15-869

Lecture 3
(Marker-based) Motion Capture

Leonid Sigal
Human Motion Modeling and Analysis
Fall 2012

(some slides taken and/or inspired by Vladen Koltun's course slides from Stanford)

Projects

Capture Project

- Details to be posted most likely later today
- Responsibility of a group is to arrange for everyone in class to get captured (outside of class time) using chosen device

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Final Project

- Never too early to start thinking about your project
- Look at the blog for ideas and also post your own
- Is it expected that you use data from capture project?
  Yes, unless you nature of the project is such that you

Brief Review

Last Class: Surface capture

Virtualizing the world (exact replay)
Perceptually viable

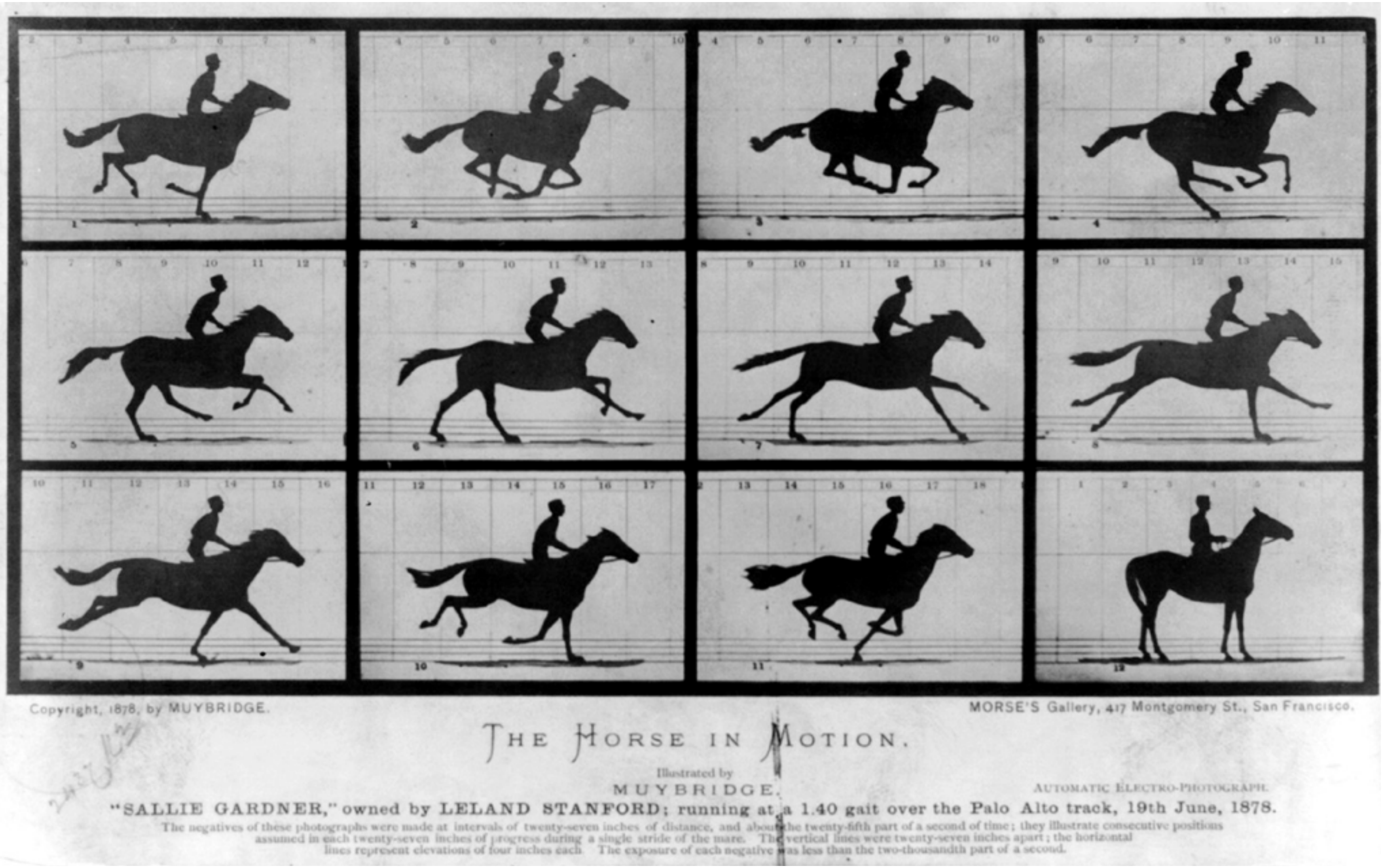
This Class: Motion capture more broadly

Practical systems for capturing motion
- Allow (some) editing of motion
- Can be used as measuring tools

Plan for Today's Class

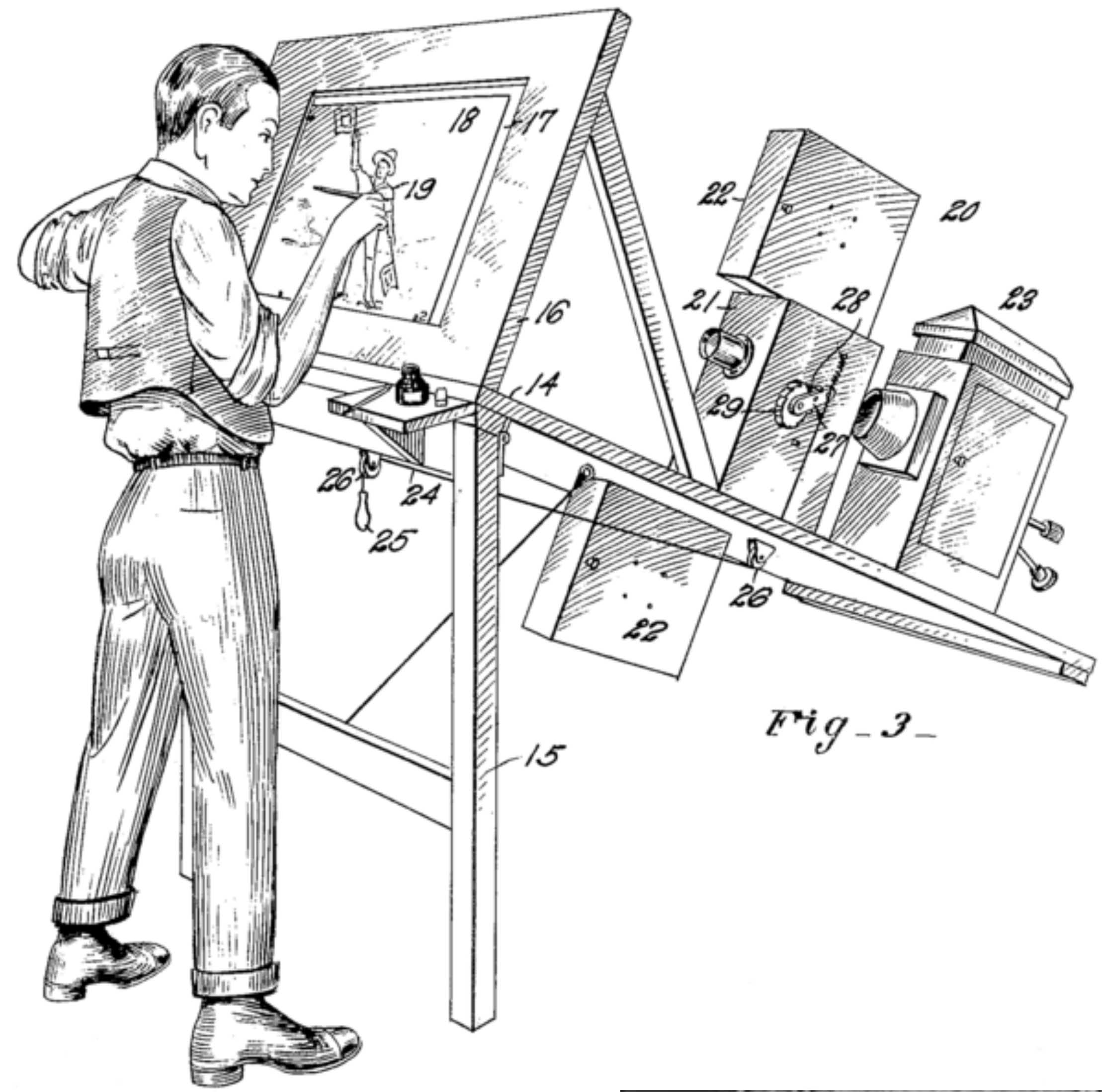
- Brief history of motion capture
- Review of various motion capture systems and technologies
- Motion capture pipeline
  (mostly as it relates to marker-based optical systems)
- Surface vs. skeletal capture
- Discussion regarding the benefits and shortcomings of motion capture

History: Remember Muybridge



History: Rotoscoping

- Animators traced characters over recorded actor's motion (typically frame-by-frame)
- Invented by Max Fleicher in (1915)
- Used for Betty Boop cartoon
- Used by Walt Disney for Human Characters in Snow White and Seven Dwarfs (1937)



History (aside): Multiplane Camera

- Moves a number of pieces of artwork past the camera at various distances
- Creates illusion of depth and true 3D
- Background and foreground moving in opposite directions creates effect of camera rotation
- Used by Walt Disney for the scene where Queen drinks her potion in Snow White and Seven Dwarfs (1937)

History: Jurassic Park

- Dinosaurs animated using armatures equipped with sensors that measured angles
- CG models driven with keyframes created by armatures

[Knep, Hayes, Sayre, Williams, ILM, 1995]

History: Late 90s

- Motion capture becomes mainstream in Hollywood and in Games
- Mostly used for VFX (not full featured animated films)

Motion Capture Systems

Inside In

Electromechanical Suites

Optical Fiber

Accelerometer Based

Inside Out

Electromagnetic

Semi-passive

Optical

Outside In

Marker-based Optical
(active, passive markers)

Marker-less Optical

Benefits

Motion Capture Systems

Inside In	Inside Out	Outside In
Electromechanical Suites	Electromagnetic	Marker-based Optical (active, passive markers)
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Benefits

Portable	Could be portable	Not very portable
Can capture any motion anywhere	Low accuracy	Can be very precise

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What was the big takeaway last class?

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What was the big takeaway last class?

Correspondences, Correspondences, Correspondences

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Electromechanical Suites

- Exo-skeletons/armatures worn over the subject
- Rods connected by potentiometers
- Potentiometers: record analog voltage changes (like nobs on the radio) and convert to digital values; are only able to record change from the original orientation (calibration is critical)

[Gypsy]

Pro:

Con:

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[Gypsy]

Pro:

- Real-time
- High accuracy
- Inexpensive
- Self-contained
- No correspondences

Con:

- Restrictive
- Needs to match body proportions
- No global position

History: Jurassic Park

- Dinosaurs animated using armatures equipped with sensors that measured angles
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[Knep, Hayes, Sayre, Williams, ILM, 1995]

Optical Fiber

- Typically used for data gloves
- Fiber-optic sensors along the fingers
  - Finger bending, bends fiber
  - Bent fiber attenuates light
  - Attenuated light converted to measurement

Pro:

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Why?

Inertial Suites

- Inertial sensors (gyros)
  - Accelerometer: measures acceleration
  - Gyroscope: measures orientation

[Xsens]

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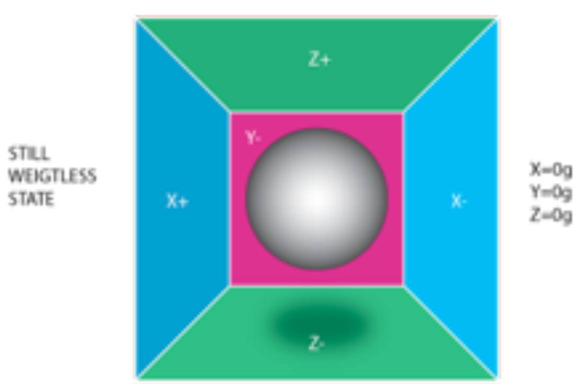

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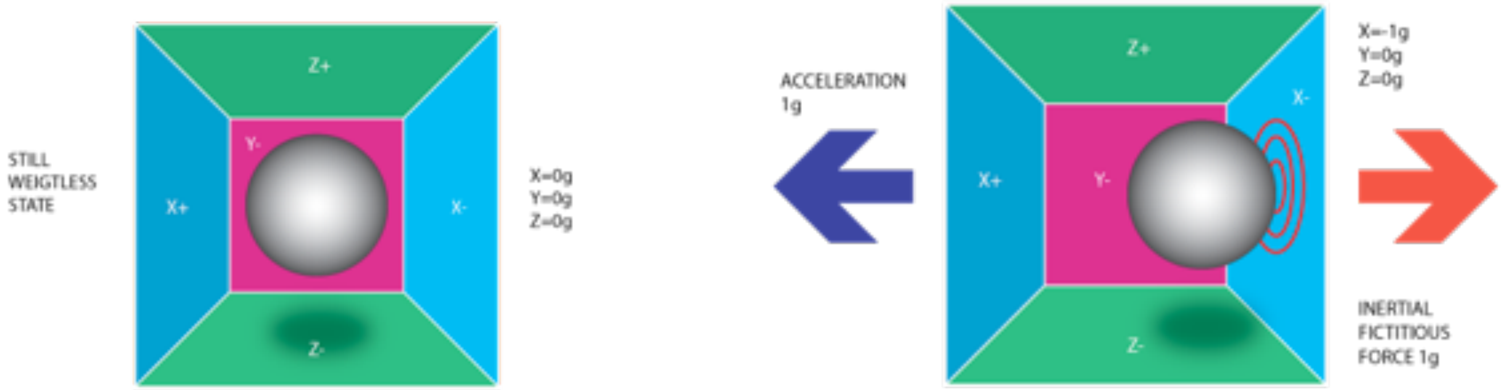

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- Can drift

Inertial Suites

- Inertial sensors (gyros)
  - Accelerometer: measures acceleration
  - Gyroscope: measures orientation
  - Ultrasonic: measures distance

[Xsens]

Pro:

- Real-time
- Inexpensive
- Self-contained
- No correspondences

Con:

- Restrictive
- No global position
- Can drift

Practical Motion Capture in Everyday Surroundings

Daniel Vlasic - MIT
Rolf Adelsberger - MERL, ETH Zurich
Giovanni Vannucci - MERL
John Barwell - MERL
Markus Gross - ETH Zurich
Wojciech Matusik - MERL
Jovan Popović - MIT

Motion Capture Systems

Inside In	Inside Out	Outside In
Electromechanical Suites	Electromagnetic	Marker-based Optical (active, passive markers)
Optical Fiber	Semi-passive	Marker-less Optical
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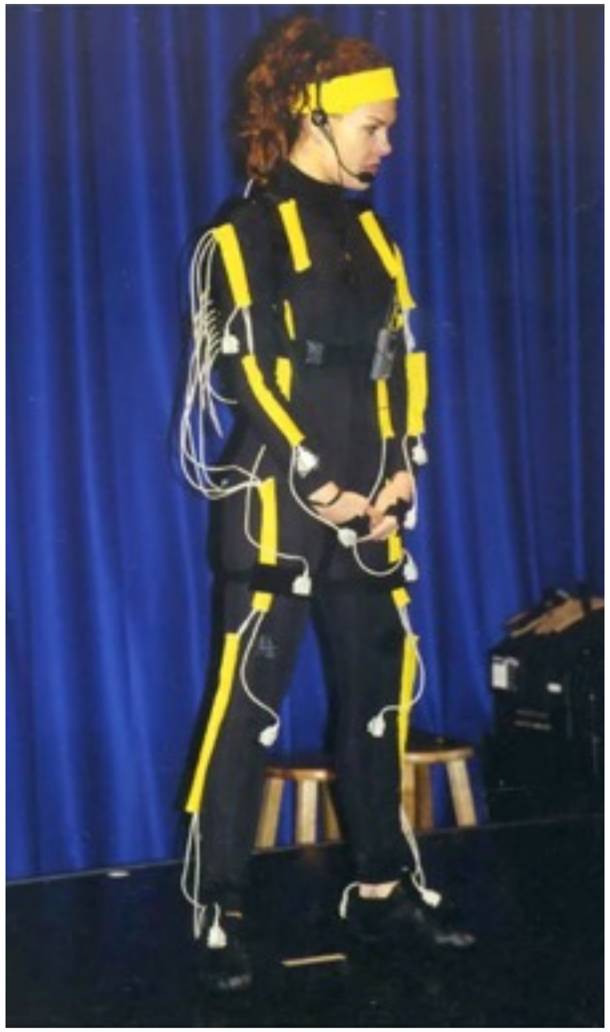
Electromagnetic

- External transmitters establish magnetic fields in space
- Sensors can then measure the position and orientation
- Data from sensors transmitted back wirelessly or across wire

Pro:

Con:



[JZZ Technologies]

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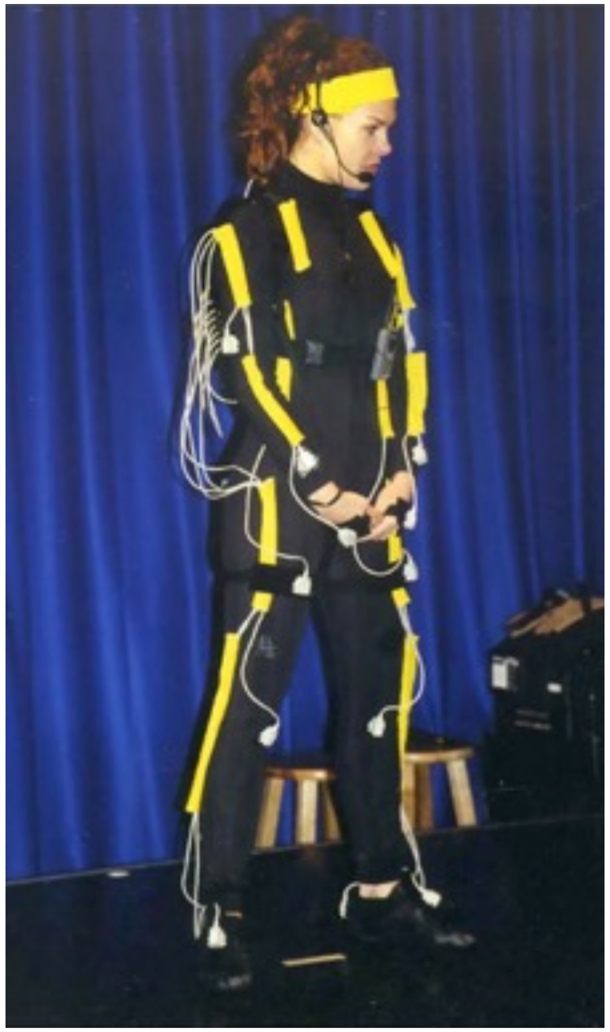

