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published in
Gait and Posture
2014

DOI (link to publisher)
10.1016/j.gaitpost.2014.03.194


Volume 40, Issue 1, May 2014 ISSN 0966-6362
ELSEVIER
GAIT
&
POSTURE

Gait & Posture 40 (2014) 215–219

Contents lists available at ScienceDirect

Gait & Posture

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

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

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ARTICLE INFO

Article history:
Received 27 June 2013
Received in revised form 24 March 2014
Accepted 31 March 2014

Keywords:
Local dynamic stability
Exercise
Walking

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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http://dx.doi.org/10.1016/j.gaitpost.2014.03.194
0966-6362/

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

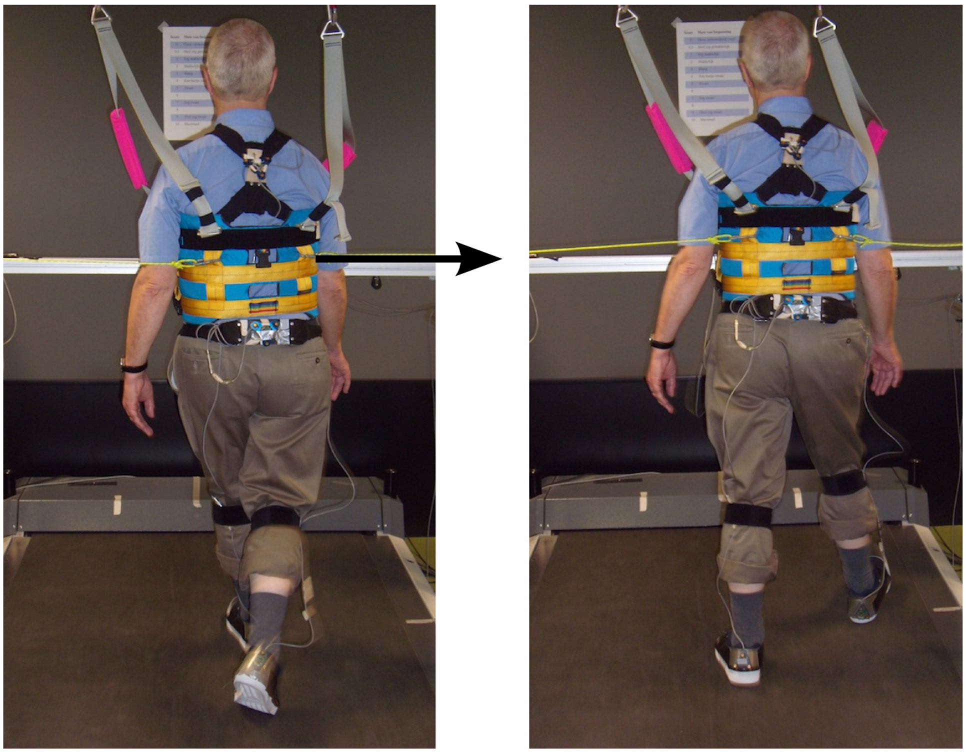

Fig. 1. *Left*: subject at the moment of perturbation during left-sided stance-phase, the arrow indicates the direction of the perturbation. *Right*: subject at the moment of first heel contact after perturbation during the stance-phase of the left leg.

parameters for state-space reconstruction (time delay and number of embedded dimensions) were estimated. The average mutual information procedure suggested a time-delay of 10 samples and the global false nearest neighbour analysis suggested that 5 embedded dimensions were appropriate. LyE was calculated according to Rosenstein's algorithm [22]. In short: for each time point in state-space, a nearest neighbour was found and tracked for several strides, resulting in time–distance curves. The divergence curve was calculated as the mean of the natural log of these time–distance curves. LyE was calculated as the slope of the linear fit through the first 50 samples (approximately the time needed for 1 step), which corresponds to the initial period of rapid exponential divergence. The LyE reflects the rate of kinematic divergence of the system after very small perturbations, hence a higher LyE indicates lower local stability.

For the gait variability measures of trunk movements during unperturbed gait, the medio-lateral trunk velocity time-series of the 50 strides were time normalized to 101 samples per stride (0–100%). Variability of medio-lateral trunk velocity was calculated over the entire stride cycle (VAR_{ML}), over the stance-phase of the (to be) fatigued leg ($VAR_{ML\text{-}ST}$, 11–50% of the stride cycle) and over the swing-phase of the (to be) fatigued leg ($VAR_{ML\text{-}SW}$, 61–100% of the stride cycle). These variability measures were calculated as the mean of the standard deviations of medio-lateral trunk velocities at each increment of normalized time of the included part of the stride cycle.

