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Measuring movement symmetry using tibial-mounted accelerometers for people recovering from total knee arthroplasty

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ABSTRACT

Background: The purpose of this investigation was to examine movement symmetry changes over the first 26 weeks following unilateral total knee arthroplasty in community environments using skin-mounted tibial accelerometers. Comparisons to healthy participants of similar age were also made.
Methods: Patients (N = 24) with unilateral knee osteoarthritis (mean (SD), 65.2 (9.2) years) scheduled to undergo total knee arthroplasty and a control group (N = 19 healthy people; mean (SD), 61.3 (9.2) years) were recruited. The total knee arthroplasty group participated in a standardized course of physical rehabilitation. Tibial acceleration data were recorded during a Stair Climb Test and 6-Minute Walk Test. Tibial acceleration data were reduced to initial peak acceleration for each step. An inter-limb absolute symmetry index of tibial initial peak acceleration values was calculated.
Findings: The total knee arthroplasty group had greater between limb asymmetry for tibial initial peak acceleration and initial peak acceleration absolute symmetry index values five weeks after total knee arthroplasty, during the Stair Climb Test and the 6-Minute Walk Test.
Interpretation: Tibial accelerometry is a potential tool for measuring movement symmetry following unilateral total knee arthroplasty in clinical and community environments. Accelerometer-based symmetry outcomes follow patterns similar to published measures of limb loading recorded in laboratory settings.

1. Introduction

Improving lower limb movement symmetry is an important rehabilitation goal for patients recovering from unilateral total knee arthroplasty (TKA). Following unilateral TKA, patients have asymmetrical lower limb movements during tasks such as sit–stand transitions and walking, and this asymmetry is correlated with poor functional outcomes (Boonstra et al., 2010; Christiansen et al., 2011; Mizner and Snyder-Mackler, 2005; Yoshida et al., 2008). To determine the impact of impaired movement symmetry on performance of functional tasks during daily activity, it is important to perform measurements in a natural living environment. Measurement of movement symmetry in community environments would serve to: 1) provide clinicians a practical method for assessing movement patterns and 2) serve as a means for providing patients with feedback on their movement patterns during functional activity.

Movement symmetry following TKA has often been measured in motion analysis laboratories equipped with cameras, electromyographic signal recording systems, and/or force platforms in a confined motion capture area (Christiansen and Stevens-Lapsley, 2010; Mizner and Snyder-Mackler, 2005; Stacoff et al., 2007; Yoshida et al., 2012). In addition, motion analysis systems have been used for providing feedback to patients during movement pattern re-training after lower limb joint surgeries (Isakov, 2007; McClelland et al., 2012; White and Lifeso, 2005). However, the equipment used to measure movement asymmetry and provide patients feedback during rehabilitation is not practical for common clinical use and difficult to use in community settings that patients encounter during daily living. Assessment of movement symmetry has historically been performed by motion capture and analysis of ground reaction forces. An alternative method for measuring movement patterns is the use of accelerometers (Liikavainio et al., 2007a; O'Leary et al., 2008; Turpin et al., 2012). Use of accelerometers to quantify movement patterns is a relatively inexpensive alternative which allows for assessing movements in community environments, and has established validity, with positive correlations to force-plate measurement systems (Liikavainio et al., 2007a; Neugebauer et al., 2012; Rowlands and Stiles, 2012; Stiles et al., 2013).

The purpose of this study was to examine use of portable, skin-mounted tibial accelerometers to measure changes in lower limb movement symmetry for patients with unilateral TKA during a Six-Minute Walk Test (6MWT) and Stair Climb Test (SCT). It was hypothesized that tibial acceleration would identify movement asymmetry in the TKA group compared to a group of healthy subjects (CTL) for both the

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6MWT and SCT. It was also hypothesized that movement asymmetries measured by tibial acceleration would have a similar pattern to those measured in movement analysis laboratories, where asymmetry was the greatest at 4–6 weeks after TKA and returned to preoperative levels by 26 weeks. Finally, it was expected that differences in tibial acceleration symmetry between the TKA and CTL groups would be greater during the SCT than the 6MWT, because the SCT test has a relatively higher loading demand.

2. Methods

2.1. Participants

This was an observational cohort study. Twenty-four people with knee osteoarthritis (OA) were scheduled to undergo unilateral TKA. Participants in this study were control group subjects for ongoing investigations with standardized rehabilitation protocols from June 2006 to October 2012. Inclusion criteria were 1) age 50 to 85 years old and 2) ≤half the level of pain on the non-surgical knee compared to the surgical knee before surgery (numerical pain rating scale of 0–10). Exclusion criteria were 1) uncontrolled hypertension, 2) uncontrolled diabetes, 3) BMI > 35 kg/m^2, 4) neurologic impairment, or 5) other unstable lower-extremity orthopedic problems. The Colorado Multiple Institutional Review Board approved the studies, and written informed consent was obtained from all participants.

