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Short communication

Integrating dynamic stereo-radiography and surface-based motion data for subject-specific musculoskeletal dynamic modeling

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ABSTRACT

This manuscript presents a new subject-specific musculoskeletal dynamic modeling approach that integrates high-accuracy dynamic stereo-radiography (DSX) joint kinematics and surface-based full-body motion data. We illustrate this approach by building a model in OpenSim for a patient who participated in a meniscus transplantation efficacy study, incorporating DSX data of the tibiofemoral joint kinematics. We compared this DSX-incorporated (DSXI) model to a default OpenSim model built using surface-measured data alone. The architectures and parameters of the two models were identical, while the differences in (time-averaged) tibiofemoral kinematics were of the order of magnitude of 10° in rotation and 10 mm in translation. Model-predicted tibiofemoral compressive forces and knee muscle activations were compared against literature data acquired from instrumented total knee replacement components (Fregly et al., 2012) and the patient's EMG recording. The comparison demonstrated that the incorporation of DSX data improves the veracity of musculoskeletal dynamic modeling.

1. Introduction

Musculoskeletal modeling frameworks such as OpenSim (Delp et al., 2007) and AnyBody (Damsgaard et al., 2006) enable in-depth mechanistic understanding of normal or pathological movements. These musculoskeletal modeling tools require specification of skeletal kinematics and external loads to create subject-specific computer simulations. Skeletal kinematics data have traditionally been obtained with surface-based motion capture systems. These systems have many advantages such as being non-invasive, easy to use, and relatively inexpensive. However, the accuracy of surface-measured kinematic data is compromised by soft tissue artifacts (STAs). The magnitudes of STAs, as assessed using external fixation devices or radiographic imaging, can reach more than 15 mm at bony landmarks (Maslen and Ackland, 1994; Sati et al., 1996) and up to 40 mm on the thigh (Barre et al., 2013; Cappozzo et al., 1996; Tsai et al., 2009, 2011).

The past decade has witnessed the increasing use of dynamic stereo-radiography (DSX) and similar (e.g., bi-planar fluoroscopy) systems for measuring in vivo three-dimensional (3D) joint kinematics (Berthonnaud et al., 2005; Brainerd et al., 2010; Hanson et al., 2006; Tashman and Anderst, 2003). A DSX system, for example, is capable of measuring joint kinematics with static accuracy of ±0.2 mm in translation and ±0.2 degree in rotation and dynamic accuracy of ±0.4 mm in translation and ±0.6 degree in rotation (Anderst et al., 2009). The differences between surface-based model-derived and DSX-measured kinematics have been found to be substantial – the overall mean (±SD) RMS differences were up to $9.1 \pm 3.2^\circ$ in rotation and 8.8 ± 3.7 mm in translation for tibiofemoral kinematics during running (Li et al., 2012). However, DSX and similar systems currently can image only one small body region or single joint at a time due to their limited fields of view, and only for a short duration due to radiation exposure restrictions.

This work aimed to establish an approach that incorporates in vivo joint kinematics obtained from a DSX system and full-body kinematics from a surface-based motion capture system to create subject-specific musculoskeletal dynamic models, and to evaluate the resulting model veracity in terms of joint force and muscle activation predictions.

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2. Methods

We modeled a patient with subtotal left lateral meniscectomy (30-year-old male, height 187 cm, mass 112 kg) who participated in an Institutional Review Board (IRB) approved experimental study of meniscus transplantation efficacy. The patient performed a static upright standing trial and gait trials (at 1.0 m/s) on a dual-belt instrumented treadmill. A customized DSX system imaged the tibiofemoral motion of the meniscetomized knee in one gait trial and the intact knee in another. An eight-camera motion capture system (Vicon-MX, Oxford, UK) measured the full-body motion with a set of retro-reflective spherical surface markers (1 cm diameter) placed according to the Plug-in-Gait marker set protocol (Davis et al., 1991). The sampling frequency for both systems was set at 100 Hz. The ground reaction forces (GRFs) were measured at 1000 Hz by two force plates (Bertec Corporation, Columbus, OH) embedded in the treadmill. Electromyography (EMG) data for seven lower limb muscles – vastus medialis, rectus femoris, vastus lateralis, biceps femoris, semimembranosus, tibialis anterior, and medial gastrocnemius – were collected at 1000 Hz using a wireless EMG system (ZW180, Zero Wire, Milano, Italy). The recorded data across different systems were synchronized using a precision pulse generator (Model 565, Berkeley Nucleonics Corporation, San Rafael, CA). High-resolution CT scans (slice spacing: 0.625 mm) of both knees were also collected.

