CSIC5011 Project 2: Topological Data Analysis on 3-Dimensional Patella Shape as New Biomarker for Knee Arthroplasty Type Classification

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INTRODUCTION

Knee Osteoarthritis (OA)

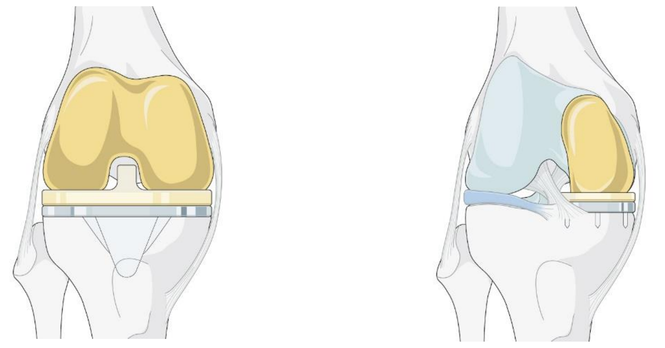
- a chronic degenerative disease with no cure.
- Affects over ~1.1 billion people 16.0% of global population in 2020 (Cui et al., 2020)
- Affects over ~700,000 people 16.6% of Hong Kong population in 2016 (Kan et al., 2019)

Arthroplasty is the last resort for late-stage knee OA

- 4354 joint replacement surgeries
- 34,352 patients on waiting list

(Hospital Authority, 2023)

- Direct cost has increased by 10-fold in past decades from 0.28% to 1~2.5% of GDP with an estimation of 40 billion US dollars (Lee et al., 2022)
- Around 20% dissatisfaction rate (Choi et al., 2016)



Total knee arthroplasty (TKA)   Unicompartmental knee arthroplasty (UKA)

Topological Data Analysis (TDA)

- a computational method that applies principles from topology to extract and analyze complex structures in data (Wasserman, 2018)
- may extract essential information in the quantification of shapes and morphology like tensile deformation and osteophytes

Objective: Utilize TDA to extract complex structures from 3-dimensional (3D) patella shape data and develop a new biomarker for the classification of different types of knee arthroplasty.

METHODOLOGY

Acquisition of dataset

154 knee OA patients with knee CT taken and underwent knee arthroplasty (96 TKA & 58 UKA) were retrospectively recruited from the Queen Mary Hospital, Hong Kong. Manual segmentation is conducted through ITK-SNAP by two professional radiologists.

Point cloud generation

Segmentation masks was converted into point clouds composed of a list of 3D coordinates using the pyntcloud version 0.1.3 Python package.

Topology Data Analysis

Persistent homology can be used to construct persistence diagrams and persistence landscapes to characterize complexity of patella structures

METHODOLOGY (Continue)

