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TLEM 2.0 – A comprehensive musculoskeletal geometry dataset for subject-specific modeling of lower extremity

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A B S T R A C T

When analyzing complex biomechanical problems such as predicting the effects of orthopedic surgery, subject-specific musculoskeletal models are essential to achieve reliable predictions. The aim of this paper is to present the Twente Lower Extremity Model 2.0, a new comprehensive dataset of the musculoskeletal geometry of the lower extremity, which is based on medical imaging data and dissection performed on the right lower extremity of a fresh male cadaver. Bone, muscle and subcutaneous fat (including skin) volumes were segmented from computed tomography and magnetic resonance images scans. Inertial parameters were estimated from the image-based segmented volumes. A complete cadaver dissection was performed, in which bony landmarks, attachments sites and lines-of-action of 55 muscle actuators and 12 ligaments, bony wrapping surfaces, and joint geometry were measured. The obtained musculoskeletal geometry dataset was finally implemented in the AnyBody Modeling System™ (AnyBody Technology A/S, Aalborg, Denmark), resulting in a model consisting of 12 segments, 11 joints and 21 degrees of freedom, and including 166 muscle–tendon elements for each leg. The new TLEM 2.0 dataset was purposely built to be easily combined with novel image-based scaling techniques, such as bone surface morphing, muscle volume registration and muscle–tendon path identification, in order to obtain subject-specific musculoskeletal models in a quick and accurate way. The complete dataset, including CT and MRI scans and segmented volume and surfaces, is made available at *http://www.utwente.nl/ctw/bw/research/projects/TLEMsafe* for the biomechanical community, in order to accelerate the development and adoption of subject-specific models on large scale. TLEM 2.0 is freely shared for non-commercial use only, under acceptance of the TLEM*safe* Research License Agreement.

1. Introduction

Musculoskeletal models of the lower extremity represent a valuable tool to explore various biomechanical problems, where accurate knowledge muscle and joint reaction forces is necessary. At the turn of this century, Rik Huiskes was one of the initiators to link musculoskeletal models with finite element models in a European project entitled 'Pre-clinical testing of cemented hip replacement implants: Prenormative research for a European standard'. In that project a consortium of academic and industrial partners tried to establish simplified and validated loading protocols to be used as input for finite element models and experimental testing set-ups. The project was rather successful although the protocols were not accepted as tests by the ISO-standardizing committee. It was concluded that there was still a lot of work to be done to improve the robustness of the finite element simulations and the applicability of the experimental protocols. Nevertheless, Rik was very satisfied with the results of the project as it gave a lot of information to unravel the failure scenarios that were involved. Typically Rik, with many others, was not interested in the individual patient, but focused more on the general phenomena which dominated failure of these implants. However, times are changing and over the last 10 years the demand to explain differences amongst patients has grown tremendously. Hence,

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the modeling community is challenged to incorporate the huge variability amongst patients in terms of anatomy, activity levels, loading conditions, etc. To do that, patient-specific musculoskeletal modeling tools need to be developed and this paper contributes to that goal. We can only guess how Rik would feel about this development of patient-specific simulations. One thing is for sure: without his work on hip biomechanics, we would not be at this stage where we are able to utilize these new modeling tools to assess biomechanical issues at the hip joint for an individual patient.

In the past, musculoskeletal models of the lower extremity have been used in several disparate disciplines, such as in orthopedic surgery to simulate the effects of joint replacements (Delp et al., 1994; Piazza and Delp, 2001) and tendon transfers (Piazza et al., 2003; Reinbolt et al., 2009); in neurology to model the effects of a stroke (Higginson et al., 2006), disorders of the central nervous system (Steele et al., 2012; Van der Krogt et al., 2013), and spinal cord injuries (Paul et al., 2005; To et al., 2005); in sport to optimize athletes performances (Pandy et al., 1990; Rasmussen et al., 2012), and analyses and prevent injuries (McLean et al., 2003; Manal and Buchanan, 2005); or in ergonomics for prevention of work-related musculoskeletal disorders (Wu et al., 2009).

Unfortunately, the reliability of force predictions is affected by the accurateness of many model inputs. In particular, one of the most sensitive parameters of the musculoskeletal geometry is represented by muscle moment arms (Hoy et al., 1990; Out et al., 1996), whose estimation depends on the identification of the muscle–tendon lines-of-action (Rohrle et al., 1984; Pal et al., 2007); moreover, errors in the estimated position of muscle attachment sites have been shown to affect muscle force predictions (Carbone et al., 2012).

To represent different subjects, simple linear scaling laws are usually applied to generic models, which are based on one or more cadaver specimens (Delp et al., 1990b; Klein Horsman et al., 2007; Arnold et al., 2010). However, these scaling procedures do not take into account the inter-individual variability present in musculoskeletal geometry (White et al., 1989a; Duda et al., 1996). For these reasons, subject-specific models have been shown to be necessary when exploring complex biomechanical problems, such as representing pathologies in the musculoskeletal anatomy and predicting the outcome of orthopedic surgery (van der Krogt et al., 2008; Lenaerts et al., 2009; Scheys et al., 2009; Taddei et al., 2012).

