Joint Track Machine Learning

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March 9, 2023

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Introduction

Acknowledgments

I would like to thank the McJunkin Family Charitable Foundation for their generous grant that supports this work.

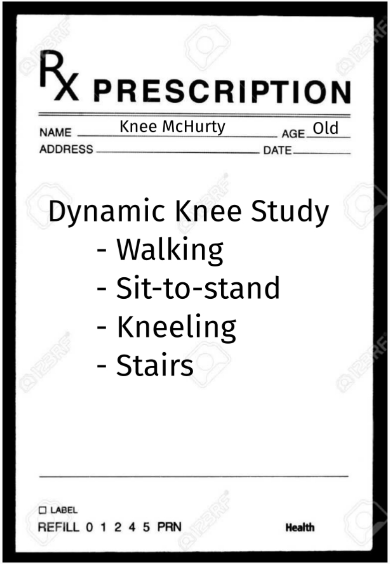
Motivation

The Problem

- Joints manifest pain during dynamic activity.
- 20% of patients receiving TKA are dissatisfied.
  - Instability, pain, unnatural [1, 3, 15].
- No reliable method of clinically assessing and quantifying joint dynamics.
  - Too much human supervision, too time consuming

Our Proposition

Orthopaedic surgeons and clinicians would readily adopt a practical and inexpensive technology that allows them to measure a patient's knee kinematics during activities of daily living.



Constraints

- It must fit within a standard clinical workflow
- The technology must utilize equipment commonly found in hospitals
- There must not be significant human supervision nor interaction to generate an examination report.

Background

Rigid Body Transformations

Homogeneous Transformation Matrix

$$T_B^A = \begin{pmatrix} & R_B^A & & P_{B,origin}^A \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Rotation Matrices

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_x & -s_x \\ 0 & s_x & c_x \end{pmatrix}$$

$$R_y = \begin{pmatrix} s_y & 0 & c_y \\ 0 & 1 & 0 \\ c_y & 0 & -s_y \end{pmatrix}$$

$$R_z = \begin{pmatrix} c_z & -s_z & 0 \\ s_z & c_z & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Rigid Body Transformations

Translation

$$\begin{pmatrix} v'_x \\ v'_y \end{pmatrix} = \begin{pmatrix} v_x \\ v_y \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \end{pmatrix}$$

$$\rightarrow$$

$$\begin{pmatrix} v'_x \\ v'_y \\ 1 \end{pmatrix} = \begin{pmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} v_x \\ v_y \\ 1 \end{pmatrix}$$

Rotations

$$R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_x & -s_x \\ 0 & s_x & c_x \end{pmatrix}$$

$$R_y = \begin{pmatrix} s_y & 0 & c_y \\ 0 & 1 & 0 \\ c_y & 0 & -s_y \end{pmatrix}$$

$$R_z = \begin{pmatrix} c_z & -s_z & 0 \\ s_z & c_z & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Homogeneous Transformation Matrices

$$\begin{aligned}\vec{v}' &= \begin{pmatrix} & \mathrm{R}_{3\times3} & & \vec{t}_{3\times1} \\ 0 & 0 & 0 & 1 \end{pmatrix} \tilde{\vec{v}} \\ &= T_B^A \tilde{\vec{v}}\end{aligned}$$

Now we have a notation that allows us to describe arbitrary movement between reference frames.

Projective Geometry

$$\begin{pmatrix} x_s \\ y_s \\ z_s \\ 1 \end{pmatrix}_i = T_{scene}^{cam} \tilde{\mathrm{p}}_{\mathrm{i}}^{\mathrm{obj}}$$

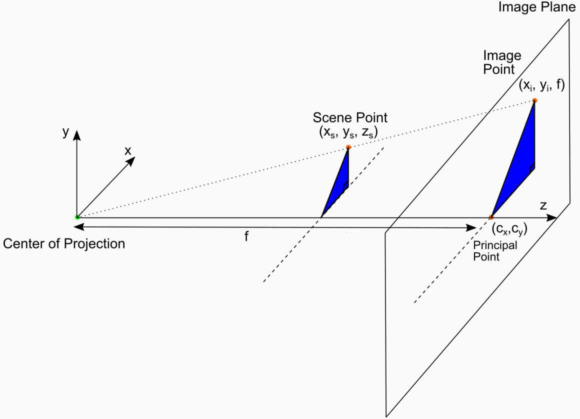
$$\begin{pmatrix} \tilde{x}_{img} \\ \tilde{y}_{img} \\ \tilde{z} \\ 1 \end{pmatrix} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \vec{x}_s$$

Where

$$x_{img} = \frac{\tilde{x_{img}}}{\tilde{z}} = \frac{f}{z_s} x_s$$

$$y_{img} = \frac{\tilde{y_{img}}}{\tilde{z}} = \frac{f}{z_s} y_s$$

Note: We are still in the camera's reference frame



Pixel Coordinates

Convert camera coordinates into image coordinates.

