A New Deformation Pose Estimation Algorithm for the Fully Automatic Design of Patient Specific Knee Prosthesis: Preliminary Results

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Abstract

In the context of automatic landmarks localization with statistical shape models for the design of customized TKA prosthesis, the first step consists of registering a model, represented by the mean mesh of some healthy femoral bones, towards the segmented femur of the patient. The most complex aspect of the mesh-to-mesh correspondence in this case lies in the fact the source (model) and the target mesh can differ largely (partial view of the femur, anatomy that lies away from the mean) which makes common correspondence approaches inefficient. In this paper, we introduce a contribution to an algorithm from the field of object recognition that produces a reliable registration. By adding the concept of global deformability in the algorithm, we are able to improve the precision of the algorithm (mean mesh-to-mesh distance improved from 2.77mm to 0.79mm) and its robustness to anatomy far off the mean (better standard deviation and Hausdorff distance) on synthetic data . The next step will be to assess it in its application field i.e. the automatic localization of knee landmarks for the design of patient-specific knee prosthesis.

1 Introduction

Customized TKA implants aim at improving accuracy, functional results and finally cost of total knee replacement surgery (Hafez and Moholkar, 2017)(Schwechter and Fitz, 2012). In such procedures,

disparity between patient anatomy and knee implant geometry may result in choosing the «least worse compromise» and thus negatively influence post-operative result (Li et al., 2019). The pre-operative automatic planning workflow under development consists of the deformation of a template implant from anatomical landmarks and measurements (anatomical parameters) according to pre-defined mechanical constraints. Some of the methods considered in the past to automatically localize regions of interest in the knee include learning-based (Xue et al., 2015), CNN-based (Yang et al., 2015) or atlas-based (Mahfouz et al., 2009) procedures. We believe an approach based on statistical shape model(SSM) would be beneficial as it has been shown for premorbid anatomy prediction in shoulder surgery (Salhi et al., 2019) (Abler et al., 2018).

The selected procedure depends on the deformation of a SSM created from healthy femur bones towards the current anatomy of the patient. The success of this process relies on a nice initial rigid correspondence between the SSM (commonly presented by the mean of the femur bones) and the patient segmented femur. This kind of mesh-to-mesh correspondences is well studied (Guan et al., 2018) but the common approaches will eventually fail in our scenario due to the following issues:

1. The segmented femur could only be a partial view of the femur anatomy depending on the imaging output.

2. The process must be fully automatic and thus, robust to far-off position, flip and able to detect bone side (right or left).

3. The patient anatomy may vary largely from the SSM mean making the source mesh and target mesh being potentially very different in terms of shape.

Lots of our constraints are also experienced in the object recognition field that addresses the problem of recognizing free-form objects in points cloud. Point-pair features based algorithms as described in (Drost et al., 2010) tackle the first two issues nicely but the last one remains unsolved. In this paper, we propose a contribution to an existing pose estimation algorithm that accounts for all the above issues.

2   Material and Methods

2.1   Statistical Shape Model

The statistical shape model was generated from 20 cadaveric femurs scanned at CHRU Brest including 12 right and 8 left femur bones (Asvadi et al., 2019).

2.2   Framework

For the purpose of the study, an applicative framework (Tailor) was developed in C++. The deformation material relies on Statismo (Lüthi et al., 2012) and a planning application (KneeSuite) is included.

2.3   Processing pipeline

The algorithm is based on the ones described in (Drost et al., 2010) and (Vidal et al., 2018) that compares point-pair features (PPF) from an object to point-pair features from a scene in order to select the best transformation according to a voting scheme. With our contribution, the algorithm is now able to account for the deformability of the object to be detected by considering a set of possible global deformation described by the SSM as input. With a single deformation model, the wrong pair can be selected if the pair representing the true anatomical match is too different from the mean shape on the

patient segmented femur. Using different deformations as input solves the issue. The algorithm computes the best transformation as well as the best deformation from the initial ones as output.

2.4 Validation

The preliminary validation pipeline consists of registering and deforming the femur SSM towards synthetic data with a first run not accounting for deformation and a second run that accounts for 18 different deformations. The synthetic data used for the validation are computed by randomly deforming, side-flipping and space transforming the femur reference shape of the SSM. For the second run, the 18 deformations (9 left and 9 right) account for three different variations of the two principal deformation modes of the SSM. The validation pipeline involves the initial rigid registration step performed by our PPF algorithm followed by the deformation step described above. The precision is then assessed by computing distance measurements (mean distance, Hausdorff distance and RMS distance) between the registered mesh and the synthetic input data.

3 Results

The distance measurements are presented in Table 1. Accounting for deformations (Run 2) improves all measurements. There is a significant decrease of the mean distance mean from 2.77mm to 0.79mm. The mean standard deviation is also reduced from 1.87mm to 0.68mm. All maximum measurements (Hausdorff) are improved by more than 70%.

	Mean (mm)			RMS			Hausdorff (mm)		
	Mean (SD)	Min	Max	Mean (SD)	Min	Max	Mean (SD)	Min	Max
Run 1	2.8 (1.9)	0.6	12.0	4.5 (2.9)	0.8	17.0	17.4 (11.3)	3.1	61.0
Run 2	0.8 (0.7)	0.2	3.7	1.0 (0.9)	0.3	4.4	3.8 (3.9)	0.9	18.3

Table 1: Distance measurement results

4 Discussion and further work

We presented a new algorithm for the initial correspondence of a SSM with a patient segmented femur. The algorithm, based on robust object-recognition algorithms (Drost et al., 2010)(Vidal et al., 2018) accounts for the deformability of the SSM in the initial pose computation. It shows promising results in term of robustness on synthetic data. Accounting for deformability definitely improves the precision of the registration. A further analysis of the enhancement in terms of standard deviation, maximum distances and Hausdorff distances shows that the algorithm behaves especially well to far off the mean inputs thus greatly boosting the performances in these extreme cases. The next step consists of a validation of its use in the localization of landmarks which will be used for the design of patient-specific knee implants.

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