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Electromagnetic

- External transmitters establish magnetic fields in space
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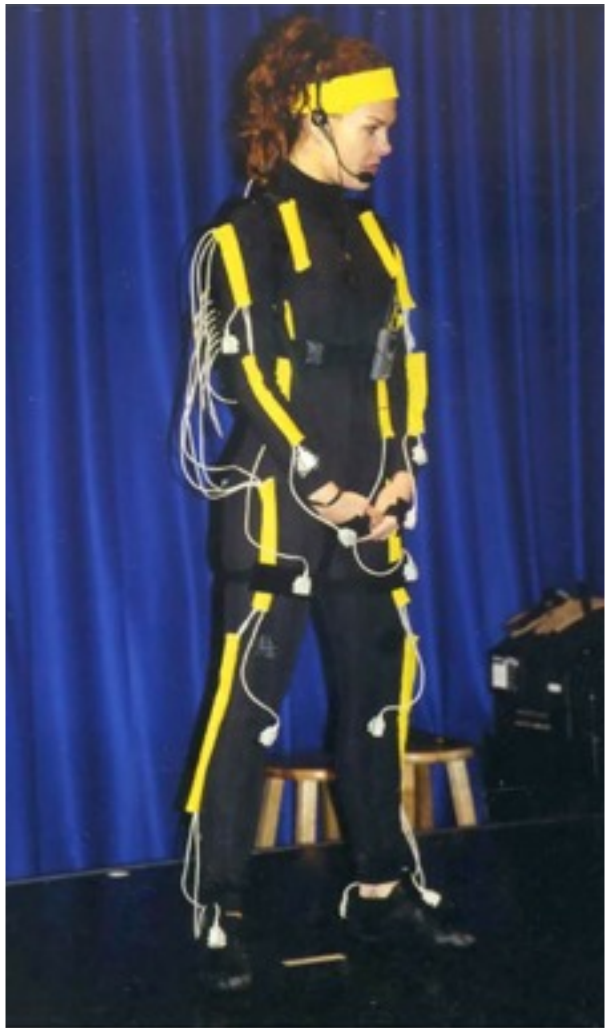
Pro:

- Real-time
- No correspondences

Con:

- Limited range
- Noise
- Interference from metal objects
- Expensive



[JZZ Technologies]

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- Multi-LED IR projectors in the environment emit spatially varying patterns
- Photo-sensitive marker tags decode the signals and estimate their position

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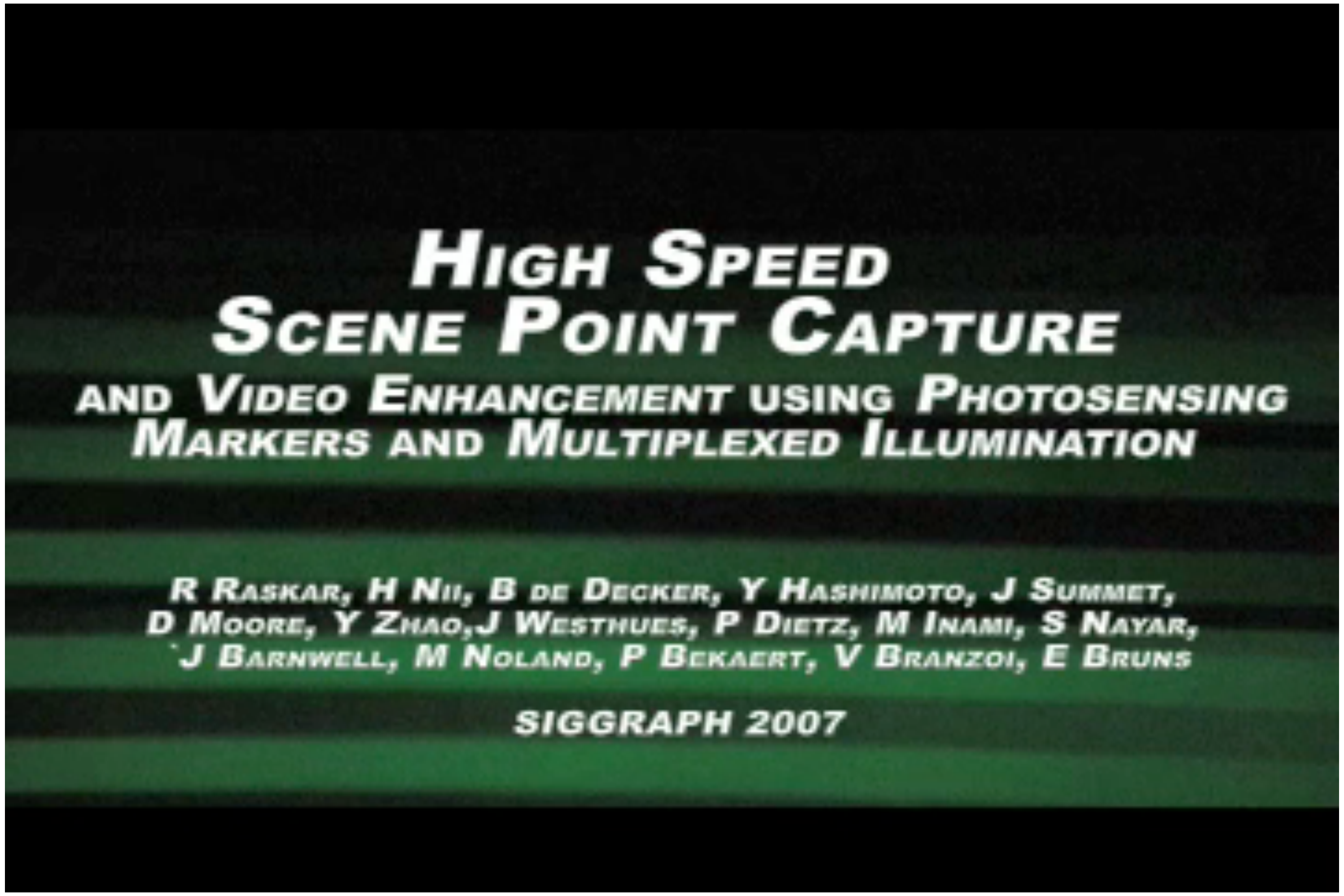

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Pro:

Con:

Semi-passive

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- Photo-sensitive marker tags decode the signals and estimate their position

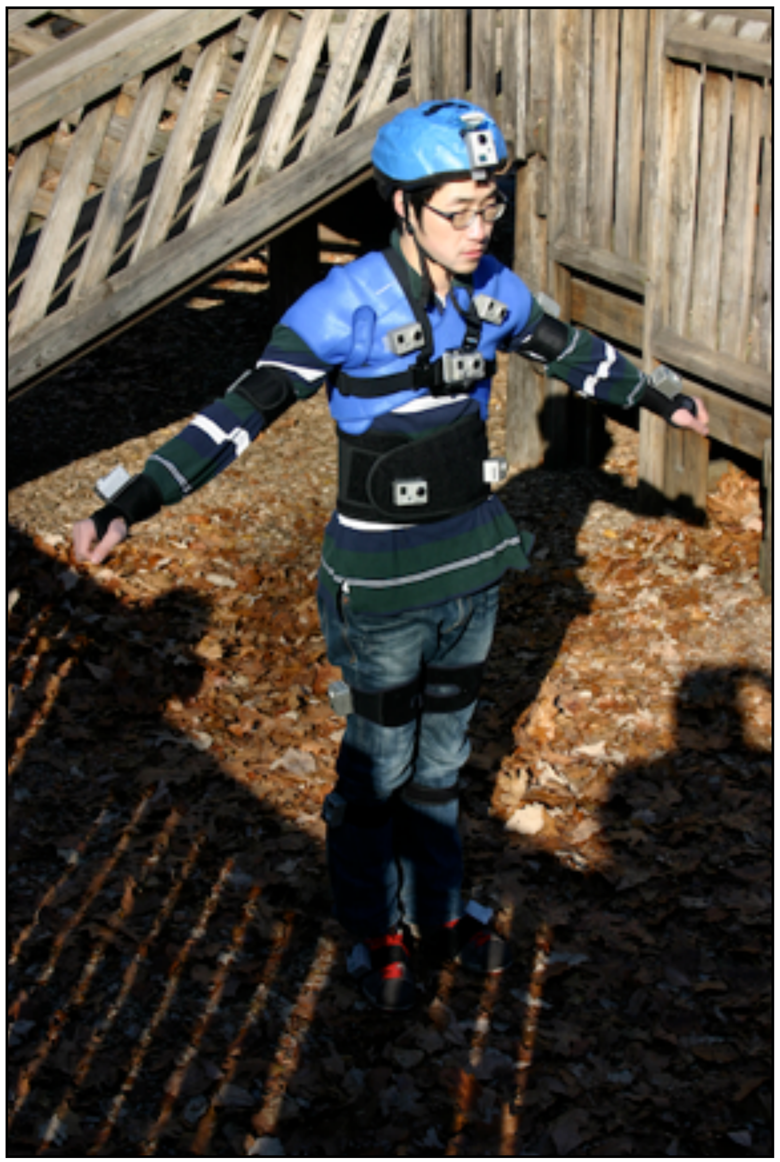
Pro:

- Real-time
- Inexpensive
- High speed
- No correspondences

Con:

- Accuracy (?)
- No global position

Optical Inside-Out System



HD Hero by GoPro
720p at 60 fps
~260 dollars/camera

[Shiratori, Park, Sigal, Sheikh, Hodgins, Siggraph 2011]

Optical Inside-Out System

[Shiratori, Park, Sigal, Sheikh, Hodgins, Siggraph 2011]

Optical Inside-Out System

[Shiratori, Park, Sigal, Sheikh, Hodgins, Siggraph 2011]

Optical Inside-Out System

Structure from Motion

...

...

[Tomasi and Kanade, IJCV 1991], [Hartley and Zisserman, 2004], [Snavely et al., SIGGRAPH 2006]

[Shiratori, Park, Sigal, Sheikh, Hodgins, Siggraph 2011]

Optical Inside-Out System

Scale Invariant Features (SIFT)

...

...

[Lowe, IJCV 2004]

[Shiratori, Park, Sigal, Sheikh, Hodgins, Siggraph 2011]

Optical Inside-Out System

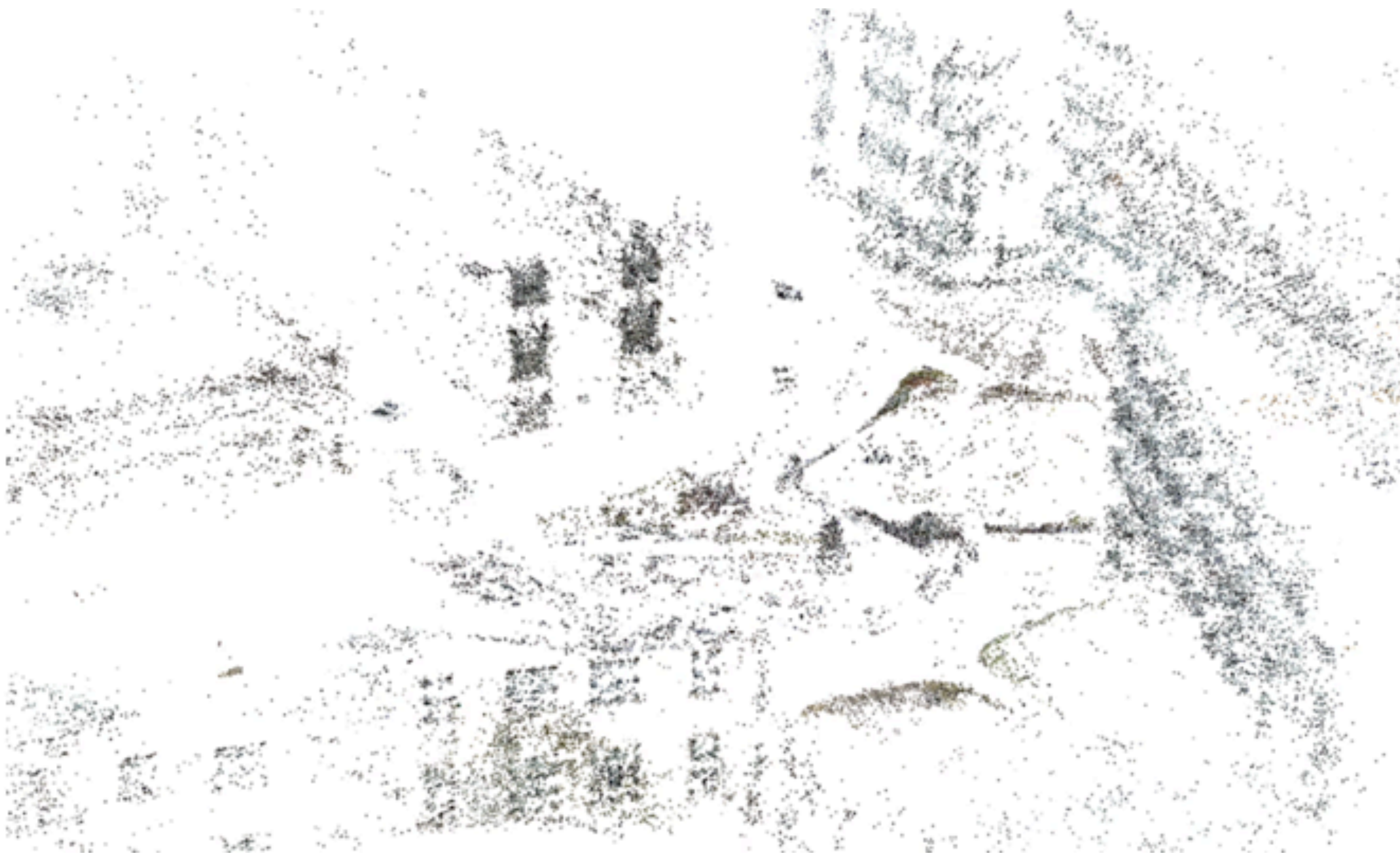
Correspondences with feature + geometry matching

[Hartley and Zisserman, 2004]

[Shiratori, Park, Sigal, Sheikh, Hodgins, Siggraph 2011]

Optical Inside-Out System

3D scene reconstruction



[Shiratori, Park, Sigal, Sheikh, Hodgins, Siggraph 2011]

Optical Inside-Out System

camera reconstruction

[Shiratori, Park, Sigal, Sheikh, Hodgins, Siggraph 2011]

Optical Inside-Out System

Pro:

- Portable
- Inexpensive
- Gives global position

Con:

- Low quality
- Very long processing time

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Optical Systems

(most popular and practical method at the moment)

- Subject surrounded by cameras
- Sensing is done at the cameras (and/or connected computers)
- Cameras need to be calibrated

Pro:

- Adaptable
- Minimally intrusive
- Highly accurate

Con:

- Limited in use (space need to be outfitted)

Optical Marker-less Systems

Stereoscopic 3D Reconstruction

Pros	Cons
Can provide temporal correspondence	**Requires accurate spatial correspondence**
High accuracy	Sparse reconstruction
Accuracy depends on the number of cameras	Does not provide normal information
Can identify concavities	

Requires accurate spatial (and temporal) correspondence

Voxel-Carving

Pros	Cons
Does not require spatial correspondences	Does not provide temporal correspondence
Trades off density with computation	Redundant computation
Easy to code	Requires accurate silhouettes
Camera work with few cameras	Does not provide normal information
	Accuracy depends on the number of cameras
	Convex Hull

No correspondences across time make it mainly suitable for playback

Optical Marker-less Systems

Pro:

- Non-intrusive
- Should be accurate (every pixel on the body is, in a sense, a measurement)

Con:

- Still in research phase
- Many difficulties exist
- Reliable spatio-temporal correspondences is key challenge

Active Marker-based Systems

- Resolve correspondence by activating one LED marker at a time (very quickly)
- LEDs can be tuned to be easily picked up by cameras

[PhaseSpace]

Weta used for “Rise of the Planet of the Apes”

ILM used for “Van Helsing”

Active Marker-based Systems

- Resolve correspondence by activating one LED marker at a time (very quickly)
- LEDs can be tuned to be easily picked up by cameras (How?)

