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Analysis of gait within the uncontrolled manifold hypothesis: Stabilisation of the centre of mass during gait

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ABSTRACT

This study investigated the feasibility of the uncontrolled manifold approach (UCM) to analyse gait data variability in relation to the control of the centre of mass (COM) in adults with and without neuropathology.

The proposed method was applied to six able-bodied subjects to characterise mechanisms of normal postural control during stance phase. This approach was repeated on an early stroke patient, who attended the laboratory three times at three monthly intervals, to characterise the variability of COM movement during walking with and without an orthosis. Both able-bodied subjects and the stroke participant controlled COM movement during stance but utilized a different combination of lower limb joint kinematics to ensure that the COM trajectory was not compromised. Interestingly, the stroke subject, despite a higher variability in joint kinematics, was able to maintain a stable COM position throughout stance phase. The stabilisation of the COM decreased when the patient walked unaided without the prescribed orthosis but increased over the six months of study. The UCM analysis demonstrated how a stroke patient used a range of lower limb motion pattern to stabilise the COM trajectory. It is suggested that this analysis can be used to track changes in these movement patterns in response to rehabilitation. As such we propose that this approach could have clinical utility to evaluate and prescribe rehabilitation in stroke patients.

1. Introduction

Many stroke survivors present with an altered ability to walk. Compensatory actions and gait strategies are often adopted to achieve a safe walking activity. Motor control is a key issue for those people who have suffered from a stroke and for whom limited joint coordination impairs their mobility. An understanding of how the central nervous system (CNS) compensates to control motion following a stroke may inform subsequent therapy.

The theory of the uncontrolled manifold (UCM) has been recently introduced (Latash et al., 2007; Scholz and Schöner, 1999) to investigate how the CNS acts with respect to selected motor tasks by choosing combinations of different musculoskeletal elements that are involved in the performance of the task. That is to say the CNS may employ a variety of different approaches to achieve a task. Exploiting this approach it may be possible to predict which motor variables the CNS controls and what are the elements/degree of freedoms (DOFs) that it has to organise for that particular motor task to be performed. This theory can thus be seen as an analysis of the variability of a selected functional task in a multi-degree of freedom system. The variability can either be "good", if the task goal remains unaltered, or "bad", if deviations from it occur. The UCM itself is a subspace of all possible combinations of motor elements (elemental variables) that lead to a consistent value of a performance variable. For example all the different combinations of lower limb joint angles that together place the centre of mass (COM) in a certain position in 3D space define a UCM subspace. It is defined "uncontrolled" because the control of the variability within it is unnecessary as all the combinations (i.e., set of lower limb joint angles) within that subspace preserve the performance variable value (i.e., 3D position of the COM) (Scholz and Schöner, 1999). Thereby, the UCM approach can also be seen as a method to quantify synergies. In this context, a synergy refers to an organization of elemental variables that stabilises a performance variable (Latash and Anson, 2006). A practical example could be to use the UCM approach to understand

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how the CNS organises joint angles (elemental variables) to allow a smooth COM movement (performance variable) and thus produce safe locomotion. It is important to mention that variability across trials is partitioned into two components: one that lies within the UCM and one that is perpendicular to the UCM. These two variabilities, expressed as indexes of variance across repetitions of the same task, are used to verify the hypothesis about the aspects of movement that are controlled. If the variance within the UCM is bigger than the one perpendicular to it, the hypothesis about the stabilisation of the selected motor task is accepted.

This analysis can provide clinicians with a better understanding of motor coordination and its relationship to rehabilitation approaches providing an explanation as to how different dynamic resources can lead to a successful motor performance. Having information on the behaviour of the system will allow a more specific and individualised treatment to accelerate recovery as the target of intervention (musculoskeletal elements) can be identified. Which movement variations should be encouraged and which discouraged? An answer to this question will advance clinical practice and outcomes for stroke survivors.

The UCM analysis method has recently been used to verify the control of motor task predominately related to the upper extremity, sit-to-stand, standing and hopping performances of able-bodied and impaired subjects (Auyang et al., 2009; Domkin et al., 2002; Freitas et al., 2006; Hsu et al., 2007; Reisman and Scholz, 2003; Scholz et al., 2003; Scholz and Schöner, 1999; Yang et al., 2007; Yen and Chang, 2010). Less consideration has been given to gait and the relative motor redundancy it contains. Five papers were found that used the UCM (or covariation analysis similar to UCM) in the analysis of gait.

