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# Biomechanical changes at the knee after lower limb fatigue in healthy young women

Heather S. Longpré [a], Jim R. Potvin [b], Monica R. Maly [c,*]

[a] School of Rehabilitation Science, Institute for Applied Health Sciences, Rm 403, McMaster University, 1400 Main Street West, Hamilton, ON L8S 1C7, Canada
[b] Department of Kinesiology, Ivor Wynne Centre, Rm 219A, McMaster University, 1400 Main Street West, Hamilton, ON L8S 1C7, Canada
[c] School of Rehabilitation Science, Institute for Applied Health Sciences, Rm 435/403, McMaster University, 1400 Main Street West, Hamilton, ON L8S 1C7, Canada

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ABSTRACT

*Background:* The purpose of this study was to identify changes in knee kinematics, kinetics and stiffness that occur during gait due to lower limb neuromuscular fatigue.
*Methods:* Kinematic, kinetic and electromyographic measures of gait were collected on healthy, young women ($n = 20$) before and after two bouts of fatigue. After baseline gait analysis, two bouts of fatiguing contractions were completed. Fatigue was induced using sets of 50 isotonic knee extensions and flexions at 50% of the peak torque during a maximum voluntary isometric contraction. Fatigue was defined as a drop in knee extension or flexion maximum voluntary isometric torques of at least 25% from baseline. Gait analyses were completed after each bout of fatigue. Dynamic knee stiffness was calculated as the change in knee flexion moment divided by the change in knee flexion angle from 3 to 15% of the gait cycle. Co-activations of the biceps femoris and rectus femoris muscles were calculated from 3 to 15% and 40 to 52% of gait. Repeated measures analyses of variance assessed differences in discrete gait measures, knee torques, and electromyography amplitudes between baseline and after each bout of fatigue.
*Findings:* Fatigue decreased peak isometric torque. Fatigue did not alter knee adduction moments, knee flexion angles, dynamic knee stiffness, or muscle co-activation. Fatigue reduced the peak knee extension moment.
*Interpretation:* While neuromuscular fatigue of the knee musculature alters the sagittal plane knee moment in healthy, young women during walking, high intensity fatigue is not consistent with known mechanical environments implicated in knee pathologies or injuries.


## 1. Introduction

A decrease in the strength of the quadriceps, defined as a reduction in maximum torque generating capacity (Enoka, 2002), is thought to alter knee biomechanics and impair the ability to mediate loads across the knee (Lewek et al., 2004; Rice et al., 2011; Slemenda et al., 1997, 1998; Zeni et al., 2009). For example, an elevated peak knee adduction moment and increased knee stiffness have been noted concurrently with muscle dysfunctions, including reduced knee extensor strength, activation failure, and impaired coordination in severe knee osteoarthritis (OA) (Zeni et al., 2009). Decreased strength of the knee extensors and flexors is also common with anterior cruciate ligament (ACL) injury and may be associated with an increased external knee flexion moment and internal knee rotation during the loading response portion of gait (Andriacchi and Dyrby, 2005; Berchuck et al., 1990; Palmieri-Smith et al., 2008).

Fatigue refers to a reduction in the efficiency and force generating capacity of muscles after prolonged exposure to activity (Gandevia et al., 1995). Thus, fatigue could lead to changes in knee loads. Fatigue of the quadriceps reduced the knee flexion angle and the peak knee extensor moment during gait in healthy, young participants (Parijat and Lockhart, 2008), and decreased the external knee flexion moment and increased the knee adduction moment during gait in sedentary, young participants (Murdock and Hubley-Kozey, 2012; Walter et al., 2010).