[PhaseSpace]

Active Marker-based Systems

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[PhaseSpace]

Infrared LEDs

Visible light filters on cameras

Active Marker-based Systems

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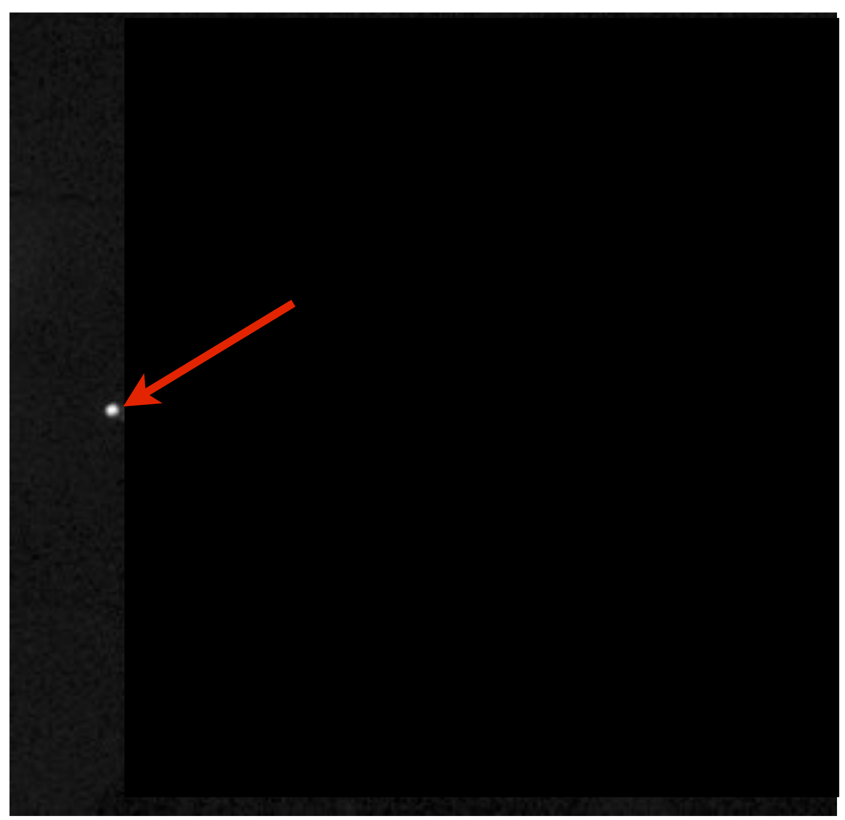

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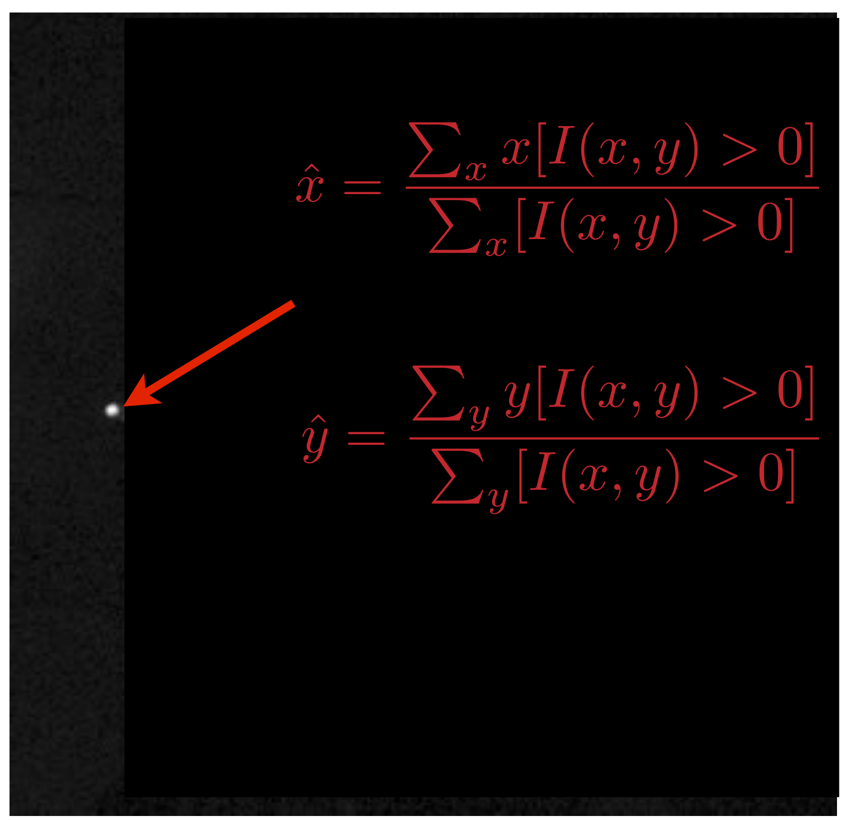
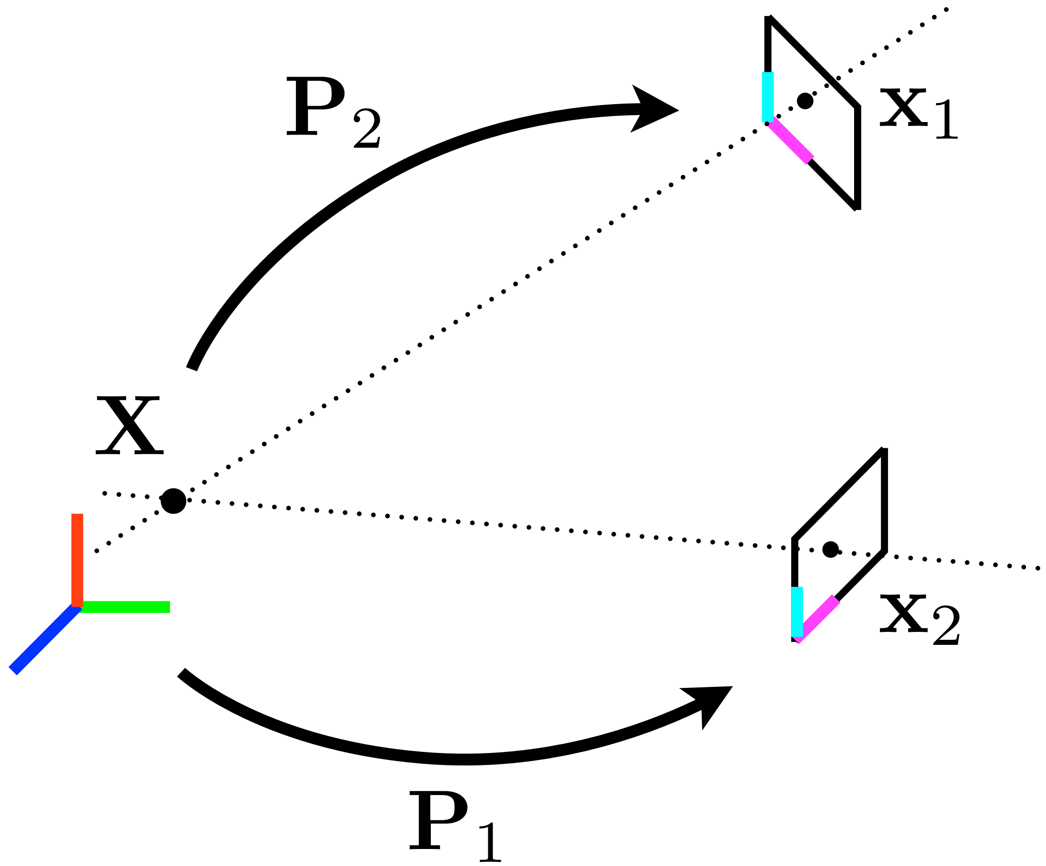


$$\hat{x} = \frac{\sum_x x[I(x,y) > 0]}{\sum_x [I(x,y) > 0]}$$

$$\hat{y} = \frac{\sum_y y[I(x,y) > 0]}{\sum_y [I(x,y) > 0]}$$

Active Marker-based Systems



$$\min_{\mathbf{X}} \|\mathbf{x}_1, \mathbf{P}_1\mathbf{X}\|_d + \|\mathbf{x}_2, \mathbf{P}_2\mathbf{X}\|_d$$

Nonlinear least squares

[PhaseSpace]

Passive Marker-based Systems

- Markers are retro-reflective balls (instead of LEDs)
- Markers are illuminated using IR lights mounted on the cameras

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Why lights need to be mounted on the cameras?

Passive Marker-based Systems

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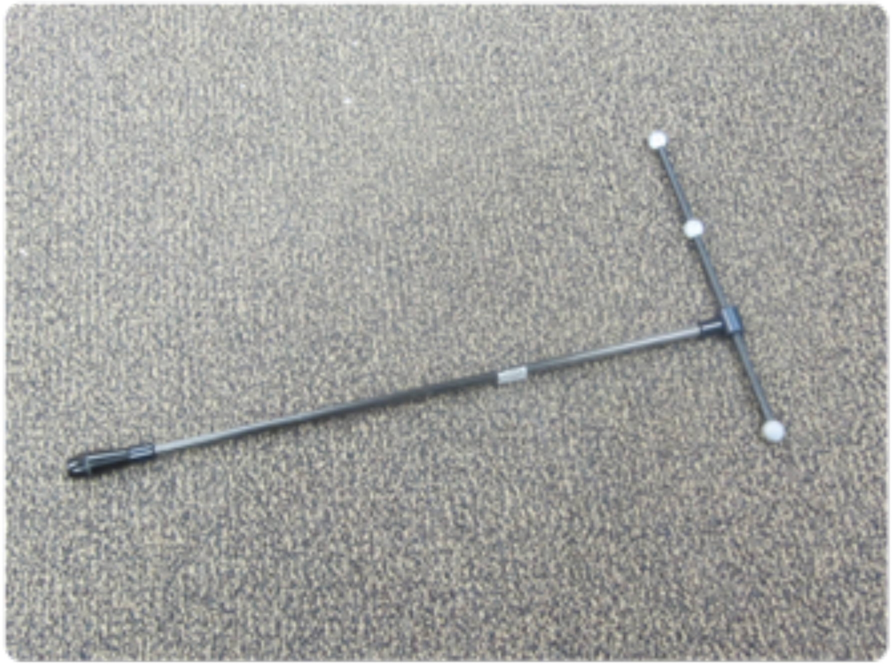
Why lights need to be mounted on the cameras?

Ensures that every marker visible from each camera is well illuminated

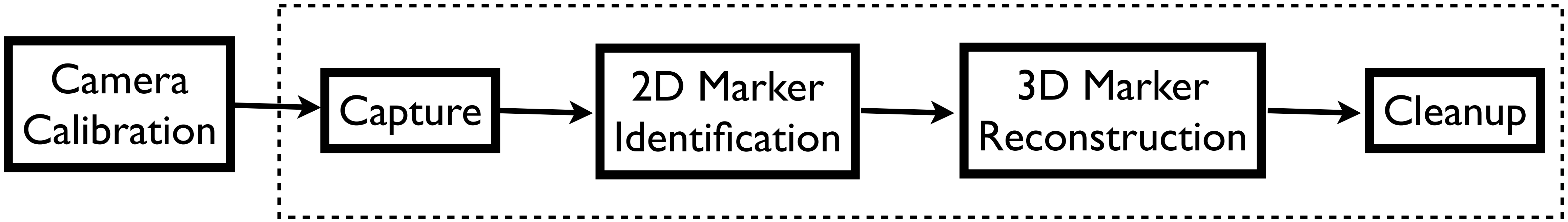
Passive vs. Active Systems

- Active systems are MUCH better at finding correspondences
- Passive systems must rely on unique relative placement of markers and temporal continuity for disambiguation
- Passive systems typically rely on more manual cleanup after captures



Passive Calibration Wand

Motion Capture Pipeline



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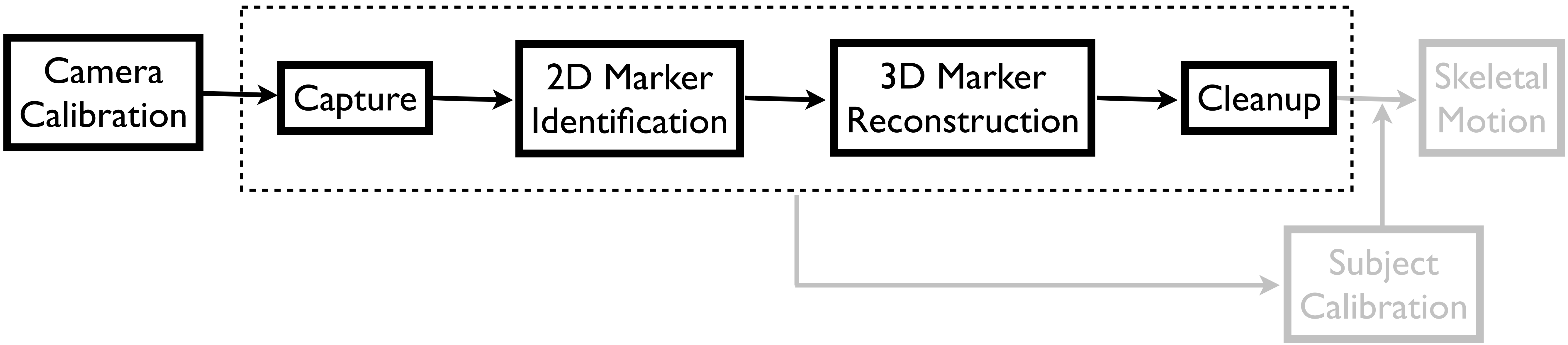

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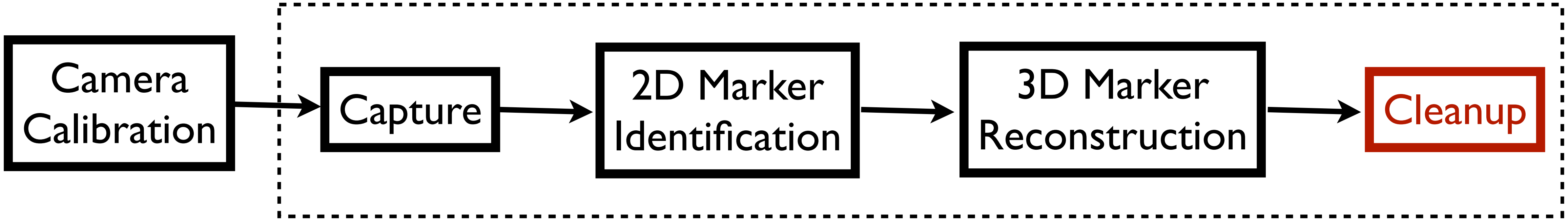
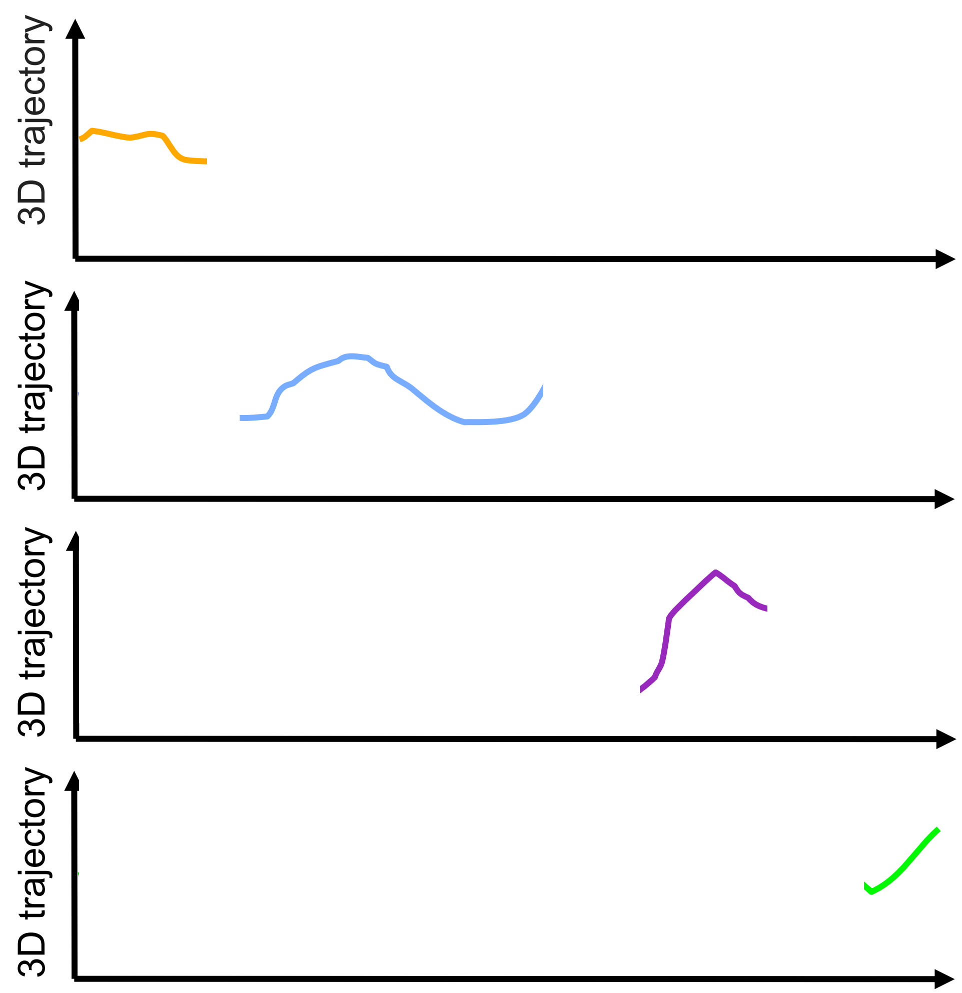


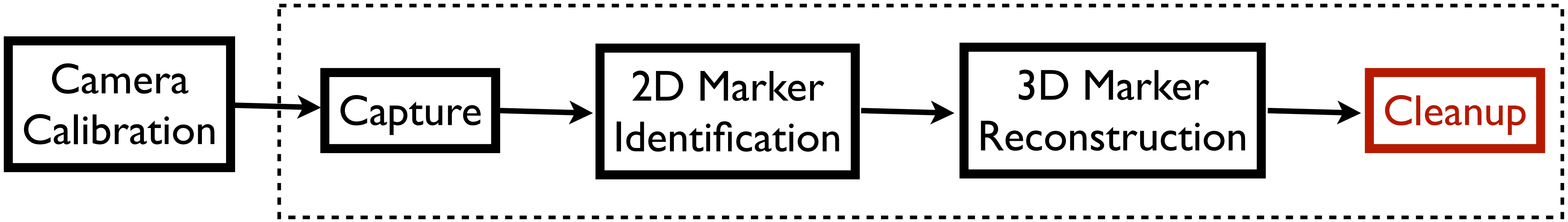
Reasons for fragmented trajectories

- Marker miss-identification
- Noise
- Occlusions



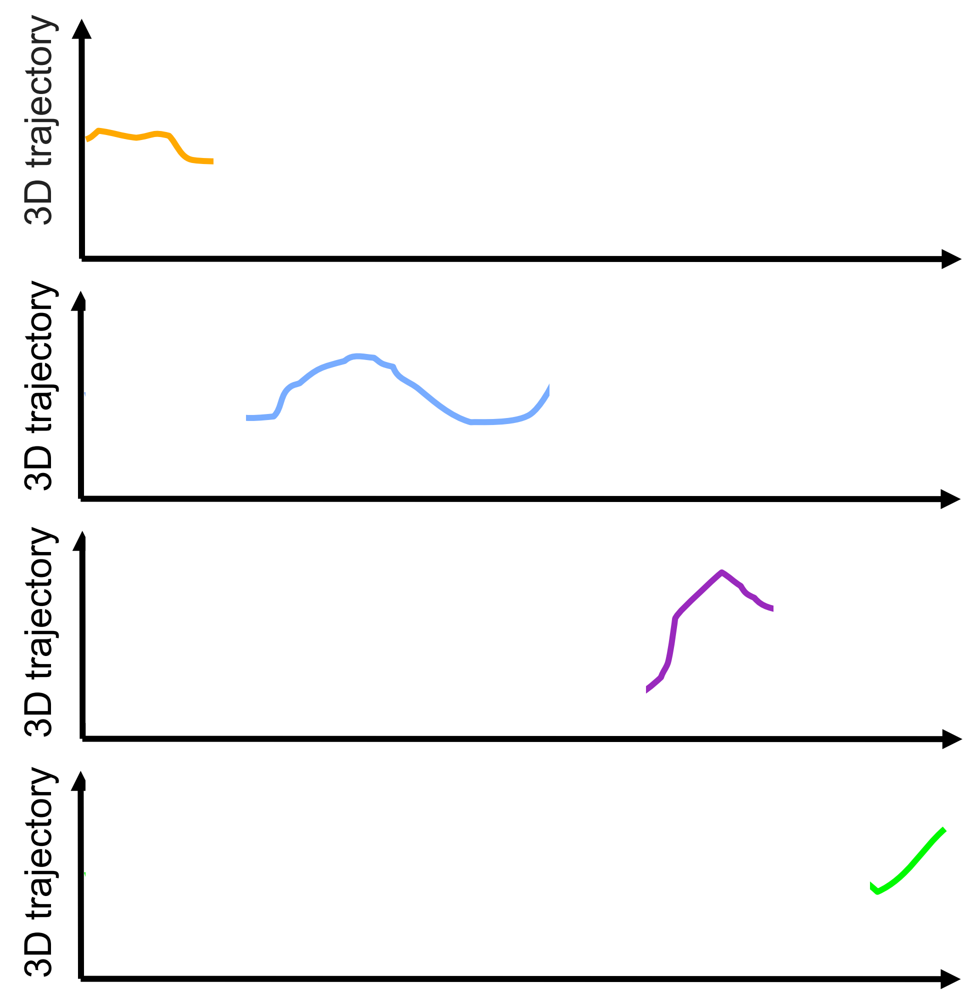
(Illustration from Park & Hodgins, Siggraph 2006)

