Development of an Elliptical Trainer with Real-Time Knee Adduction Moment Feedback

Sang Hoon Kang
Rehabilitation Institute of Chicago /
Dept. of Physical Med & Rehab, Northwestern Univ.
Chicago, IL, USA
sanghoon.kang@northwestern.edu

Song Joo Lee
Dept. of Biomedical Eng.
Northwestern Univ.
Evanston, IL, USA
song-lee@northwestern.edu

Yupeng Ren
Rehabilitation Institute of Chicago
Chicago, IL, USA
yupeng.r@gmail.com

Li-Qun Zhang
Rehabilitation Institute of Chicago/Depts. of Physical Med & Rehab, Orthopaedic Surgery, and Biomedical Eng., Northwestern Univ.
Chicago, IL, USA
l-zhang@northwestern.edu

***Abstract*— The external knee adduction moment (EKAM) is associated with knee osteoarthritis (OA) in many aspects including its presence, progression, and severity. Despite of its importance, there is a lack of EKAM estimation methods that can provide patients with knee OA a *real-time* EKAM biofeedback during training and be used for routine clinical evaluations outside motion analysis laboratories. Thus, a practical real-time EKAM estimation method, which utilizes kinematic variables from a simple 6-DOF goniometer, was developed to provide patients with knee OA a real-time feedback of their EKAM during stepping on elliptical trainers (ETs) to reduce the damaging EKAM. Feasibility of the proposed method was verified on seven healthy subjects. Combined with advantages of ETs (e.g., functional weight-bearing stepping, mitigation of delivery of impulsive forces), the real-time EKAM estimation method is expected to benefit patients with knee OA.**

Keywords—Knee Adduction Moment; Knee Osteoarthritis; Real-time Biofeedback; Center of Pressure

I. Introduction

The external knee adduction moment (EKAM), especially its peak value, is correlated with many aspects of knee osteoarthritis (OA) – which affected more than 27 million Americans [1], and contributed to functional impairments and reduced independence in older adults [2] – including its presence [3, 4], severity [3, 4], and progression [5]. Thus, *reduction* of the peak EKAM is often a major goal of knee OA rehabilitation studies [3, 5-18]. Further, in a recent study, it was found that the real-time feedback of peak EKAM is helpful to reduce peak EKAM on a treadmill in a motion analysis lab setting [19]. The peak EKAM feedback was estimated as the max. of cross-product of GRF and moment arm from knee joint center to GRF during the first 40 % of the stance instead of 3 dimensional (3-D) inverse dynamics calculation by ignoring inertial contribution [19]. Therefore, it is important to estimate the EKAM in *real-time* biofeedback gait training and outcome evaluations. Indeed, 3-D inverse dynamics calculation is difficult to do, especially outside motion analysis laboratories (e.g., for large clinical trials, routine clinical evaluations, and trainings) due to the usual requirement of complex and expensive custom-made motion capture systems potentially occupying large designated space and demanding cumbersome set-up [8, 19-22]. Therefore, a practical and reliable *real-time* EKAM estimation method is strongly needed.

Elliptical trainers (ETs) are widely used in many places for exercise and research purposes [23-25]. ETs can be used for gait trainings, because ETs allow closed-chain functional weight-bearing stepping [24, 26, 27] with reduced GRF related to musculoskeletal injuries (e.g., knee OA) [23]. Furthermore, training on multi-axis ETs, having additional motorized pivoting and/or mediolateral sliding DOFs at each footplate, is promising for knee injury prevention/rehabilitation [26, 28-30].

The goal of this research is to develop a practical and reliable *real-time* EKAM estimation method that enables us to estimate the EKAM in real-time on a modified ET (Figs. 1 and 2) throughout the whole cycle by solving the 3-D inverse dynamics with lower-limb kinematic variables measured from a simple and compact 6-degree-of-freedom (DOF) goniometer instead of a complex motion tracking system. If successful, the EKAM of patients with knee OA can i) be fed back to the patients in real-time for effective training on the multi-axis ETs, and ii) be used for outcome evaluations. To test the feasibility of the proposed method, EKAMs of seven healthy subjects at three different stepping conditions (i.e., regular stepping, knee-adducted stepping, and knee-abducted stepping) were estimated in real-time by using the proposed method, and corroborated with that from an off-line estimation by using kinematic data from an optoelectronic motion capture system (Optotrak 3020, Northern Digital, Waterloo, Canada) at the same trials. A partial preliminary study was reported before [25].

