Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

Journal of Electromyography and Kinesiology 19 (2009) 304–313

JOURNAL OF ELECTROMYOGRAPHY AND KINESIOLOGY

www.elsevier.com/locate/jelekin

Influence of gait velocity on gastrocnemius muscle fascicle behaviour during stair negotiation

M. Spanjaard [a,b,*], N.D. Reeves [a], J.H. van Dieën [b], V. Baltzopoulos [a], C.N. Maganaris [a]

[a] *Institute for Biophysical and Clinical Research into Human Movement, Manchester Metropolitan University, Alsager, United Kingdom*
[b] *Research Institute MOVE, VU University, Amsterdam, The Netherlands*

Received 27 June 2007; received in revised form 25 July 2007; accepted 25 July 2007

Abstract

The gastrocnemius medialis (GM) muscle plays an important role in stair negotiation. The aim of the study was to investigate the influence of cadence on GM muscle fascicle behaviour during stair ascent and descent. Ten male subjects (young adults) walked up and down a four-step staircase (with forceplates embedded in the steps) at three velocities (63, 88 and 116 steps/min). GM muscle fascicle length was measured using ultrasonography. In addition, kinematic and kinetic data of the lower legs, and GM electromyography (EMG) were measured. For both ascent and descent, the amount of fascicular shortening, shortening velocity, knee moment, ground reaction force and EMG activity increased monotonically with gait velocity. The ankle moment increased up to 88 steps/min where it reached a plateau. The lack of increase in ankle moment coinciding with further shortening of the fascicles can be explained by an increased shortening of the GM musculotendon complex (MTC), as calculated from the knee and ankle angle changes, between 88 and 116 steps/min only. For descent, the relative instant of maximum shortening, which occurred during touch down, was delayed at higher gait velocities, even to the extent that this event shifted from the double support to the single support phase.

Keywords: Muscle mechanics; Biomechanics; Ultrasound; Musculotendon complex

1. Introduction

The series elastic component of muscles has been shown to enhance the efficiency of human movement. Examples like jumping, walking and running show that elastic storage and release allow re-use of energy generated by muscle fascicles (Alexander and Bennet-Clark, 1977; Fukashiro et al., 2006; Fukunaga et al., 2001; Ishikawa et al., 2007; Kawakami and Fukunaga, 2006; Kurokawa et al., 2001; Roberts, 2002). Additionally, the series elastic component allows much faster shortening of the musculotendon complex (MTC) than fascicles alone could realize, resulting in high joint angular velocities (Alexander and Bennet-Clark, 1977; Fukashiro et al., 2006; Kawakami and Fukunaga, 2006; Roberts, 2002). It seems as though the MTC behaves in the most efficient way for a variety of tasks (Alexander and Bennet-Clark, 1977; Fukashiro et al., 2006; Roberts, 2002).

In a recent paper (Spanjaard et al., 2007), we studied the behaviour of gastrocnemius medialis (GM) muscle fascicles during stair negotiation using ultrasonography. GM muscle fascicles hardly shortened during the push-off phase of stair ascent, while the entire MTC clearly shortened, causing lift-off (Spanjaard et al., 2007). This behaviour seems efficient and has also been found in level walking and in walking up or down a slope (Fukunaga et al., 2001; Lichtwark and Wilson, 2006).

In stair descent, the stabilizing function of the GM muscle appeared to take priority over energetic efficiency (Spanjaard et al., 2007). The GM muscle fascicles actively shortened during the touch-down phase of stair descent, while the MTC lengthened. This implies that instead of

* Corresponding author. Address: Research Institute MOVE, VU University, Faculty of Human Movement Sciences, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands. Tel.: +31 20 5988533; fax: +31 20 5988529.
E-mail address: m.spanjaard@fbw.vu.nl (M. Spanjaard).

1050-6411/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jelekin.2007.07.006

dissipating energy, muscle fascicles generated energy causing the tendon to stretch (to a greater extent than if the fascicles were to lengthen) and the ankle joint to achieve a high stiffness, probably to provide the required stability. The energy stored in the tendon caused the fascicles to lengthen at a later stage, when the energy was finally dissipated. This process of energy production and subsequent dissipation, in a movement phase requiring only energy dissipation, appears not very efficient.

In our previous study (Spanjaard et al., 2007), movement was performed at a self-selected pace, and it is known that changes in gait velocity alter the demands placed on the musculoskeletal system. Higher gait velocity is often associated with an increase in step length, resulting in more muscle fascicle shortening and a faster rate of shortening (Gabaldon et al., 2004; Gillis and Biewener, 2001; Hoyt et al., 2005; Roberts et al., 1997). However, stair walking is a fairly constrained movement in terms of step length as it is imposed by the stairs' dimensions. Nonetheless, with higher stair walking velocities, impact forces and joint moments are expected to be larger, suggesting that the stiffness of the ankle needs to be higher and the muscle fascicles need to shorten more in both ascent and descent. The purpose of the present study was to investigate the influence of gait velocity on the behaviour of GM muscle fascicles during stair negotiation. It was hypothesized that with higher stair walking velocities GM muscle fascicles will shorten more and at a faster rate in both stair ascent and descent.