Motion Capture Pipeline



Cleanup steps (software)

- Merging of trajectories
- Hole filling
- (optional) De-noising



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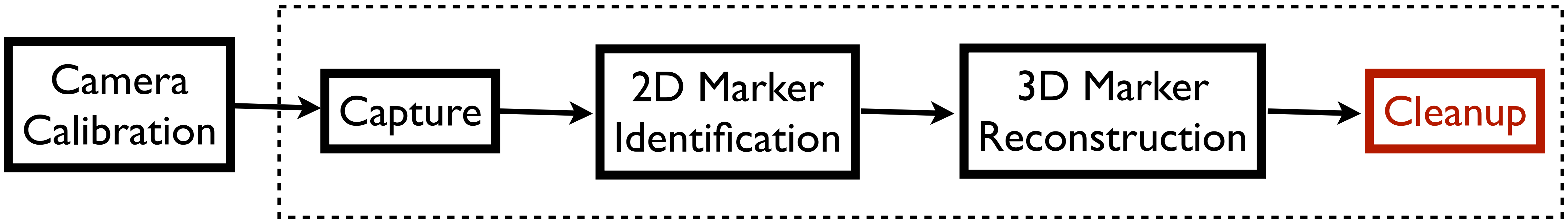
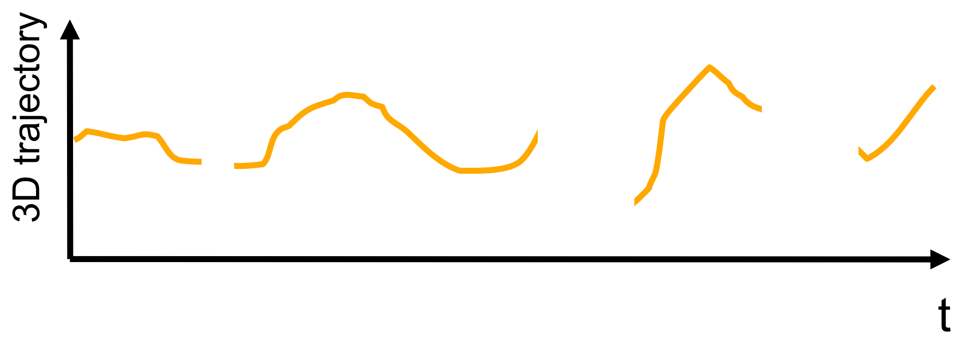


Cleanup steps (software)

- Merging of trajectories
  - Automatic: based on proximity
  - Manual: clicking and labeling



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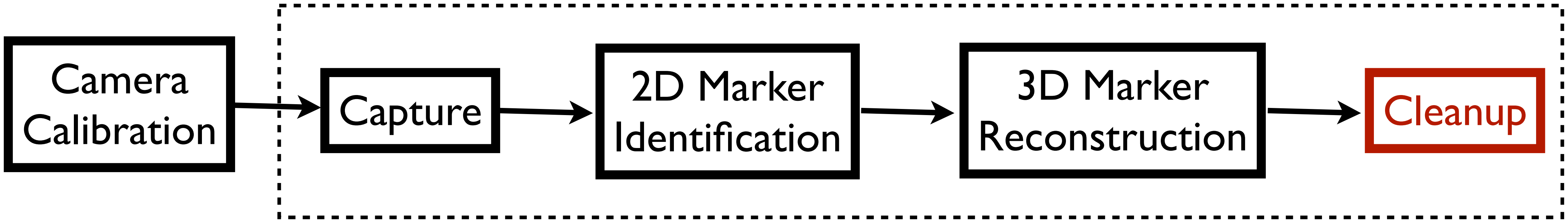

Cleanup steps (software)

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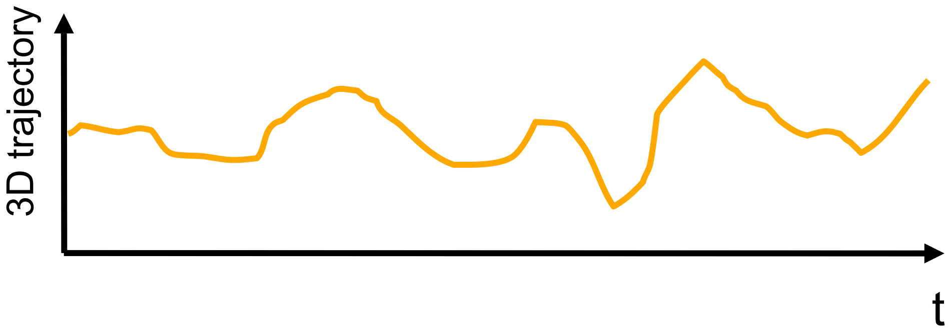
- Hole filling
  - Interpolations (e.g., splines)



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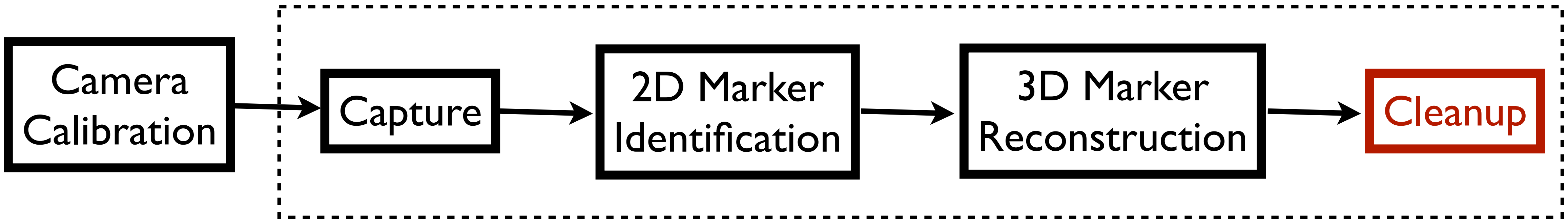

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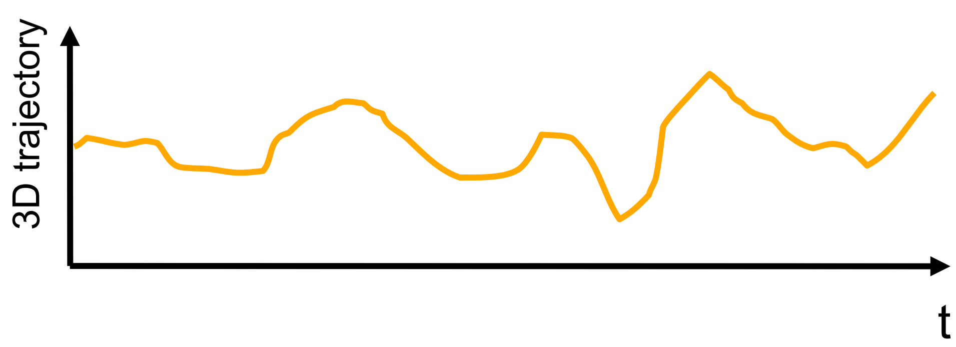

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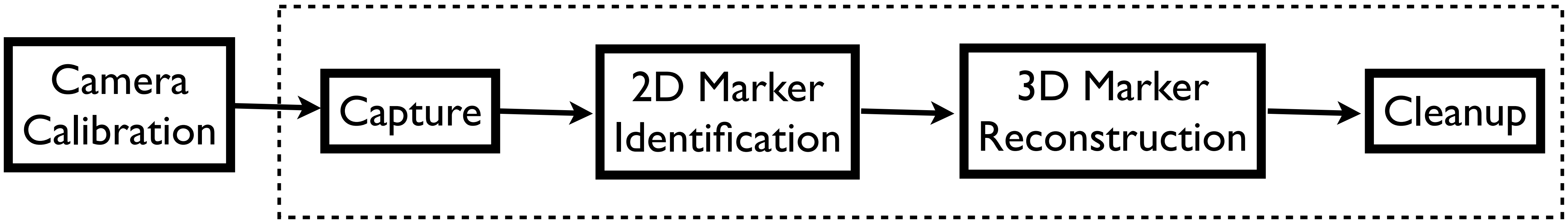
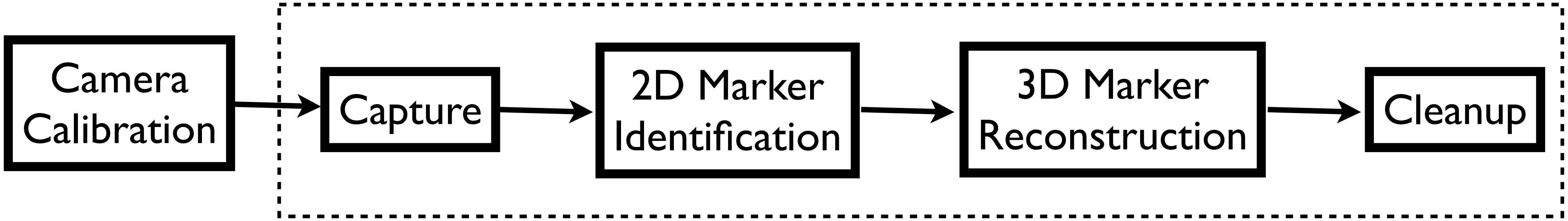
Motion Capture Pipeline



This pipeline is much like virtualization discussed in last class, all about capturing the surface of the body

Motion Capture Pipeline



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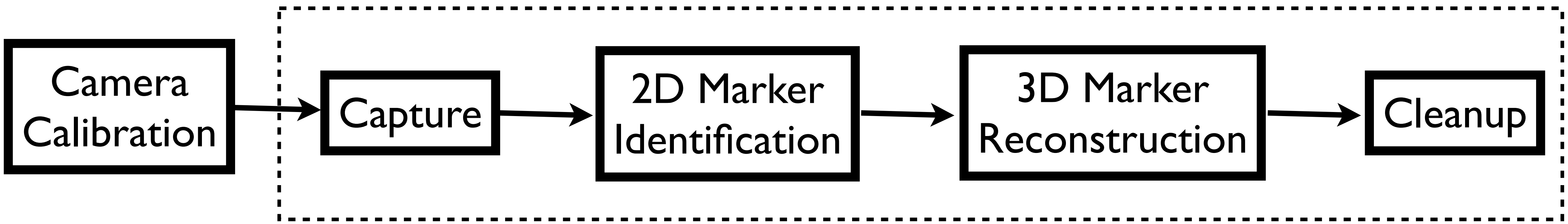
What's the big difference?

Motion Capture Pipeline



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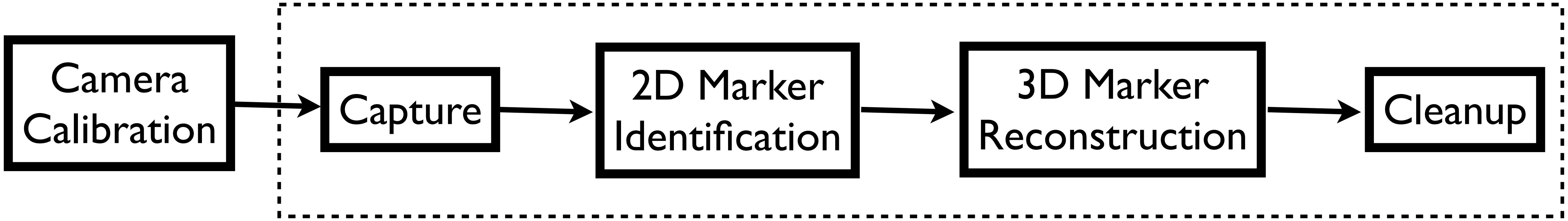
What's the big difference?

Correspondences are easier because we have fewer markers and retro-reflective markers

Capturing Many Markers



Typically:
40-50

Here:
300+

[Park & Hodgins, Siggraph 2006]

Capturing Many Markers

Camera Calibration → [Capture → 2D Marker Identification → 3D Marker Reconstruction → Cleanup]

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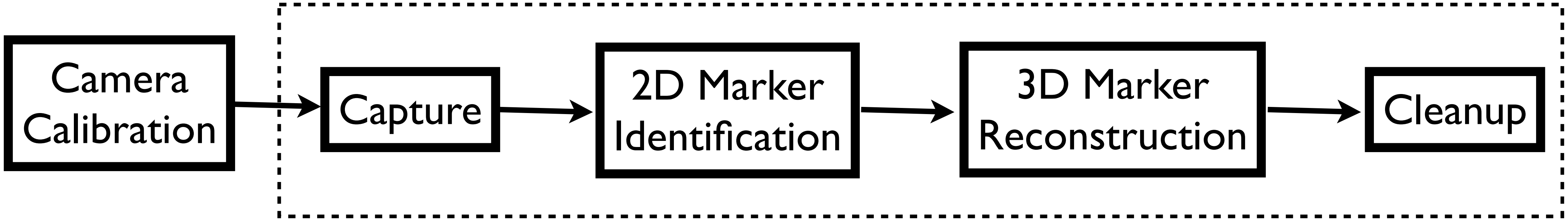
Capturing Many Markers



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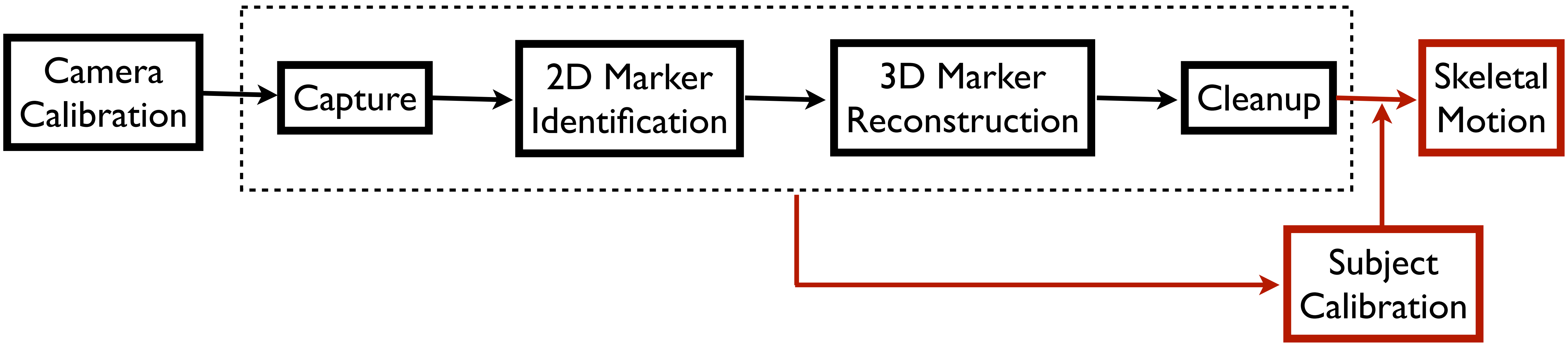
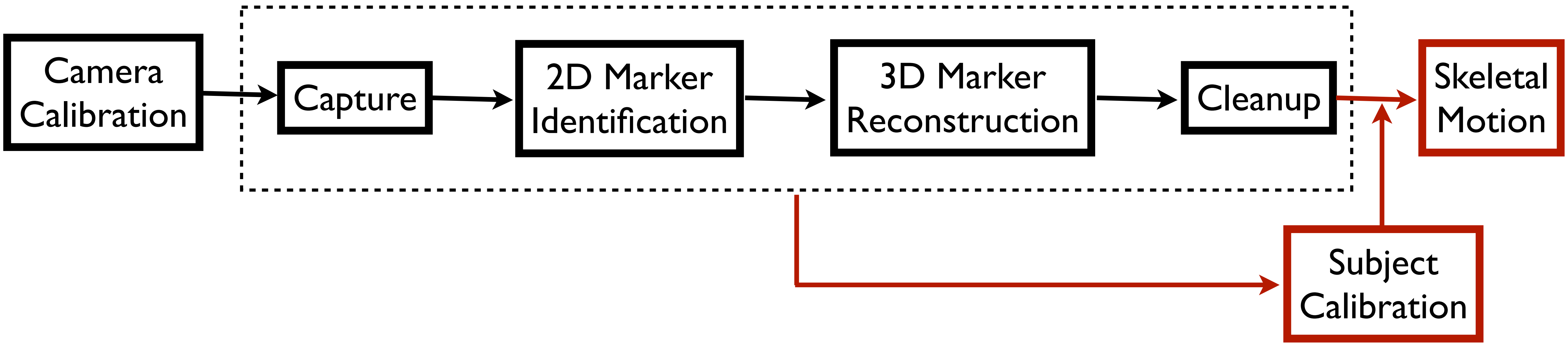


Why skeleton motion (instead of surface)?

