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Effects of unilateral leg muscle fatigue on balance control in perturbed and unperturbed gait in healthy elderly

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ABSTRACT

This study assessed effects of unilateral leg muscle fatigue (ULMF) on balance control in gait during the stance and swing phases of the fatigued leg in healthy elderly, to test the assumption that leg muscle strength limits balance control during the stance-phase.

Ten subjects (aged 63.4, SD 5.5 years) walked on a treadmill in 4 conditions: unperturbed unfatigued, unperturbed fatigued, perturbed unfatigued, and perturbed fatigued. The perturbations were lateral trunk pulls just before contralateral heel contact. ULMF was evoked by unilateral squat exercise until task failure. Isometric knee extension strength was measured to verify the presence of muscle fatigue. Between-stride standard deviations and Lyapunov exponents of trunk kinematics were used as indicators of balance control. Required perturbation force and the deviation of trunk kinematics from unperturbed gait were used to assess perturbation responses.

Knee extension strength decreased considerably (17.3% SD 8.6%) as a result ULMF. ULMF did not affect steady-state gait balance. Less force was required to perturb subjects when the fatigued leg was in the stance-phase compared to the swing-phase. Subjects showed a faster return to the unperturbed gait pattern in the fatigued than in the unfatigued condition, after perturbations in swing and stance of the fatigued leg.

The results of this study are not in line with the hypothesized effects of leg muscle fatigue on balance in gait. The healthy elderly subjects were able to cope with substantial ULMF during steady-state gait and demonstrated faster balance recovery after laterally directed mechanical perturbations in the fatigued than in the unfatigued condition.

1. Introduction

Most falls in the elderly occur during gait and many of these are not preceded by an external perturbation, such as a trip or slip [1]. One of the known risk factors for falls is low muscle strength in the lower extremities [2], but it is not well understood whether and how muscle strength would be a limiting factor in the control of steady-state gait. Observational studies have shown that leg muscle strength is associated with indicators of balance control in steady-state gait in elderly subjects [3–5], which in turn are known to be associated with fall risk [4,6]. While this supports a role of muscle strength in control of balance during steady-state gait, it does not provide insight in the underlying mechanism.

Balance control during gait can be conceptualized as control of the centre of pressure (CoP) of the ground reaction force relative to the extrapolated centre of mass of the body (a function of centre of mass position and velocity [7]). Foot placement is the main determinant of the CoP position [7] and it is predominantly

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controlled by modifying swing leg dynamics [8], which requires only low actuation moments. However, joint moments in the stance leg can, within the limitations determined by foot placement, adjust the CoP under the stance leg, to correct for 'errors' in foot placement [7]. After gait perturbations, such as trips and slips, this involves fast development of high joint moments in the stance leg to brake the movement in the direction of the fall [9,10]. Consequently, force producing capacity of muscles is a limiting factor in balance recovery after such perturbations [11,12], but it is conceivable that also stance leg balance corrections after milder perturbations could be limited by muscle strength.

Muscle fatigue, which is defined as a decrease in force producing capacity of muscles [13], would offer an experimental window onto the role of leg muscle capacity in balance control. However, limited research has been published on the effects of muscle fatigue on steady-state gait, with most studies showing only small effects [for review, see 14]. Regarding parameters that have been associated with fall risk and balance control, one study reported increased gait variability with leg muscle fatigue, indicative of decreased balance control [15], while another study reported no changes in gait variability [16] and none differentiated between the role of the stance and swing leg in gait. Inducing unilateral leg muscle fatigue would allow such differentiation.

Lyapunov exponents (LyE) and between-stride standard deviations of trunk kinematics during steady-state gait have been shown to be associated with fall risk [6]. Mechanistically these associations can be understood, because trunk movement in space integrates the effects of control over the lower extremity joints and is crucial for balance, because of the high mass and cranial location of the trunk. A recent review [17] concluded that substantial evidence supports the use of these parameters as indicators of fall risk. However, they reflect responses to very small, self-induced perturbations and it cannot be ascertained that this also reflects how well larger perturbations are resisted. Therefore, responses to external, larger perturbations might provide additional information.

To determine whether a decrease in muscle force producing capacity by unilateral leg muscle fatigue (ULMF) affects balance control in gait of healthy elderly, we induced fatigue by repetitive single-leg squats. The effects of fatigue on LyE and between-stride standard deviations of trunk kinematics during the stance-phase, swing-phase, and the complete stride were studied. In addition, the effects of moderate mechanical laterally directed perturbations during the stance-phase and the swing-phase of the (to be) fatigued leg were studied. We hypothesized that ULMF negatively affects balance control and perturbation responses when the fatigued leg is the stance leg.

