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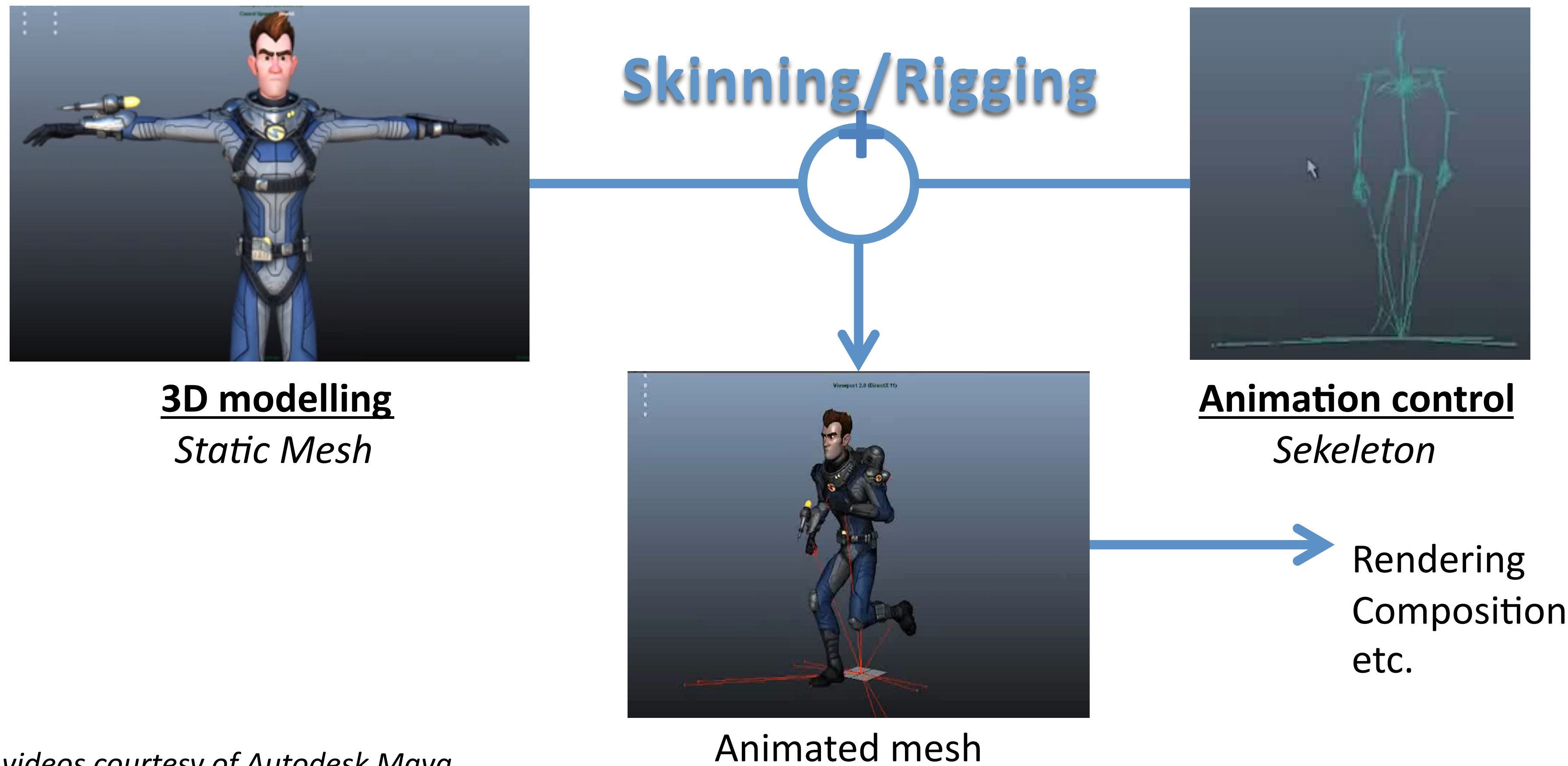
The 41st International Conference and Exhibition on Computer Graphics and Interactive Techniques