- Makes it easier to edit motion

- Gives measurable quantity for motion
  (for analysis people care about bones and joints)

Motion Capture Pipeline



Why skeleton motion (instead of surface)?

- Makes it easier to edit motion
  - Editing marker trajectories is labor intensive and can cause artifacts
- Gives measurable quantity for motion (for analysis people care about bones and joints)

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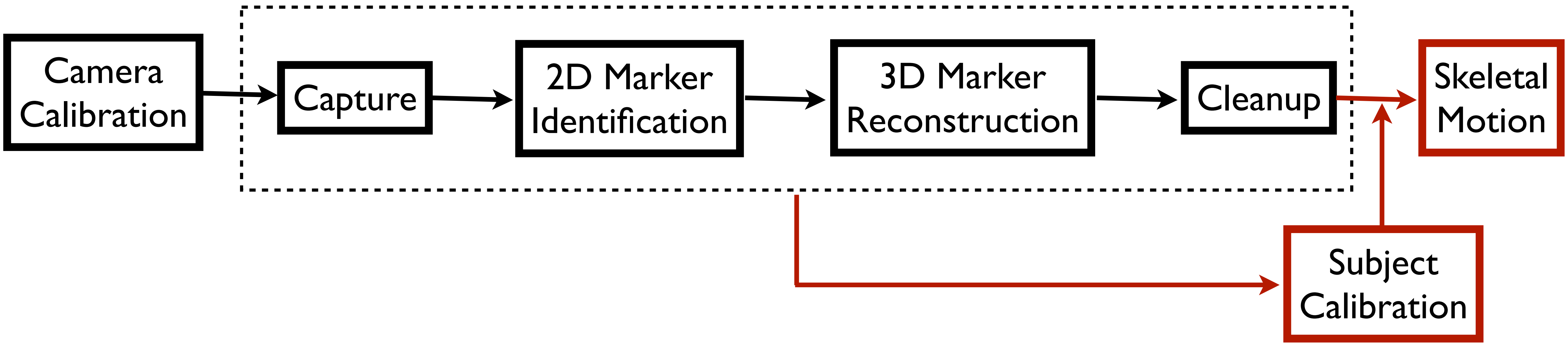
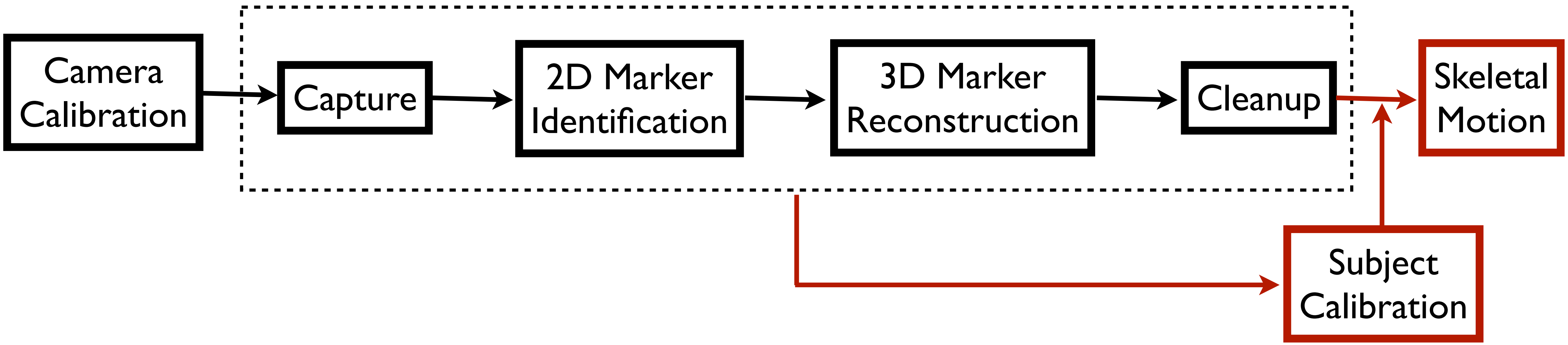


Why skeleton motion (instead of surface)?

- Makes it easier to edit motion
  - Editing marker trajectories is labor intensive and can cause artifacts
- Gives measurable quantity for motion (for analysis people care about bones and joints)
  - Makes analysis independent of marker placement

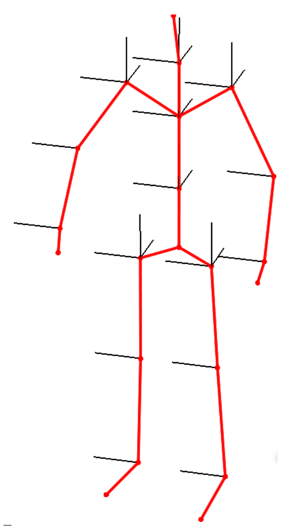
Skeletal Motion



Skeletal Motion - location and orientation of every bone

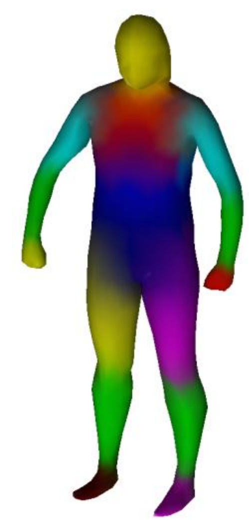
Smooth Skinning

- Embed skeleton in a canonical pose into a mesh
- Assign each mesh vertex to one or more bones (process is called painting skinning weights and can be either manual or automatic)

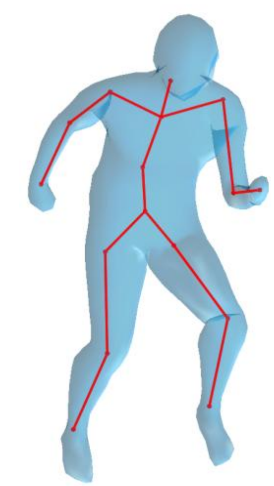


Skeleton

Skeleton Embedding



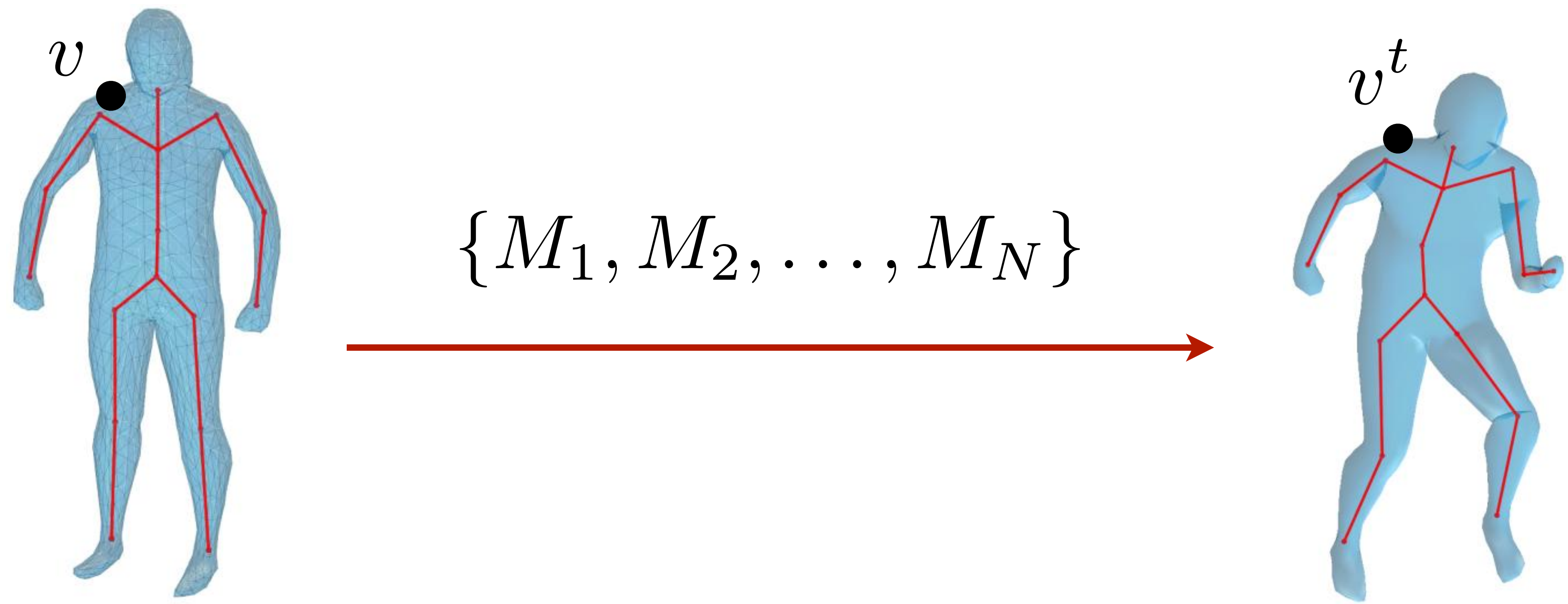
Skinning Weights



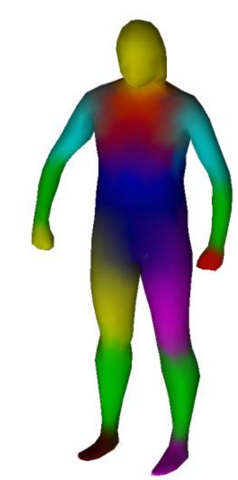
Modified Pose

[Images taken from Pons-Moll and Rosenhahn, 2011]

Smooth Skinning



$$v^t = \sum_i^N w_i M_i v \qquad \text{where} \qquad \sum_i^N w_i = 1$$



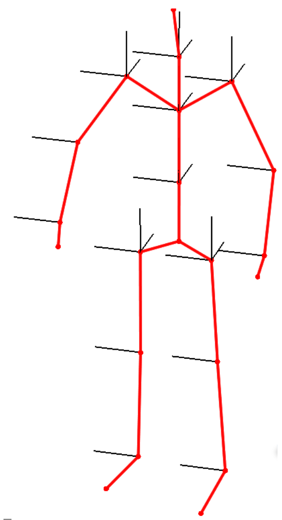
N - number of bones

M_i - 4x4 transformation from binding pose to current pose for a given bone i

[Images taken from Pons-Moll and Rosenhahn, 2011]

Smooth Skinning

Not a good method for doing this actually (causes artifacts), we'll study much better methods later in the semester



Skeleton

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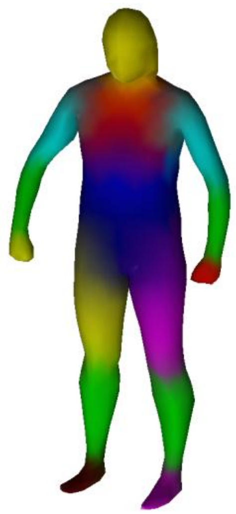

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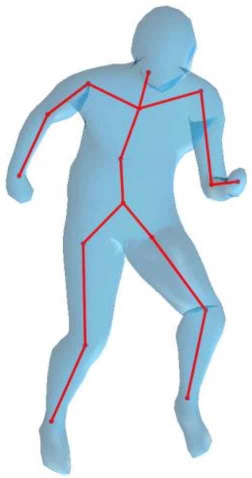

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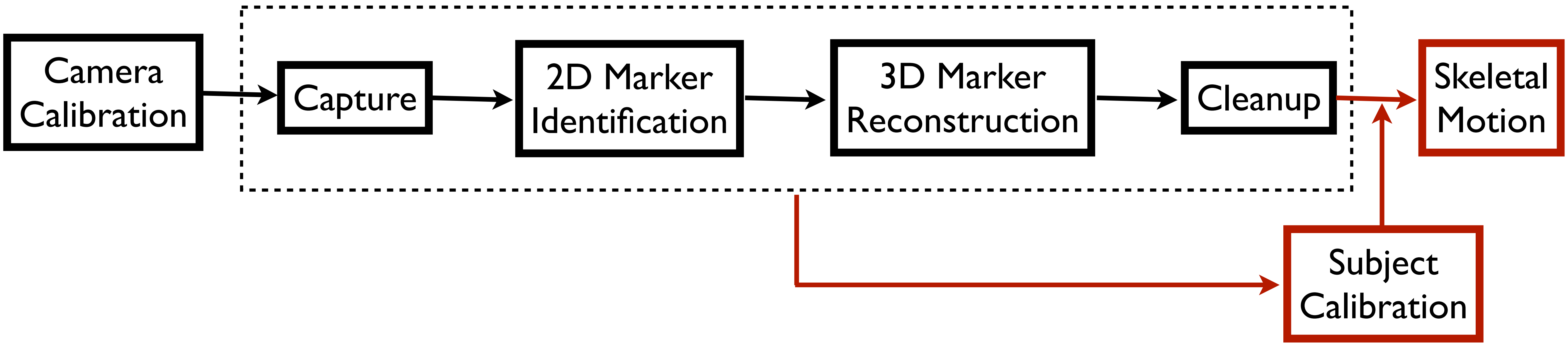
Skeletal Motion



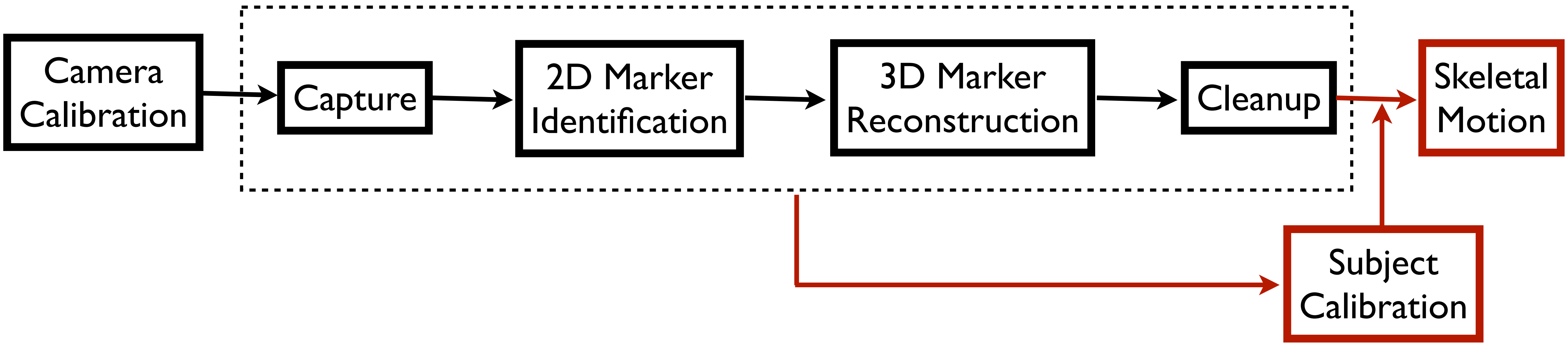
Skeletal Motion - location and orientation of every bone

Issue: What we observe is only surface motion (location of markers)

Radiostereometric Analysis

- Multiple simultaneous X-ray scans
- Image surgically inserted titanium beads into the bone
- Accuracy of bone motion < 2/10 millimeter
- Only used for corrective surgery monitoring (hip/knee replacement)

Skeletal Motion



Skeletal Motion - location and configuration of every bone

Issue: What we observe is only surface motion (location of markers)

Subject Calibration

- Give identifiers to markers (typically one needs a minimum of 3 markers per body segment)
- Create a subject skeleton (facilitated by software):
  - Bone lengths
  - Bone connections
  - Joint limits
  - Marker to bone correspondence
- Define or derive a relationship between markers and the bones (typically requires recoding a subject doing the range of motion trial)

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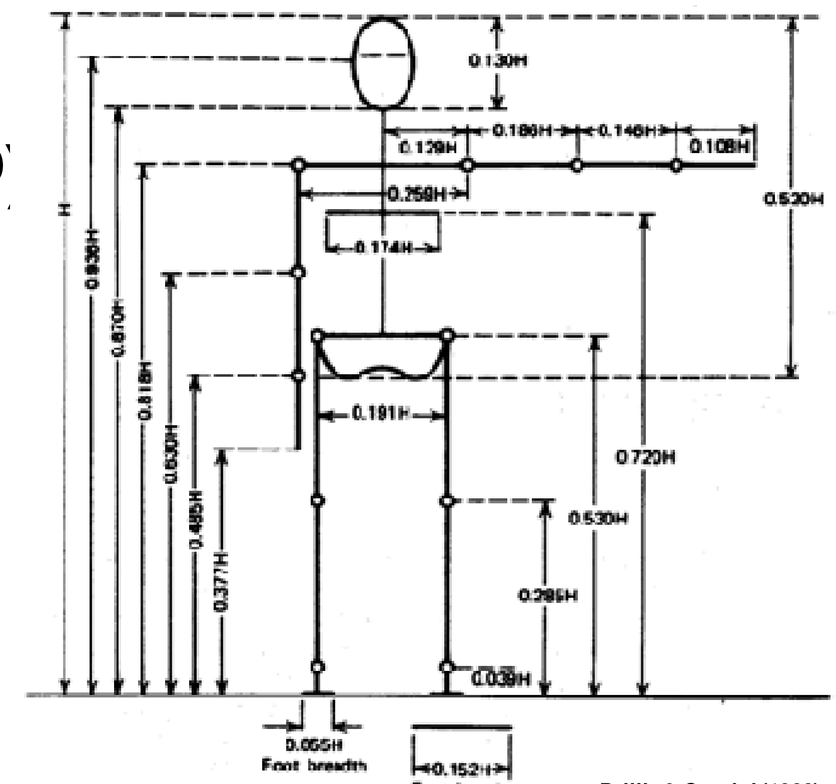

Drillis & Contini (1966)

- Define or derive a relationship between markers and the bones (typically requires recoding a subject doing the range of motion trial)