The processing of perturbation data has been described previously [19]. Perturbation onset was determined as the first sample when perturbation force was >30 N. Perturbation responses were assessed by the differences in trunk movements between perturbed gait and the reference stride pattern (determined from the average stride in unperturbed gait). The trunk movements were represented as time-normalized (0–100%) trunk linear and angular velocity time-series combined in a 6D state-space. The Euclidean norm was calculated over the differences in 6D state-space between the perturbed trial and the reference stride pattern. The reference stride patterns for the unfatigued and fatigued perturbations were calculated from the unperturbed unfatigued and fatigued trials, respectively. The outcome measures of perturbed gait were: (1) the maximal deviation from the reference stride pattern, to confirm that the initial perturbation distance was comparable between conditions; (2) the time to maximal deviation from the reference stride pattern; (3) the maximal perturbation force, as an indicator of perturbation resistance; (4) the deviation from reference stride patterns at the first heel strike after perturbations, as a measure of recovery; and (5) the timing of the first heel contact after the perturbations.

2.5. Statistics

All variables that were pairwise compared (see below) were checked for normality by inspecting QQ-plots, Shapiro–Wilk tests, and z-values for skewness and kurtosis of the differences. If necessary a correction for the violation of equality of variances was applied. Repeated measures ANOVAs were used for all other variables (see below), the normality of the residuals were explored as described for the pairwise comparisons. No relevant deviations from normality were present.

Effects of the fatigue protocol on force producing capacity were assessed using a t-test on the difference between unfatigued and fatigued M_{max}. To answer the first research question, whether ULMF affects balance in unperturbed gait (LyE_{ML}, VAR_{ML}, $VAR_{ML\text{-}ST}$, $VAR_{ML\text{-}SW}$), paired t-tests were used. To test the effects of ULMF on perturbation responses, repeated measures ANOVAs were used. The main effects of condition (unfatigued/fatigued), gait-phase of the (to be) fatigued leg during the perturbation (stance-phase/swing-phase), and the interaction between condition and gait-phase were assessed. In case of statistically significant interactions, fatigue effects were compared between gait phases using paired t-tests.

Table 1
Results (p-values) from repeated measures ANOVAs on perturbation reaction measures with condition (unfatigued/fatigued) and gait-phase (stance/swing) as independent variables.

	Condition	Gait-phase	Condition * gait-phase
D_{max}	0.181	0.281	0.476
T_{Dmax}	0.841	0.635	0.239
$F_{perturbation}$	0.102	0.553	0.020
D_{hc}	0.030	0.579	0.773
T_{hc}	0.781	0.399	0.128

D_{max}, maximal deviation from the reference stride pattern; T_{Dmax}, time to maximal deviation from the reference stride pattern; $F_{perturbation}$, maximal perturbation force; D_{hc}, deviation from reference stride patterns at the first heel strike after perturbation; T_{hc}, timing of the first heel contact after the perturbation.

For all statistical tests SPSS Statistics 20 was used. p-Values < 0.05 were considered statistically significant.

3. Results

Subjects were substantially fatigued as indicated by an average decrease of M_{max} of 17.2% (SD 8.6%, $p < 0.001$).

In unperturbed gait, there were no effects of fatigue on LyE_{ML} ($p = 0.411$), VAR_{ML} ($p = 0.973$), $VAR_{ML\text{-}ST}$ ($p = 0.643$) and $VAR_{ML\text{-}SW}$ ($p = 0.269$).

Table 1 displays the results of repeated measures ANOVAs on perturbation responses. There were no main effects of condition and gait-phase on maximal perturbation force. There was, however, an interaction ($p = 0.020$). As depicted in Fig. 2a, less force (4%) was required to perturb subjects in the fatigued condition during the stance-phase of the fatigued leg ($p = 0.005$), while fatigue had no effect on required perturbation force during the swing-phase of the fatigued leg ($p = 0.850$). As expected, given the position control of the perturbation, no effects were found on the maximal initial deviation from the reference stride pattern and the time to the maximal initial deviation from the reference stride pattern.

The deviation from unperturbed walking at first heel contact after the perturbation was smaller in the fatigued than in the unfatigued conditions ($p = 0.030$, Fig. 2b), but there was no effect of gait-phase, nor an interaction with gait-phase. The timing of the first heel contact after the initiation of the perturbation was not affected by fatigue or gait-phase, but tended to be delayed (see Fig. 2c) after the perturbations during the stance-phase of the fatigued leg ($p = 0.087$, with $p = 0.128$ for the interaction between condition and gait-phase, see Table 1).