Men exhibit faster fatigue rates compared to women. Mechanisms for fatigue resistance in women may include a lower absolute muscle mass providing the same amount of work for a given task, a lower proportion of the more fatigable type II muscle fibers, or differences in blood flow and muscle metabolism (Clark et al., 2005; Hicks et al., 2001; Pincivero et al., 2000a, 2000b, 2003). Since men tend to have greater muscle mass and absolute strength than women (Clark et al., 2005; Hicks et al., 2001; Hunter et al., 2004; Kent-Braun et al., 2002; Pincivero et al., 2000a, 2000b, 2003), they use a lower proportion of their strength reserve in performing the same task. Therefore, women may be more susceptible to fatigue-induced decreases in strength and the resultant changes at the knee. It is uncertain whether altered gait mechanics, due to lower limb fatigue, would occur in a sample of only young, healthy women (Cortes et al., 2012; Lucci et al., 2011; Murdock and Hubley-Kozey, 2012; Parijat and Lockhart, 2008; Thomas et al., 2010).

Fatigue-induced co-activation of opposing muscle groups may affect knee joint loads. Since knee joint reaction moments are net quantities,

* Corresponding author.
*E-mail addresses:* longpre@mcmaster.ca (H.S. Longpré), potvinj@mcmaster.ca (J.R. Potvin), mmaly@mcmaster.ca (M.R. Maly).

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co-activation of opposing muscle groups will reduce the total net joint moment. This will translate into an apparent decrease in torque generating capacity of the muscles surrounding the joint (Bennell et al., 2008; Busse et al., 2006; Ebenbichler et al., 1998; Heiden et al., 2009). Furthermore, co-activation increases the resistance to angular joint motion (rotational stiffness). This stiffness represents the rotational resistance contributions from the muscles and other soft tissues controlling knee excursion (Dixon et al., 2010; Zeni and Higginson, 2009; Zeni et al., 2009). Higher stiffness, due to greater antagonistic hamstrings activity during the loading portion of gait, occurs in severe knee OA compared to healthy individuals (Zeni and Higginson, 2009).

This study aimed to identify the biomechanical changes at the knee that occur during gait in response to neuromuscular fatigue of the knee extensor and flexor muscles in healthy, young women. Our goal was to determine whether the effects of fatigue on knee kinetics and kinematics would further our understanding of the contributions of muscle dysfunction to knee loading patterns. We hypothesized that neuromuscular fatigue around the knee would increase the knee adduction moment, increase co-activation of the quadriceps and hamstrings, and increase dynamic knee stiffness during gait.

## 2. Methods

### 2.1. Participants

A convenience sample of 20 healthy women (age 18 to 30 years) completed this study. Inclusion criteria included regular physical activity, and no contraindications to exercise on the Physical Activity Readiness Questionnaire (Thomas et al., 1992). Exclusion criteria included pregnancy and a history of knee pain, injury, or surgery. Participants were recruited from the local student population. Written, informed consent was obtained from the participants and this study was approved by the McMaster University Faculty of Health Sciences Research Ethics Board.

### 2.2. Design

The participants came to the laboratory for two visits, one week apart (Fig. 1). The first visit was an orientation to familiarize participants with the equipment and protocol. This was incorporated in the study design to facilitate maximal performance during the second visit.

The second visit consisted of gait analyses before and after two separate bouts of fatigue. Baseline (BL) gait analysis was performed to establish points of reference prior to fatigue. This was followed by a measure of baseline isometric peak knee extensor and flexor torques, followed by the first round of fatiguing contractions. Upon reaching fatigue, the participants performed the first post fatigue gait analysis (PF1). This was followed by a second round of fatiguing contractions to ensure that participants remained fatigued and had not recovered. The final post fatigue gait analysis (PF2) was performed quickly after achieving fatigue.