Robust and Accurate Skeletal Rigging from Mesh Sequences

Binh Huy Le and Zhigang Deng

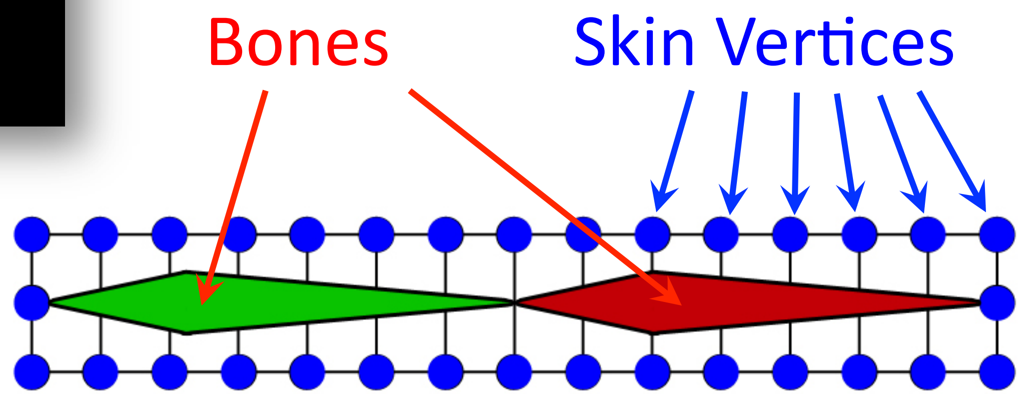
UNIVERSITY of HOUSTON

Character Animation Pipeline



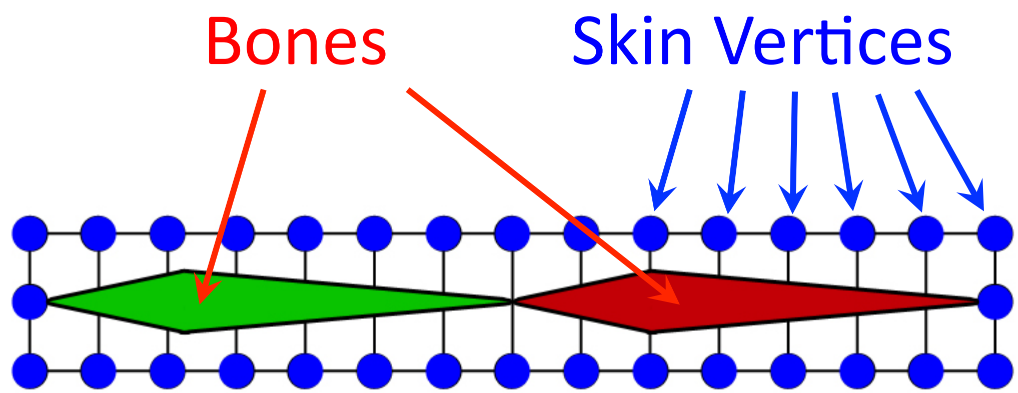
(*) videos courtesy of Autodesk Maya

Skeleton-Based Linear Blend Skinning