II. External Knee Adduction Moment Estimation Method on Elliptical Trainers

A. Modified Elliptical Trainer with the 6-DOF Goniometer

An ET (Reebok Spacesaver RL) was instrumented with 6-axis force/torque (F/T) sensors (JR3, Woodland, CA) to measure 3-D force ($\mathbf{F}_{F/T}$) and moment ($\mathbf{M}_{F/T}$) vectors on both sides underneath the footplate (Fig. 1) with subtraction of footplate's gravitational and inertial components. To accurately measure 3-D ankle angles, the upper 3-DOF part of the 6-DOF goniometer, similar to the 6-DOF knee goniometer [31, 32], was firmly strapped to the flat and bony anteromedial surface of tibia/shank using neoprene bands to reduce the goniometer's

The authors would like to acknowledge the support of the NSF, NIH and NIDRR.

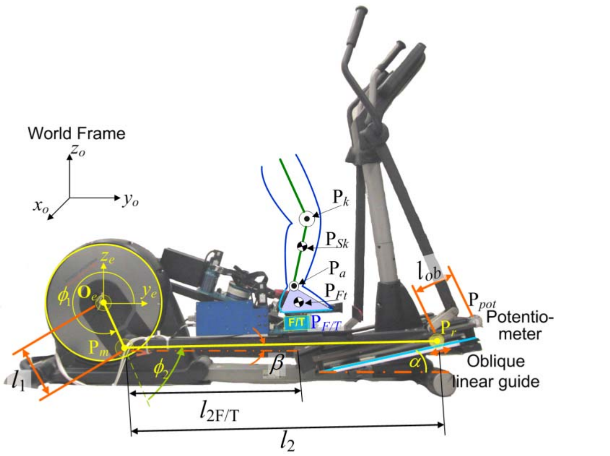

Fig. 1. A modified elliptical trainer with a right leg. The ET was instrumented with a 6-axis F/T sensor (blue box written F/T, $\mathbf{P}_{F/T}$) underneath eath footplate to measure 3-D reaction forces and torques (step length: ~0.47m). $\mathbf{P}_{Sk}$ and $\mathbf{P}_{Ft}$ denote shank and foot center of mass (COM), respectively. A precision potentiometer ($\mathbf{P}_{pot}$) measured distance (l_{ob}) along the oblique α=20° angled linear guide. l_1, l_2, and $l_{2F/T}$, the constant lengths, were 0.24m, 1.19m, and 0.77m, respectively.

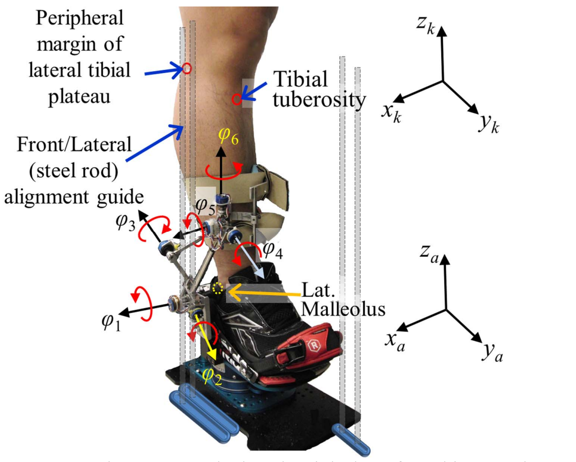

Fig. 2. A 6-DOF goniometer attached to the right leg of a subject on the ET. The upper part was firmly strapped to the flat and bony anteromedial surface of tibia/shank to reduce the goniometer's slip on subject's skin, and the lower part was attached to the lateral side of the footplate while aligning one potentiometer of the goniometer with lateral malleolus. The easily removable long steel rods as alignment guides at the lateral and front sides of the footplate assisted initial alignment of the ankle and knee joints.

slip on subject's skin, and the lower 3-DOF part was attached lateral to the footplate, which had no motion relative to the foot because of the foot straps (Fig. 2) [26, 28-30].

