Journal of Biomechanics 46 (2013) 43–49

Contents lists available at SciVerse ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Ambulatory measurement of the knee adduction moment in patients with osteoarthritis of the knee

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ARTICLE INFO

Article history:
Accepted 29 September 2012

Keywords:
Osteoarthritis
Gait
Joint moment
Biomechanics
Knee
Rehabilitation
Measurement system
Shoe
Inertial sensor

ABSTRACT

High knee joint-loading increases the risk and progression of knee osteoarthritis (OA). Mechanical loading on the knee is reflected in the external knee adduction moment (KAdM) that can be measured during gait with laboratory-based measurement systems. However, clinical application of these systems is limited. Ambulatory movement analysis systems, including instrumented force shoes (IFS) and an inertial and magnetic measurement system (IMMS), could potentially be used to determine the KAdM in a laboratory-free setting. Promising results have been reported concerning the use of the IFS in KAdM measurements; however its application in combination with IMMS has not been studied.

The objective of this study was to compare the KAdM measured with an ambulatory movement analysis system with a laboratory-based system in patients with knee OA. Gait analyses of 14 knee OA patients were performed in a gait laboratory. The KAdM was concurrently determined with two the systems: (i) Ambulatory: IFS and IMMS in combination with a linked-segment model (to obtain joint positions); (ii) Laboratory: force plate and optoelectronic marker system.

Mean differences in KAdM between the ambulatory and laboratory system were not significant (maximal difference 0.20 %BW∗H in late stance, i.e. 5.6% of KAdM range, $P > 0.05$) and below clinical relevant and hypothesized differences, showing no systematic differences at group level. Absolute differences were on average 24% of KAdM range, i.e. 0.83 %BW∗H, particularly in early and late stance. To achieve greater accuracy for clinical use, estimation of joint position via a more advanced calibrated linked-segment model should be investigated.

1. Introduction

High knee joint-loading due to e.g. malalignment, laxity, injury or obesity, increases the risk and progression of knee osteoarthritis (OA) (Englund, 2010; Hunter and Wilson, 2009). Knee OA is more common in women and elderly people. 1.5% of adults above 55 suffer from painful, severe knee OA. 10% has mild to moderate knee OA (Peat et al., 2001). Knee OA involves cartilage destruction, subchondral bone-thickening and new bone formation. It results in knee pain, instability, stiffness and swelling and could lead to knee arthroplasty. Patients frequently experience limitations in daily life activities and a decline in mobility (Andriacchi et al., 2004; van Dijk et al., 2006). To identify abnormal joint loading on the knee, the measure of the net external knee adduction moment (KAdM) during gait could be used. The KAdM reflects the internal loading on the medial compartment of the knee (tibio-femoral force) (Zhao et al., 2007). Increased KAdM peaks (20–40%) have been observed in patients with medial knee OA (Foroughi et al., 2009; Baliunas et al., 2002). Bracing, heel wedges, osteotomy, gait modifications, and weight management are used to minimize knee joint-loading in these patients (Brouwer et al., 2007; Simic et al., 2010; Glass, 2006; Hunter et al., 2012). To better direct and evaluate such

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http://dx.doi.org/10.1016/j.jbiomech.2012.09.030

treatments in knee OA, objective knee-load measurement via the KAdM may be important in clinical practice.

Currently, measurement of the KAdM is restricted to optoelectronic marker systems and force plates in gait laboratories. However, available and well-equipped laboratories in hospitals and rehabilitation centers are often lacking. Furthermore, optical markers have line of sight problems resulting in missing data, and targeted foot positioning on force plates causes an adaptation of the gait pattern (Schepers et al., 2007; Luinge and Veltink, 2005; Cutti et al., 2010; Best and Begg, 2006). Therefore, there is a need for feasible and validated measurements in clinical practice.

Recently, ambulatory movement analysis systems have been introduced, including instrumented force shoes (IFSs) for kinetic measurements, and inertial and magnetic measurement systems (IMMSs) for kinematic measurements. Application of these systems is not restricted to gait laboratories and could be used at any place and any time. IFSs have been applied and proven accurate in measuring ground reaction force (GRF) and center of pressure (CoP) in healthy subjects (Faber et al., 2010a; Schepers et al., 2007) and patients (Schepers et al., 2009; van den Noort et al., 2011; van den Noort et al., 2012). IMMSs with appropriate anatomical calibration procedures (i.e. sensor-to-segment calibration) were successfully evaluated to measure segmental orientations and joint angles (Luinge and Veltink, 2005; Cutti et al., 2010; van den Noort et al., 2009; Zhou et al., 2008).

The combination of IFSs and IMMSs could potentially be used to determine the KAdM of knee OA patients in laboratory-free setting. However, with IMMSs, it is difficult to obtain positions of segments or joints (Schepers et al., 2010), while for net joint-moment calculations joint positions are required, in addition to GRF and CoP measurements (Hof, 1992). Several methods have been suggested to obtain positions with IMMS, such as linked-segment models that represents skeletal geometry (Faber et al., 2010b), ambulatory position information using a magnetic source worn on the body (Schepers et al., 2010) or kinematic coupling algorithms (Roetenberg et al., 2010). Previously, (van den Noort et al., 2012) showed that segment orientations and fixed segment lengths could be used as input in a linked-segment model to obtain joint positions, that have been used in combination with IFS data to determine the KAdM. Estimation errors of the KAdM were found to be 0.78 %BW*H (22% of the KAdM range) in particularly late stance (BW is bodyweight, H is body height), while clinical relevant differences between medial knee OA patients and healthy controls are reported to vary about 1 %BW*H (20–40 % KAdM range) (Baliunas et al., 2002; Foroughi et al., 2009; Thorp et al., 2006).