So while the initial resistance against the perturbations was reduced with fatigue, when standing on the fatigued leg only, recovery one step after the perturbation was more complete in the fatigued state. There was a trend towards a somewhat slower recovery step, again only when standing on the fatigued leg.

4. Discussion

We hypothesized that the effects of changes in force producing capacity of leg muscles by ULMF would result in decreased balance control during unperturbed and perturbed gait. The results of the present study, however, did not support this. This included a measure of the variability of trunk movements during the stance-phase of the fatigued leg ($VAR_{ML\text{-}ST}$), which, potentially, is the most sensitive steady-state gait measure to be affected by ULMF.

The present results add to earlier studies that reported no or minor effects of leg muscle fatigue on balance during steady-state gait, or even changes that would appear to enhance balance [for a recent review and studies, see 23,24]. The present fatigue protocol was different from previously used protocols in that unilateral leg muscle fatigue was induced, whereas other induced bilateral fatigue. On the other hand, most studies also used repetitive voluntary leg movements, such as isokinetic knee extension [16] and sit-to stand transfers [15,24] with pace controlled by metronome. In all of these protocols, the knee extensor muscles are probably most fatigued. It should be noted that the intention here was not to obtain an ecologically valid fatigue stimulus, as the study aimed to reveal the mechanism of how muscle force producing capacity might affect balance control during gait rather than to describe potential effects of fatigue in real life. Our fatigue protocol appeared to be effective in reducing force producing capacity, as evidenced by the decrease in maximal knee extension moment.

In contrast with the present study, Helbostad et al. [15] did report increased kinematic variability of steady-state gait with leg muscles fatigue, indicating that fatigue negatively affected balance control. Subjects in their study were older (79 versus 63 years) and likely had a lower force producing capacity initially and after fatigue, which consequently may have been more limiting. Barbieri et al. [23] showed in increase in gait variability with leg muscle fatigue in young adults. However, they studied the approach phase of stepping down a curb during which foot placement in relation to the curb appears to be strictly controlled.

In support of our hypothesis, ULMF did result in a decreased maximal perturbation force when perturbations occurred during the stance-phase of the fatigued leg, but not during its swing-phase. Since the size of the perturbations in terms of displacement

