Clinical Biomechanics 26 (2011) 65–70

Contents lists available at ScienceDirect

Clinical Biomechanics

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

Robust features of knee osteoarthritis in joint moments are independent of reference frame selection

Scott C.E. Brandon *, Kevin J. Deluzio

Department of Mechanical and Materials Engineering, Queen's University, Kingston, ON, Canada

ARTICLE INFO

Article history:
Received 22 February 2010
Accepted 31 August 2010

Keywords:
Gait
Inverse dynamics
Joint model
Joint moments
Knee
Loads
Lower extremities
Mechanics
Osteoarthritis
Reference frame
Coordinate system

ABSTRACT

Background: Changes in lower-limb joint moments are important outcome measures for treatment and prevention of knee osteoarthritis. However, it is known that both the magnitude and amplitude of joint moments are affected by the choice of anatomical reference frame. The purpose of this study was to identify features of joint moment waveforms that, regardless of the choice of reference frame, are different for subjects with knee osteoarthritis as compared to asymptomatic control subjects.
Methods: External joint moments during the stance phase of gait were calculated for 44 subjects with moderate knee osteoarthritis and 44 asymptomatic subjects. Moments were then expressed using four anatomical reference frames: Joint Coordinate System, Plane of Progression, Proximal, and Distal. Principal component analysis was used to extract features of the moment waveforms that differed between control and osteoarthritis groups across all reference frames.
Findings: Principal component analysis revealed that, regardless of the choice of reference frame, subjects with knee osteoarthritis exhibited significantly decreased overall hip adduction moment magnitudes, increased overall knee adduction moment magnitudes, decreased knee internal rotation moment amplitudes, and increased early-stance ankle adduction magnitudes.
Interpretation: The four robust features identified in this study are sensitive to the effect of knee osteoarthritis, but independent of changes in the anatomical reference frame. These features can be solely attributed to the pathogenesis of the disease, and not to the artifact of reference frame selection.

1. Introduction

Subjects with medial compartment knee osteoarthritis have been shown to exhibit changes in joint moments at the ankle, knee, and hip (Astephen et al., 2008a; Baliunas et al., 2002; Gok et al., 2002; Mundermann et al., 2005). These changes are considered to be risk factors for disease progression (Chang et al., 2005; Miyazaki et al., 2002) and have been implicated as predictors of surgical outcome (Prodromos et al., 1985). The external knee adduction moment has received particular attention due to its correlation with medial compartment loading (Zhao et al., 2007) and osteoarthritis severity (Maly et al., 2008; Miyazaki et al., 2002).

It has been shown that lower-limb joint moments, particularly in the transverse plane, are sensitive to the choice of anatomical reference frame (Schache and Baker, 2007; Schache et al., 2007). Both the magnitude and temporal location of local maxima and minima throughout the gait cycle are significantly altered when expressed in differing anatomical reference frames (Schache and Baker, 2007). This makes it difficult to compare joint moments between studies. Furthermore, Newell et al. (2008) found that the ability to detect changes in knee adduction moments due to knee osteoarthritis depends on the choice of anatomical reference frame. Using different anatomical reference frames can even influence whether or not a gait modification is found to successfully reduce the knee adduction moment (Schache et al., 2008).

While the Joint Coordinate System developed by Grood and Suntay (1983) is widely accepted as the standard for expression of lower-limb joint kinematics (Wu and Cavanagh, 1995), there is no standard anatomical reference frame for the expression of joint moments (Schache et al., 2008). Moments can be expressed using the Distal segment coordinate system (Gok et al., 2002; Kaufman et al., 2001), the Proximal segment coordinate system (Schache and Baker, 2007), or the Joint Coordinate System (Astephen et al., 2008a; Landry et al., 2007), which is a combination of both systems. Another option, referred to in this paper as the Plane of Progression (PoP) frame, projects anterior–posterior and inferior–superior moments from the Distal frame onto the plane of progression (Baliunas et al., 2002; Mundermann et al., 2005; Sharma et al., 1998). These four reference frames are shown in Fig. 1.

All of these reference systems are mathematically correct, and may be appropriate for specific analyses, depending on the parameters of interest (Schache and Baker, 2007; Schache et al., 2008). Without

---

* Corresponding author. 130 Stuart St, McLaughlin Hall, Queen's University, Department of Mechanical and Materials Engineering, Kingston, ON, Canada K7L 3N6.
E-mail address: brandon@me.queensu.ca (S.C.E. Brandon).