B. Kinematics

Four frames of reference were defined (Figs. 1 and 2). For the right leg, the positive directions of the x, y, and z axes of the world frame (WF) were lateral, anterior, and upward directions, respectively. An ET frame (ETF), the orientation of which is the same that of as the WF, was defined with its origin at $\mathbf{O}_e$. Ankle anatomical frame (AAF), the three orthogonal axes of which are x_a, y_a, and z_a axes, denoted a frame attached to the foot with its origin at the midpoint between the medial and lateral malleolus ($\mathbf{P}_a$). The y_a-axis (long axis) of the AAF was defined as the projection of a vector from $\mathbf{P}_a$ to the 2nd metatarsal head onto the footplate; z_a-axis as the upward direction vector orthogonal to the footplate surface from $\mathbf{P}_a$; and x_a-axis as the cross product of y_a- and z_a-axis vectors, similar to [33]. Tibial (knee) anatomical frame (TAF; x_k, y_k, and z_k axes) represented a frame attached to the tibia with its origin (tibial origin) at the midpoint between the peripheral margins of medial and lateral tibial plateaus ($\mathbf{P}_k$). The z_k-axis (long axis) of the TAF was defined as the vector from $\mathbf{P}_a$ to $\mathbf{P}_k$; y_k-axis as the cross product of the z_k-axis and a vector from the medial to lateral tibial plateaus; and x_k-axis as the cross product of y_k- and z_k-axis vectors [34].

1) Kinematics of the Elliptical Trainer

The angle (β=ϕ_1+ϕ_2) between the footplate and the ground was needed for the EKAM estimation to determine foot orientation (${}^e\boldsymbol{\theta}_{Ft}$). A precision potentiometer at ${}^e\mathbf{P}_{pot}$(=[${}^ex_{pot}$ ${}^ey_{pot}$ ${}^ez_{pot}$]^T)[1] measured distance (l_{ob}) from ${}^e\mathbf{P}_{pot}$ to the anterior end (${}^e\mathbf{P}_r$=[${}^ex_r$ ${}^ey_r$ ${}^ez_r$]^T) of the long beam (Fig.1). Because $\mathbf{P}_r$ was moving along an oblique linear guide, l_{ob} and the angle (α=20°) of the linear guide completely determined ${}^ey_r$ and ${}^ez_r$. Also, ${}^ey_r$ and ${}^ez_r$ could be obtained from the following kinematic relation of the ET:

$$\begin{bmatrix} {}^ey_r \\ {}^ez_r \end{bmatrix} = \begin{bmatrix} \cos(\phi_1) & \cos(\phi_1+\phi_2) \\ \sin(\phi_1) & \sin(\phi_1+\phi_2) \end{bmatrix} \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} \tag{1}$$

where l_1 and l_2 denote the length of the short beam ($\mathbf{O}_e$ to $\mathbf{P}_m$) and that of the long beam, respectively (Fig. 1). Thus, one can obtain ϕ_1 and ϕ_2 by solving (1) with l_1, l_2, and ${}^ey_r$ and ${}^ez_r$ obtained from l_{ob}. Although two sets of solutions (postures of the two beams) were possible, a proper one could be selected during stepping on the ET with a known initial position of the footplate (initial posture of the two beams), unless subjects changed the stepping direction. With ϕ_1 and ϕ_2 obtained, the center of F/T sensor position (${}^e\mathbf{P}_{F/T}$) could be calculated by replacing l_2 in (1) with $l_{2F/T}$ (Fig. 1).

2) Kinematics of the 6-DOF Goniometer

The goniometer needed two steps of calibration to measure the 3-D ankle angles for real-time EKAM estimation. It was calibrated offline to find zero angles with a calibration plate [31, 32]. Note that the calibrated zero angles were different from the zero anatomical ankle angles (i.e., 0° dorsiflexion/ planar-flexion, 0° inversion/eversion, and 0° internal/external rotation). To obtain each subject's zero anatomical angles, a two-step on-line initial alignment was then performed at footplate's lowest position where subjects bore ~100% bodyweight at that leg using long steel rods (as alignment guides) at lateral and frontal slots (Fig. 2). The lateral side guides, extension of which passed the sagittal projection of $\mathbf{P}_{F/T}$, overlapped each other in the sagittal plane (y_a-z_a plane), and the front ones overlapped in the frontal plane (x_a-y_a plane). In the frontal plane, 2nd metatarsal head, midpoint between the lateral and medial malleolus, and the long axis of tibia were aligned with front-side guides (Fig. 2). In the sagittal plane, the subjects' lateral malleolus and peripheral margin of lateral tibia plateau were then aligned with lateral guides so that the peripheral margin of lateral tibia plateau, the lateral malleolus, and $\mathbf{P}_{F/T}$ were all in a line (Fig. 2).

