# Automated Generation of Personalized Skeletal Models for Use in Musculoskeletal Applications

# 1 Introduction

Musculoskeletal models have been useful for a variaty of tasks, including ... and currently substantial progress has been recently made towards predictive applications (MOCO, Falisse), which could enable real clinical applications.

The majority of clinical applications, however, will require providing a highly accurate representation of the musculoskeletal system, i.e. a subject-specific model, to physician, surgeon or physioterapist that will evaluate intervention options. Building a musculoskeletal model requires availability of anatomical geometries from medical images or other source, to which apply techniques to build a skeletal kinematic and kinetic model adn finally,mostly through mapping technique, musculo-tendon actuators are mapped onto these skeletal models and used to run muscle-driven simulations.

MANUAL MODELS: However, despite the availability of specific tools (NMSBuilder) and codified procedures (Modenese) subject-specific models have not been used in any routine clinical scenario yet. Assemblying the models from the anatomical geometries is still a procedure requiring specialised operators, and requires a time that exceeds the 10h, making impossible to use this technology in a large cohorts. AUTOMATED MODELS: Other methods have been proposed in previous literature for generating musculoskeletal models. There are methods to build models using statistical shape models. But these models are not shared, or not comprehensive (no feet) or not appropriate for certain population, e.g. juvenile. Other methods have not been used extensively (Lenahrt).

Previous literature includes studies where automated tools had been proposed.

Previous studies have presented various approaches to generate subject-specific models based on medical images. These methods are lengthy and require specialised personalle, so they are not realistically usable in a clinical envirement, requiring robust and fully automated approaches to generate MSK models. We have recently proposed a method to automated method to generate muscle geometries, now we integrate that with an approach to generate the skeletal model.

Aim of this paper is presenting an approach to create skeletal models from bone geometries in a completely automated way. The workflow can be executed in negligible computational time and generate models can than be used as baselines for kinematics and kinetics evaluation of patients or more further processing towards the construction of complete musculoskeletal models.

## 2 Methods

### 2.1 Automated methods

A set of methods available in previous literature (LIST STUDIES) and others developed ad hoc for this study were implemented (Table 1) and collected in a MATLAB toolbox (Msk-GEN) forked, but strongly modified and further developed, from GIBOK-KNEE toolbox by Renault et al.

The toolbox implements a workflow (Figure 1) that, taking as input reconstructed bone geometries of the lower limb (in .stl format at the moment), analyses each bone of the lower limb and generates joint parameters using combinations of inertial axes definition, geometrical feature detection and articular surfaces identification, depending on the algorithm. Specific details of the algorithms are available in the publications reported in Table 1 and, for the MSK-GEN algorithms, in appendix.

The computed joint parameters were then employed as input for another set of scripts that generated kinematic models usable in OpenSim 4.1. This functionality used the OpenSim API.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Bone | Landmarks | Joint | Approach | Description |
| Pelvis |  | Pelvis-ground | Kai et al | The sacrum has been negletted because it si a challenging bone to segment from MRI scans |
|  |  |  | Msk-GEN |  |
| Femur |  | Hip joint | Kai et al |  |
|  |  |  | Renault et al |  |
|  |  | Knee joint | Miranda et al |  |
|  |  |  | Renault et al. | ellipsoid |
|  |  |  |  | cylinder |
|  |  |  |  | sphere |
|  |  |  |  | Artic surfaces |
| Tibia |  |  | Kai et al |  |
|  |  |  | Miranda |  |
|  |  |  | Renault et al | Cond centroids |
|  |  |  |  | Ellipse on AS layer (from prox art surf) |
|  |  |  |  | PIA on AS layer |
| Patella |  |  | Rainbow |  |
|  |  |  | Renault et al | Volume ridge |
|  |  |  |  | Ridge line |
|  |  |  |  | PIA of articular surfaces |
| Talus |  | Talocrural joint | Msk-GEN |  |
| Talus |  | Subtalar joint | Msk-GEN |  |
| Foot |  |  | Msk-GEN | Identifies plane of foot and BL |

### 2.2 Anatomical Datasets for verification

To ensure a valid verification of the proposed workflow, subject-specific models were generated with the automated implementation of the technique (*automated models*) and tested against models generated from publicly available datasets and previously employed in published research. In these previous publications, each of the datasets was employed to create a subject-specific model, referred to as *manual models*, following the procedure of Modenese et al. (2018).

The datasets, summarized in Table 2, were selected with the aim of testing some frequent application of use, such as reconstructions from CT or MRI. Also, the considered datasets are intended to test individual variability of bones because of the differences in gender and age and various reference systems for the bones reconstructions.

Table 2

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Dataset | Gender | MSK conditions | Description |  | Bone Models Quality |
| In vivo | M | No | Adult male | MRI | Good |
| LHDL | F | No | Elderly | CT | Excellent |
| TLEM2 | M | No | Elderly | CT | Excellent |
|  |  |  |  | MRI | Good |
| JIA | ? | JIA | Juvenile | MRI | Scarse |

All joint parameters obtained from the automated and manual models were compared in the ground reference system, exploiting the fact that both NMSBuilder and the Matlab toolbox are making their calculations using the image reference system where the bones were segmented.

### 2.2 Manual models

### 2.3 Automated procedure

The proposed automated procedure consists on building reference system employing the geometry of each bone of the lower limb and then use these reference system to:

1. Identify joint parameters to build the model
2. Identify bony landmarks for registration in the kinematics and kinetics simulations

Pelvis

The pelvis bones are processed accounting only for the iliac wings. The sacrum has been negletted because it si a challenging bone to segment from MRI scans, and that worsens the quality of the data. Given the triangular geometry of the pelvis, the inertial axes are calculated (REF) and used to define a provisional reference system centred at the centre of mass of the geometry. The most distal and proximal points are then identified as ASIS and PSIS, depending on their location and relative distance. The ISB reference system is then defined from these landmarks.

# 4 Result

Which methods failed in which dataser

# 5 Discussion

This set of techniques will enable multiple applications at multiple joints, automating the generation of individual joints as required by specific study. With minor modification our approach could generate models for hip joint studies from CTs, applicable to falls and bone strength. We could also generate shank and ankle complex models like those employes by Montefiori in seconds. Our algorithm automatically extracts articular surfaces, that coud be used for fast setup of contact models (SMITH). Finally, our implementation of the ankle joint is particularly robust and would allow detailed studies of the foot and ankle behaviour.

The anatomical datasets that we have used for generating our models consist of bone geometries of various quality from various medical image types. Although the datasets were selected to test the algorithms on both genders, for adults and juvenile datasets, with bone geometries derived from MRI and CT, a potential limitation of the study is that our algorithms might not work in presence of patients with major deformities, or extremely sparse data. For example, in our implementation the algorithms of Kai et al. will fail if the medial condyle of the femur is not larger than the lateral one. This limitation is however shared with methods based on statistical shape models or other data approaches, that are only effective within the dataset of creation.

In this work we have just presented a basic model, but we are currently working on the integration of a patello-femoral joint and automated muscle generation for highly discretized and standard muscle path actuators, so that complete musculotendon models can be generated in minutes.