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The effect of muscle fatigue on the last stride before stepping down a curb

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The stride before landing may be important during stepping down. The aim of this study was to analyze variability of the kinematics and muscle activity in the final stride before stepping down a curb, with and without ankle and knee muscle fatigue. Ten young participants walked at self-selected speed and stepped down a height difference (10-cm) in ongoing gait. Five trials were performed before and after a muscle fatigue protocol (one day: ankle muscle fatigue, another day: knee muscle fatigue). The analysis focused on the trailing leg during the last but one and the last step on the higher level. Kinematics and muscle activity were recorded. Fatigue increased variability of foot-step horizontal distance in the last step on the higher level of the trailing limb, as well as in the first steps on the lower level for both limbs. This appeared due to an increase in the range of motion of the knee joint after both fatigue protocols. Participants additionally showed an increased ankle and hip ROM and decreased knee ROM. Our results suggest a loss of control under fatigue reflected in a higher variability of trailing and leading limb-step horizontal distances, with compensatory changes to limit fatigue effects, such as a redistribution of movement over joints.

1. Introduction

Problems with transitions between levels in gait, such as when stepping from a curb, are common causes of falls [1–3]. In level walking, muscle fatigue destabilizes motor control and consequently increases variability and decreases the stability [4] of gait. Such problems might have even more impact in negotiating level changes. In stepping down, with quadriceps or triceps surae muscle fatigue, subjects appeared to use compensatory strategies to redistribute work performed to unfatigued muscles and to enhance balance control [5]. Leg muscle fatigue did not cause changes in stride length and foot placement before stepping over an obstacle in young adults [6]. However, it is unknown whether leg muscle fatigue affects the last stride (approach phase) before stepping down.

The approach to a curb may be of crucial importance in preventing falls, since the stepping strategy appears to be planned based on visual information obtained during the penultimate step [7]. Moreover, adequate foot placement in the last step before the curb may be fundamental, since errors may result in a misstep on the curb [8,9]. Step lengths of the last steps of the approach phase appear to be modulated to achieve optimal foot placement, to allow the last step on the high level, and to land close to the curb [9–11]. Finally, foot placement and the stance phase of the trailing leg on the higher level co-determine foot placement of the leading leg on the lower level, which is crucial for reducing the angular momentum gained in stepping down [12].

Therefore, the aim of the study was to analyze foot placement relative to the curb in the final stride before stepping down, with and without ankle and knee muscle fatigue. We additionally explored fatigue effects on kinematics and muscle activity (EMG) to reveal potential causes of changes in foot placement and potential compensatory adjustments. We expected an increased variability of foot placement of the trailing limb on the higher level and of the leading limb on the lower level.

2. Materials and methods

After signing informed consent, 10 healthy volunteers (age: 27.60 ± 2.79 years; weight: 69.21 ± 10.76 kg; height: 1.80 ± 0.08 m) participated in the present study that had been approved by the local ethics committee.

For each participant, data collection was performed on two days with a one-week interval. The participants performed stepping down tasks before and after one of two fatigue protocols: (a) knee muscles: repeated sit-to-stand movements from a chair without arm supports, with arms across the chest, at a frequency of 0.5 Hz controlled by a metronome [5,6]; (b) ankle muscles: repeated standing calf raise exercise [5] at the same frequency. In the latter exercise, participants were allowed

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to touch the back of chair with their hands to ensure balance. The order of the fatigue protocols was balanced over subjects, to avoid order effects. The fatigue protocol was stopped when the participant indicated that he or she was unable to continue, when the movement frequency fell below and remained below 0.5 Hz after encouragement, or after 30 min. The endurance time during the fatigue protocol was recorded.

Before and after the fatigue protocol, the participants performed five trials of stepping down a 10-cm elevation. Subjects walked at self-selected speed over a raised platform over a length of 10 m and halfway they stepped down onto the lower part of the platform. Starting position was adjusted to make sure that participants stepped down with the right leg. The participants wore their own shoes. No rest period was allowed between trials and testing was started as soon as possible after the fatigue protocol and the time between the fatigue protocol and the gait trials (<3 min) was expected not to allow full recovery [13].

An optical system with 3 × 3 cameras (Optotrak Northern Digital Inc., Waterloo, Ontario, Canada) was used to record kinematics at a rate of 50 Hz. Neoprene bands, with clusters of three infrared Light Emitting Diodes were attached to the participant's body, at the pelvis (level of the posterior superior iliac spines), and at the thigh, shank and heels of the right and left leg. Cluster positions were related to anatomical landmarks based on separate pointer measurements [14]. The accuracy of the Optotrak system was within 0.3 mm. To enhance reliability, camera positions were maintained in throughout data collection, markers were placed by the same researcher in all sessions and remained in place during a session.

