwell & Cusumano, 2015; Dingwell et al., 2010; Krishnan et al., 2013; Papi et al., 2015; Qu, 2012; Robert et al., 2009; Rosenblatt et al., 2014; Srivastava et al., 2016; Toney & Chang, 2013, 2016; Verrel et al., 2010). Despite this, the effects of the walking speed on this motor control strategy have not been exhaustively explored. In particular, only a limited set of studies has investigated the influence of the walking speed on the structure underlying stride-to-stride variability by using the UCM approach (Black et al., 2007) or other alternative ones (Dingwell & Cusumano, 2015; Dingwell et al., 2010; Verrel et al., 2010). The walking speed is indeed a key variable underlying the dynamic control of locomotion and can be even more significant when gait patterns are altered by neuromuscular adaptations due to ageing and/or neuro-musculo-skeletal diseases (Andriacchi, Ogle, & Galante, 1977; McGibbon, 2003; Monaco, Rinaldi, Macri, & Micera, 2009; Rinaldi & Monaco, 2013).

According to this evidence, the present study aimed at analysing the effects of the walking speed on the organization of stride-to-stride variability underlying the stabilisation of the centre of mass (CoM) position, by using the UCM approach. This study grounds on the evidence that the speed alters the biomechanical demand underlying the control of the CoM position during steady walking (Lee & Farley, 1998; Orendurff et al., 2004), and affects both energy consumption (Ortega & Farley, 2005) and dynamical stability (Dingwell & Marin, 2006). In this respect previous authors observed that subjects exhibit better local dynamic stability at slower speeds despite an increased variability (Dingwell & Marin, 2006). In addition, the walking speed can significantly affect the inter-joint coordination variability (Chiu & Chou, 2012; Jeng, Liao, Lai, & Hou, 1997), and the structure underlying gait cycle fluctuations (Jordan, Challis, & Newell, 2007; Jordan & Newell, 2008). Thus, the organization of stride-to-stride variability of joint angles, under the UCM framework, was expected to be affected by the walking speed, as well.

Here, we tested the hypothesis that the coordinative mechanism underlying joint angle variance during the stance phase is compatible with a kinematic synergy that stabilizes the position of the CoM. In addition, we tested the hypothesis that the speed affects the partitioning of DoFs-related variance onto and orthogonal to the UCM.

2. Materials and methods

Raw data used in this study were collected as part of an independent work (Monaco et al., 2009). Therefore, a brief summary of procedures and setup will be reported in the next sections.

2.1. Participants and experimental setup

Eight (five females and three males; 26.0 ± 2.0 years old; body mass 61.4 ± 8.6 kg; height 1.64 ± 0.16 m; leg length 0.83 ± 0.09 m) healthy young adults volunteered to participate in the experimental sessions after signing informed consent. Participants were asked to walk on a treadmill at controlled speeds set in accordance with the Froude (*Fr*) number:

$$v = \sqrt{Fr \cdot l \cdot g}$$

where v is the walking speed in m/s, l is the leg length, from the external surface of the greater trochanter to the lateral malleolus in m, and g is the gravitational acceleration (9.8 m/s^2). Five different values of Fr were used: $Fr_1 = 0.050$, $Fr_2 = 0.075$, $Fr_3 = 0.100$, $Fr_4 = 0.150$, $Fr_5 = 0.175$. For each subject, trials were performed in random order. All participants wore the same type of light comfortable walking shoes provided by the research team before the experimental sessions.

The 3D kinematics of 20 reflective markers, placed in accordance with the Davis protocol (Davis, 1997), was acquired by using a five camera ELITE$_{PLUS}$ System (BTS, Milano, Italy) at a sample frequency of 100 Hz, as describe elsewhere (Monaco et al., 2009). According to the calibration procedure, the root mean squared of the maximum measurement error was lower than 1 mm. For each trial, data acquisition started after 3 min of acclimatization period at final walking speed (i.e., Fr_1-Fr_5), and lasted 30 s. Between two consecutive trials, participants spent at least 3 min sitting on a chair to reduce their fatigue, in accordance with previous literature (Haddad, van Emmerik, Whittlesey, & Hamill, 2006). In addition, they were allowed to have a longer resting time if they felt tired (self-evaluation), albeit this condition never occurred.