Subject Calibration

- Give identifiers to markers (typically one needs a minimum of 3 markers per body segment)
- Create a subject skeleton (facilitated by software):
  - Bone lengths
  - Bone connections → Based on the anatomy (all humans have the same)
  - Joint limits
  - Marker to bone correspondence
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  - Joint limits ⟶ Based on the anatomy (could be custom)
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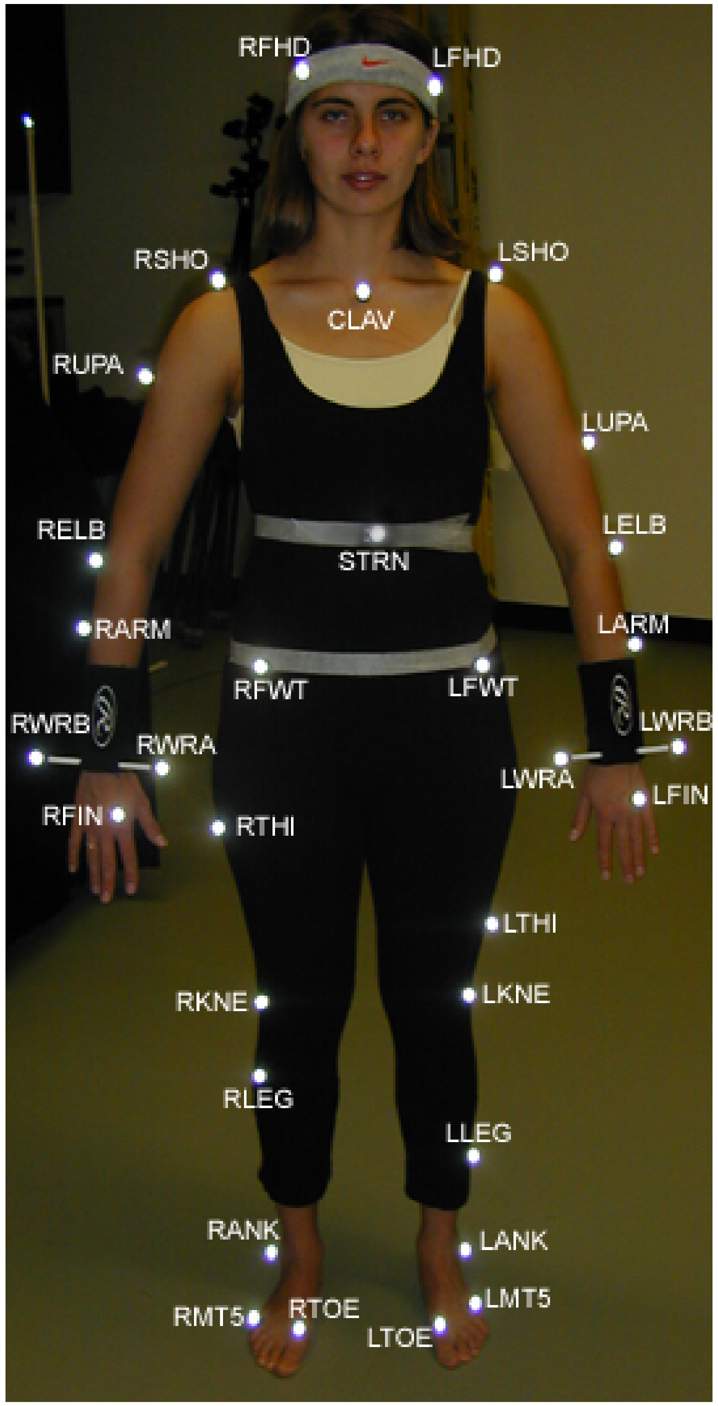
Subject Calibration: Useful Notes

- Placing markers at bony anatomical landmarks minimizes sliding and allows regression-based methods for localization of certain joints (e.g., hip)

- Regression models often are defined and verified by looking a cadavers



Subject Calibration: Useful Notes

- Placing two markers on the opposite sides of joint, allows one to easily define joint center (average) and axis.

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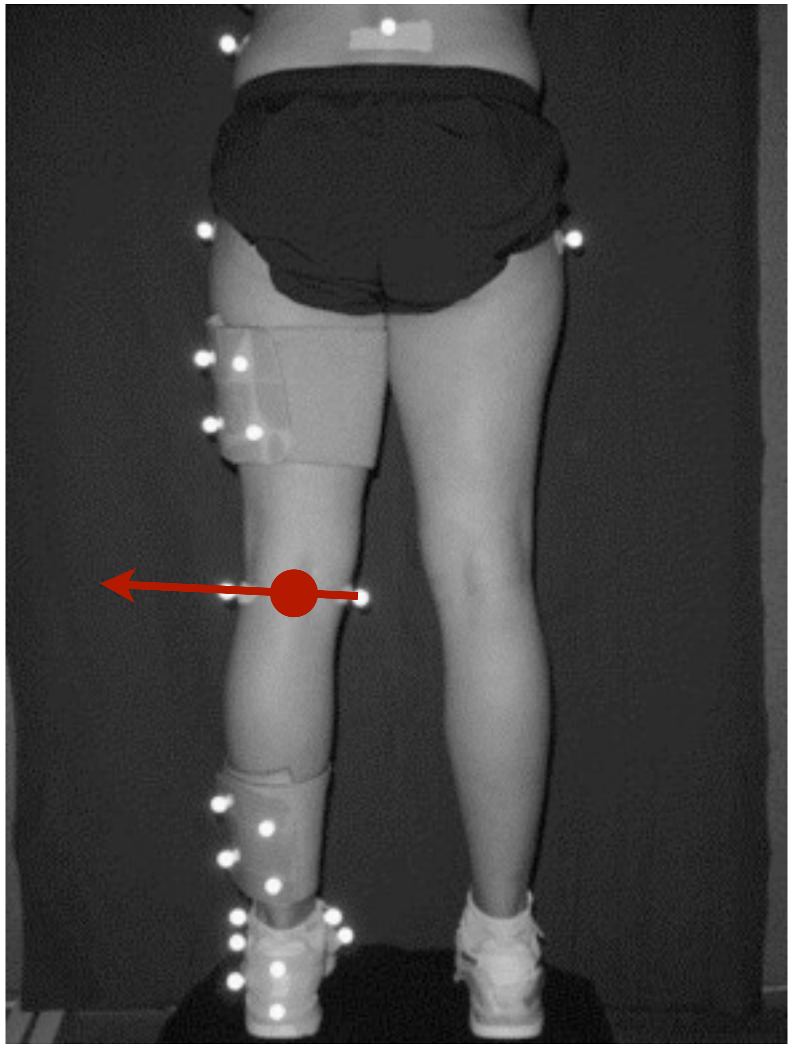

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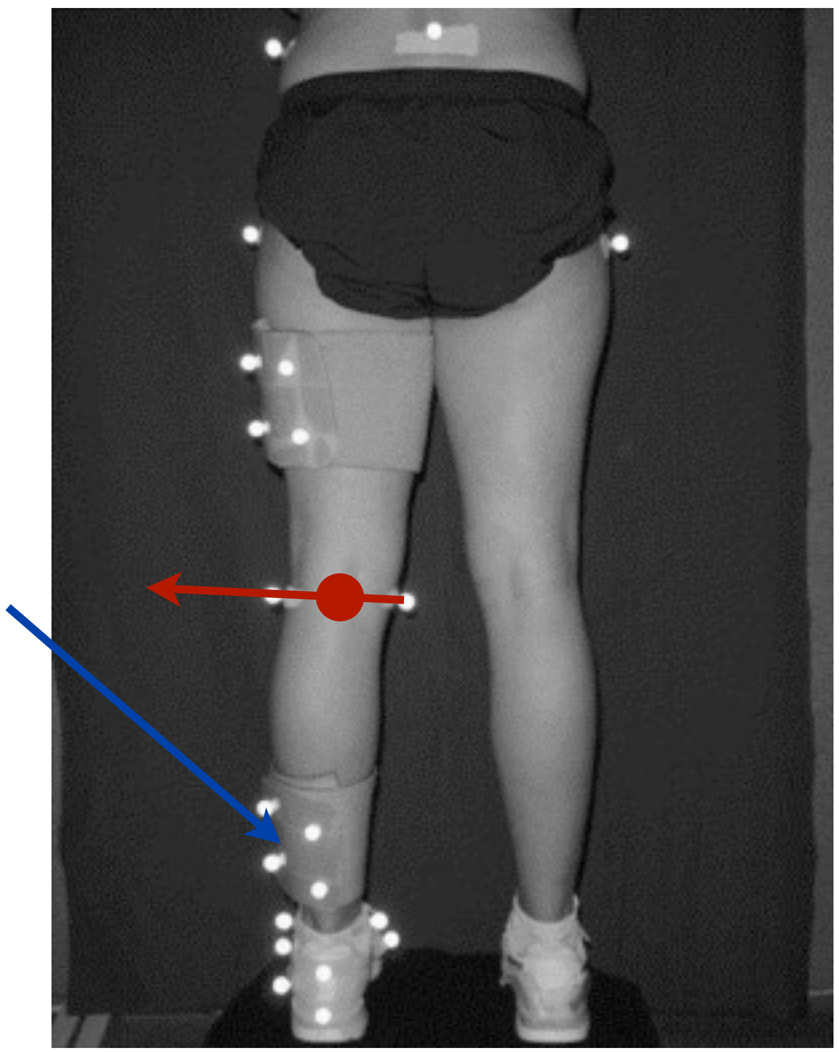
- Placing two markers on the opposite sides of joint, allows one to easily define joint center (average) and axis.

Additional marker(s) on the segment allow measuring of twist



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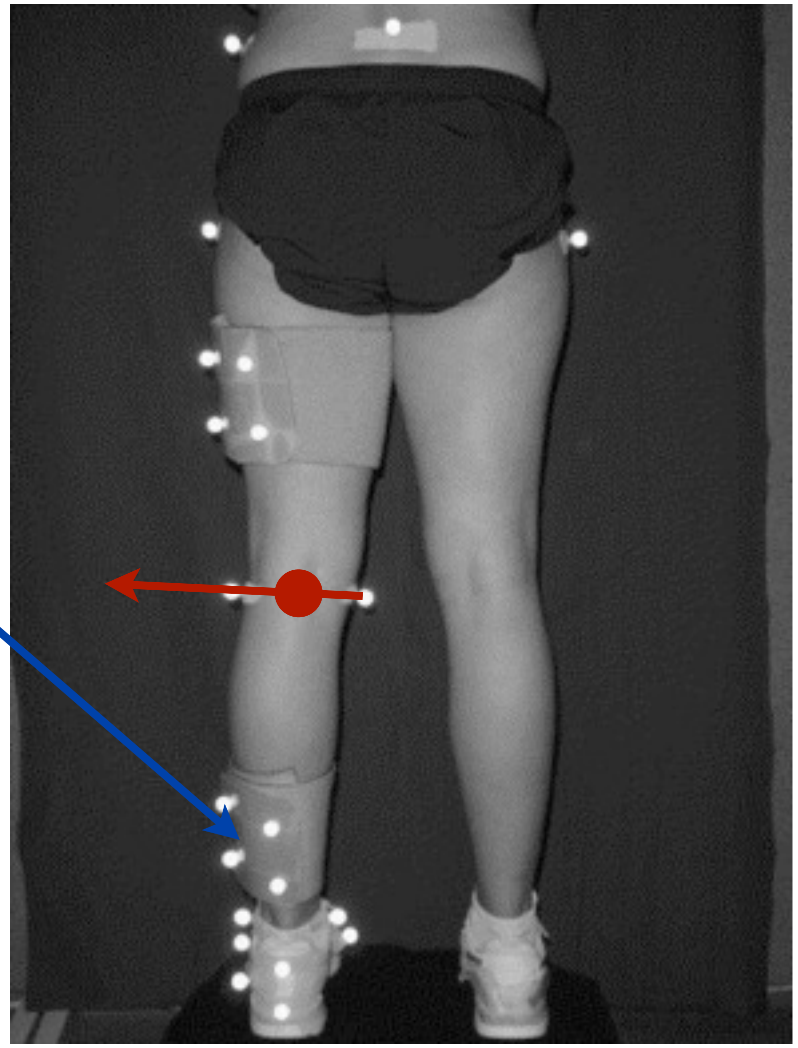
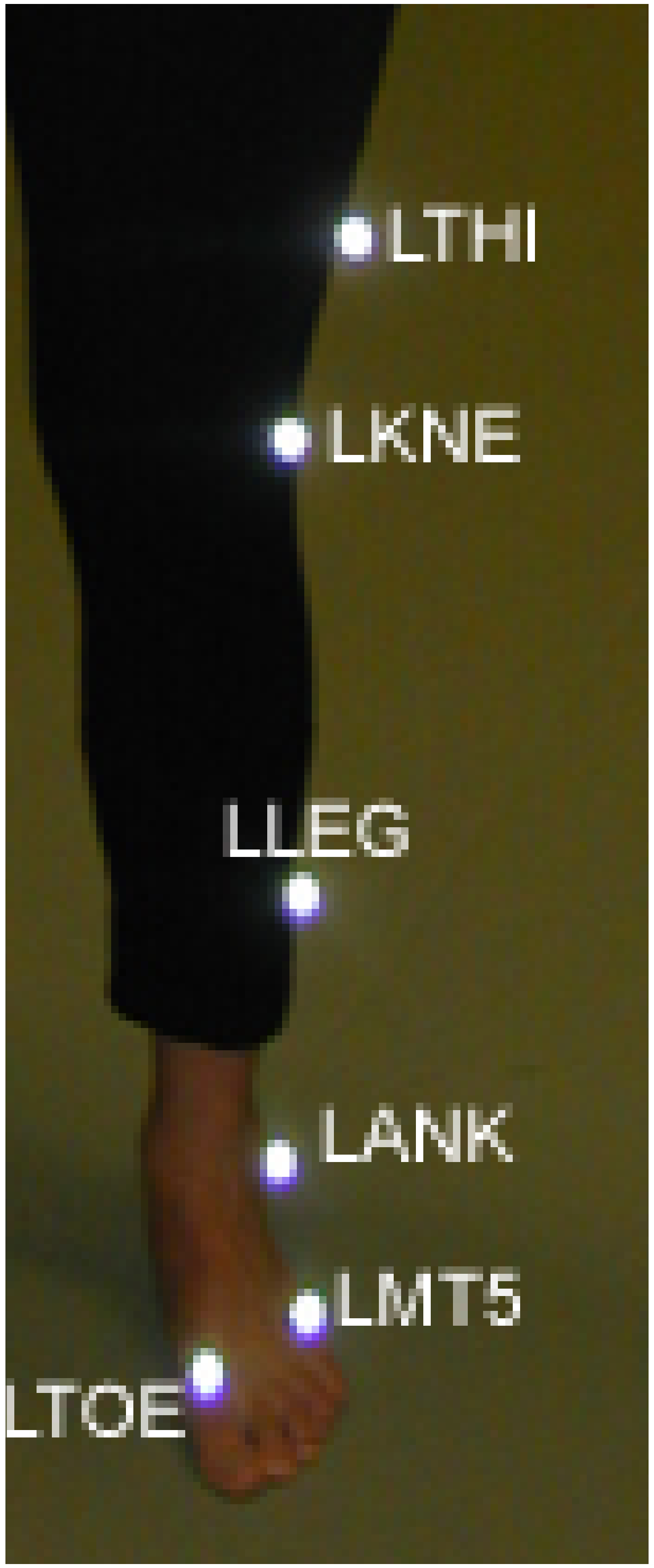


Disadvantage: In this case impedes the movement

Subject Calibration: Useful Notes

- Markers on one segment can define a plane
- Joint is then estimated as an offset from joint markers in that plane



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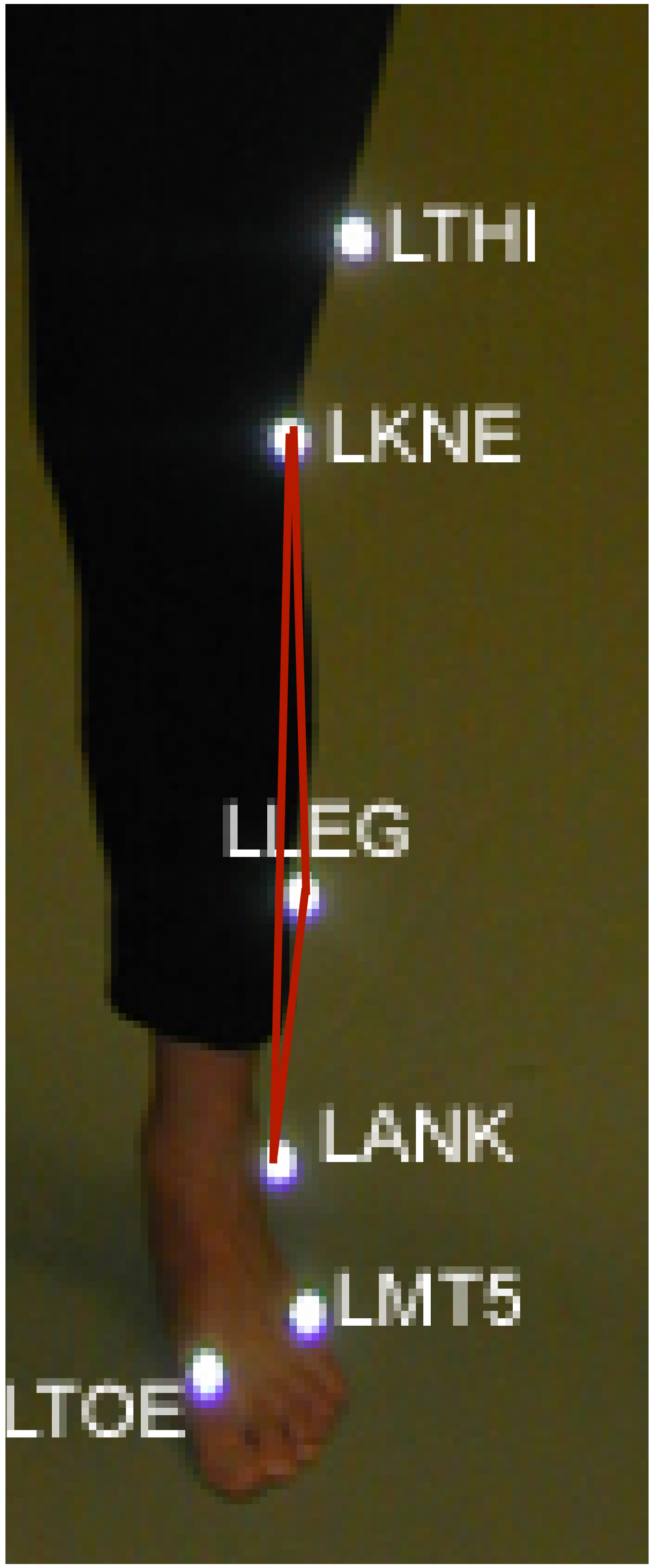