Kinematic data were filtered with a bidirectional second order low-pass Butterworth filter with a cut-off frequency of 20 Hz. Step-foot horizontal distances of the trailing and leading feet to the level change were determined in steps $N-2$, $N-1$, N and $N+1$ (Fig. 1). The horizontal distances were calculated as the distance of the calcaneus landmark to the step. The step length, step width, step duration and step velocity were analyzed for each step. The coordinates of the Optotrak markers defined seven body segments: two feet, two lower legs, two upper legs, and a pelvis. Knee, ankle and hip joint angles of the both legs leg were estimated using a 3D linked-segment model [15] and the ranges of angular motion (ROM) of the left hip, knee and ankle joints in the sagittal plane were calculated.

EMG was recorded, synchronized with kinematic data, using disposable Ag/AgCl surface-electrodes (BlueSensor; lead-off area 1.0 cm^2, inter-electrode distance 2.0 cm). After abrasion and cleaning with alcohol, electrodes were attached over the left rectus femoris, biceps femoris, tibialis anterior and gastrocnemius lateralis in the left limb. Electrodes and EMG data collection followed to the SENIAM guidelines [16]. In addition, the same researcher positioned the electrodes before all measurements. EMG signals were band-pass filtered (10-500 Hz), amplified (20 times, Porti-17TM, TMS, Enschede, The Netherlands; input impedance $>10^{12}$ Ω, common mode rejection ratio >90 dB), and stored on disc (22 bits AD converted, resolution 71.5 nV/bit, sample rate 1000 samples/s). Off-line, EMG signals were band-pass filtered between 20 and 300 Hz and rectified and low-pass filtered at 15 Hz. The average amplitudes in each complete step were determined and values were normalized to peak values of the corresponding signals in the unfatigued trials of each participant. The between trial variability of kinematic, ROM and muscle activity was expressed as the standard deviation.

Before and after the fatigue protocol, muscle strength of the quadriceps and triceps surae muscles was measured, according to the muscle that we intended to fatigue, using custom-made dynamometers [17]. Subjects were firmly secured with straps fastening hips and shoulders. For knee extension, the participants were seated in a backward inclined chair, with a 90° hip angle (180° is full extension) and 120° knee angle (180° is full extension) and the lower leg tightly strapped to a strain gauge transducer (KAP, E/200 Hz, Bienfait BV Haarlem, The Netherlands) placed ~25 cm distal from the knee joint, which measured the force exerted at the shin. For ankle extension, the participants were seated in an upright chair with their knee 90° flexed and their ankle in 20° dorsiflexion and, the fore-foot positioned on a 10 cm × 10 cm force transducer (AMTI M3-1000, Watertown, USA) that was mounted in the push-off platform. Forces were sampled at 1 kHz. Two attempts of maximal voluntary isometric contractions (MVIC) were made with the left limb before and after the stepping down trial. The means of the two attempts were calculated for each participant.

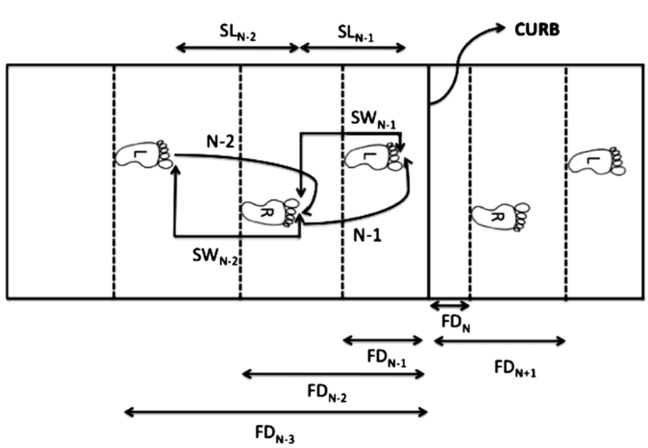

Fig. 1. A top view of steps analyzed in the study. Dashed line represents the foot placement. SL – step length; SW – step width; FD – foot distance; L – left leg (trailing foot); R – right leg (leading foot).