At the alignment, the rotation matrix (${}^a_{lj}\mathbf{R}_i$) from the last (6th) frame of the goniometer moving with the TAF to the AAF,

[1] The leading superscripts denote the frame of reference: o, e, a, and k denote the world, the ET, the ankle, and the tibial (knee) frame, respectively.

being computed with the 6 angles (φ_i; i=1,2,…,6), was saved. With ${}^{a}_{lf}\mathbf{R}_i$, the rotation matrix from the TAF to the AAF, ${}^{a}_{k}\mathbf{R}$, during stepping on the ET could be computed as follows [31]:

$$ {}^{a}_{k}\mathbf{R} = {}^{a}_{lf}\mathbf{R}\,{}^{a}_{lf}\mathbf{R}_i^{-1} \qquad (2)$$

where ${}^{a}_{lf}\mathbf{R}$ denotes the rotation matrix from the last frame of the goniometer to the AAF, being computed using the 6 angles of the goniometer. ${}^{a}_{k}\mathbf{R}$ completely describes the 3-D ankle rotation. Theoretically, any Euler or fixed angle set will result in the same EKAM, although the resulting equation of the EKAM may be seemingly different depending on the angle set chosen. The *x-y-z* Euler angle set was chosen to describe the 3-D ankle angle and, if needed, any other angle set can be used instead.

Motion capture systems have their own difficulties: a longtime preparation of attaching markers for visual/non-visual motion tracking, occlusion of the leg of interest for visual motion tracking systems (e.g., optical marker dropouts), drifts in velocity and position computation using accelerometer data, magnetic sensors' distorted sensing due to the magnetic fields of other devices and/or structures [35], and the 6-DOF goniometer's slip on subject's skin that can be reduced. Nevertheless the goniometer can be an alternative to other systems because of its practical *merits*: occupation of small space around the footplate; fairly lower-cost than other systems; and convenient connection to any analog to digital (A/D) data acquisition system with a user-selected sampling rate within the system's capability.

C. Modified 3-D Inverse Dynamics

A modified 3-D inverse dynamics, which does not require center of pressure (COP), was developed for the EKAM estimation with respect to (w.r.t) the TAF [8, 20, 21, 36]. Using the inverse dynamics, internal knee adduction moment was calculated and the EKAM was then obtained as the negative of the calculated internal knee adduction moment [13, 37].

Generally, the COP – which is required for the well-established 3-D inverse dynamics calculation – is computed from the following relation between the COP, $\mathbf{F}_{F/T}$, and $\mathbf{M}_{F/T}$ with an *assumption that there is no pure moment* exerted on the force plate in the horizontal plane (i.e., zero pure moments about x_a axis (T_x=0) and that about y_a axis (T_y=0)).

$$\begin{bmatrix} {}^{a}M_{F/T\_x} \\ {}^{a}M_{F/T\_y} \end{bmatrix} = \begin{bmatrix} {}^{a}F_{F/T\_z}\,y_{cop} - {}^{a}F_{F/T\_y}\,z_{off} \\ -{}^{a}F_{F/T\_z}\,x_{cop} + {}^{a}F_{F/T\_x}\,z_{off} \end{bmatrix} + \begin{bmatrix} T_x \\ T_y \end{bmatrix} \qquad (3)$$

where ${}^{a}F_{F/T\_x}$, ${}^{a}F_{F/T\_y}$, and ${}^{a}F_{F/T\_z}$ denote x_a, y_a, and z_a direction components of measured $\mathbf{F}_{F/T}$, respectively; ${}^{a}M_{F/T\_x}$ and ${}^{a}M_{F/T\_y}$ denote the x_a and y_a direction components of measured $\mathbf{M}_{F/T}$, respectively; z_{off} the z_a direction known distance from $\mathbf{P}_{F/T}$ to the top surface of the footplate; x_{cop} and y_{cop} denote x_a and y_a direction distances from $\mathbf{P}_{F/T}$ to COP, respectively. Note that (3) is a general relation – which can be easily found in the technical notes or user manuals of force plate manufacturers (e.g., AMTI or Bertec) – because of the inclusion of possible *non-zero* T_x and T_y. The assumption is valid when the foot is not constrained to the ground (or footplate) such as over-ground walking [38-40]. However, in the case of the modified ET, the assumption may be violated because of the possible existence of the non-zero T_x and/or T_y, considering that no relative motion between the foot and the footplate was allowed (i.e., foot was strapped to the footplate). Thus, in this case, COP may not be able to be computed unless T_x and T_y are separately measured. It should be noted that the goal of this specific research is not to find the COP but to estimate the EKAM.