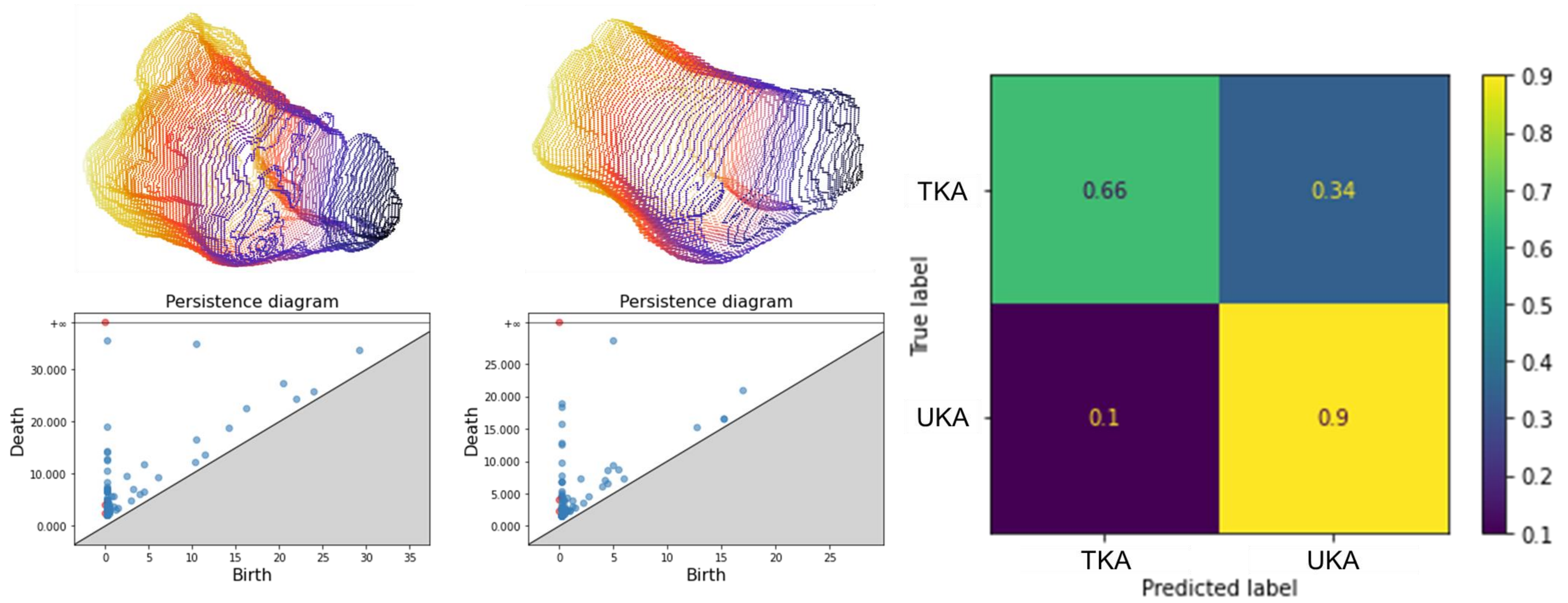
represented by point clouds. For a point cloud $X = \{x_1, x_2 ..., x_n\} \subseteq R^d$, we first construct a filtration of simplicial complexes by considering the Vietoris-Rips $R_\epsilon(X) = \{\sigma | \forall\, x_i, x_j \in \sigma, \|x_i - x_j\| \leq \epsilon\} \subseteq R^d$, where ϵ is a scale parameter, and $\|x_i - x_j\|$ denotes the distance between nodes x_i, x_j.

Then, we compute the homology groups $H_k(VR_\epsilon(X))$ for each $i \geq 0$ in x_i and for increasing values of ϵ. Persistent homology tracks the changes in these homology groups as ϵ increases. The values of ϵ at which the Betti numbers β_i change are called the birth and death times. These numerical results could be visualized in a persistence diagram by plotting each feature as a point with birth time on the x-axis and death time on the y-axis. Features that persist on a larger scale appear higher in the figure.

Feature selection and data analysis

Based on ML algorithms, persistent landscapes have been employed to transform the information stored in the persistence diagram into readable representations, which gives a more direct view of the topological features of different patella point clouds. The dimensionality of the extracted features was further reduced from hundreds to 25 using principal component analysis (PCA). To classify the knee arthroplasty types, we employed a logistic regression model with the L-2 penalty with the processed topological features. The model was evaluated with a confusion matrix, and the average area under the receiver operating characteristic curve was obtained with 5-fold cross-validation.

RESULTS



TKA   UKA

RESULTS (Continue)

The topological features extracted from patella 3D shapes have achieved an average AUC of 77.8 (± 0.052). 90% of UKA and 66% of TKA cases were correctly classified.

CONCLUSION

In conclusion, the application of TDA has enabled us to identify a unique set of features pertaining to patella shape. These features hold promise as novel biomarkers for the classification of different types of knee arthroplasty. By considering these new markers into the assessment of knee OA, surgical decisions quality, post-operative outcomes and increased patient satisfaction may be improved. With future analyses and information fusion of tibia and femur using the same method, the performance may improve further.

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CONTRIBUTION

Tianshu JIANG: Introduction, coding, experiments, poster making

Xiao MENG: Study design, methodology, reference, presentation