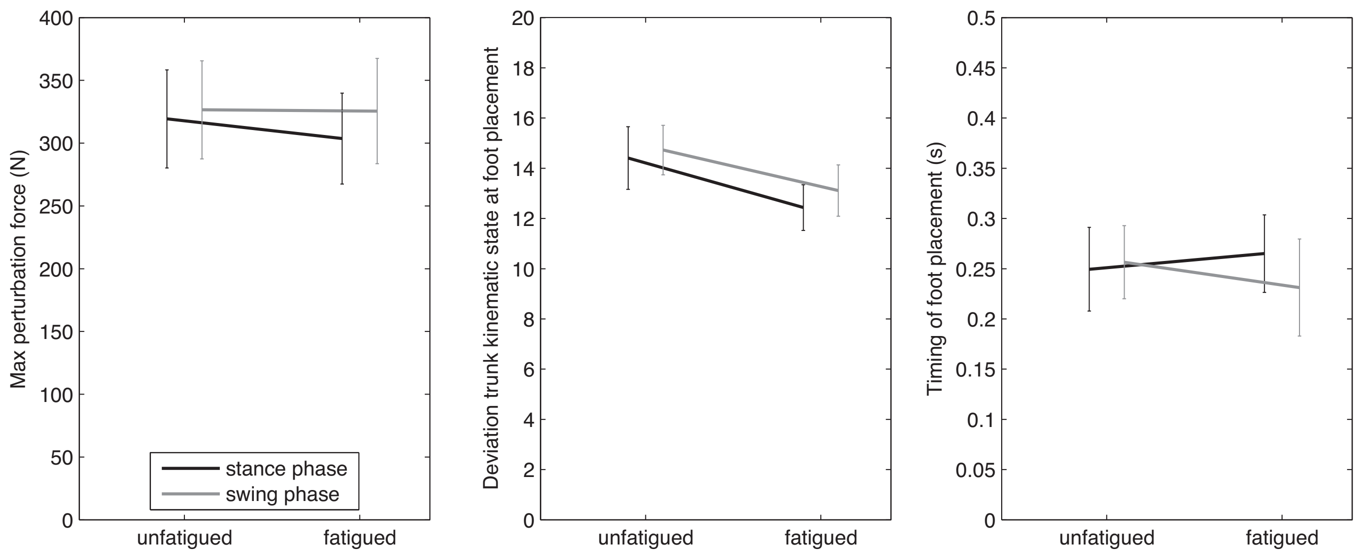

Fig. 2. The mean perturbation responses after perturbation in the stance and swing phases of the (to be) fatigued leg in the conditions before and after the fatigue protocol. The left panel shows the maximum perturbation force; the middle panel shows the deviation of the trunk kinematic state from unperturbed gait at the first heel contact after the perturbation; the right panel shows the time of the first heel contact after the perturbation relative to the onset of the perturbation. Error bars indicate the standard error of the mean.

and rate of displacement was controlled, the maximal perturbation force is a measure of how well subjects resisted the perturbations. Thus, subjects had lower initial resistance against perturbations when standing on the fatigued leg. At the first heel contact after the perturbation, subjects had returned to the reference gait pattern more when fatigued compared to unfatigued, while the timing of the first heel contact after perturbations was not significantly affected by fatigue. This implies that fatigue enhanced the rate of recovery after perturbations. Possibly, the fatiguing exercise resulted in increased arousal, due to which subjects responded more quickly to the perturbations [25]. It is unlikely that the enhanced rate of recovery after perturbations was the result of learning, as subjects had experienced many more identical perturbations on a previous day as part of a larger research protocol. The timing of the first heel contact after perturbations did tend to be delayed after the perturbations during the stance-phase of the fatigued leg. This suggests that subjects needed more time to reach the same deviation from the reference stride at the first heel contact after perturbations during the stance-phase of the fatigued leg, compared with perturbations during the swing-phase of the fatigued leg and implies a slightly less enhanced rate of recovery.

Muscle fatigue does not only reduce force producing capacity, but has also other local effects (reduced proprioception, discomfort) [26]. Furthermore, while ULMF was used to separate the effects of fatigue of the stance leg with fatigue of the swing leg, fatigue effects are not only local but also systemic (psychological, increased heart rate and breathing frequency, increased body temperature) [26]. Therefore, the results in this study are not solely attributable to the effects of reduced leg muscle strength, but are also be affected by other local and systemic effects of exercise.

The results of the present and previous studies suggest that leg muscle fatigue does not challenge balance control of gait to the limits of most subject's ability. This also suggests that lack of muscle strength is not a limiting factor for control of balance in gait when no major perturbations occur. Possibly, adaptive strategies, such as increasing step width [15,24] offset the limitations caused by leg muscle fatigue or weakness. These strategies may vary between subjects, limiting the chances of finding significant results. The more rapid recovery after perturbations in the fatigued state found in the present study suggests that increased arousal or increased attention towards balance may contribute to limiting the effects of fatigue on balance. The effect of fatigue may have been limited by the use of treadmill walking in the present study, as this creates a predictable environment, known to reduce between-stride standard deviations and LyE of trunk kinematics compared to overground walking [27]. In addition, subjects walked at a fixed, imposed and rather low gait speed. Also it should be noted that the LyE of trunk movement reflects local dynamic stability averaged over the entire gait pattern, which may have limited sensitivity to fatigue which was induced unilaterally and which may moreover be phase-dependent. Finally, it should be kept in mind, that this and previous studies mainly focussed on fatigue of the knee extensor muscles. It could be that fatigue of other muscles imposes more severe limitations on balance control in gait. A simulation study suggests that the force producing capacity of especially the hip abductor and ankle extensor muscle may be more limiting in gait than capacity of the knee extensors [28].

In conclusion, while the results confirmed that the force producing capacity of leg muscles may limit the initial resistance against mild gait perturbations, overall leg muscle fatigue did not decrease balance in steady-state and mildly perturbed gait. Evidently, the healthy elderly subjects were able to cope with substantial unilateral leg muscle fatigue during steady-state gait and even demonstrated an enhanced rate of recovery when confronted with laterally directed mechanical perturbations.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

References

[1] Robinovitch SN, Feldman F, Yang Y, Schonnop R, Leung PM, Sarraf T, et al. Video capture of the circumstances of falls in elderly people residing in long-term care: an observational study. Lancet 2013;381:47–54.

[2] Rubenstein LZ. Falls in older people: epidemiology, risk factors and strategies for prevention. Age Ageing 2006;35(Suppl. 2):ii37–41.

