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Handling images of patient postures in arms up and arms down position using a biomechanical skeleton model

Abstract: Deformable image registration is gradually becoming the tool of choice for motion extraction during adaptive radiotherapy. Achieving a motion vector field that accurately represents the anatomical changes requires a tissue specific transformation model. Therefore, widely used spline based models most likely fail in appropriately reproducing large anatomical changes such as the arms of the patient being positioned up and down. We present the application of a tissue specific biomechanical model with the goal to mimic patient motion even in presence of large motion. Based on the planning CT, delineated bones are used to represent the rigid anatomy of the patient. We implement ball-and-socket joints between corresponding bones in order to achieve mobility of the skeleton. An inverse kinematics approach enables the propagation of motion between individual bones across their joints, leading to an articulated skeleton that can be controlled by feature points on one or more bones. The transformation of each bone initializes a chainmail based soft tissue model to also propagate the motion into the surrounding heterogeneous soft tissue. Representation of different postures like arms up and down can be achieved within less than 1 s for the skeleton and ~10 s for the soft tissue. Especially for large anatomical changes, the kinematics approach benefits from the direct articulation at specific joints, considerably lowering the degrees of freedom for motion description. Being the input for the chainmail based soft tissue model, the transformed bones guarantee for its meaningful initialization. The proposed biomechanical skeleton model is promising to facilitate the registration of patients' anatomy, being positioned with arms up and arms down. The results encourage further refinement of the joints and the soft tissue model.

Keywords: biomechanical model, inverse kinematics, chainmail, posture modelling, head and neck cancer.

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1 Introduction

Changes in the anatomy of the patient during the course of high precision radiotherapy pose a challenge. While immobilization devices can be used to considerably reduce large anatomical deformations prior the actual treatment sessions, follow-up scans are often acquired without considering the positioning of the patient during his past treatment or even are acquired at other institutions. This often leads to large anatomical changes between pre-treatment and post-treatment scans, which have to be dealt with in follow-up analyses. For example head and neck cancer patients often have their arms positioned up during radiotherapy treatment and positioned down during follow-up imaging, hence leading to large anatomical changes between both scans.

Conventional intensity-based image registration methods used in radiotherapy, trained to perform well enough for small-ranged motions, will most likely fail to reproduce such large anatomical changes. Tissue specific biomechanical models gain increased popularity, produce good results and even bear the potential to accurately represent large anatomical motion.

In this contribution, we demonstrate the use of an in-house developed biomechanical motion model [1] for the

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purpose of registration of a challenging arms up vs. arms down posture.

2 Material and methods

2.1 Patient data

The data used for evaluation in this study consists of a pre-treatment CT scan and a post-treatment CT scan of the head and neck area. The patient had his arms positioned above the head for the pre-treatment case and positioned down for the post-treatment case, respectively. The data set used originates from The Cancer imaging Archive (TCIA) [2], obtained from the Head-Neck Cetuximab collection [3]. Image resolution of both CT scans is 1.37 x 1.37 x 3.75 mm.

2.2 Biomechanical head and neck model

Registration of the pre-treatment CT scan with the patient having his arms up to the post-treatment CT scan with arms positioned down is performed using a recently developed biomechanical head and neck motion model [1]. It consists of a kinematic model to describe the posture changes of the skeleton and a chainmail based model to deform the soft tissue. Resulting displacement vector fields (DVFs) are then used to resample images of the deformed anatomy.

Kinematics describes the motion of multiple linked rigid bodies. We apply this concept to the anatomy of the patient by treating the bones as rigid bodies, which are connected by their corresponding anatomical joints. The geometry of the bones is obtained from delineated and subsequently triangulated structures in the CT image. The joints are implemented as ball and socket joints, allowing for three degrees of freedom.