A volumetric model-based tracking process determined 3D tibiofemoral kinematics with sub-millimeter accuracy using recorded DSX images and CT-acquired bone models (Anderst et al., 2009). The recorded surface-marker data, GRFs, and EMG were processed and prepared for subsequent modeling steps using a “Gait Extract Toolbox” (Dorn, 2008): the GRFs were low-pass filtered at 20 Hz, and EMG data were high-pass filtered at 20 Hz, rectified and low-pass filtered at 5 Hz.

Two distinct models, a default model and a DSX-incorporated (DSXI) model, were developed in OpenSim (Fig. 1). The default model was based on the latest generic OpenSim model (Arnold et al., 2010) and made subject-specific by employing the surface-based kinematics data alone. The tibiofemoral joint was modeled as a 1-DOF joint: two rotations (external–internal and abduction–adduction) and three translations (anterior–posterior, lateral–medial and proximal–distal) between femur and tibia were constrained by cubic spline functions of flexion–extension knee angles based on literature data (Walker et al., 1988). The DSXI model was based on the same model by Arnold et al. (2010) but integrated the DSX-measured tibiofemoral kinematics with the surface-based whole-body kinematics: the tibiofemoral joint was defined as a 5-DOF joint (external–internal rotation, abduction–adduction, flexion–extension, and anterior–posterior and lateral–medial translations were independent); the proximal–distal translation was specified as a cubic spline function of the knee flexion–extension angle based on DSX-measured kinematics. We chose to model the tibiofemoral joint as a 5-DOF joint instead of a 6-DOF joint, which would have required inclusion of the knee ligaments as restraints. The chosen approach greatly reduced the computational cost and avoided introducing more modeling variables or unknowns (e.g., ligament force–length properties). The constraint of the proximal–distal translation as a function of flexion–extension accounted for the effect of ligamentous constraints without explicitly modeling the ligaments. The proximal–distal translation DOF was chosen, given that the residual force in that direction would otherwise be relatively large.

The local coordinate systems (CS) on the femur and tibia in the two models were unified into a common anatomical knee CS (see Fig. 1) defined based on consistently identifiable anatomical landmarks and embedded in the DSX data/model (Tashman et al., 2004). In doing so, the literature-based knee kinematic constraints in the default model remained unchanged in the common anatomical knee CS, while functions describing the constraints were transformed.

For both models, the standard OpenSim procedures, including scaling, inverse kinematics (IK), residual reduction algorithm (RRA), and computed muscle control (CMC) algorithm (Delp et al., 2007; Thelen et al., 2003), were applied to create dynamic simulation of the gait motion. The implementation of the DSXI model required modification of the scaling and IK procedures that determined the joint kinematics input to the later dynamic simulation and prediction steps (i.e., RRA, CMC and Joint Reaction analysis). In the scaling procedure, both models were scaled according to the patient's anthropometric measurements and the surface marker data from the static standing trial; in the DSXI model, the DSX-measured knee position in the static trial was set as the neutral posture. In the IK procedure, the default model derived the joint angles of the entire body by matching the model virtual marker motions with the measured surface marker motions, whereas the DSXI model incorporated both surface-measured kinematics and DSX-measured knee kinematics – the knee joint angles were forced to equal DSX measurements while the remaining joints angles were determined such that the virtual marker motions best matched the measurements (Lu and O'Connor, 1999). The compressive tibiofemoral force was calculated using the Joint Reaction analysis in OpenSim (Steele et al., 2012).