2. Methods

2.1. Subjects

Ten healthy male volunteers with average age 24.9 ± 3.2 years, height 1.82 ± 0.06 m and mass 79.9 ± 9.1 kg, gave their written informed consent to participate in this study. The same subjects participated in a previously reported study (Spanjaard et al., 2007). The study was approved by the ethics committee of the Institute for Biophysical and Clinical Research into Human Movement at the Manchester Metropolitan University.

2.2. Measurements

The experimental set-up has been described in detail previously (Spanjaard et al., 2007). Participants negotiated a custom-built steel staircase made out of four steps. The steps (riser: 17 cm $\times$ going: 30 cm $\times$ width: 90 cm) were independently mounted on the floor.

A 9-camera VICON 612 system (VICON motion systems Ltd., Oxford UK) was used to acquire kinematic data. Retro-reflective markers were placed on bony landmarks, directly on the skin, or on tight-fitting clothing using double-sided tape. In total, 34 markers were placed on the body according to the standard "plug-in-gait" model of the VICON system implemented in the Bodybuilder software module for 3D segment modelling and calculation of upper and lower limb kinematics. For exact placement of the markers see Spanjaard et al. (2007).

Forceplates were used to collect kinetic data during stair negotiation. Three force plates (Kistler 9286A, 27×52 cm) with built-in amplifiers were embedded in the first three steps (from the ground), and one force plate (Kistler 9253A, 40×60 cm) with an external amplifier (Kistler 9865C) was embedded in the floor, in front of the staircase.

The GM muscle fascicle behaviour was assessed in vivo by ultrasound scans recorded in real-time during the stair negotiation trials. For these measurements, an ultrasound system (Aloka SSD-5000, Tokyo, Japan) was used. A linear 7.5 MHz probe (UST-579T-7.5) with 60 mm field of view was tightly secured around the left lower leg in the mid-sagittal plane of the GM muscle with a custom-built fixation device. The fixation device was made of a plastic cast, moulded to fit the general contour of the calf, with a window for the probe. The probe was held rigidly by the cast, which was securely fixed on the calf using Velcro straps. The experimenter supported the probe cable to ensure that no probe-movement, relative to the GM muscle, occurred. Sampling rate was 22 Hz and image resolution was 768×576 pixels. The ultrasound scanning was synchronized with the kinematic, kinetic and EMG data using an external trigger.

The electrical activity of the GM muscle of the left leg was recorded using a Bagnoli EMG system (gain 1000, bandwidth 20-450 Hz; Delsys Inc. Boston, MA, USA), with a sampling rate of 2000 Hz. The recording electrodes for the GM muscle were placed proximal to the ultrasound scanning probe in the mid-sagittal plane of the muscle.

2.3. Protocol

In order to scale the generic human plug-in-gait model in the VICON software (Oxford Metrics Inc.), anthropometric measurements were taken for each participant before measurements began. Subsequently, the markers, EMG electrodes and ultrasound probe were positioned and data collection was initiated.

Subjects performed three trials of stair descent and three trials of stair ascent, at different gait velocities: 63, 88 and 116 steps/min, dictated by an audible metronome. Subjects walked barefoot, in a step over step fashion. Before the trial started, the subjects stepped on the spot in rhythm with the metronome on top of the platform (stair descent), or on the ground just in front of the ground forceplate (stair ascent), and started every trial with their right foot. The trial ended when the subject was on the top platform, or on the ground, off the forceplate. When a subject was not able to perform the trial at the correct pace, a new trial at the same pace was performed.

2.4. Data analysis

The phase between the first touchdown point of the left foot and the second touchdown point of the left foot (two steps above/below) was considered a steady-state stride cycle (Andriacchi et al., 1980). From marker positions and forceplate data, VICON software was used to calculate kinematics and kinetics in 3D using the plug-in-gait model, while only the sagittal plane information was used for further processing. From the steady-state stride cycle, the kinematic and kinetic data of the ankle and knee were transported from "VICON workstation" software to Matlab (The Mathworks, Inc, Natick, MA).

The GM muscle fascicle lengths were measured from the recorded ultrasonographic images. On each ultrasound frame from the steady-state stride cycle, GM muscle fascicle length was measured manually using Matlab. Muscle fascicle length was measured using the assumption that the fascicular trajectory was