Positions of the joints are approximated using a nearest neighbour approach between a pair of corresponding bones, as described in [1]. A more detailed and joint specific positioning is done for a) the glenohumeral joints between humeri and scapulae, b) the acromioclavicular joints connecting scapulae and clavicles, c) the costovertebral joints between the ribs and the vertebrae and d) the intervertebral joints between adjacent vertebrae.

a) The rotation centre of the glenohumeral joint is approximated to lie in the middle of the humeral head. To find that position, a distance transformation is applied to the humerus, resulting in a map of distances of every voxel to the nearest surface of the bone. The maximum of these distances approximates the middle of the humeral head and is set as the position of the rotational glenohumeral joint.
b) To find the position of the acromioclavicular joint, the medial axes of the clavicle and the scapula are calculated. The joint is then positioned in the middle of the nearest distance between the points of both axes.
c) The costovertebral joint connects attaches the rib to the vertebral body. The position of this joint is approximated by calculating the medial axis of the rib and the centre of the vertebral body, using a distance map. Both points, the centre of the vertebral body and that point on the medial axis of the rib, having the nearest distance to the former, are connected by a line. Along this line, the first intersections with the rib and vertebra geometries are determined. The position of the joint is then approximated to lie halfway the distance of these two points.
d) The position of the intervertebral joint is approximated to be in the middle of the line, connecting the centroids of two adjacent vertebrae.

All of the bones and the joints are chained together in a kinematic graph, represented as a tree topology (see **Figure 1**). The fifth thoracic vertebra is chosen as the root element of the tree, which denotes the referential bone for the motion propagation along this graph. The multibody physics toolkit Simbody [4] is used to set up the kinematic model and to calculate the motion propagation of multiple bones across the joints. By using an inverse kinematics approach, the position and orientation of all the bones in the kinematic tree can be calculated after directly applying a transformation to one or more bones. With each bone of the skeleton being connected in the kinematic tree, the whole skeleton can be articulated according to the kinematic model.

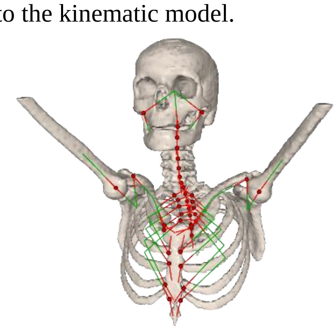

Figure 1: Illustration of the arms up posture of the skeleton, which is the initial position for the kinematic model. The bones are connected to their corresponding joints (red), represented by the kinematic tree (green).

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Transformations of the bones are then propagated into the surrounding soft tissue using a chainmail based model [1]. Based on the underlying Hounsfield Units, tissue specific parameters for translation, rotation and shear are determined to describe the deformation behaviour. Being initiated by the transformation of the bones, the motion propagation into the soft tissue diminishes according to its covered distance. Images of the deformed anatomy are resampled using the inverse of the DVF resulting from the biomechanical model.

2.3 Point-based arms up to arms down registration

Initially, both images are rigidly pre-registered in the area of the thoracic vertebrae to minimize the offset of the anatomy. A total of 33 bones in the head and neck region were manually delineated and connected by 42 implemented joints. In order to guide the registration of the pre-treatment arms up posture to the post-treatment arms down posture, corresponding points are defined on both images in those bones, undergoing the largest transformations. For the exemplary dataset used, this applies to the humeri, scapulae and the skull, on which three corresponding points each are defined manually. To obtain the first set of points, three voxels are marked on each of these bones in the pre-treatment CT scan. Followed by an interactive rigid matching of each bone to the ones in the post-treatment CT scan, the corresponding second set of points can be found by applying the resulting transformation.

These corresponding points then define the initial transformations of the bones, which are propagated by the kinematic model to the remaining bones in the skeleton and by the chainmail based model to the surrounding soft tissue. Residual errors on the corresponding points of the bones are calculated. Images of the generated arms down posture are resampled and compared to the original arms down images.

3 Results

Registration of the pre-treatment CT scan to the post-treatment CT scan resulted in a mean residual error for the used 15 corresponding points on the humeri, scapulae and skull of 1.29 mm. Error statistics per bone are shown in **Table 1**.

Table 1: Residual errors of the corresponding points per bone after registration.

Bone	Average error [mm]	Error range [mm]
Skull	0.6	0.43 – 0.86
Scapula left	1.17	0.84 – 1.74
Scapula right	1.84	1.06 – 3.14
Humerus left	1.08	0.53 – 1.63
Humerus right	1.78	1.45 – 1.99

As shown in **Figure 2**, large transformations of the humeri along with rotations of the scapulae and an extension of the