The dependent variables of interest were statistically analyzed with SPSS 18.0 for Windows® ($\alpha < 0.05$). Normal distribution of the data was verified by the Shapiro–Wilk test. The endurance times in the two fatigue protocols, and the MVIC values before and after fatigue were compared through Student *t*-tests for paired samples. The other dependent variables and their standard deviation were compared through one way ANOVAs for repeated measures with fatigue as the independent factor, with three levels: before fatigue (data averaged over two sessions), ankle muscle fatigue, and knee muscle fatigue. Tukey Post hoc tests were used to find the differences among levels.

3. Results

The participants performed the ankle fatigue protocol longer (19.6 ± 9.7 min) than the knee fatigue protocol (6.7 ± 7.2 min; $t_9 = 4.27$, $p < 0.002$). After the fatigue protocol, the maximal voluntary isometric contraction had decreased by on average 15% for the ankle (pre-fatigue: 128.59 ± 45.27 N; ankle muscle fatigue: 109.70 ± 28.17 N; $t_9 = 2.34$, $p < 0.04$) and by on average 4% for the knee (pre-fatigue: 242.94 ± 9.43 N; knee muscle fatigue: 233.20 ± 7.49 N; $t_9 = 5.27$, $p < 0.001$). Before fatigue, the trials before ankle and knee muscle fatigue were similar and not significantly different for all gait variables.

For the foot-distance (Fig. 2), the results of the ANOVA tests may be indicative of an effect of fatigue on the trailing (left) foot-step distance in $N-1$ ($F_{2,98} = 7.52$; $p < 0.002$) and $N+1$ ($F_{2,98} = 5.75$; $p < 0.005$), without significant differences for the leading foot-step distance. The foot-distance was increased in step $N-1$ ($p < 0.02$), and decreased in $N+1$ ($p < 0.02$) with ankle muscle fatigue. With knee muscle fatigue, there was no change in the foot-distance. Both ankle and knee muscle fatigue caused increased variability of foot-distance in step $N-1$ and $N+1$ ($F_{2,18} = 4.50$; $p < 0.03$, and $F_{2,18} = 3.98$; $p < 0.04$, respectively) for the trailing foot and in step N for the leading foot ($F_{2,18} = 9.19$; $p < 0.005$).

The results of the ANOVA tests may be indicative of an effect of fatigue on the spatial-temporal parameters, joint ROM and EMG (Table 1). After both fatigue protocols, the participants showed decreased knee ROM ($F_{2,98} = 76.37$; $p < 0.001$; and $F_{2,98} = 41.26$; $p < 0.001$, respectively) and increased ankle ROM ($F_{2,98} = 50.75$; $p < 0.001$; and $F_{2,98} = 43.19$; $p < 0.001$, respectively) for both steps ($N-2$ and $N-1$).

With ankle muscle fatigue, the participants reduced step length ($F_{2,98} = 10.24$; $p < 0.001$) and step duration ($F_{2,98} = 6.95$; $p < 0.02$) and increased the activity of biceps femoris ($F_{2,98} = 22.83$; $p < 0.001$) in $N-2$, and increased the activity of rectus femoris ($F_{2,98} = 10.01$; $p < 0.001$) in $N-1$. In addition, they increased hip ROM ($F_{2,98} = 11.60$; $p < 0.001$; $F_{2,98} = 12.13$; $p < 0.001$, respectively) in both steps.

With knee muscle fatigue, the participants increased step width ($F_{2,98} = 7.39$, $p < 0.002$; and $F_{2,98} = 8.02$; $p < 0.003$, respectively) and decreased the activity of biceps femoris ($F_{2,98} = 22.83$; $p < 0.001$, and $F_{2,98} = 10.29$; $p < 0.001$, respectively) and tibialis anterior ($F_{2,98} = 9.74$; $p < 0.001$, and $F_{2,98} = 4.81$; $p < 0.01$, respectively) in both steps. Besides, they decreased step duration ($F_{2,98} = 4.28$; $p < 0.03$), and the activity of rectus femoris ($F_{2,98} = 10.01$; $p < 0.001$) and gastrocnemius lateralis ($F_{2,98} = 3.64$; $p < 0.03$), and increased step velocity ($F_{2,98} = 8.92$; $p < 0.001$), and hip ROM ($F_{2,98} = 11.60$; $p < 0.001$) in $N-1$.

With respect to between trial variability (Table 2), with ankle muscle fatigue, increased variability of knee ROM ($F_{2,18} = 81097$; $p < 0.004$), and decreased variability of hip ROM ($F_{2,18} = 5.30$; $p < 0.04$) were found in $N-1$. With knee muscle fatigue, variability of knee ROM ($F_{2,18} = 9.11$; $p < 0.009$) was increased in $N-2$.