Without the COP, the net ankle and knee moments can, however, be computed. No relative motion between the foot and the footplate indicates that the two can be regarded as a one rigid body, and the $\mathbf{F}_{F/T}$ and $\mathbf{M}_{F/T}$ being exerted to the footplate are, thus, directly transmitted to the foot as written below:

$$m_{Ft}\,{}^{a}\mathbf{a}_{Ft} = {}^{a}\mathbf{F}_{F/T} + {}^{a}\mathbf{F}_{a} + m_{Ft}\,{}^{a}\mathbf{g} \text{ and} \qquad (4)$$

$$\begin{aligned} {}^{a}\mathbf{I}_{Ft}\,{}^{a}\ddot{\boldsymbol{\theta}}_{Ft} &= \left({}^{a}\mathbf{P}_{F/T} - {}^{a}\mathbf{P}_{Ft}\right) \times {}^{a}\mathbf{F}_{F/T} + \left({}^{a}\mathbf{P}_{a} - {}^{a}\mathbf{P}_{Ft}\right) \times {}^{a}\mathbf{F}_{a} \\ &\quad - {}^{a}\dot{\boldsymbol{\theta}}_{Ft} \times {}^{a}\mathbf{I}_{Ft}\,{}^{a}\dot{\boldsymbol{\theta}}_{Ft} + {}^{a}\mathbf{M}_{F/T} + {}^{a}\mathbf{M}_{a} \end{aligned} \qquad (5)$$

where m_{Ft} denotes foot mass; ${}^{a}\mathbf{I}_{Ft}$ foot inertia matrix; ${}^{a}\mathbf{a}_{Ft}$ the linear acceleration of the foot COM ($\mathbf{P}_{Ft}$); ${}^{a}\mathbf{g}$ gravitational acceleration w.r.t. the AAF; ${}^{a}\mathbf{F}_{a}$ and ${}^{a}\mathbf{M}_{a}$ force and moment vectors acting on the ankle origin from the shank. ${}^{a}\mathbf{F}_{a}$ and ${}^{a}\mathbf{M}_{a}$ can be obtained by solving (4) and (5) that represent translational and rotational motions, respectively. Obviously, (4) and (5) do not require the COP, and, if COP is needed for the real-time EKAM estimation, a real-time online computation of it is required. Instead of the COP, for each subject, (5) needed the fixed distances (${}^{a}\mathbf{P}_{F/T}$–${}^{a}\mathbf{P}_{Ft}$) and (${}^{a}\mathbf{P}_{a}$–${}^{a}\mathbf{P}_{Ft}$) that can be obtained off-line. The foot and shank masses and inertia matrices also are fixed values for each subject, and can be estimated from anthropometric data [38, 39]. Therefore, the COP computation is no longer needed for the computation of the ankle forces (${}^{a}\mathbf{F}_{a}$) and moments (${}^{a}\mathbf{M}_{a}$). Thus, COP is not required for the estimation of the EKAM (and also other two direction, flexion and internal rotation, external knee moments) that is, in turn, obtained with the computed ${}^{a}\mathbf{F}_{a}$ and ${}^{a}\mathbf{M}_{a}$ and the inertial forces and moments of shank. Thus, the EKAM (and other two direction external knee moments) on the ET can be estimated using the modified 3-D inverse dynamics without COP.

This modified 3-D inverse dynamics was utilized for the real-time estimation of the EKAM (and other two direction external knee moments) with kinematic data from the 6-DOF goniometer (hereafter called 'Real-time method'), and also for an off-line estimation method (hereafter called 'Off-line method') with kinematic data obtained from an optoelectric system (Optotrak 3020). The Off-line method represents typical analysis performed at motion analysis laboratories.

III. Experiments

A. Subjects

Seven healthy males (age: 25.3±5.8years; height: 1.81± 0.06m; leg length: 0.840±0.074m; body mass: 77.6±5.5Kg; body mass index: 23.86 ±1.99Kg/m^2) participated in this study approved by the institutional review board of Northwestern University and gave informed consent.

