Multi-View Stereo Reconstruction of Total Knee Replacement from X-Rays

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Knee Replacement and Examination

Problem Overview

- Prostheses implanted in knee joint as treatment for osteoarthritis
- Interested in non-invasive, postoperative examination
- CT produces artifacts in the presence of prostheses
- Use collection of 2-D X-ray images to reconstruct 3-D shape

Methodology

- 2-D X-rays acquired from different points of view around joint
- Multi-view stereo reconstruction
- Active contours approach
- Edge-based and region-based functional
- Calculus of variations and gradient descent to obtain surface
- 3-D level-set implementation

Total Knee Replacement Diagram and Input Data

- Artificial prosthesis
  - Two pieces: curved femoral component and stemmed tibial plate
  - Radiopaque
- Bones
  - Femur — thigh bone; patella — knee cap; tibia — shin bone; fibula — lateral calf bone
- Input Data
  - Rotating sensor acquires images at equally spaced angles from semi-ring outside the knee

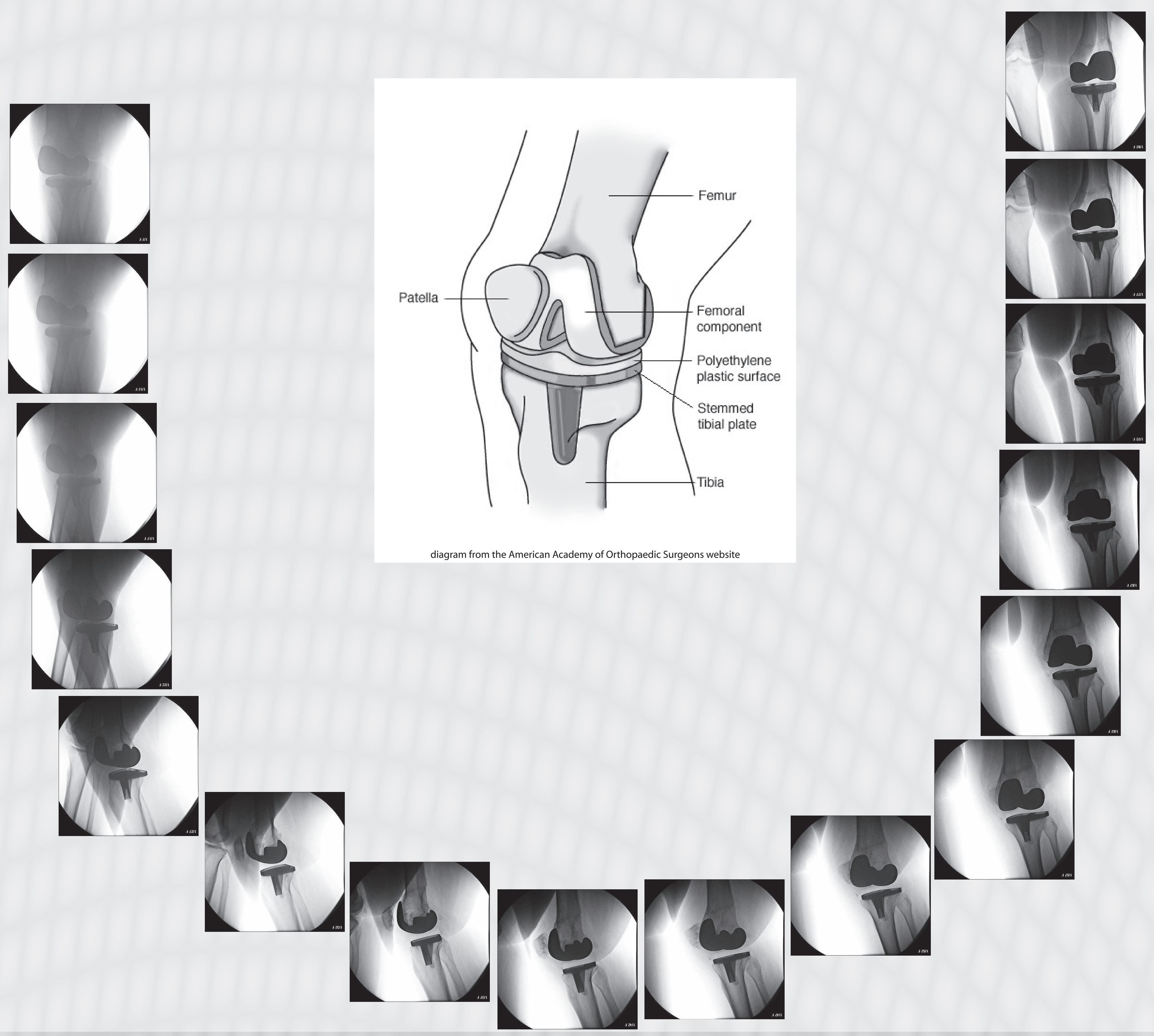
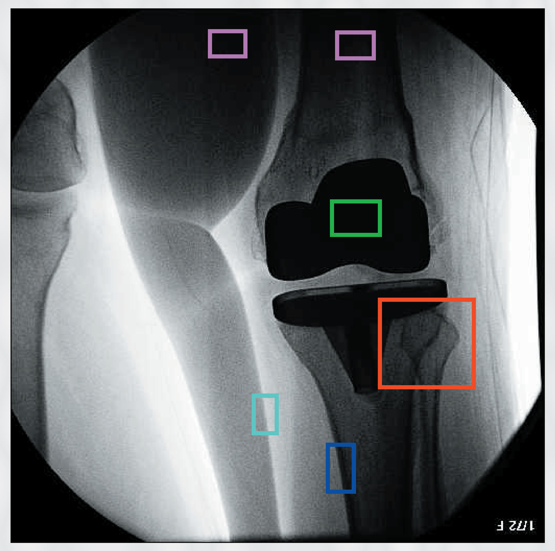