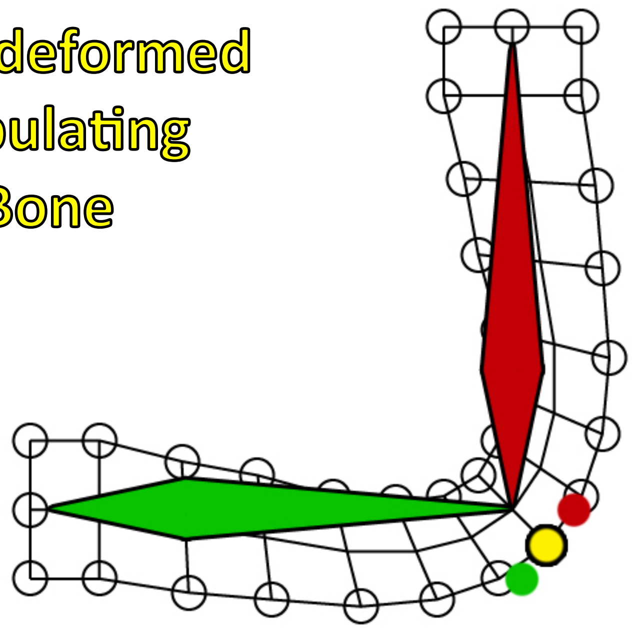
Skeleton-Based Linear Blend Skinning

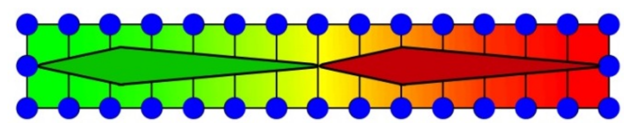
Manipulating the Red Bone



Skeleton-Based Linear Blend Skinning

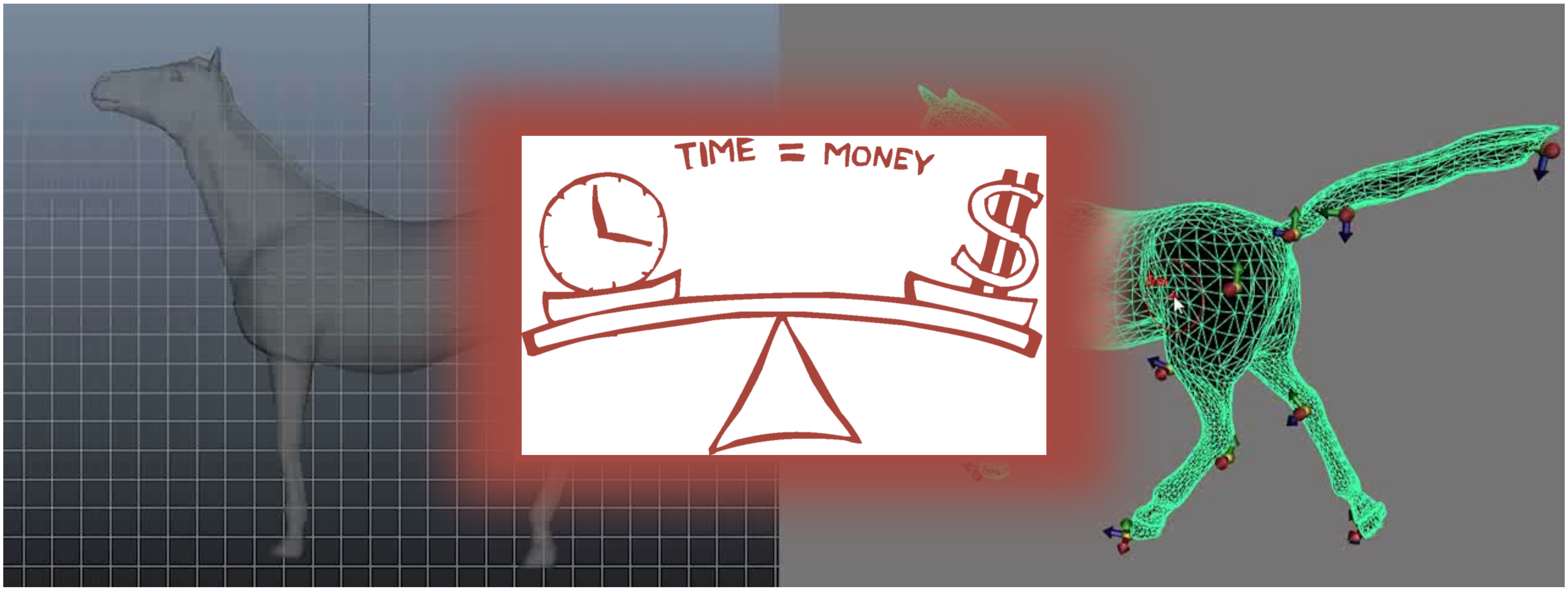
Yellow Vertex deformed while manipulating the Red Bone





