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Model-based approach for human kinematics reconstruction from markerless and marker-based motion analysis systems

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ABSTRACT

Modeling tools related to the musculoskeletal system have been previously developed. However, the integration of the real underlying functional joint behavior is lacking and therefore available kinematic models do not reasonably replicate individual human motion. In order to improve our understanding of the relationships between muscle behavior, i.e. excursion and motion data, modeling tools must guarantee that the model of joint kinematics is correctly validated to ensure meaningful muscle behavior interpretation. This paper presents a model-based method that allows fusing accurate joint kinematic information with motion analysis data collected using either marker-based stereophotogrammetry (MBS) (i.e. bone displacement collected from reflective markers fixed on the subject's skin) or markerless single-camera (MLS) hardware. This paper describes a model-based approach (MBA) for human motion data reconstruction by a scalable registration method for combining joint physiological kinematics with limb segment poses. The presented results and kinematics analysis show that model-based MBS and MLS methods lead to physiologically-acceptable human kinematics. The proposed method is therefore available for further exploitation of the underlying model that can then be used for further modeling, the quality of which will depend on the underlying kinematic model.

1. Introduction

A number of neuromuscular pathologies lead to dysfunction of the locomotor system that can show a variety of disorders (i.e. spasticity, weakness, and lack of coordination). Among the clinically-relevant physiological signals to be analyzed are the joint and limb displacements using motion analysis methods associated or not with electromyography. One important challenge for clinicians is to understand the relationships between the observed motion patterns and muscle behavior (Dallmeijer et al., 2011). Unfortunately, no fully satisfactory data analysis tools are currently available to perform patient data interpretation (Van Sint Jan, 2005). Modeling tools have been previously developed but are not entirely satisfactory because of a lack of integration of the real underlying functional joint behavior (Van Sint Jan, 2005). In order to improve our understanding about the relationships between muscle behavior (i.e. excursion) and motion data, modeling tools must guarantee that the joint kinematics in the model are correctly validated to ensure meaningful interpretation and avoid imprecise muscle estimation (Van Sint Jan, 2005). Once a proper generic model (GM) is available, clinical individual input motion data must be fused accordingly. The obtained GM, once properly adjusted and validated, could then be used in further simulation to obtain clinically relevant muscle information (length, moment arms) that are difficult to estimate directly in clinical settings. Quality of the obtained muscle information strongly relies on the underlying bone and kinematic data used to create the joint models that will be crossed by the muscle spatial path.

By its nature, marker-based stereophotogrammetry (MBS) data might include important soft tissue artifact (STA) (Leardini et al., 2005). Therefore, using MBS data to estimate joint centers might lead to poor accuracy (Sholukha et al., 2011a). Several methods minimizing STA have been previously developed (Leardini et al., 2005). Some methods addressed each segment separately by computing the optimal bone pose from marker location (Soderkvist and Wedin, 1993; Challis, 1995). STA compensations can also be addressed by developing a mechanically-based model of the joints as further discussed in this paper. Several models of

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Abbreviations: AF, anatomical frame; AL, anatomical landmark; DoF, degree-of-freedom; GCS, global coordinate system; GM, generic model; IK, inverse kinematics; LCS, local coordinate system; LL, lower limb model (including pelvis); MA, motion analysis; MBA, model-based approach; MBS, marker-based stereophotogrammetry; MLS, markerless single-camera hardware; STA, soft tissue artifact; TF, technical frame; UpL, upper limb model (including pelvis and spine)

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the ankle and knee joints based on universal and hinge joints were previously proposed (Andersen et al., 2009, 2010; Reinbolt et al., 2005). Methods based on coupled degrees-of-freedoms, or DoFs (Van Sint Jan et al., 2002), were also performed using spatial parallel mechanisms (Di Gregorio et al., 2007; Feikes et al., 2003) that take into account properties of anatomical structures (e.g. shape of articular surfaces or keeping ligament length constant). In order to be applicable in daily motion analysis, current models should integrate the above anatomical aspects using more advanced fusion methods.

Typically, a global optimization method based on mechanical modeling could be applied to adjust model parameters to specific motion. Different sets of joint constraints related to joint kinematics (e.g. joint surface geometry, ligament information and joint mechanism) were previously implemented in order to assess their influence on the lower limb kinematics during gait (Duprey et al., 2010). This approach requires implementation of collision detection and reaction mechanism procedures such as the ones available from commercial multibody dynamics software.

The method presented herein allows fusing validated joint kinematic information with relatively crude motion analysis (MA) data collected using either MBS or markerless single-camera (MLS) hardware. The obtained kinematical model can then be used for further modeling of muscle components (e.g. muscle moment arm or excursion by addition of relevant data).

This paper extends the model-based approach (MBA) (Fohanno et al., 2013; Marin et al., 2010; Nicolas et al., 2007; Poppe, 2007) for human motion data reconstruction using a novel scalable registration method that combines validated joint kinematics with limb segment poses. The new MBA proposed in this paper uses a scalable generic model with joint constraints to improve the realism of skeleton kinematics obtained from MBS or MLS systems. It has been applied for most large human joints (upper and lower limbs). This approach is an improvement of a previously published double-step registration method (Sholukha et al., 2006), developed for lower limbs MA.

2. Materials and methods

2.1. Morphology and joint kinematic data collection for model building

2.1.1. Human materials

Generic morphological bone models for the lower and upper limbs (LL and UpL, respectively) were collected during past European-funded projects (VAKHUM, see http://www.ulb.ac.be/project/vakhum/, LHDL, see http://www.livinghuman.org/ and DHErgo, see http://www.dhergo.org) from fresh-frozen cadaveric specimens obtained from the Université Libre de Bruxelles (ULB) Body Donation program using medical imaging (Van Sint Jan et al., 2002) (Fig. 1). Due to the complex methodology of the data collections, LL and UpL were obtained on different cadavers.

