論文内容の要旨

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Hip osteoarthritis (OA) is a major cause of disability worldwide, yet the quantitative imaging tools required to monitor its musculoskeletal sequelae remain limited by two chronic bottlenecks: (i) the labor-intensive nature of manual 3-D annotation and (ii) the scarcity of longitudinal data needed to model disease-driven bone remodelling. This dissertation introduces an integrated, two-stage framework that confronts both obstacles simultaneously. First, a Bayesian active-learning (BAL) segmentation module couples Monte-Carlo-dropout uncertainty with a hybrid representation-enhanced sampling strategy that balances density and diversity, thereby selecting only the most informative MR or CT slices/volumes for expert review. Evaluated on lower-extremity MRI (four quadriceps muscles) and CT (22 bones and muscles), the scheme achieves near-upper-bound Dice scores while requiring annotation of merely 10 %-24 % of the training data; the resulting Ratio of Annotation Correction peaks at 79 % on MRI and converges more rapidly than competing uncertainty- or similarity-based baselines, confirming that representative samples are identified early in the active-learning loop . A systematic comparison of slice-wise versus volume-wise acquisition further reveals that slice-wise querying maximizes diversity for modest datasets, whereas volume-wise annotation streamlines clinical workflows on larger 3-D studies, offering actionable guidance for future protocol design.

The second stage addresses the lack of large longitudinal cohorts by predicting disease-related femoral deformations from a single, cross-sectional CT scan. Leveraging the inherent symmetry of bilateral femurs, the pipeline fuses geometric encodings of a patient's contralateral "normal" surface with embedded demographic and OA-severity vectors in a lightweight MLP backbone. On a proof-of-concept set of 367 unilateral-OA CT scans spanning Kellgren-Lawrence grades 0-4 and Crowe grades 0-3, the geometry-encoding (GE) model already surpasses PointNet, DGCNN and SnowflakeNet across seven surface metrics; introducing Clinical-Context Awareness (GE + CCA) reduces point-to-face error by ≈0.09 mm, L1 Chamfer distance by 0.36, and Hausdorff distance by ≈1.2 mm relative to GE alone, while preserving shape completeness (F-score) . Qualitative reconstructions demonstrate that the network captures both subtle early-stage deviations and severe femoral-head collapse, thereby enabling patient-specific forecasts of structural deterioration without serial imaging.

Together, these contributions yield four principal advances. (1) A novel uncertainty-, density- and diversity-aware BAL sampler cuts labeling effort while safeguarding segmentation accuracy, offering the first systematic volumetric extension for musculoskeletal imaging . (2) A domain-specific analysis of acquisition granularity provides practical recommendations for balancing annotation time and algorithmic benefit. (3) A multimodal deformation-prediction network, trained on non-longitudinal data, integrates geometric correspondence with clinical context to forecast OA-related shape change more faithfully than current point-cloud autoencoders. (4) Extensive validation across MRI and CT modalities demonstrates the framework's robustness and translational potential: it not only trims annotation costs by up to four-fifths but also supplies clinically meaningful, vertex-level predictions of femoral remodelling that could inform early intervention strategies.

By jointly easing data curation and enriching biomechanical insight, the proposed framework lays the groundwork for scalable, personalised musculoskeletal analysis. Future work will explore semi-supervised extensions to exploit residual unlabeled data, algorithmic acceleration of the hybrid sampling procedure, and fully longitudinal studies to quantify temporal predictive accuracy.

論文審査結果の要旨

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本論文では以下の二つの課題に取り組んだ：1)高い人的コスト要する筋骨格セグメンテーションのアノテーション削減、2)長期縦断データの不足を補う股関節形状の変形予測。1)の課題に対して、不確実性・密度・多様性を考慮したBayesian Active Learningを提案し、MRI/CTともに10-24 %のデータでDice 0.9超を達成し手動アノテーションの負担を最大80 %削減した。2)の課題に対しては、対側骨形状と臨床情報を含めて符号化した軽量MLPにより単一CTからOA関連大腿骨変形を高精度に予測し、PointNet等の従来手法を凌駕した。委員からは臨床的許容精度、位置／インデックス符号化の妥当性、段階的変形予測の可能性、など多面的な質問があり、候補者は追加解析・図表の挿入等で的確に応答し内容を補強した。以上より、提案手法はアノテーション効率と形状予測精度の両立に寄与し、筋骨格疾患の早期介入へ大きく貢献することを確認した。