[3] Callisaya ML, Blizzard L, McGinley JL, Schmidt MD, Srikanth VK. Sensorimotor factors affecting gait variability in older people – a population-based study. J Gerontol A Biol Sci Med Sci 2010;65:386–92.

[4] Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: a 1-year prospective study. Arch Phys Med Rehabil 2001;82:1050–6.

[5] Kang HG, Dingwell JB. Effects of walking speed, strength and range of motion on gait stability in healthy older adults. J Biomech 2008;41:2899–905.

[6] Toebes MJ, Hoozemans MJ, Furrer R, Dekker J, van Dieen JH. Local dynamic stability and variability of gait are associated with fall history in elderly subjects. Gait Posture 2012;36:527–31.

[7] Hof AL, van Bockel RM, Schoppen T, Postema K. Control of lateral balance in walking – experimental findings in normal subjects and above-knee amputees. Gait Posture 2007;25:250–8.

[8] van Dieen JH, Spanjaard M, Konemann R, Bron L, Pijnappels M. Balance control in stepping down expected and unexpected level changes. J Biomech 2007;40:3641–9.

[9] Pijnappels M, Bobbert MF, van Dieen JH. Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. Gait Posture 2005;21:388–94.

[10] Redfern MS, Cham R, Gielo-Perczak K, Gronqvist R, Hirvonen M, Lanshammar H, et al. Biomechanics of slips. Appl Ergon 2001;44:1138–66.

[11] Pavol MJ, Owings TM, Foley KT, Grabiner MD. Influence of lower extremity strength of healthy older adults on the outcome of an induced trip. J Am Geriatr Soc 2002;50:256–62.

[12] Pijnappels M, van der Burg PJ, Reeves ND, van Dieen JH. Identification of elderly fallers by muscle strength measures. Eur J Appl Physiol 2008;102:585–92.

[13] Bigland-Ritchie B, Woods JJ. Changes in muscle contractile properties and neural control during human muscular fatigue. Muscle Nerve 1984;7:691–9.

[14] Barbieri F, Santos PCR, Lirani-Silva E, Vitorio R, Gobbi LT, van Dieën JH. Systematic review of the effects of fatigue on spatiotemporal gait parameters. J Back Musculoskelet Rehabil 2013;26:125–31.

[15] Helbostad JL, Leirfall S, Moe-Nilssen R, Sletvold O. Physical fatigue affects gait characteristics in older persons. J Gerontol A Biol Sci Med Sci 2007;62:1010–5.

[16] Granacher U, Wolf I, Wehrle A, Bridenbaugh S, Kressig RW. Effects of muscle fatigue on gait characteristics under single and dual-task conditions in young and older adults. J Neuroeng Rehabil 2010;7:56.

[17] Bruijn SM, Meijer OG, Beek PJ, van Dieen JH. Assessing the stability of human locomotion: a review of current measures. J R Soc Interface 2013;10:20120999.

[18] Bruijn SM, van Dieen JH, Meijer OG, Beek PJ. Is slow walking more stable. J Biomech 2009;42:1506–12.

[19] Bruijn SM, Meijer OG, Beek PJ, van Dieen JH. The effects of arm swing on human gait stability. J Exp Biol 2010;213:3945–52.

[20] Bruijn SM, van Dieen JH, Meijer OG, Beek PJ. Statistical precision and sensitivity of measures of dynamic gait stability. J Neurosci Methods 2009;178:327–33.

[21] England SA, Granata KP. The influence of gait speed on local dynamic stability of walking. Gait Posture 2007;25:172–8.

[22] Rosenstein MT, Collins JJ, De Luca CJ. A practical method for calculating largest Lyapunov exponent from small data sets. Physica D 1993;65:117–34.

[23] Barbieri F, Lee YJ, Gobbi LT, Pijnappels M, van Dieën JH. The effect of muscle fatigue on the last stride before stepping down a curb. Gait Posture 2013;37:542–6.

[24] Barbieri FA, Dos Santos PC, Vitorio R, van Dieen JH, Gobbi LT. Effect of muscle fatigue and physical activity level in motor control of the gait of young adults. Gait Posture 2013;38:702–7.

[25] Lambourne K, Tomporowski P. The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. Brain Res 2010;1341:12–24.

[26] Paillard T. Effects of general and local fatigue on postural control: a review. Neurosci Biobehav Rev 2012;36:162–76.

[27] Dingwell JB, Cusumano JP, Sternad D, Cavanagh PR. Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. J Biomech Eng 2001;123:27–32.

[28] van der Krogt MM, Delp SL, Schwartz MH. How robust is human gait to muscle weakness. Gait Posture 2012;36:113–9.