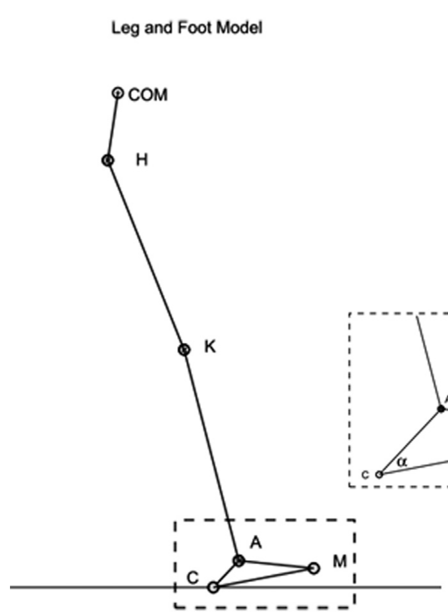

Fig. 1. Leg and foot stick model.

Only two (Black et al., 2007; Verrel et al., 2010) considered the COM trajectory as a performance variable but only at heel strike. Three studies (Krishnan et al., 2013; Robert et al., 2009; Rosenblatt et al., 2014) analysed the temporal evolution of the UCM approach through the gait cycle but none did this with the COM movement as the performance variable.

The exploratory study reported here, therefore, investigated the potential usefulness of UCM analysis of postural control during the stance phase of walking using the COM as the performance variable. It is known that stabilisation of the COM is key to walking ability so that was the rationale for selecting the COM trajectory as the relevant performance variable.

We hypothesised that different combinations of lower limb joint angles (kinematic synergy) can be used to control the COM movement while walking. The specific aims of this study were to (a) determine the feasibility of undertaking UCM analysis of stabilisation of the COM during the stance phase of gait, (b) to find out if such analysis could provide more knowledge of COM stabilisation than 'standard' biomechanical analysis techniques, (c) explore whether the UCM analysis could identify differences between a stroke survivor with walking difficulty and adults without a brain lesion and the stroke survivor walking with and without a custom-made ankle-foot orthosis (AFO).

2. Methods

2.1. Participants

Six adults (three female, three male; height: 168.9 ($\pm$ 10.5) cm, mass: 68.2 ($\pm$ 9.9) kg, age: 29.8 ($\pm$ 6.7) years) with no known neurological pathology participated in the study. In addition, one 81 years old male (80 kg, 180 cm) was recruited two months after experiencing a stroke. He presented a left side hemiplegia of the upper and lower body. He was prescribed a 5mm polypropylene AFO with carbon fibre reinforcement at the malleoli level. The AFO and shoes combination were tuned at 10° of forward inclination. All participants provided written consent for the study which was approved by the local ethics committee (West of Scotland REC3).

2.2. Equipment and experimental procedure

A twelve-camera motion capture system (Vicon, Oxford Metrics Ltd., UK) was used to collect experimental data at 100 Hz while participants walked at comfortable speed on a flat surface of 6 m in length. The gait analysis protocol developed within the Bioengineering Department at University of Strathclyde was followed for data collection and processing (Papi et al., 2011).

Ten walking trials were recorded with able-bodied subjects and the data derived from their left leg were used in the subsequent analysis. The stroke participant was assessed three times at three monthly time points. Six trials were collected during walking with and without AFO at each visit. Data from the hemiplegic leg were considered.

2.3. Data processing

Initial data processing was performed using Nexus software (Oxford Metrics Ltd., UK). Hip, knee and ankle sagittal angles, and the 3-D coordinates of anatomical landmarks were output. Data were time normalised to 100% of stance phase.

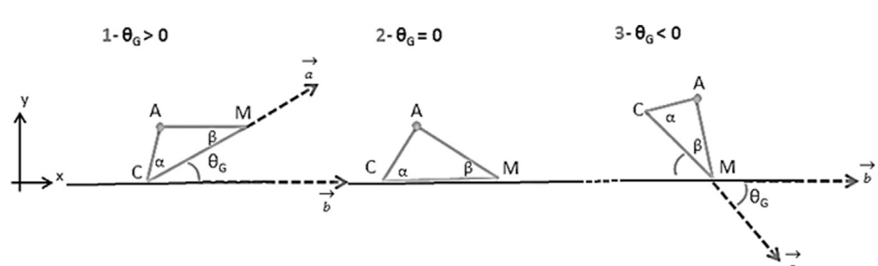

Fig. 2. Positions of the foot on the ground at the three identified key points depending on θ_G value.