0268-0033/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2010.08.010

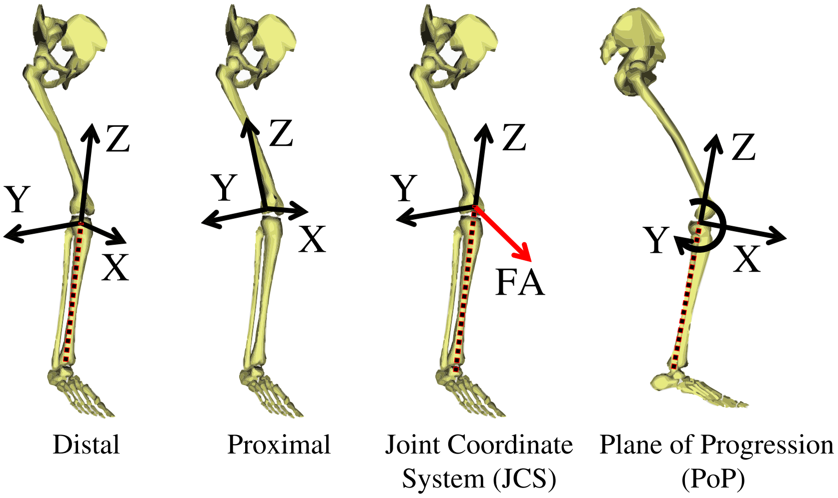

Fig. 1. Four alternative anatomical reference frames, shown using the knee for example. The Distal frame follows the distal segment in three dimensions, while the Proximal frame follows the proximal segment. The Joint Coordinate System (JCS) frame uses the flexion axis from the Proximal frame, the internal rotation axis from the Distal frame, and a floating adduction axis, FA, that is perpendicular to both of these axes. The Plane of Progression (PoP) frame fixes the flexion axis perpendicular to the plane of progression, while the adduction and internal rotation axes are taken from the Distal frame and projected onto the plane of progression.

evidence demonstrating the superior reliability, anatomical relevance, or diagnostic capability of one anatomical reference system over the others, it is difficult to dictate a standard. However, Newell et al. (2008) found that it is possible to select robust parameters for the knee adduction moment that are not affected by the choice of anatomical reference system. Other moments at the hip, knee, and ankle may also be important for characterizing knee osteoarthritis and developing future gait interventions (Huang et al., 2008; Mundermann et al., 2005); it is therefore important to investigate additional robust features of knee osteoarthritis in lower-limb joint moments.

Principal component analysis (PCA) was shown to be a particularly useful tool for detecting features of the knee adduction moment that are sensitive to the effects of knee osteoarthritis but are independent of the choice of reference frame (Newell et al., 2008). Principal component features are measureable biomechanical changes. Additionally, the biomechanical features extracted using PCA are objective (Chau, 2001; Deluzio et al., 1995) and encompass variation throughout the entire gait cycle (Astephen and Deluzio, 2004; Landry et al., 2007). For these reasons, PCA is well suited for detecting robust features of lower-limb joint moments across all reference frames.

The purpose of this study was to identify features of joint moment waveforms using PCA that, regardless of the choice of anatomical reference frame, are different for subjects with knee osteoarthritis as compared to asymptomatic control subjects.

2. Methods

2.1. Subjects

Forty-four subjects with radiographically confirmed medial knee osteoarthritis were recruited from the Orthopaedic and Sports Medicine Clinic of Nova Scotia. Forty-four asymptomatic subjects were recruited for the control group through postings on the Dalhousie University campus. All subjects gave informed consent and the study was approved by the Institutional Review Board. Subjects were excluded if they had any other forms of arthritis, neuromuscular disorders, trauma or major surgery to the lower limb, or a history of stroke or cardiovascular disease. Osteoarthritis subjects were included based on radiographic Kellgren–Lawrence (KL) scores between 1 and 3, and were also assessed using the Western Ontario and McMaster Universities (WOMAC) scale. Additionally, osteoarthritis subjects were screened for bilateral osteoarthritis through a clinical examination, and were excluded if the contralateral limb was in the same or worse condition as the affected limb. The limb of interest was randomized for control subjects.

2.2. Gait

Gait analysis methods have been described previously (Landry et al., 2007). Subjects performed at least 4 walking trials at self-selected speed in their own low-top walking shoes. Kinematic data were collected from the affected limb at 100 Hz using an Optotrak 3D motion analysis system (Northern Digital Inc., Waterloo, ON, Canada). Segment orientation was obtained using least-squares optimization of rigid tracking clusters (Challis, 1995). Marker triads were placed on the pelvis, thigh, shank, and foot in addition to single markers placed over the greater trochanter, lateral epicondyle, and lateral malleolus. The right and left anterior superior iliac spine (ASIS), medial epicondyle, fibular head, tibial tuberosity, medial malleolus, second metatarsal head, and calcaneus were digitized as virtual points to allow the creation of anatomical reference frames (Cappozzo et al., 1995). Unilateral ground reaction forces and moments were collected at 1000 Hz using an AMTI force platform (Advanced Mechanical Technology Inc., Watertown, MA, USA).

Marker coordinate data were smoothed using a Butterworth filter with a 10 Hz cutoff frequency. Joint kinematics were calculated using the Joint Coordinate System (JCS) (Grood and Suntay, 1983). Net lower-limb external joint moments were calculated using a standard inverse dynamics approach implemented in MATLAB (The MathWorks, Natick, MA, USA) (Landry et al., 2007). Segment inertial parameters were estimated from regression equations based on anthropometric measures (Clauser et al., 1969). Joint moments were time normalized, using cubic spline interpolation, to 101 points representing each percent of the stance phase of gait. The intra-subject mean moment was obtained for each subject across all walking trials. Moments were also normalized to body mass, then resolved into components along anatomical axes in each of the four alternative reference frames: JCS, PoP, Distal, and Proximal. Anatomical axes are defined by the landmarks used to construct segment coordinate systems, while each anatomical reference frame represents a unique combination of axes taken from the proximal and distal segment coordinate systems.

2.3. Segment coordinate systems

Ankle and knee joint centers were defined as the midpoint of the inter-malleolar and inter-epicondylar axes, respectively. Hip joint