B. Experimental Procedure

Each subject's anthropometric data of foot and shank including lengths, masses, and inertia matrices were taken [38, 39], and entered to the real-time EKAM estimation program, which estimates EKAM and other two direction external knee moments in real-time based on the modified 3-D inverse dynamics. To corroborate the estimated EKAM from the Real-time method with that from the Off-line method, lower-limb motion during stepping on the ET was recorded with an Optotrak 3020. Three marker clusters, each of which has 4 optical markers attached to a rigid shell, were placed on the subject's right foot, shank, and thigh [41]. The 6-DOF goniometer was strapped to the flat and bony anteromedial surface of subject's right tibia/shank with the initial alignment described in Section II.B.2) while aligning one potentiometer of the goniometer with lateral malleolus (Fig. 2). Before collecting data, subjects practiced to the stepping on the ET for ~3 min and foot straps were adjusted to minimize foot motion relative to the footplate. Subjects were then asked to do three different types of stepping – regular stepping, knee-adducted stepping, and knee-abducted stepping – at their comfortable pace for ~1.5 min per condition with adequate rests in between. During the ET trials, subjects did not hold onto the handles. The marker data were collected using an Optotrak 3020 at 50Hz sampling rate and synchronized with all other measured signals. 100Hz sampling rate was used for measuring 6-axis forces and torques from the 6-axis F/T sensor, 3-D ankle angle from the goniometer, and the l_{ob} from the front potentiometer to compute the EKAM estimate using the Real-time method. On completion of the ET trials, anatomic landmarks were digitized using additional optical markers to establish relationships between landmarks and marker locations, similar to [41]. Landmarks include right leg's 2^{nd} metatarsal head, medial and lateral malleoli, peripheral margins of medial and lateral tibial plateaus, and medial and lateral femoral epicondyles, sacrum, and left and right anterior superior iliac spines.

C. Data Analysis

3-D knee angle was obtained from the Optotrak data [34]. Following [23], the elliptical cycle (EC) was defined as starting and ending at the time when the footplate reached the most anterior. Ten cycles' data were selected from each subject's each type of stepping. The EKAM estimate was normalized i) to body weight times height with the unit of %BW×HT, and ii) to body weight times leg length with the unit of %BW×LL for the case of regular stepping to compare the results with a previous study [23]. The normalized EKAM was time normalized using the EC (0-100%) and, for each subject's each type of stepping, mean of 10 cycles was then obtained. Other two direction external knee moments during regular stepping were normalized in the same manner. Similarly, 3-D ankle and knee angles were time normalized and averaged across the cycles. Differences in stepping speed among the three conditions were determined with repeated measure ANOVA. The Pearson correlation coefficient, *r,* was used with linear regression to test the association between the EKAM estimates from the Real-time method and ankle eversion angles, between the EKAM estimates from the Real-time method and knee adduction angles, and between the EKAM estimates from the Real-time method and that from the Off-line method. To determine the agreement between the EKAM estimates from the Real-time method and that from the Off-line method, the limits of agreement (LOA) [42] and intraclass correlation coefficient (ICC(2,1)) [43] between the two sets of EKAM estimates were computed. The one sample *t*-test was performed

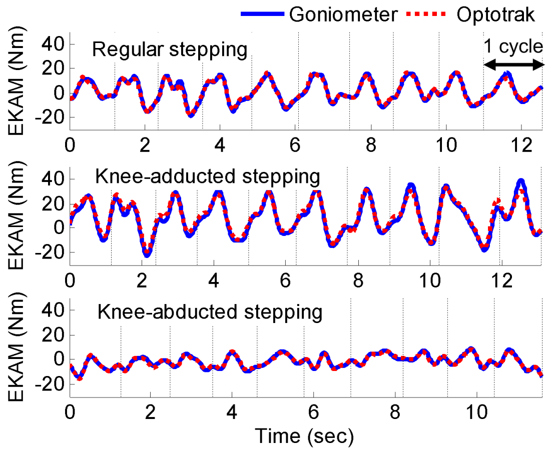

Fig. 3. A representative EKAM estimation results of a subject during 10 cycles of stepping at the three different conditions. From the top to the bottom plot, EKAM estimate during regular stepping, that during knee-adducted stepping, and that during knee-abducted stepping, respectively.

to determine if ankle angle was always dorsiflexed on the ET during regular stepping. Significance level was taken as 0.05.

D. Experimental Results

Among the stepping speed of the three conditions (regular stepping: 36.3±8.3 rev/min; knee-adducted stepping: 34.3±10.2 rev/min; knee-abducted stepping: 37.2±11.9 rev/min), no significant difference was found. A representative EKAM estimation results of a subject from the Real-time method and from the Off-line method are shown in Fig. 3. In this case, the estimated EKAM from the Real-time method was close to that from the Off-line method for all the three types of stepping. Moreover, peak EKAM at each cycle was increased in knee-adducted stepping but decreased in knee-abducted stepping compared to that of regular stepping.