2.1.2. Lower limb data collection

Twelve of these specimens were used to collect in-vitro LL joint kinematics data for the hip, knee and ankle joints using 6 DoFs instrumented spatial linkage (Sholukha et al., 2004; Van Sint Jan et al., 2006). Hip kinematics data were obtained by manually mobilizing the thigh along each anatomical plane. Knee joint passive motion was collected from full flexion to full extension by pulling on the quadriceps muscle tendon against gravity. Ankle joint passive motion was obtained similarly from full dorsiflexion to full plantarflexion by pulling on the Achilles' tendon. Results of polynomial fitting of the joint flexion/extension DoF versus five other DoFs for tibiofemoral motion were previously published (Sholukha et al., 2006). Patella-femoral joint six DoFs were fully guided by tibiofemoral joint flexion/extension DoF.

2.1.3. Shoulder complex data collection

Data related to the shoulder complex were not previously published and more details are given here. In-vitro joint kinematic data related to the shoulder complex were collected on 2 fresh-frozen specimens. Before data collection, technical frames (TFs) made of reflective markers were rigidly attached to the segments-of-interest. TF location relative to bone anatomical landmarks (ALs) were obtained from medical imaging by virtual palpation (Van Sint Jan, 2007). Similarly, in-vivo motion data related to the shoulder complex were obtained from 3 volunteers with TF clusters fixed on each segment-of-interest for which ALs were previously manually palpated (Salvia et al., 2009). Motion data were collected along each anatomical planes (passively and actively for the specimens and volunteers, respectively).

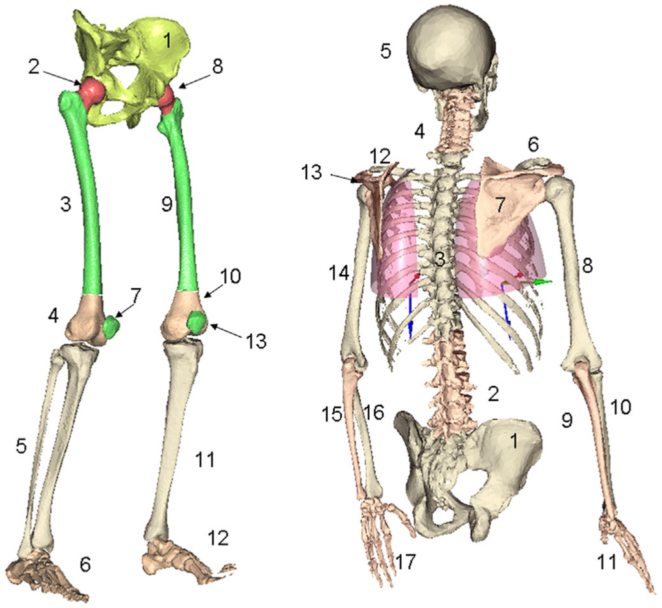

Fig. 1. Generic models and segment numbering used in this study. A total of 30 links and 144 DoFs are present in the model (LL: 13 links numbered from 1 to 13, 72 DoFs; UpL: 17 links numbered from 1 to 17, 72 DoFs). Note that each femoral bone was divided into three parts (head, diaphysis and distal epiphysis) to allow customized reorientation of these components by the method presented in this paper. Ellipsoid surfaces are included on both side of the thorax to constrain scapular gliding using their principal axes (van der Helm, 1994; van der Helm and Pronk, 1995). The topology of the model is presented in Table 1.

2.1.4. Other joints integrated in the model

The overall model also includes supplementary joint models next to the above-mentioned joint segments (see Table 1). These supplementary models are related to the spine, forearm, wrist and ankle joints. Comparison of MBS and MLS results is given in Annex B of the supplementary materials.

2.1.5. Joint center determination

For in-vitro data, all joint centers were obtained from medical imaging. Joint center determination was evaluated using previously-published work based on fitting by primitive geometrical objects (e.g., quadric surfaces for the femoral condyles, or spheres for the femoral head) (Sholukha et al., 2011a). For in-vivo data, joint centers were obtained from previously-published regression methods (Sholukha et al., 2009, 2011a) applied on the above-located ALs.

2.1.6. Joint kinematics representation

For the LL bones, anatomical frames (AFs) were built according to the recommendations of the ISB (Wu et al., 2005) to describe results according to clinical conventions. Distal segment (relative to thorax) and joint (relative to proximal link) motion data were derived using body pose representation by translation (origin to origin) and attitude vectors (helical rotation, Cappozzo et al., 1995; Woltring, 1994). For UpL bones, the projections of each DoF related to the clavicle, scapula and humerus pose vectors on the thorax anatomical frame were calculated and retained in an internal look-up table as part of the model. In total 144 (2 proximal bones, 2 linear and parabolic fitting, 6 DoFs proximal and 6 DoFs humerus bones) plots were processed by linear and parabolic fittings. Then shoulder pose prediction was implemented as described in the next section.

2.1.7. Weighted multiple regression for the shoulder model

This approach allowed predicting the 6 DoFs-dependent motion of the clavicle and scapula from the combination of up to 6 DoFs humerus behavior relative to the thorax (Sholukha et al., 2011b). Let us define for the current frame of motion $Q_i = c_i|q_i|, \quad i = 1, \ldots, 6$, where c_i and q_i are predefined binary (value 0 or 1) weight coefficients and the value of humerus *i*th DoF. Then, a set of normalized weight coefficients is defined as $w_i = Q_i/S, \quad i = 1, \ldots, 6$, where $S = \sum_{i=1}^{6} Q_i$. These weight coefficients reflect the "weight" of particular humerus DoFs. Using these weights