The EMG data recorded simultaneously with the kinematics were used to compare the muscle activation predictions by the models. To estimate the muscle activations, EMG data were normalized according to the minimum and maximum values over multiple repeated gait cycles (the average ± one standard deviation). The tibiofemoral in vivo compressive load data measured from an instrumented total knee replacement (TKR, age: 83 years, weight: 64.6 kg, height: 166 cm) publicly available (https://simtk.org/home/kneeloads) (Fregly et al., 2012) were used for comparing the joint compressive force predictions by the two models (Fig. 2).

3. Results

The tibiofemoral compressive forces predicted by the DSXI model were in closer agreement with in vivo TKR measurements than the default model (Fig. 2). The maximum compressive forces during gait predicted by the DSXI model were 2.2 times body weight (BW) in both the meniscectomized and intact knees; the maximum compressive forces predicted by the default model were 3.8 times BW in the meniscectomized knee and 4.0 times BW in the intact knee. The default model not only over-estimated the tibiofemoral compressive forces, but also seemed to amplify the difference between the intact and injured knees (Fig. 2).

The muscle activations predicted by both models were generally consistent with the muscle activation patterns estimated from the EMG data recorded during gait (Fig. 3). The activations of quadriceps (e.g., rectus femoris) and hamstrings (e.g., biceps

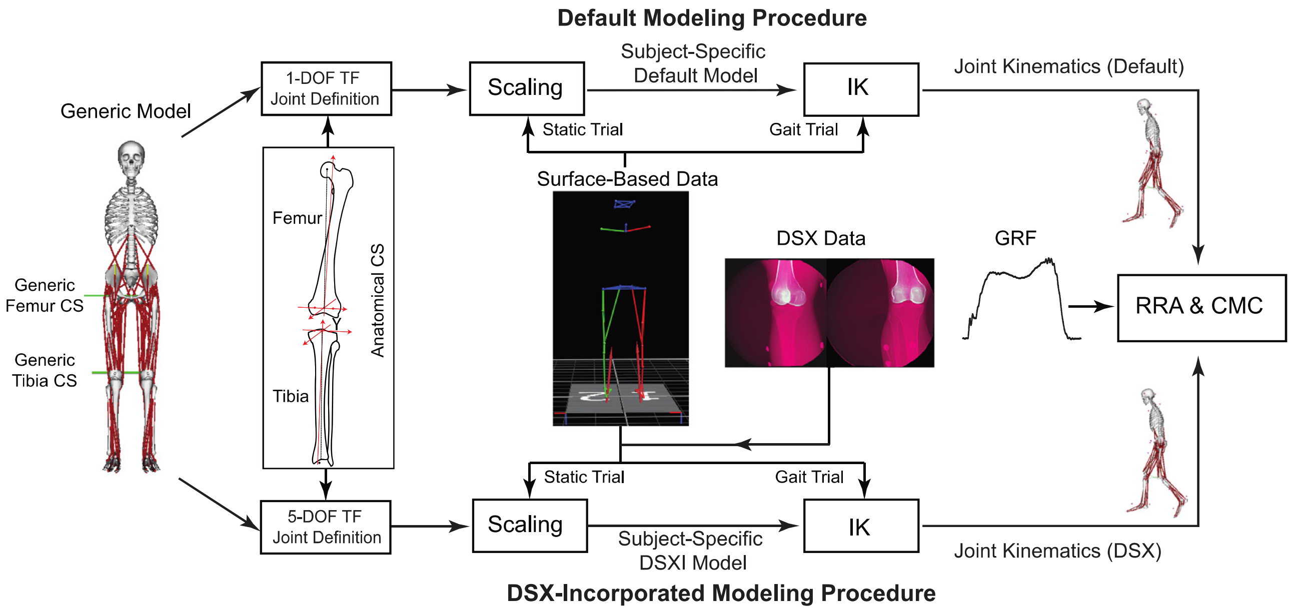

Fig. 1. Flowchart comparing procedures for constructing the two subject-specific musculoskeletal dynamic models in OpenSim.