The group of healthy individuals was recruited from the community with the intent of having a group similar in age (50–85 years) and sex distribution to the TKA group. In addition to the exclusion criteria for the TKA group, volunteers for the healthy group were excluded if they had knee pain >2/10 on an intermittent basis, had any knee pain with regular activity, and did not exercise at least three days per week.

2.2. Intervention

Within 2 weeks following baseline testing, all TKA group participants received a unilateral TKA. Rehabilitation following TKA included acute (2–4 days), home-based (1–2 weeks) and outpatient (1.5–2.5 weeks) intervention phases before a final 26-week follow-up testing session (Stevens-Lapsley et al., 2012). All treatment sessions were performed by a physical therapist.

2.3. Outcome measures

Participants performed all testing in the stairwell and hallway of an office building. The two functional outcome measures were: 1) a Stair Climb Test (SCT) and 2) the 6-Minute Walk Test (6MWT). TKA group participants were tested 1–2 weeks before surgery and at 5 (range 4–6) and 26 weeks after surgery. Not all time-points were tested for each participant in the TKA group, as accelerometer testing was a secondary outcome measure and primary outcomes were prioritized for participants who could not complete the entire testing protocol. In addition, participants were not tested at 26 weeks after surgery in one study. Healthy group participants were tested once to provide reference data collected during the SCT (n = 12) and 6MWT (n = 19). Sample sizes are reported for each time point in the results section.

2.3.1. Tibial acceleration

Acceleration along the tibial longitudinal axis was measured using skin-mounted triaxial accelerometers (Delsys, Boston, MA, USA) (range ± 10 g) (Fig. 1). Accelerometers were rectangular in shape with a mass of 4 g, and were dimensionally 20 × 33 × 5 mm. An accelerometer was placed on the anteromedial surface of each tibia (66% height from inferior medial malleolus and knee medial joint line) before participants performed the two functional outcome tests. The longitudinal accelerometer axis was visually aligned along the tibial longitudinal axis and mounted with adhesive tape and an elastic wrap. Firm tension

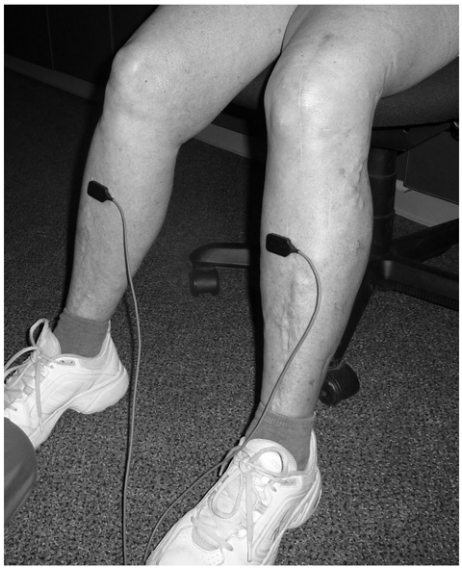

Fig. 1. Accelerometers attached to the tibia.

of the elastic wrap was used to preload the skin to damp potential artifact introduced by soft tissue between the tibia and the accelerometer (Forner-Cordero et al., 2008). Data were recorded (1000 Hz) with a portable biosignal monitor (Delsys, Boston, MA, USA) worn on a waist belt.

After data collection, accelerometer data were filtered (Butterworth, 4th order, cut-off 40 Hz) and voltage converted to gravitational units. Initial peak acceleration (IPA) was calculated from the acceleration signals during the four middle steps of ascending and descending the stairs and of the first and last minute of the 6MWT for each leg. IPA was the peak tibial acceleration after foot contact. The average IPA value over the four steps was used for analysis for each condition. To account for acceleration due to gravity, acceleration was measured along the vertical axis of the tibia with the participant standing in an upright posture prior to functional testing. This stationary acceleration measurement was subtracted from the acceleration values recorded during movement. In this way, the influence of gravity on the acceleration signal was accounted for in the natural orientation of the tibia when the participant was standing.

An absolute symmetry index (Herzog et al., 1989) was calculated to compare the absolute differences in IPA between limbs (Eq. (1)). An absolute symmetry index value of zero would indicate perfect symmetry.

$$\text{Absolute symmetry index} = 2 * |(\text{IPA}_L - \text{IPA}_R)/(\text{IPA}_L + \text{IPA}_R)| * 100\%, \quad \text{where } \text{IPA}_L = \text{average initial peak acceleration for left limb} \quad \text{and} \text{IPA}_R = \text{average initial peak acceleration for right limb} \tag{1}$$

2.3.2. Stair Climb Test

Subjects were positioned at the base of a 10-step stairwell in an office building and instructed to ascend and descend the stairs “as quickly as possible, but safely” (Fig. 2). Subjects were allowed to perform any step pattern desired (including stepping on each step with both feet, alternating foot contacts each step, or skipping steps). If needed, subjects were allowed to use a cane or a handrail in the stairwell during stair walking for balance control. Subjects performed two trials of the SCT with the second trial used for time as well as accelerometer data analysis. The timed stair walking test has been shown to be a reliable and valid measure of physical function for people with and without knee OA (LeBrasseur et al., 2008; Lin et al., 2001).