Constructing subject-specific models without intensive manual intervention represents a significant challenge. Indeed, several recent studies have focused on developing such subject-specific models based on imaging or functional measurements (Blemker et al., 2007; Scheys et al., 2011; Hainisch et al., 2012; Hausselle et al., 2014) but their clinical application on a large scale has not been demonstrated.

An interesting approach to obtain subject-specific models is to register or morph the medical images of the subject to a previously built template or atlas, containing muscle–tendon attachment sites and lines-of-action (Pellikaan et al., 2014), or muscle volumes (Carbone et al., 2013). However, no musculoskeletal model in literature is linked to such a template or atlas. The Twente Lower Extremity Model (Klein Horsman et al., 2007) represents so far the most complete and consistent dataset of the lower extremity, including both musculoskeletal geometry and muscle–tendon architecture based on one single cadaver specimen. Unfortunately, lack of detailed medical images of that cadaver specimen makes it impossible to apply any image-based subject-specific scaling technique.

The aim of this paper is to present a new comprehensive musculoskeletal geometry dataset of the lower extremity, based on medical images and dissection measurements of a single cadaver specimen. This dataset, named Twente Lower Extremity Model 2.0, consists of a coherent set of medical imaging data (CT and MRI), segmented bone, muscle and subcutaneous fat (including skin) volumes, coordinates of muscle attachment sites and lines-of-action, ligament attachment sites and lines-of-action, bony wrapping surfaces, and joint centers and axes of rotation. TLEM 2.0 was purposely built to be easily combined with image-based scaling techniques, in an attempt to accelerate the application of subject-specific models. The complete dataset is made freely available at *http://www.utwente.nl/ctw/bw/research/projects/TLEMsafe* to the scientific community to be used for non-commercial use only, under acceptance of the TLEM*safe* Research License Agreement.

2. Methods

2.1. Cadaver specimen

Measurements were performed on the right lower extremity of a fresh cadaver (male, white, age 85 years, estimated mass 45 kg), with no clear pathologies affecting the musculoskeletal system. The leg length, measured from the anterior superior iliac spine to the medial malleolus, was 813 mm.

In the specimen we distinguished 6 segments: pelvis, femur, patella, tibia (including fibula), talus and foot (consisting of hindfoot, midfoot and phalanges). During the whole measurement session, the foot bones were fixed to each other and the foot was fixed to a wooden plate, in order to avoid internal movements.

2.2. Medical imaging

Prior to the dissection of the specimen, computed tomography (CT) and magnetic resonance images (MRI) of both lower extremities, from the most proximal extremity of the iliac crest to the most distal tip of the foot, were acquired at the Department of Radiology of the Radboud University Medical Center (Fig. 1A). For the CT, a Siemens SOMATOM® Sensation 16 Scanner (Siemens AG, Munich, Germany) was used, with voxel size of 0.977 mm × 0.977 mm × 0.75 mm. For the MRI, T1 weighted axial spin echo (SE) scan was taken using a Siemens 3T MAGNETOM® Skyra (Siemens AG, Munich, Germany), with different slice thickness between series covering the joint regions (3 mm) and series covering the shaft of femur and tibia (8 mm), and an in-plane resolution of 1 mm × 1 mm. To improve the quality of the images and avoid crystallization damage of soft tissues, the scans were performed before freezing of the cadaver specimen.

2.3. Cadaver measurements

After thawing of the cadaver, a complete dissection of the lower extremity specimen was performed at the Department of Anatomy of the Radboud University Medical Center. The cadaver was divided at the level of L5, then the two lower extremities were separated. The right lower extremity specimen was not fixed in a specific position, so that segments and joints could be moved freely (except for the foot being fixed to a wooden plate) in order to facilitate the measurements. First, skin and subcutaneous fat were removed (Fig. 1B). Then, reference frames with retro-reflective markers were attached to the pelvis, femur, patella, tibia and foot segments. The Brainlab Kolibri™ image-guided surgery platform (Brainlab AG, Munich, Germany) was used to measure the position of points in three-dimensional space with respect to the corresponding reference frame fixed to the bones. This 3-D navigation system had a spatial accuracy of 0.231 ± 0.137 mm (RMS ± SD) and an average orientation error of 0.383° (Wiles et al., 2004).

2.3.1. Muscle attachment sites, lines-of-action, mass and volume

For each muscle, fat at the intermuscular connection was removed, resulting in muscles that were only connected to the bones at origin and insertion. After the identification, each muscle was excised and contours of its origin and insertion were measured with the Brainlab Kolibri™ system (Fig. 1C). The number of points measured to define each muscle attachment site depended on its shape and size. In total, 55 muscle actuators were analyzed, and 98 muscle–tendon attachment sites were measured. In case of a curvature of the muscle line-of-action, via point and underlying bone contours were measured. Then, tendon, remaining fat and excessive connective tissue were removed from the dissected muscle. Muscle weight was measured using a scale with an accuracy of 1.0 g. Muscle volumes were measured using the water dislocation method, using a scaled cylinder with an accuracy of 1.0 ml.

2.3.2. Joint geometry

After removal of all muscles, but with ligaments still intact, geometrical behavior of hip, knee, patellofemoral, talocrural and subtalar joints were measured. Each joint was manipulated by hand, the movement being limited by bone contact