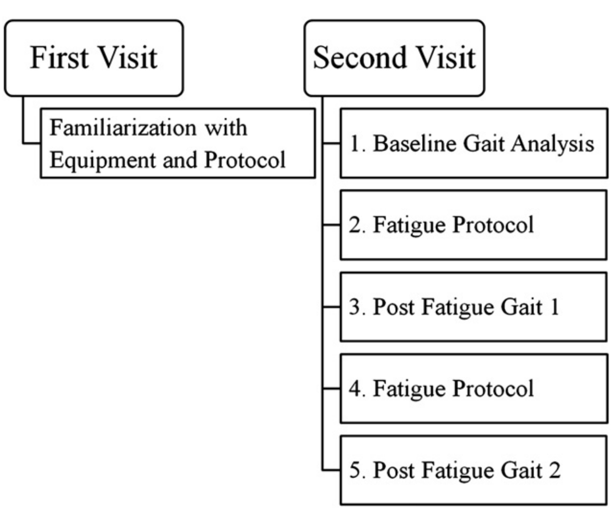


**Fig. 1.** Study design flow chart.

### 2.3. Measures

#### 2.3.1. Gait analysis

Marker motion during gait was measured using a Vicon MX 8 camera motion capture system sampling at 100 Hz (Vicon Motion Systems, Oxford, UK) and synchronized with three force platforms measuring ground reaction forces and moments sampled at 1000 Hz (Ives and Wigglesworth, 2003) (Advanced Mechanical Technology Inc., Watertown, MA). Eighteen reflective markers were affixed to the right and left anterior and posterior superior iliac spines, mid thighs, lateral epicondyles, mid shanks, lateral malleoli, calcanei, and 2nd metatarsal heads. Six additional reflective markers were affixed to the left and right iliac crests, greater trochanters, medial epicondyles, and medial malleoli during static standing calibration trials as digital landmarks. These 6 additional markers were removed before beginning the gait trials, but the other 18 markers remained affixed throughout the protocol including all gait analyses and fatiguing contractions. The marker placement and gait protocols used in this study were based on Vicon's plug-in-gait lower limb model, with the additional markers used for digital landmarking.

Gait analysis was used to capture external knee joint moments and angles. The participants walked barefoot at self-selected speeds. Gait trials were considered successful when the right foot alone fell in full contact with one of the force platforms. Five gait trials were collected for each participant at BL, PF1, and PF2. Gait trials were completed within a 10-minute window of achieving fatigue to avoid recovery (Cheng and Rice, 2005; Parijat and Lockhart, 2008). Kinematic and kinetic gait variables were calculated (C-Motion, Inc., Germantown, MD, USA) using inverse dynamics (Winter, 1984). Marker and force platform data were filtered with a dual-pass fourth order Butterworth low-pass filter at a cut-off frequency of 6 Hz. Knee joint moments were calculated using the Joint Coordinate System floating axis model (Grood and Suntay, 1983). Joint moments were normalized to body mass, and moments and angles were time normalized to the gait cycle (C-Motion, Inc., Germantown, MD, USA). Discrete measures including peaks, maximums, and minimums were extracted from joint moment and angle waveforms from 5 gait trials.

#### 2.3.2. Electromyography

Electromyographic (EMG) signals were collected during gait and during peak torque measurements to determine lower limb muscle contributions to these activities. The EMG was pre-amplified through dual differential amplifiers with input impedance > 100,000 MΩ, CMRR > 100 dB at 65 Hz and equivalent input noise of <1.2 μV RMS nominal. Each participant-mounted amplifier had an input impedance of 31 KΩ, signal-to-noise ratio of >50 dB, and a gain of 2000 (MA 300, Motion Lab Systems, Inc., Baton Rouge, LA, USA). EMG data was bandpass filtered between 20 and 450 Hz, synchronized with the motion capture system, and sampled at 1000 Hz. Activity of the rectus femoris, vastus lateralis, and biceps femoris was monitored using stainless steel surface electrodes with a 17 mm inter-electrode distance affixed to the skin along the orientation of the muscle fibers. The rectus femoris and biceps femoris are antagonists, biarticulating the knee and hip. Altered vastus lateralis function resulted in significant changes in knee kinematics during stair climbing; therefore this muscle was selected as a possible explanatory variable for altered knee mechanics during gait (Hinman et al., 2002; Pincivero et al., 2006). A reference electrode was placed over the tibial tubercle. Electrode locations were