diagram from the American Academy of Orthopaedic Surgeons website

Problem Formulation

X-Ray Image Characteristics

X-rays of the knee joint with implanted prosthesis have certain characteristics that must be taken into account in reconstructing 3-D shape.



- One bone behind another does not result in occlusion, but pixel intensity is darkened in the overlap region
- Prosthesis has no texture
- Bones and background soft tissue may share pixel intensity values
- Bones and prostheses exhibit strong edges
- Other strong edges exist

Active Contours Methods and Level-Set Implementation

An initial contour is evolved to minimize an energy functional by flowing in the direction of the first variation. In a level-set implementation, the contour is represented implicitly as the zero level set of a function φ that is negative inside the contour and positive outside the contour.

- 2-D edge-based functional: $E^{(\mathrm{edge})}(C) = \oint_C g(C(s))\, ds$
- 2-D region-based functional: $E^{(\mathrm{region})}(C) = \iint_R f(u,v)\, du\, dv$
- Level-set function update
  - edge-based: $\varphi_t^{(\mathrm{edge})} = (\kappa g - \langle \nabla g, \mathbf{n}\rangle)\,\mathbf{n}$
  - region-based: $\varphi_t^{(\mathrm{region})} = f\mathbf{n}$
- Geometric quantities in terms of level-set function
  - curvature: $\kappa = -\nabla \cdot \left(\frac{\nabla\varphi}{|\nabla\varphi|}\right)$
  - normal vector: $\mathbf{n} = \frac{\nabla\varphi}{|\nabla\varphi|}$

Multi-View Geodesic Active Regions

Taking the characteristics of X-rays into account, we lift the geodesic active regions functional (Paragios and Deriche, 2002) to the multi-view stereo setting. This new functional is a convex combination of two terms:

- $E^{(\mathrm{edge\text{-}MV})}(S) = \sum_{i=1}^{N} \oint_{C_i} g(C_i(s_i))\, ds_i + c \oint_{C_i} ds_i,$

  where $g(I) = \frac{1}{1+|\nabla I|^p}$, $p \in [1,2]$

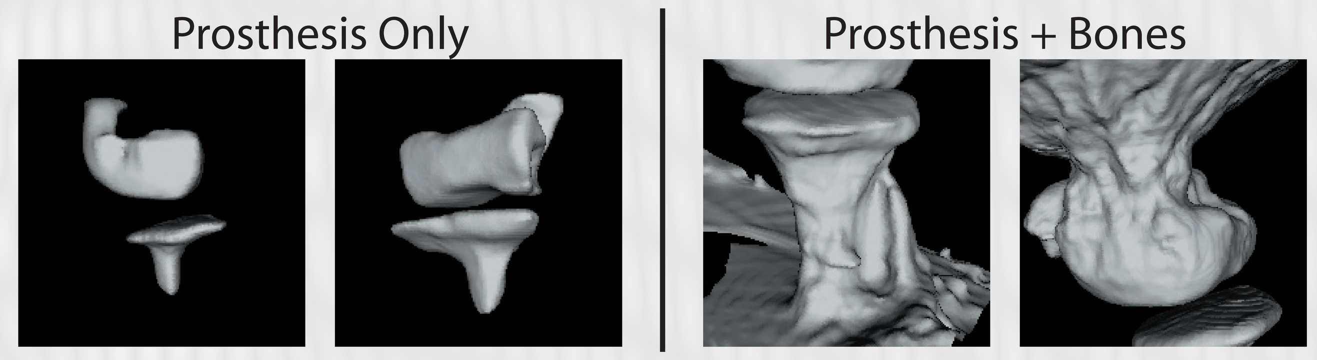
- $$E^{(\mathrm{region\text{-}MV})}(S) = -\sum_{i=1}^{N} \iint_{\pi_i(S)} \log\left(p_R(I_i(u_i,v_i))\right) du_i dv_i - \sum_{i=1}^{N} \iint_{\Omega_i - \pi_i(S)} \log\left(p_{R^c}(I_i(u_i,v_i))\right) du_i dv_i.$$

Results and Future Directions

Surface Evolution

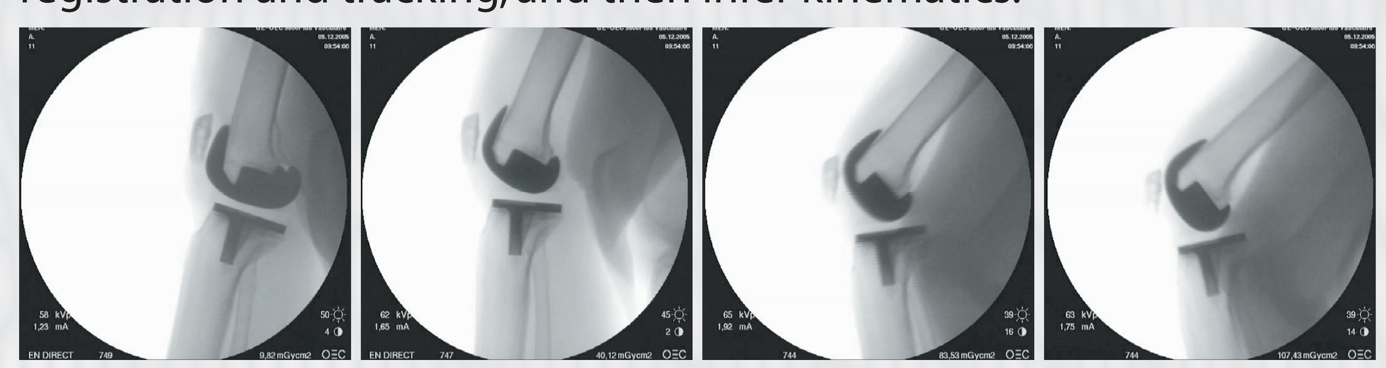
Recovered Surfaces

Prosthesis Only | Prosthesis + Bones



Understanding Kinematics

The eventual goal is to understand the 3-D motions and forces at work in the post-operative joint. Recovering the 3-D shape is a first stage in this process. Combined with dynamic imaging from one point of view (see image sequence below), the next stage is to perform 2-D/3-D registration and tracking, and then infer kinematics.



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