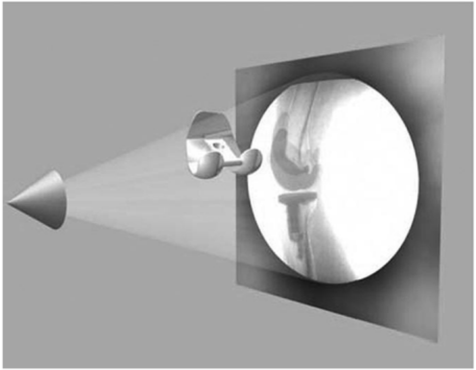
$$p_x = k_x x_{img} + c_x$$
$$p_y = k_y y_{img} + c_y$$

Where

$$k \equiv \text{ Pixel Spacing}$$
$$c \equiv \text{ Image Focal Point}$$

Model-Image Registration

If we know the projective parameters of the fluoroscopy machine, can we tinker with $T_{implant}^{cam}$ so that our virtual projection matches the fluoroscopic image?



From [13]

Historical Methods

Overview

Many different approaches have attempted to solve the model-image registration problem.

- Pre-computed projections
- Skin-mounted motion Capture
- Biplane Imaging
- Iterative Projections

Pre-Computed Projections

- Saving space and memory by pre-computing as much as possible.
- Pre-computed distance maps [17, 11].
- Pre-computed shape libraries [2]

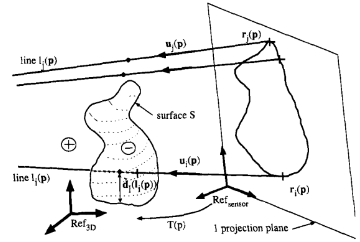
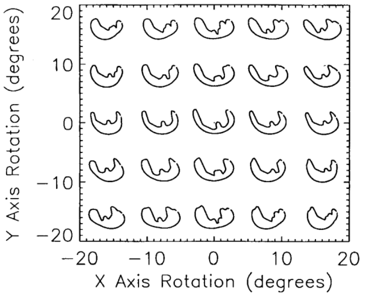


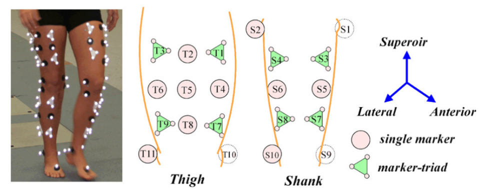
Fig. 2. Projection line to surface distance computation.

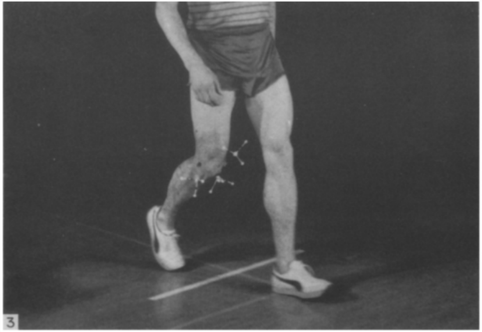


Limitations of Pre-Computed Projections

- Requires an accurate contour from the input image in order to perform calculations.
    - Human supervision vs. inaccuracy.

Motion Capture (MoCap)





- Can measure motion of MoCap beads very accurately.
- Skin-mounted [6, 9, 12].
- Bone pins [10] (any volunteers?).

Limitations of Motion Capture

Skin Mounted

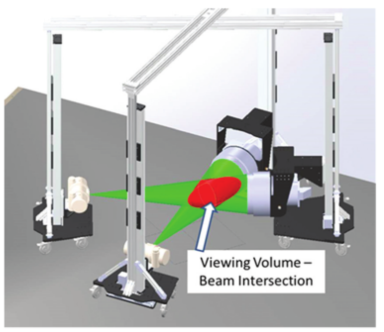
- Doesn't accurately describe underlying skeletal motion with clinical accuracy [6, 9, 12].

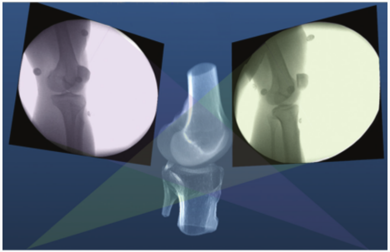
Bone Pins

- Bone Pins
- Need I say more?

Biplane Imaging

- Utilizes multiple cameras to resolve 3D position and orientation[7, 5].
  - Highly accurate.
  - Gold Standard.



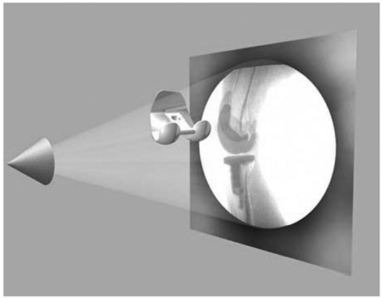


Limitations of Biplane Imaging

- Not many hospitals have biplane fluoroscopy setups.
- Clinically impractical

Iterative Projections

- Take advantage of modern computational graphics pipelines to quickly perform projection matching.
- Image/Intensity similarity metrics [13]
- Feature/Contour similarity metrics



Limitations of (historic) Iterative Projection Methods

- Requires human supervision for:
    - Pose initialization
    - Escaping local minima
    - Implant detection
- Chaotic and Noisy objective function

Model-based Roentgen Stereophotogrammetry (MBRSA)

- Uses implanted tantalum beads for motion tracking [16]
- Extremely accurate [8, 14]
- Gold standard Measurement [4]

- Involves additional surgical procedures for inserting tantalum beads
- Human supervision
- Typically requires bi-plane imaging.

Aims

Aims

Aims 1/2
Joint Track Machine Learning and Overcoming Single-Plane Limitations

Aim 3/4
Pilot Trials and Standardized Kinematics Exam

Aim 5
Joint Track Auto Toolkit

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