Skinning Weights

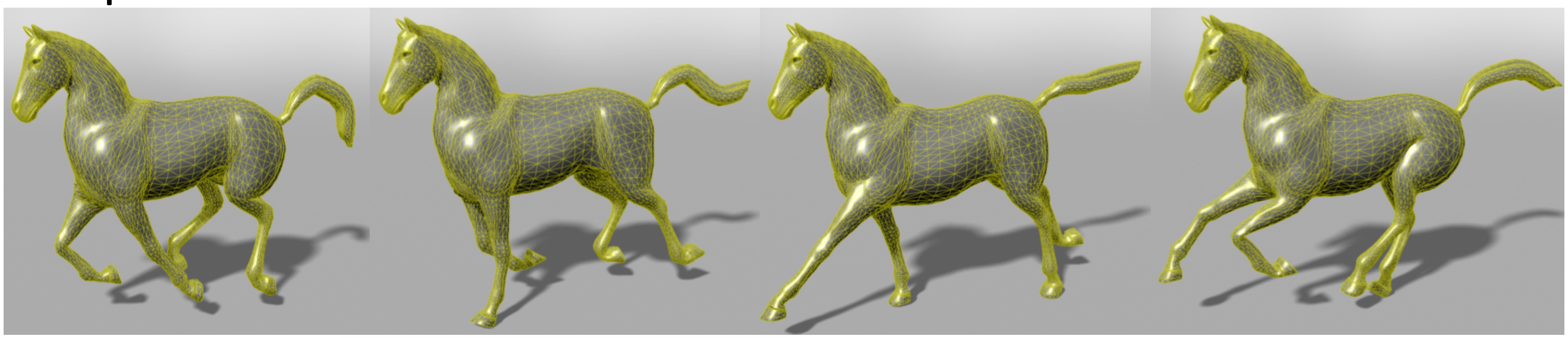
Rigging in Practice



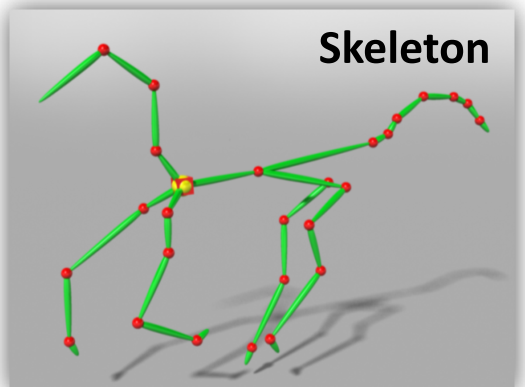
Skeleton Design **Skinning Weight Painting**

Rigging from Examples

- Input



- Output



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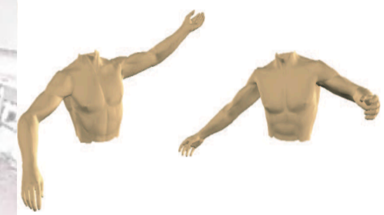
Rigging from Examples

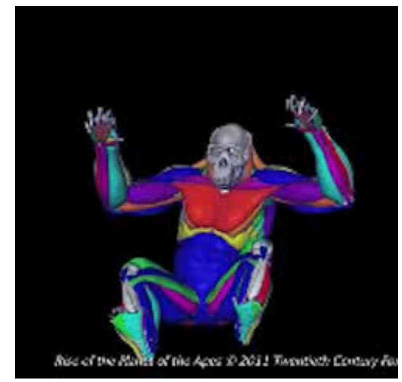
- Data Sources: performance capture, simulation

Marker-based mocap with dense markers
[Park and Hodgins 2006]

Performance Capture of Interacting Characters with Handheld Kinects
[Ye et al. 2012]



Any 3D model
Authoring tools
[Mohr and Gleicher 2003]



Weta Digital's Tissue System

- Applications:

Auto Rigging & Animation Editing

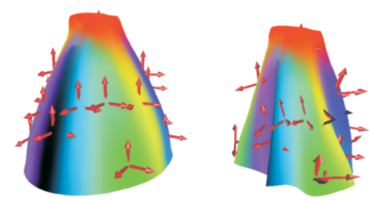
Skin Retargeting

Reverse Engineering
For Interactive Editing

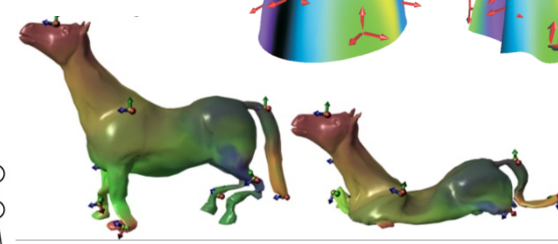
Rigging from Examples

- Previous Works – no Skeleton
  - Skinning Mesh Animations [James and Twigg 2005]

  - Fast and Efficient Skinning of Animated Meshes [Kavan et al. 2010]

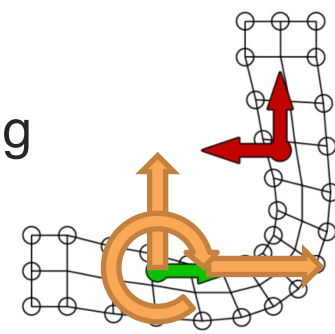


  - Smooth Skinning Decomposition with Rigid Bones [Le and Deng 2012]



✓ Compression, GPU rendering

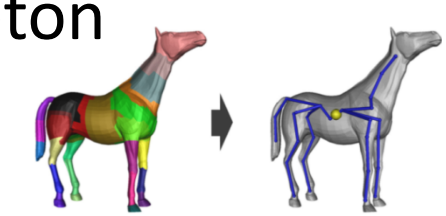
× Animation editing

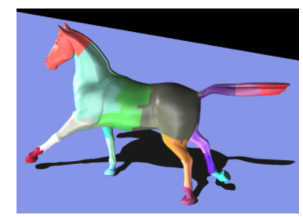


6 DoFs

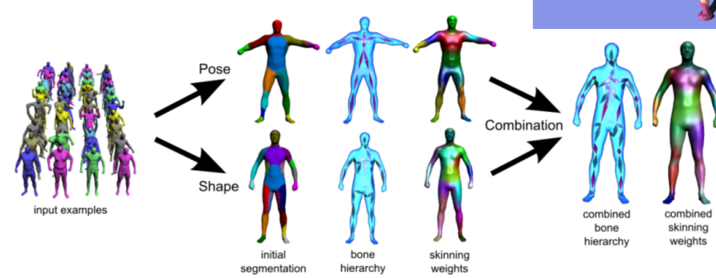
Rigging from Examples

- Previous Works – with Skeleton
  - Example-Based Skeleton Extraction
    [Schaefer and Yuksel 2007]

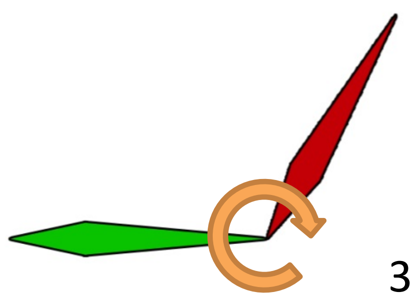




  - Automatic Conversion of Mesh Animations
    into Skeleton-based Animations
    [de Aguiar et al. 2008]
  - Learning Skeletons for Shape and Pose
    [Hasler et al. 2010]