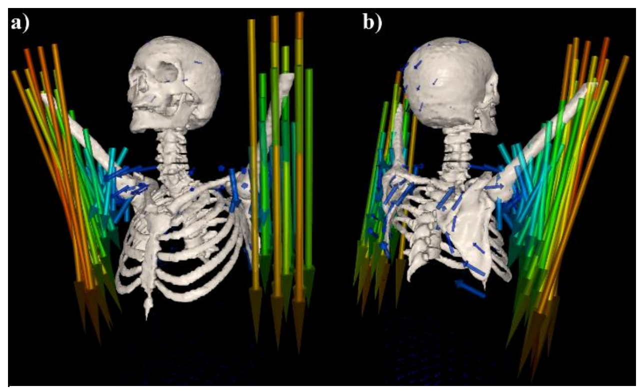

Figure 2: Illustration of the DVF after registration of the arms up scan to the arms down scan, shown in 3D view from a) the front and b) the back.

neck are represented in the DVF, resulting from the skeletal transformation and the soft tissue deformation.

The resampled image of the generated arms down posture is shown as a volume rendering (see **Figure 3**). The generated posture is also compared to the original arms down posture using image fusion, shown in frontal and transversal views (see **Figure 4**).

Computational performance of the registration process was measured on an i7-2600 3.4GHz processor. Single threaded calculations resulted in computation times of the kinematic model within the order of 0.01 s for a single input transformation. In our scenario with 15 corresponding input points, the calculation of the posture of the whole skeleton took less than 1 s. For the soft tissue model, the deformation process accounted for ~10 s and the image resampling step finished within additional ~15 s.

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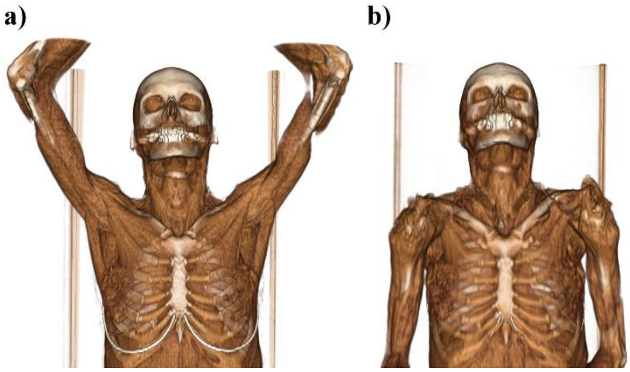

Figure 3: Volume rendering of a) the original arms up image and b) the resampled arms down image after registration. Volume rendering was done using 3D Slicer (http://www.slicer.org) [5].

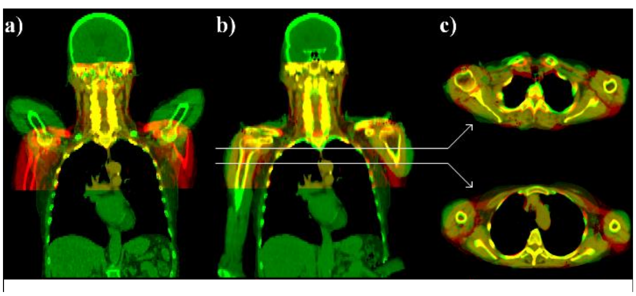

Figure 4: Image fusion of the original arms down posture (red) and in a) the original arms up posture (green). In b), the generated arms down posture after registration (green) overlays the original arms down posture (red). In c), two transversal slices taken from the positions as illustrated by the white lines are shown.

4 Discussion

Presented results show that registration of large arms up arms down postures with our biomechanical head and neck motion model is feasible. The kinematic model for the skeleton is able to match the arms down posture quite efficiently and accurately. Although the overall residual errors in those bones that initialize the modelled posture are quite low, they could be further reduced by refining the joint positions especially in the shoulder area.

The image fusion shown in **Figure 4** shows minor mismatches in the anterior thoracic area, which may be caused by different breathing phases. Breathing motion was not accounted for in this study, however this could be easily addressed by putting three additional corresponding points on the sternum.

The kinematic model for the skeletal transformation ensures to maintain rigidity of the bones, even in presence of very large motion. This leads to a meaningful initialization of the chainmail based soft tissue model. However, a few unreasonable deformations can be observed in **Figure 3** and **Figure 4**, particularly in the area above the shoulder, where large rotations occur. This will be investigated in the future. A limitation can also be found in the necessity of delineated bones, which are usually not part of the contoured volumes during treatment planning.

5 Conclusion

The presented biomechanical head and neck motion model shows promising results in registering an exemplary arms up and arms down posture. Small residual errors for the bones, reasonable soft tissue deformation and a time efficient calculation are achieved and warrant for further research.

Author's Statement

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