One can find similarities between the kinematic and kinetic variables obtained in this study (Fig. 4) and those in previous ET studies [23, 24], although, in those studies, subjects' two feet were not strapped to the corresponding footplates. Similar to the ankle dorsiflexion angle reported in [24], the ankle dorsiflexion angle measured had two peaks (at ~34% and ~70.1% of the EC) and ankle was always dorsiflexed throughout the whole EC ($p \leq 0.0193$). Note that planar-flexion in the interval of the 0 to ~30 % of the EC was reported in [23]. This difference in ankle dorsiflexion angle may stem from the difference in the location of the driving wheel of the two ETs that can influence on the kinematic structure of ETs and the consequent subject's foot trajectory: a front-drive ET was used in [23], in contrast to the rear-drive one used in this study. The locations of two peaks of external knee flexion moment (one at ~10.3% and another at ~75.8%) were similar to those in [23] (Fig. 4(c)). Differences between the peak values of each component of the 3-D external knee moment measured and those in [23] were smaller than ~2 standard deviations in [23].

The peak value of mean normalized EKAM from the Real-time method was strongly and positively correlated with corresponding mean ankle eversion angle measured with the goniometer (Fig. 5; r= 0.79; p<0.001). Biomechanically, it is reasonable because increase in the eversion angle may increase the length of the mediolateral moment arm from the knee joint to the GRF on the ET and thus increase the EKAM.

The peak value of mean normalized EKAM from the real-time method was also significantly and positively correlated with the peak mean knee adduction (i.e., varus) angle obtained from the Optotrak data (Fig. 5(b); r=0.46; p= 0.0434). Varus knee alignment is known as one of the best predictors of a high EKAM [7].

Peak value of normalized EKAM estimate from the real-time method was strongly and positively correlated with that from the Off-line method (Fig. 5(c); r=0.9628; p<0.001). Moreover, high ICC(2,1) between the two (0.9580; 95% confidence interval: [0.9404, 0.9698]) close to unity, and the near unity slope (0.9055; 95% confidence interval: [0.8699, 0.9411]) of the regression line between the two indicate that the proposed real-time EKAM estimation method well agreed with the Off-line method [43]. Median difference [42] between the two estimates (0.06%BW×HT) was smaller than that (0.12%BW×HT) in [20]. The LOA (5^{th} and 95^{th} percentile of the difference between the two estimates) were [-0.384, 0.679]%BW×HT, and magnitude of both limits were smaller than the peak EKAM difference between healthy controls and patients with knee OA (0.89%BW×HT) [44] and between patients with doubtful/minimal knee OA and moderate/severe knee OA (1.3%BW×HT) [4], further supporting the agreement between the two methods.

IV. Disscussions and Conclusions

The EKAM estimate from the practical real-time estimation method using the compact and inexpensive goniometer with few minutes of preparation was well agreed with that from the Off-line method using a large and expensive motion capture system with cumbersome setup.

Combined with the ETs' advantages, the real-time EKAM estimation method may be used for a (subject-specific) real-time biofeedback training of patients with knee injuries including knee OA instead of asking them to follow a pre-specified gait pattern with real-time biofeedback of kinematic variables [3, 6-8, 15-17] or foot pressure [18]; for routine clinical evaluation of the patients; and, potentially, for various clinical evaluations and therapeutic interventions.

