INTRODUCTION

External knee adduction moment (EKAM) is correlated with presence, severity, and progression of knee osteoarthritis (OA) [1], which affected more than 27 million Americans. Reduction of peak EKAM is thus often a major goal of knee OA rehabilitation [2]. Recently, real-time EKAM feedback, calculated from a 3-D inverse dynamics, was found to be helpful to reduce the peak EKAM on a treadmill in a motion analysis lab setting [3]. However, 3-D inverse dynamics calculation is difficult to implement, especially outside motion analysis laboratories, due to the usual requirement of complex and expensive motion capture systems potentially occupying large designated space and demanding cumbersome setup [3-5]. To address the issue, two EKAM prediction methods, a regression model [4] and an artificial neural network [5], were developed. However, the two methods may not be used for real-time EKAM estimation, because the former predicts only group un-normalized peak EKAM, and the latter needs percentage of stance phase [5]. Therefore, the goal of this research is to develop a practical and reliable real-time EKAM estimation method during stepping on an elliptical trainer (ET) by solving the 3-D inverse dynamics with kinematic data from a simple 6-DOF goniometer for the training and clinical evaluation of patients with knee OA.

METHODS

A healthy male (age: 19; height: 1.74m; body mass: 69Kg) participated in this study approved by the IRB of Northwestern University and gave informed consent.

An ET (Reebok Spacesaver RL; Fig. 1) was equipped with 6-axis F/T sensors (JR3, Woodland, CA) on both sides underneath the footplates.

Figure 1: A modified elliptical trainer equipped with 6-axis F/T sensors (F/T below the footplate).

To measure ankle 3-D angle, one end of the goniometer was firmly strapped to the flat and bony anteromedial surface of the leg with neoprene bands to reduce its slip on subject’s skin, and the other end was attached laterally to the footplate, which had no motion relative to the foot because of the foot straps. Before stepping, 3-D zero ankle angles were measured by the goniometer at the footplate’s lowest position by aligning the 2nd metatarsal head, the midpoint between the lateral and medial malleoli and tibial tuberosity to be in the sagittal plane (y-a-z-a plane); and the center of the F/T sensor, lateral malleolus and lateral tibial condyle’s superior margin to be in the frontal plane (z-a-x-a plane). Using the goniometer, the 3-D ankle angles were computed in real-time similar to [6]. Footplate angle, $\beta$, was determined by solving inverse kinematics of the ET’s four-bar linkage structure, and foot Cartesian position from forward kinematics (Fig. 1). The subject’s anthropometric data of foot and shank including lengths, masses, and inertia matrices were determined [7,8]. Considering that non-zero pure moments about $x_a$ and $y_a$ axes exerted to footplate’s top surface may exist because foot was constrained to
footplate, center of pressure (COP) may not be computed on the ET with the F/T sensor [7-9]. However, since the measured forces and torques were directly transmitted to the foot, a modified 3-D inverse dynamics, which does not require the COP, was developed to estimate EKAM with respect to the tibial anatomical frame (Fig. 1) [5]. The EKAM was obtained as the negative of the internal knee adduction moment calculated from the inverse dynamics. To account for regular stepping posture and possible ad/abducted knee postures of patients with knee OA and other injuries, the subject’s EKAMs at three stepping conditions (regular, knee-adducted, and knee-abducted stepping) were estimated in real-time by using the proposed method, and corroborated with that from off-line estimation by using kinematic data from an optoelectric motion capture system (Optotrak 3020, Northern Digital, Waterloo, Canada) with 3 sets of markers (4 markers/set attached to a rigid shell) attached on thigh, shank, and foot in the same trials. The Optotrak data were sampled at 50 Hz and synchronized with all other signals collected at 100 Hz. The EKAM was computed at 100Hz using a custom real-time EKAM estimation program based on the modified 3-D inverse-dynamics. Elliptical cycle was defined as starting at the time the footplate reached the most anterior position and ending at the same position [10].

RESULTS AND DISCUSSION

The estimated EKAM from the proposed real-time estimation method with 6-DOF goniometer closely matched that from the off-line method using Optotrak 3020 for all the three types of stepping (Fig. 2). Moreover, peak EKAM at each cycle was increased in knee-adducted stepping and decreased in knee-abducted stepping systematically compared to that of regular stepping. The goniometer is low-cost and its analog outputs can be conveniently connected to data acquisition systems.

CONCLUSIONS

The EKAM estimate from the practical real-time estimation method using the compact goniometer needs only a few minutes to set up, and the result well agreed with that from the off-line method using a motion capture system with much more involved setup. Combined with the ETs’ advantages of lower impact during stepping, the real-time EKAM estimation method can be used for a subject-specific real-time biofeedback training of patients with knee injuries including knee OA so that the joint moment loading can be observed in real-time with different walking patterns, which can be used for clinical evaluation of walking pattern associated with excessive joint loading, and furthermore for guided rehabilitation training to reduce the excessive joint loading.

REFERENCES