2. Methods

2.1. Subjects

The subjects (4 males, 6 females) were 63.4 (SD 5.5) years, 1.72 (SD 0.08) m, and 73 (SD 12) kg. Subjects were able to walk on a treadmill without walking aids and had no neurological or musculoskeletal impairments that could interfere with the study protocol. All subjects were informed about the aims and procedure of the study and signed informed consent. The study protocol was in agreement with the declaration of Helsinki and approved by the local ethical committee.

2.2. Design

Subjects were measured in fatigued and unfatigued conditions while they walked on a treadmill. In some of the trials the subjects were perturbed in lateral direction. To test the effect of ULMF on balance, two conditions were compared, i.e., with and without ULMF. To discriminate the effects of fatigue of the stance-leg and the swing-leg on balance control after perturbations, fatigue effects were compared between phases where the fatigued leg was in the stance-phase and in the swing-phase.

2.3. Procedure and materials

All perturbed and unperturbed walking trials were performed at a fixed, low gait speed of 0.83 m s^{-1}, to avoid speed effects on the dependent variables and to avoid fatigue from limiting gait speed [18]. Just before heel contact (Fig. 1), laterally directed pulls were applied to the trunk on the contralateral side (timed using real-time trunk kinematics) by a custom made device using a system of ropes, pulleys, clamps, and pneumatic pistons [19]. For clarity, we will describe perturbations as occurring during the stance-phase or swing-phase of the (to be) fatigued leg. The piston perturbed the subjects over a fixed distance of approximately 0.08 m. The forces exerted by the pistons were recorded.

Upon arrival in the laboratory, subjects were familiarized with unperturbed and perturbed treadmill walking. Subjects were asked which leg they preferred to use in the fatigue protocol. To verify the presence of fatigue, the maximal voluntary isometric knee extension moment at a knee angle of 120° (M_{max}) of the preferred leg was determined with a custom-made dynamometer. The highest value of three attempts (separated by 1 min of rest) was used as M_{max}. Subjects were outfitted with LED clusters on the trunk and feet to measure kinematics using an optoelectronic measurement system (Optotrak, Northern Digital Inc., Waterloo, ON, Canada). First, subjects performed an unperturbed walking trial of 300 s followed by a perturbed trial of 900 s, both trials without ULMF. Subsequently, subjects performed 3 unperturbed fatigued and 9 perturbed fatigued walking trials of 100 s in systematically varied order. The total time of perturbed and unperturbed walking in both conditions was the same. The post-fatigue trials were of shorter duration to make sure that recovery was minimal, by allowing repetitions of the fatiguing exercise between episodes of walking. In perturbed trials, subjects were, on average, perturbed every 30 s and were always informed when a perturbed trial started, but they did not have information on the timing and direction of the perturbations. Each of the fatigued walking trials was preceded by unilateral knee bending in a standing position (to a knee angle of approximately 115°) at a fixed frequency (0.25 Hz, duty cycle was 75%) until subjects were unable to reach the desired knee angle or maintain the exercise frequency. After the final walking trial, subjects performed one more unilateral knee bending exercise followed by post fatigue M_{max} assessment, the highest value of three attempts (separated by 30 s of rest) was used.

2.4. Data processing

Heel strikes were estimated as the local minima of vertical positions of the feet LED clusters. Linear and angular velocities (3D) of the trunk were calculated from the marker data.

For unperturbed gait, 5 gait measures were calculated: (1) Lyapunov exponents of medio-lateral trunk velocity (LyE_{ML}), variability of medio-lateral trunk velocity during the (2) complete stride cycle (VAR_{ML}), (3) stance-phase of the (to be) fatigued leg ($VAR_{ML\text{-}ST}$), (4) swing-phase of the (to be) fatigued leg ($VAR_{ML\text{-}SW}$). All unfatigued unperturbed gait measures were calculated from the three final non-overlapping periods of 50 strides from the unfatigued and unperturbed trial. All fatigued unperturbed gait measures were calculated from the average of 50 strides periods of the three fatigued trials.

At the start of LyE_{ML} calculation, all time-series of medio-lateral trunk velocities of 50 strides were resampled to 5000 data points [20,21]. LyE calculation consists of several steps. First, the