Disclosure

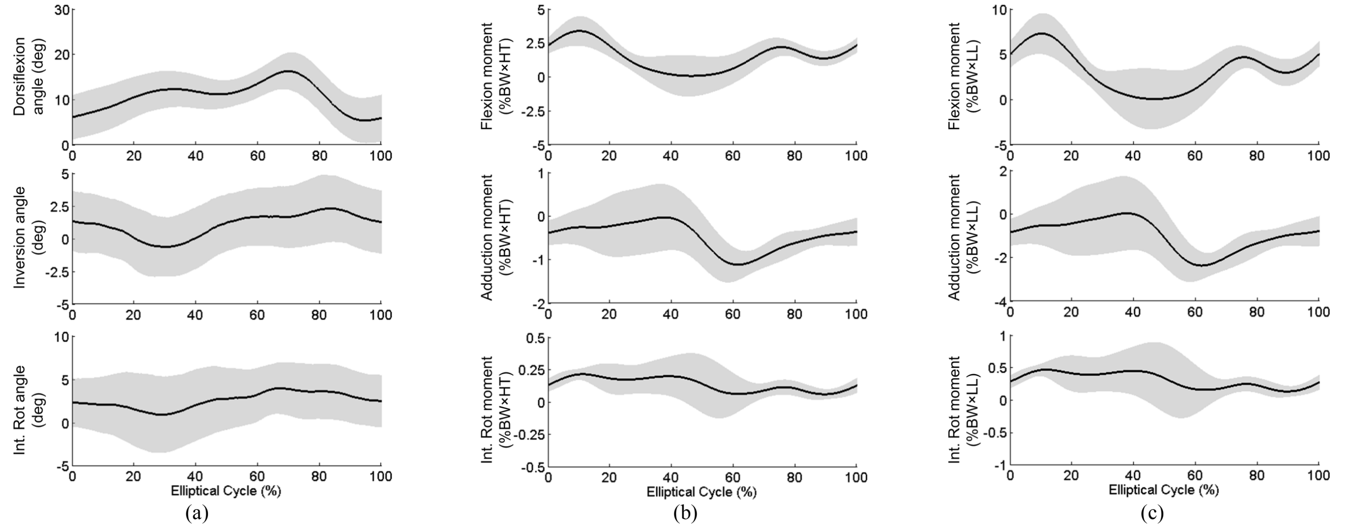

Fig. 4. Three dimensional ankle angles and external knee moments during regular stepping on the elliptical trainer. Solid lines represent mean value, shades stand for standard deviation. (a) Ankle angles during regular stepping. From the top plot to the bottom, dorsiflexion, inversion, and internal rotation angle, respectively. (b) 3-D external knee moments normalized by body weight times height (%BW×HT). From the top plot to the bottom, external flexion, adduction, and internal rotation moment, respectively. (c) 3-D external knee moments normalized by body weight times leg length (%BW×LL).

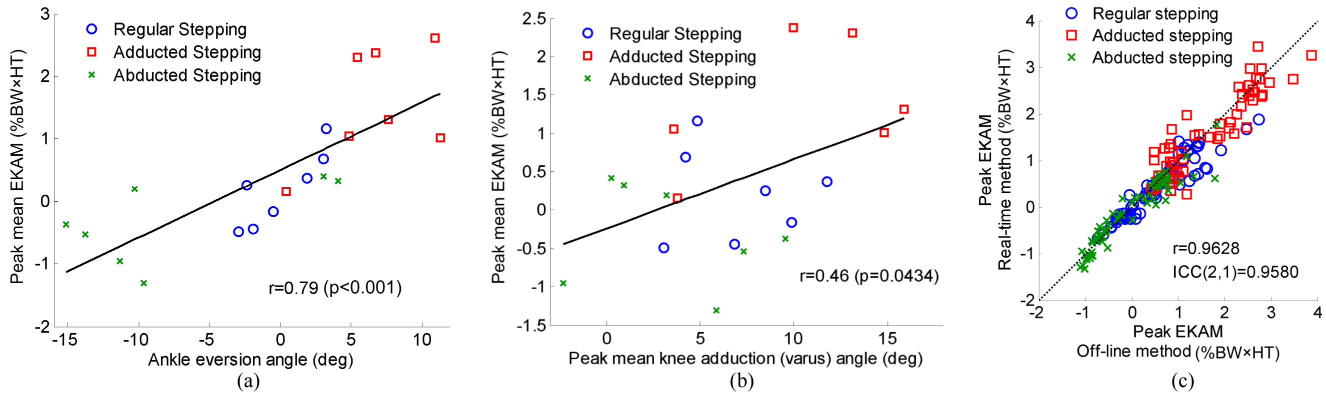

Fig. 5. (a) Relationship between peak value of mean normalized EKAM and corresponding mean ankle eversion angle from three different stepping conditions: regular, knee-adducted, and knee-abducted stepping. (b) Relationship between peak value of mean normalized EKAM and peak mean knee adduction (varus) angle from the three different stepping conditions. (c) Relationship between peak EKAM estimate from the Off-line method and that from the proposed *real-time* estimation method from the three different stepping conditions. Black dotted line represents ideal relationship between the two peak EKAM estimates with the slope of unity. Each 10 cycles of EKAM at each stepping condition of 7 subjects are displayed.

L.-Q. Zhang and Y. Ren have equity positions in Rehabtek LLC, which is involved in developing the custom elliptical trainer in this study.

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