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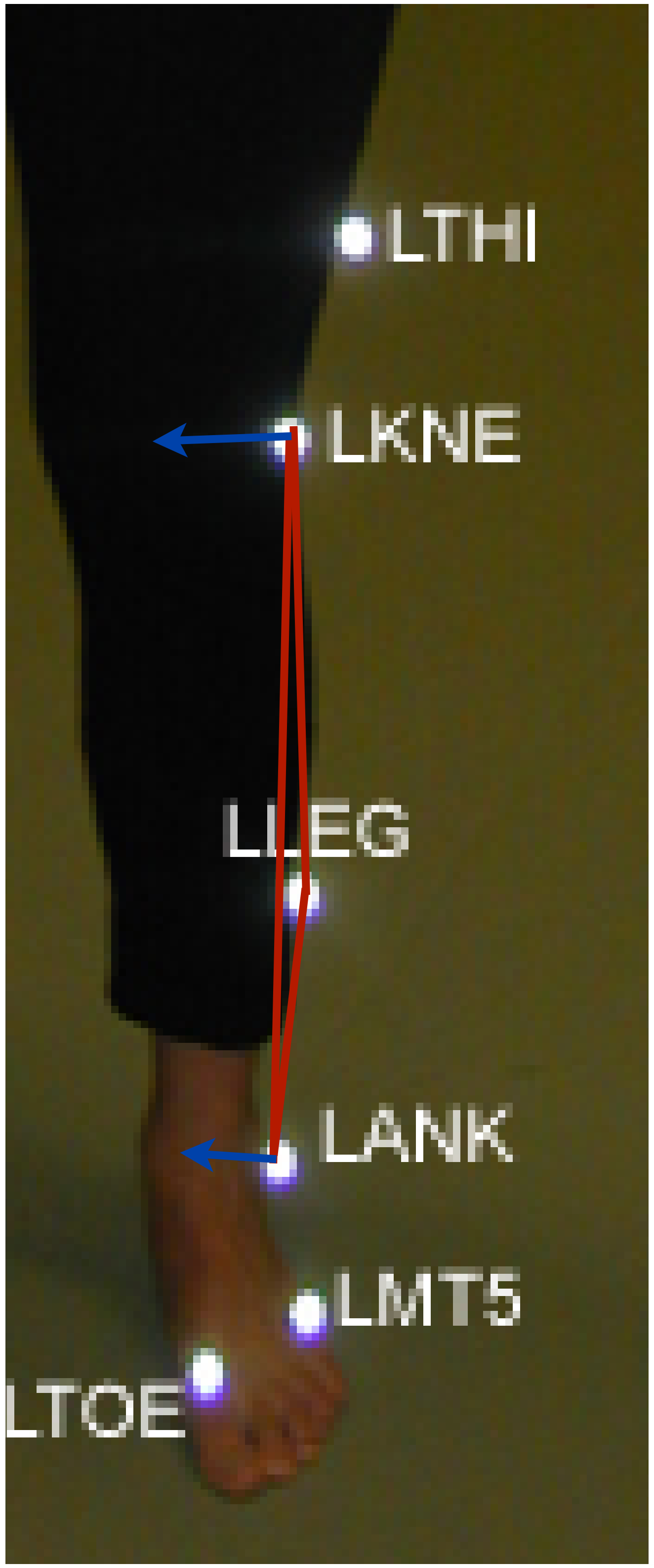

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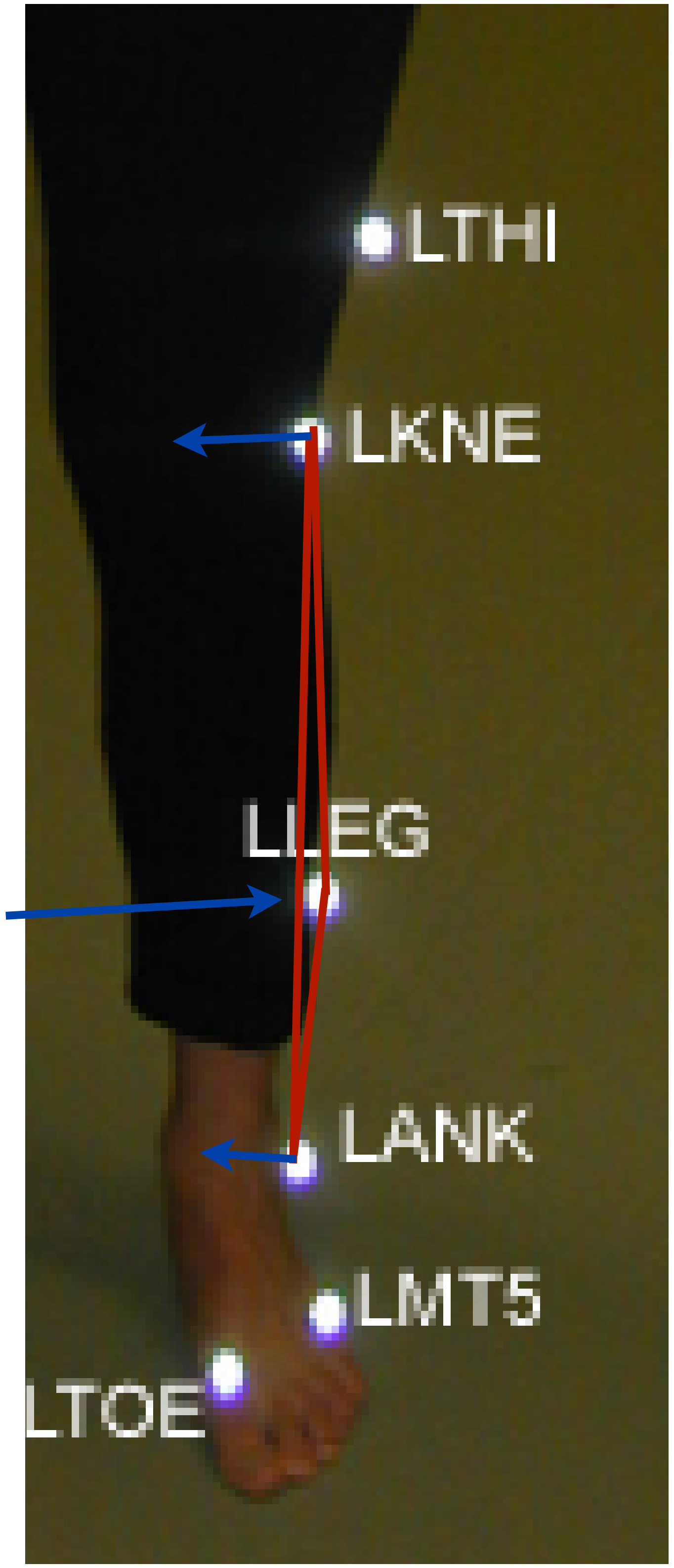

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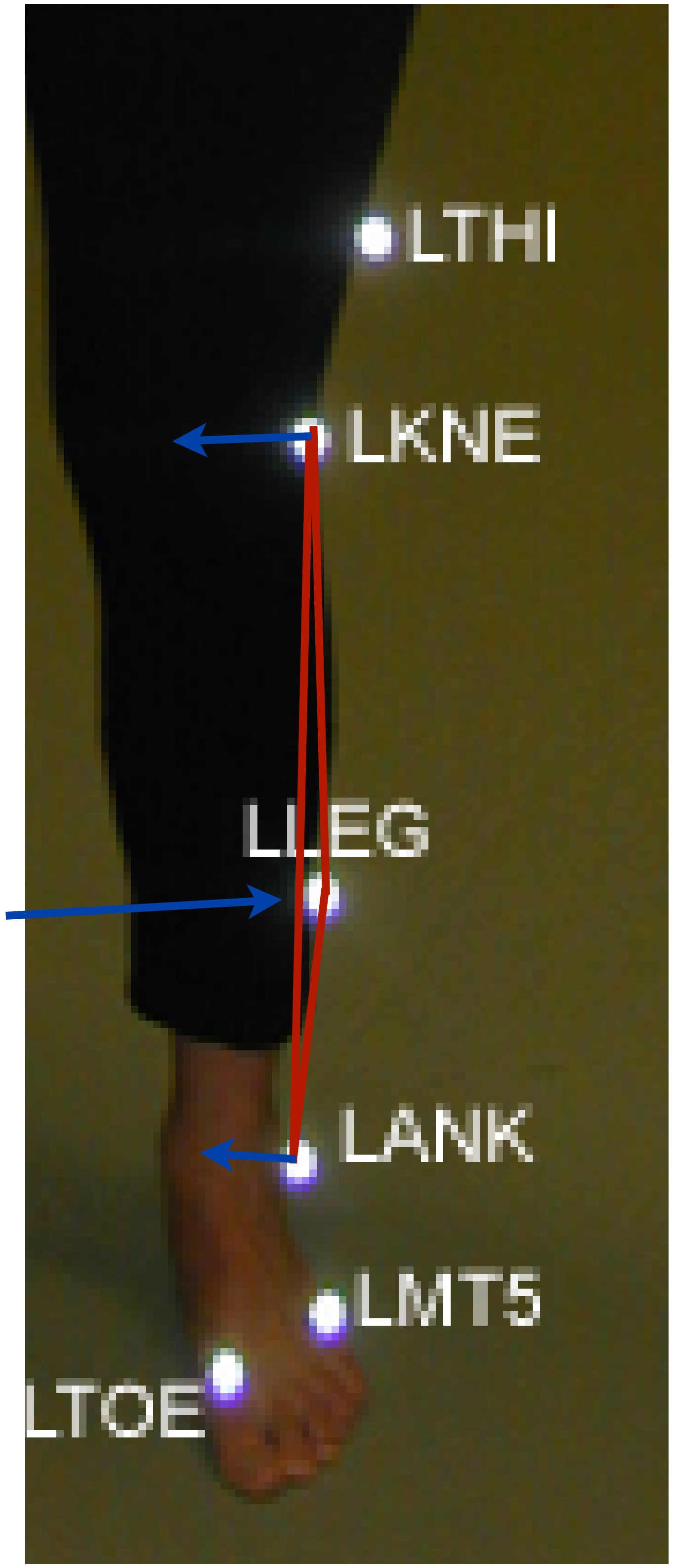
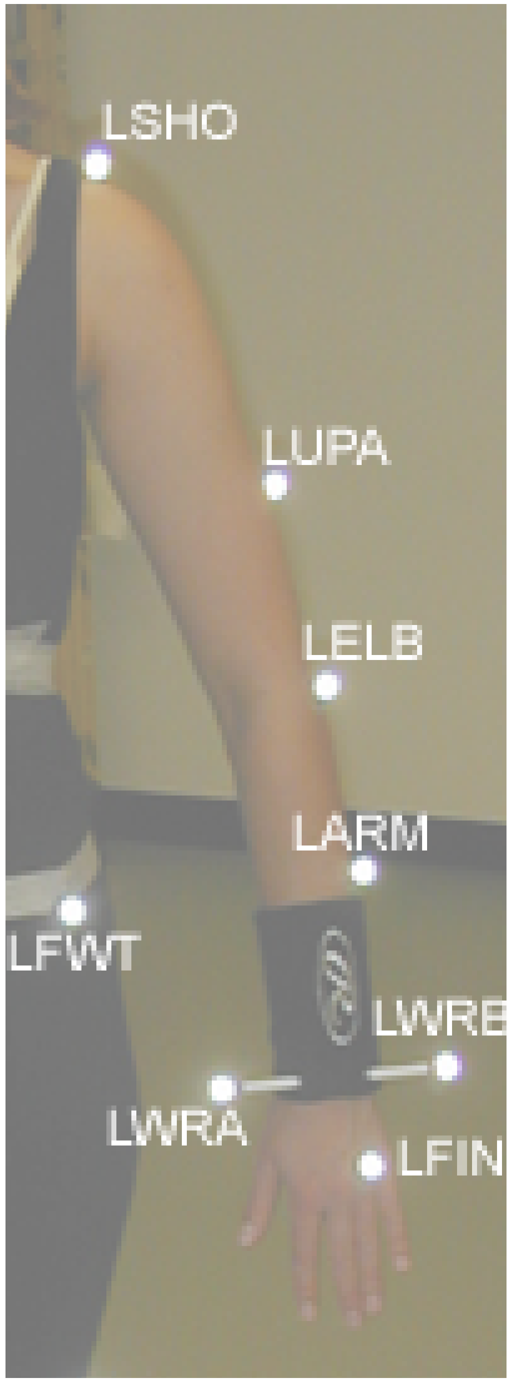


Note: A combination of all such methods is often used in practice

More General Approach



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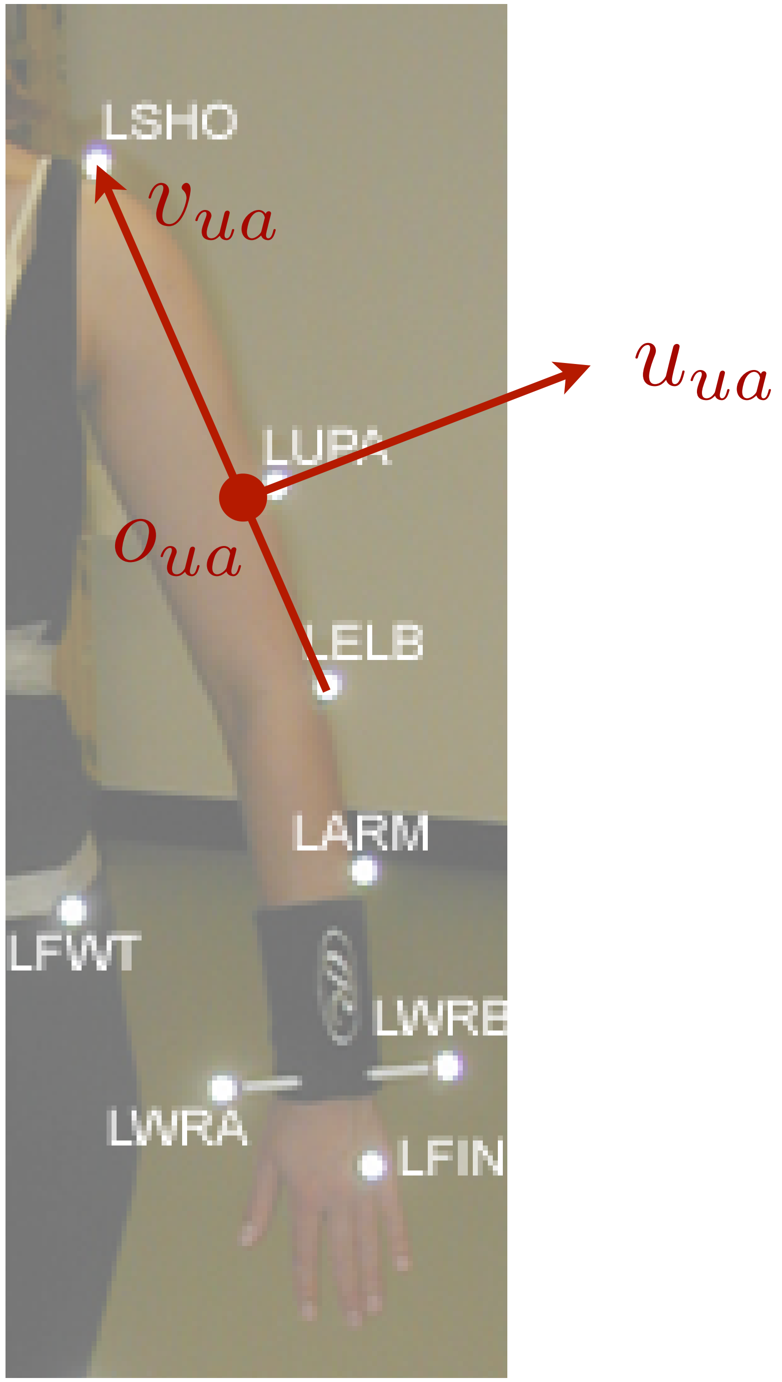
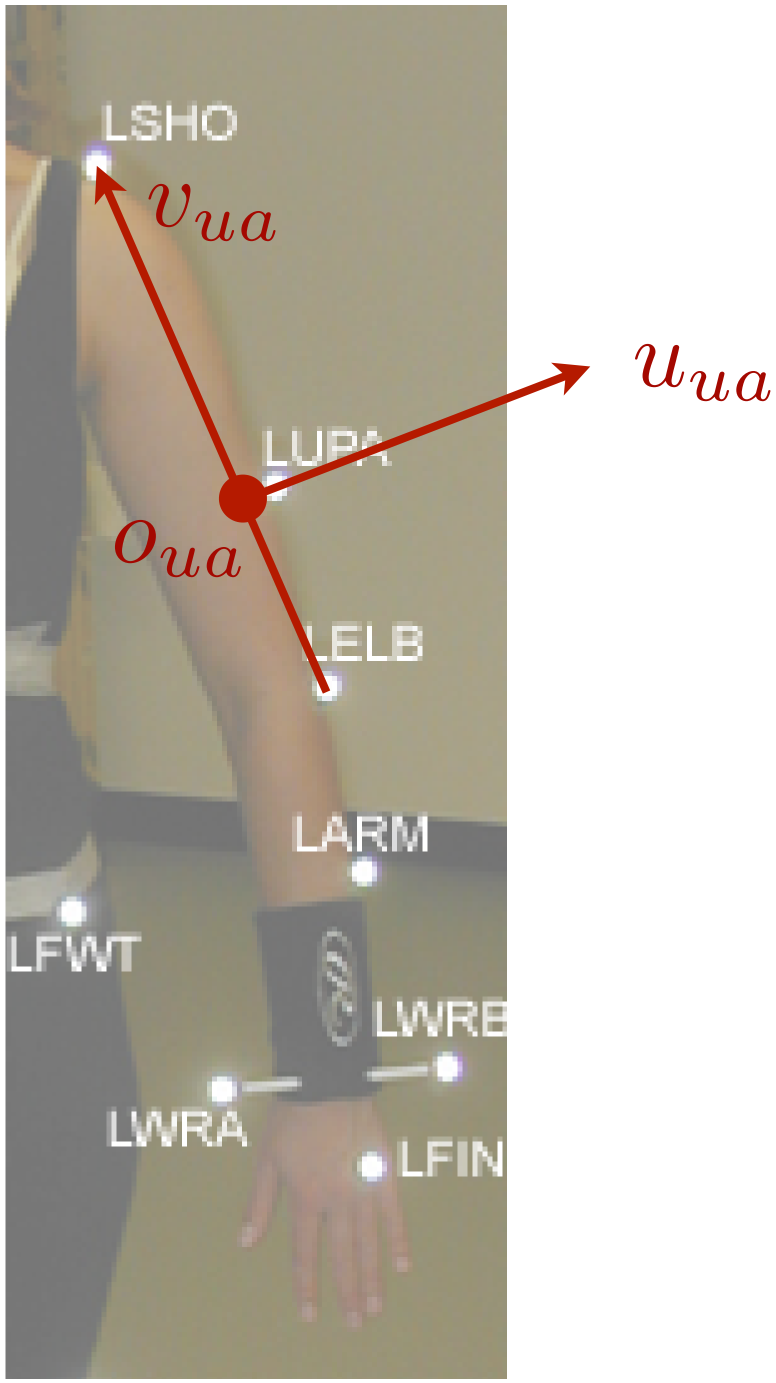