As a proof of principle, van den Noort et al. used orientations from the optoelectronic reference system, evaluating only a *part* of the system. The objective of the present study was to compare the KAdM measured with the *entire* ambulatory movement analysis system (i.e. IFS *and* IMMS) with the KAdM measured with the laboratory system (optoelectronic marker system and force plate) as reference, in patients with knee OA. Based on results of the previous study and with the aim to show clinically relevant differences, we hypothesized a difference in the KAdM between the ambulatory and laboratory system of 0.90 %BW*H.

2. Methods

2.1. Patients

Fourteen patients, who all fulfilled the American College of Rheumatology (ACR) criteria for knee OA (Altman and Gold, 2007), participated in the study (3 males, 11 females, mean age 61.0 ± 9.2 years (mean ± standard deviation), body mass 83.7 ± 14.4 kg, and body height 1.66 ± 0.11 m), with dominant medial or lateral tibiofemoral radiographic OA (Kellgren/Lawrence grade > 1). The patients were recruited from the patient population of the Reade Centre for Rehabilitation and Rheumatology (Amsterdam, the Netherlands). The Medical Ethics Committee of the VU University Medical Center (Amsterdam, the Netherlands) approved the study. Full written informed consent was obtained from all participants.

2.2. Procedure

The patients walked in a gait laboratory on a 10 m walkway at comfortable self-selected speed. Kinematic and kinetic data were collected synchronously by means of an ambulatory movement analysis system and the standard laboratory system (as a reference). The ambulatory system consisted of IFSs and an IMMS. The IFS was based on an orthopedic sandal, with 6-degrees-of-freedom ATI mini45 SI-580-20 force/moment sensors (Schunk GmbH & Co. KG) (Schepers et al., 2007; van den Noort et al., 2011, 2012). The IMMS sensor units (MTx, Xsens Technologies, the Netherlands), were attached to each force/moment sensor of the IFS and to the shanks (Fig. 1). The IFS and IMMS were wirelessly connected to a computer, via two Xbus Master devices (Xsens Technologies, the Netherlands; sample frequency 50 Hz). The laboratory system consisted of a force plate (AMTI OR6-5-1000, Watertown, MA, USA) embedded in the floor of the laboratory (sample frequency 1000 Hz), and an optoelectronic marker system (OptoTrak 3020, Northern Digital Instruments, Waterloo, Canada) with marker clusters attached to the feet (IFS), shanks and thighs (sample frequency 50 Hz).

Prior to the gait measurements, an upright static measurement and a passive standardized flexion/extension movement of the patient's knee joint were performed by the examiner (non-weight bearing, sitting posture, maximal range of motion of 90°) for anatomical calibration of the IMMS coordinate system on the shank (Cutti et al., 2010; van den Noort et al., 2009). To determine anatomical coordinate systems with the optoelectronic marker system, anatomical landmarks were palpated according to Cappozzo et al. (1995) based on ISB standards (Wu et al., 2002).

Data on three successful trials were collected per leg, i.e. a step on the force plate during normal gait, and no missing marker data of the optoelectronic system. Prior to measurements, patients had time to practice the trials.

2.3. Data analysis

For the ambulatory system, the algorithms of (Schepers et al., 2007) were used to calculate the GRF and CoP, based on IMMS and IFS data. The orientations of the IMMS sensors on heel, forefoot and shank were calculated by integration of angular velocities from the gyroscopes (Bortz, 1971). At each stride, the orientations of the heel and forefoot sensors were corrected, using zero-velocity-update and assuming equal vertical position of the foot at each stride (Schepers et al., 2007). The inclination at each stride was estimated with the accelerometers. In this way integration time was limited to minimize integration drift. An orientation correction at each stride was not possible for the shank-sensor, since the shank is moving throughout the gait cycle. Inclination was corrected at the start of each trial using the accelerometers. The heading (direction) was corrected by the

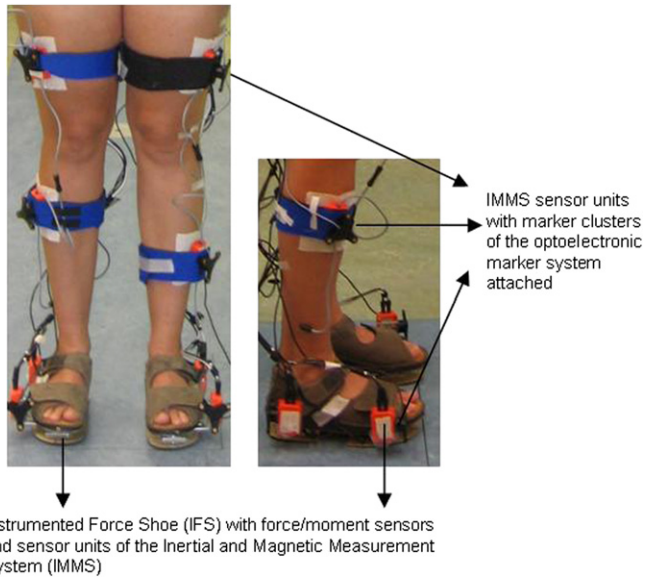

Fig. 1. Measurement set-up of instrumented force shoes (IFS), sensors of the inertial and magnetic measurement system (IMMS) and optoelectronic markers, positioned on the lower legs and feet.