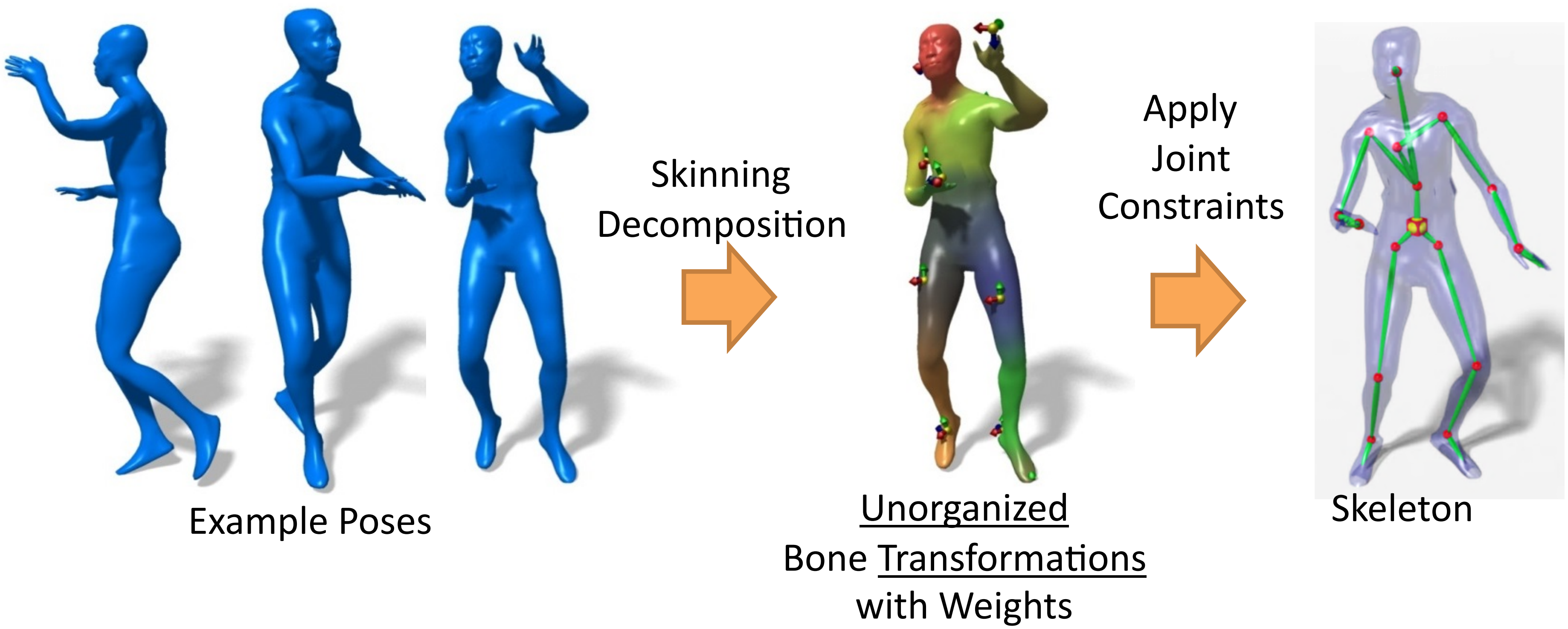
✓ Animation editing



3 DoFs

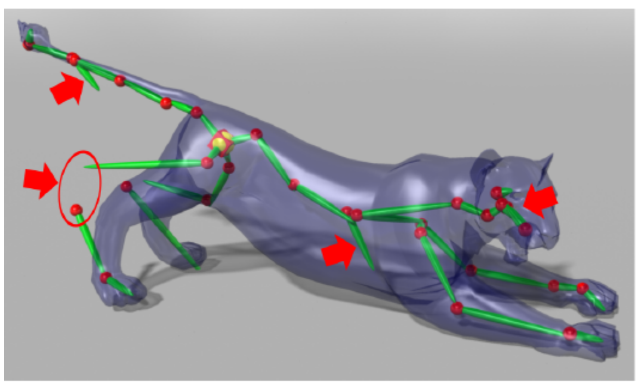
Rigging from Examples

- Previous Works – with Skeleton
  - Single-pass framework

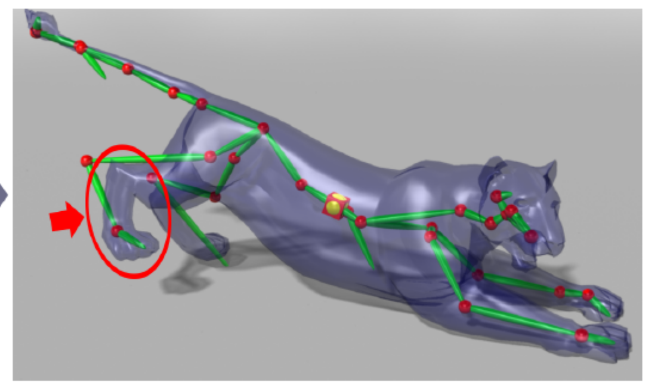


Rigging from Examples

- Previous Works – with Skeleton
  - Single-pass framework
- Limitations
  - Redundant bones
  - Accumulated error