More General Approach

$$T^{ua \rightarrow w} = \begin{bmatrix} \frac{u_{ua}}{||u_{ua}||}, & \frac{v_{ua}}{||v_{ua}||}, & \frac{u_{ua}}{||u_{ua}||} \times \frac{v_{ua}}{||v_{ua}||}, & o_{ua} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



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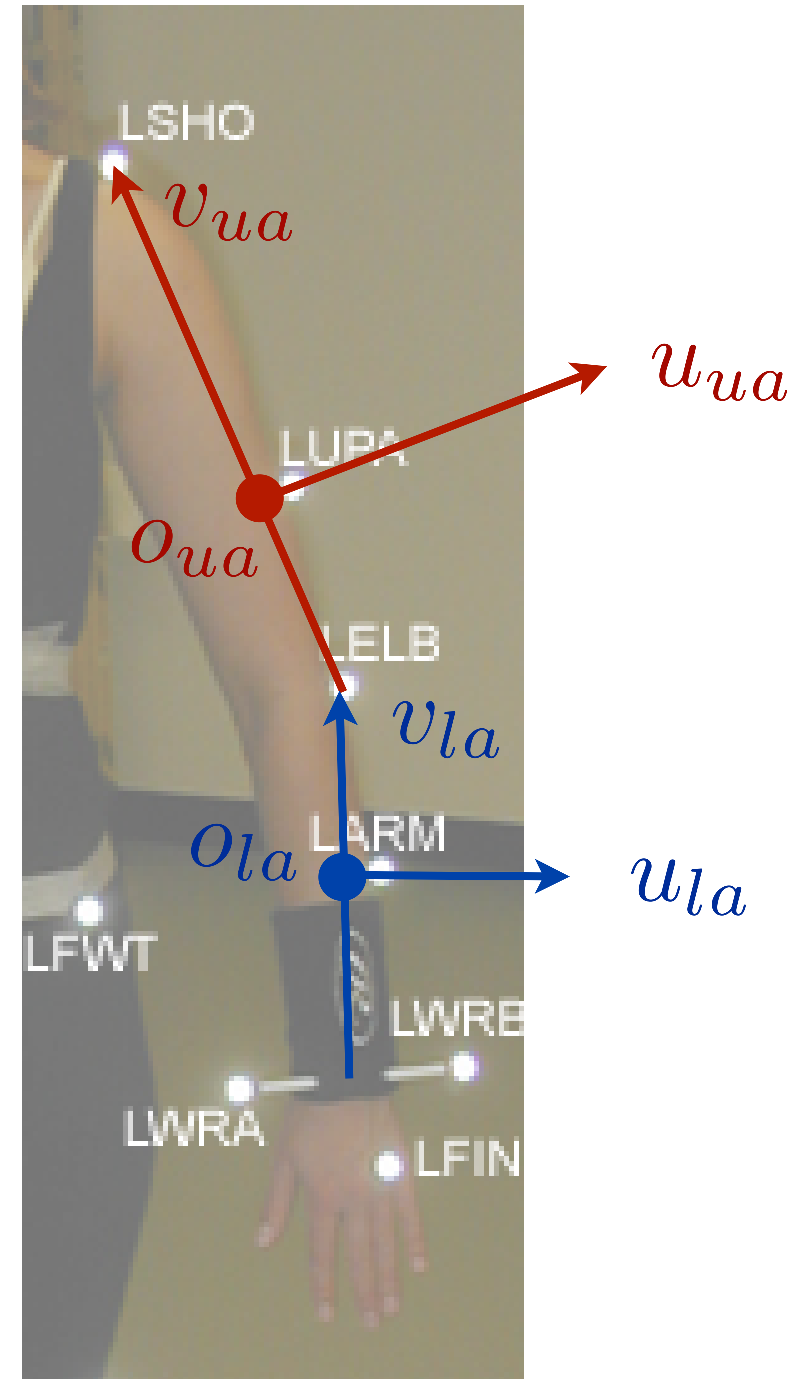

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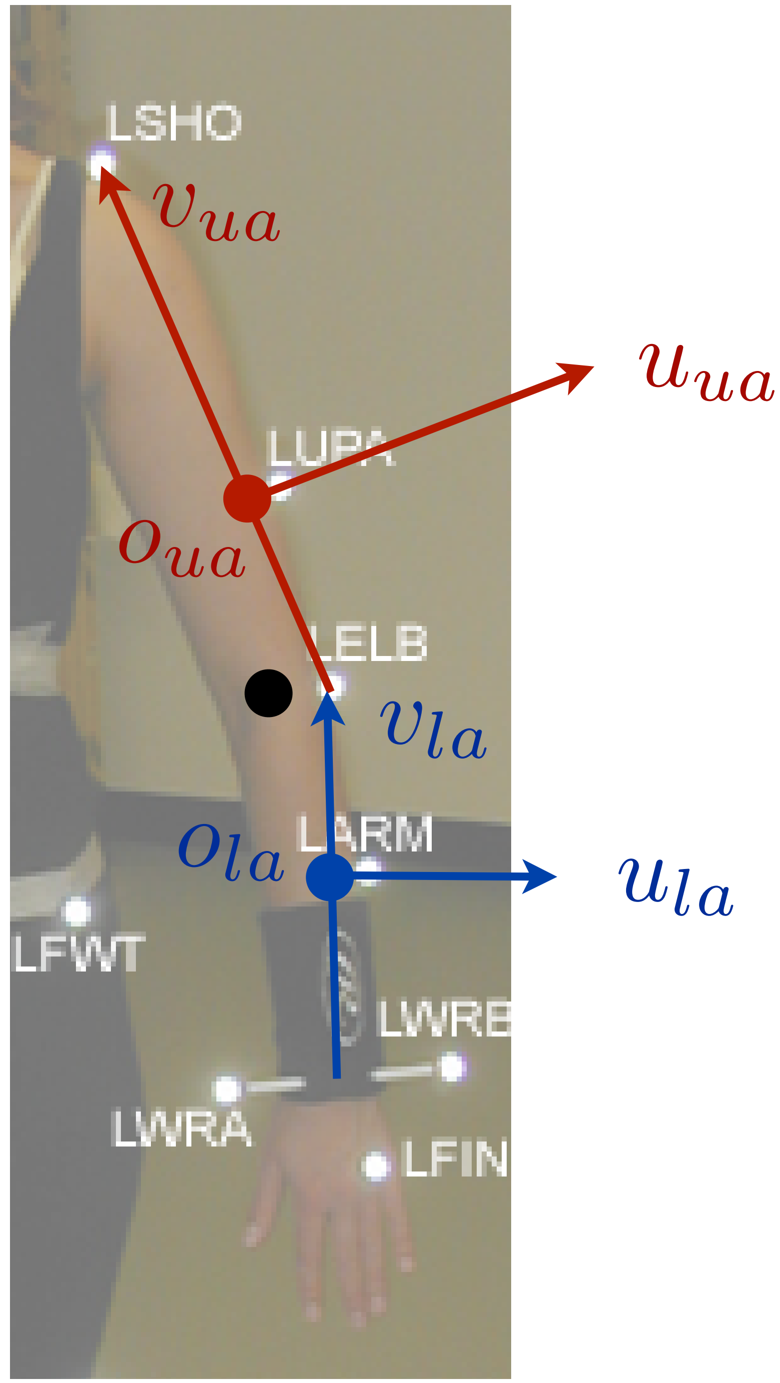

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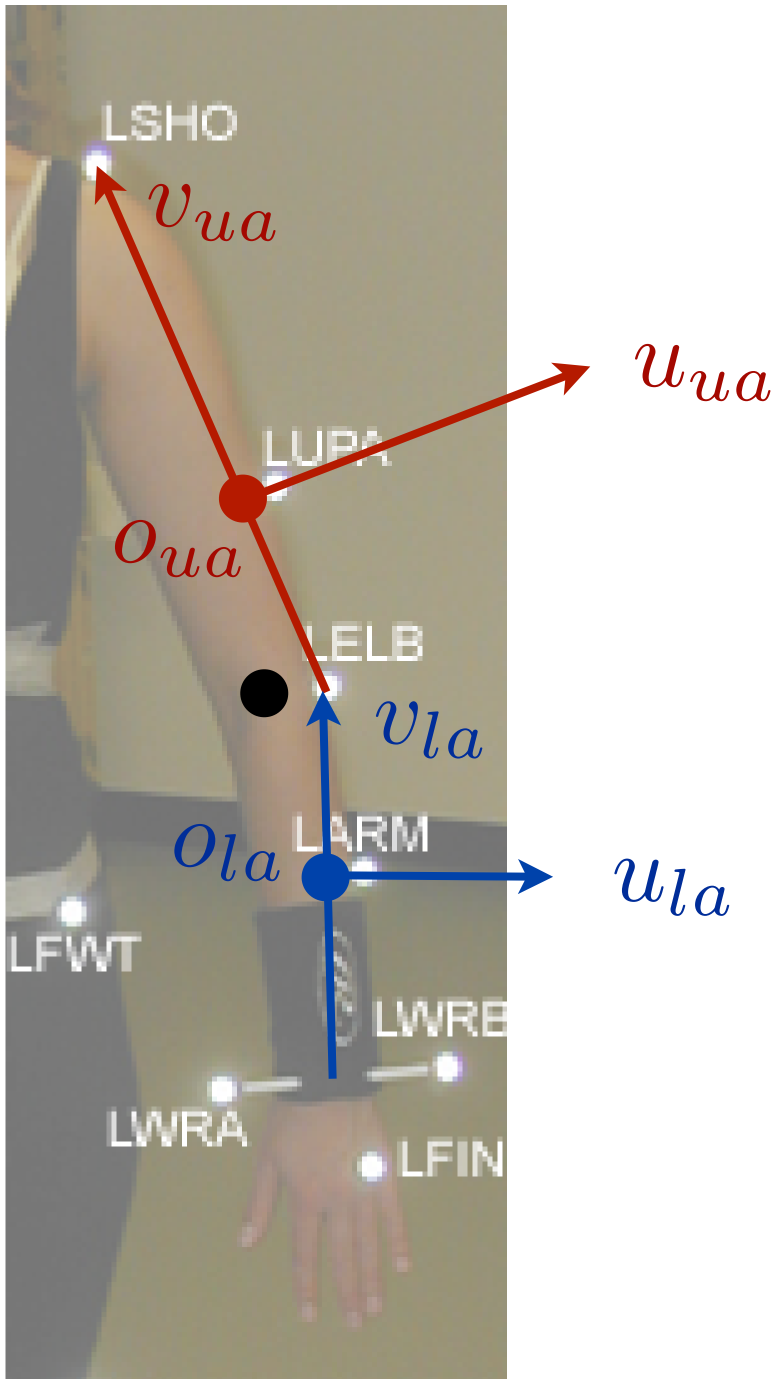
$$T^{ua \rightarrow w} \cdot p_{ua}^{(j)} = T^{la \rightarrow w} \cdot p_{la}^{(j)}$$



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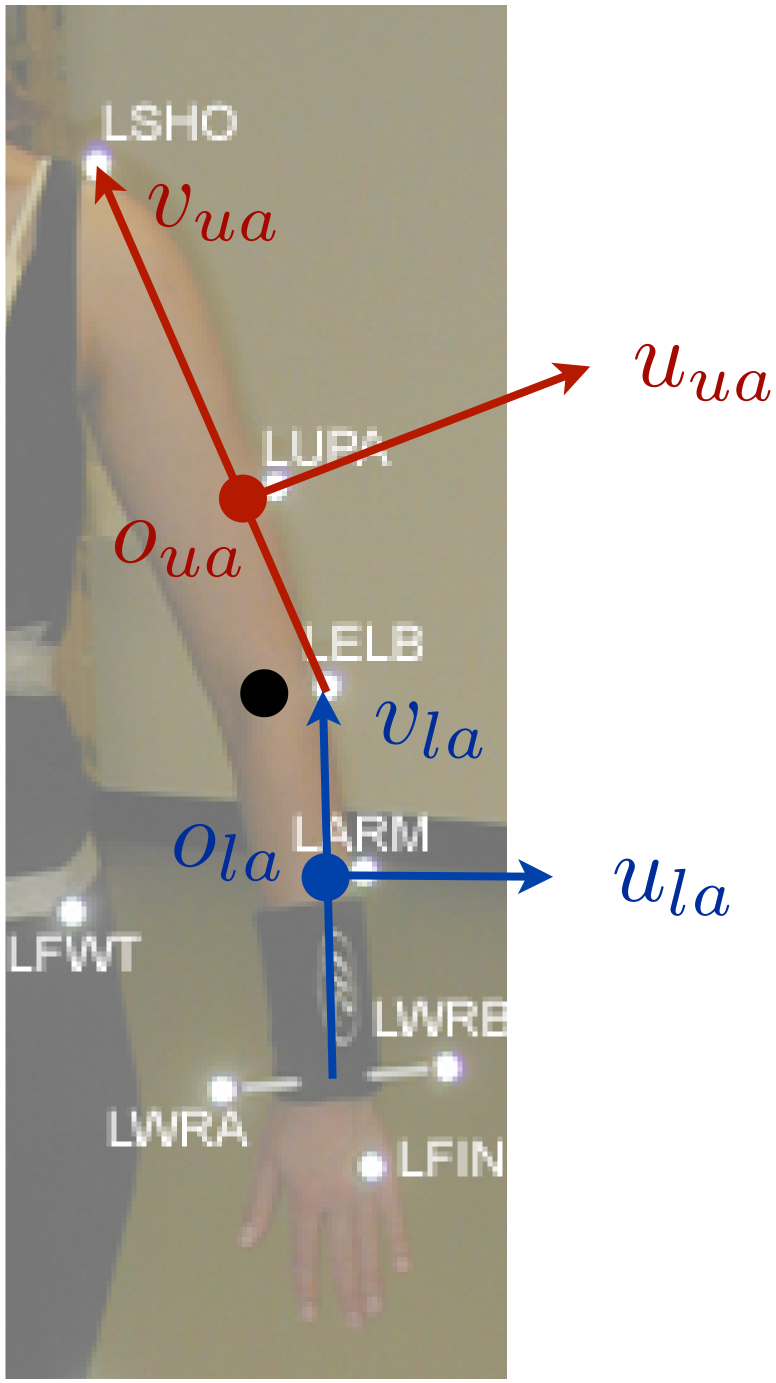
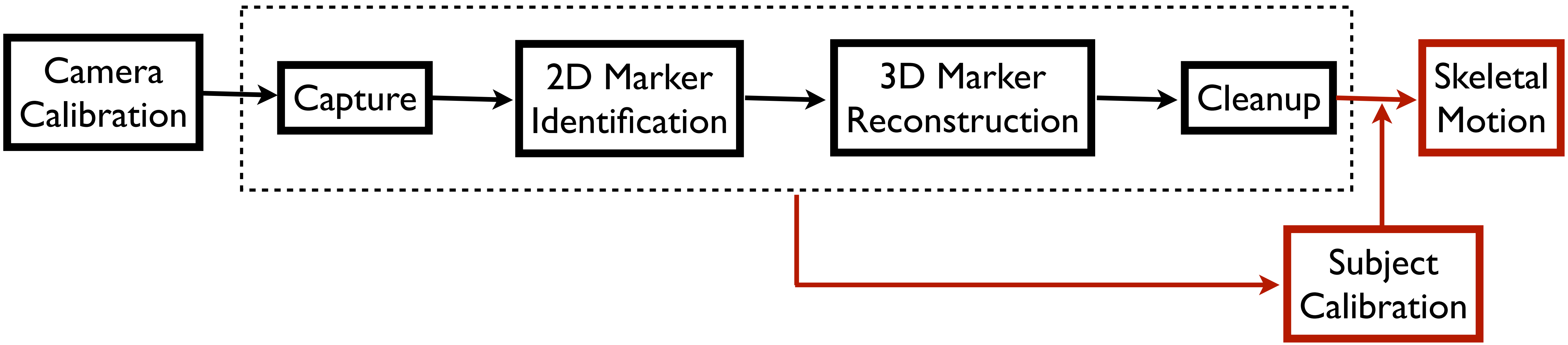
$$T_i^{ua\rightarrow w} \cdot p_{ua}^{(j)} = T_i^{la\rightarrow w} \cdot p_{la}^{(j)}, \quad \forall i$$

Least square solution for the joint offset (assuming it's a ball joint and the full range of motion is exercised)

$$T^{la\rightarrow w} = \begin{bmatrix} \frac{u_{la}}{||u_{la}||}, & \frac{v_{la}}{||v_{la}||}, & \frac{u_{la}}{||u_{la}||} \times \frac{v_{la}}{||v_{la}||}, & o_{la} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



Skeletal Motion



Given subject calibration estimating skeletal motion is typically easy

$$T_i^{ua \to w} \cdot p_{ua}^{(j)}$$

Discussion

Motion Capture Benefits

- Captures natural motion in high detail
- Relatively inexpensive (depending on the system)
- Easy to get data even for very complex motions and with subtle emotional content

- Proved very beneficial for:
  - Visual FX
  - Games
  - Biomechanical analysis

[Lord of the Rings]

Motion Capture Pitfalls

[Polar Express]

- Captures natural motion in high detail
- Difficult to edit
- Proved very unpopular for:
  - Feature animated films (e.g., Polar Express)
- Animated characters tend to be highly stylized (because of uncanny valley), and require highly stylized motion.
- Motion capture can potentially be a reference, but needs to be exaggerated; since editing is unintuitive, animators often prefer to start from scratch