No Joint Constraint

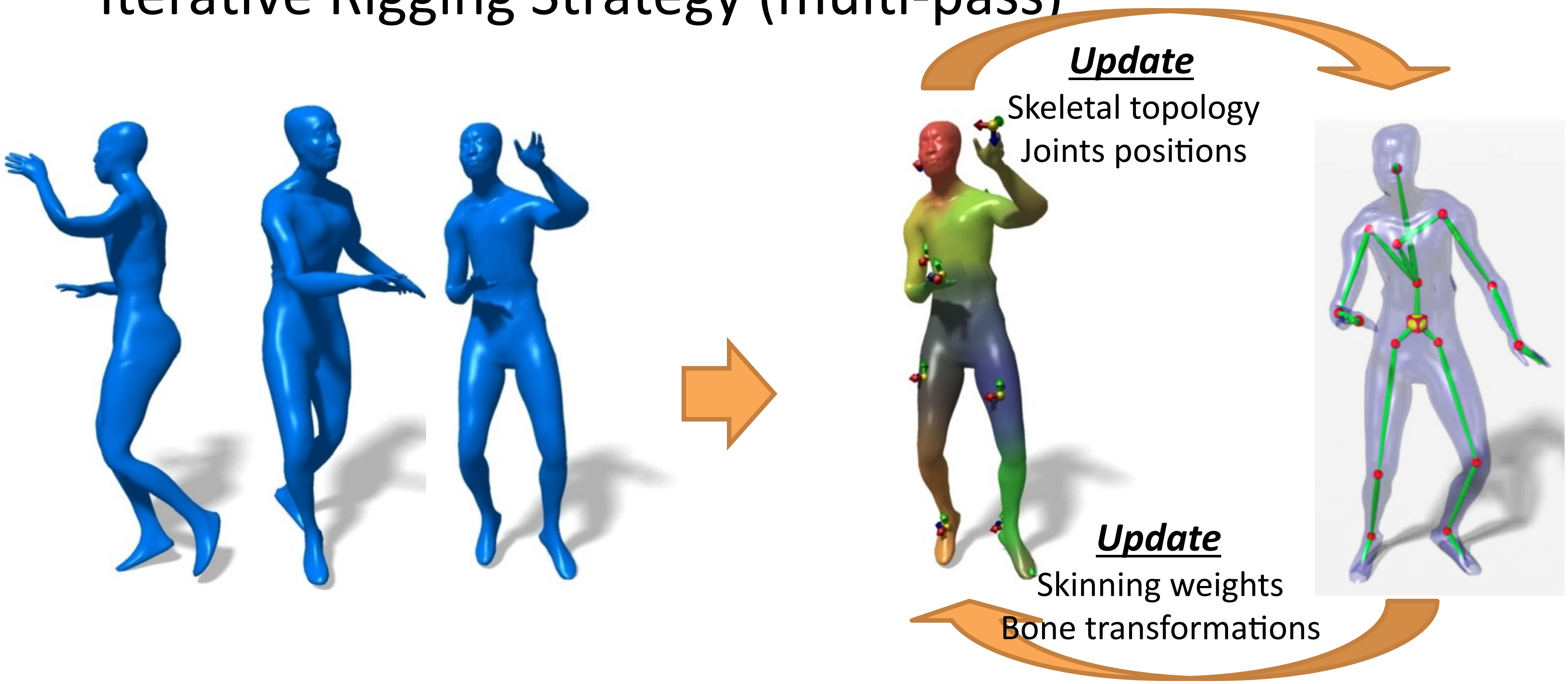


Skeleton Reconstruction

Results from an implementation of [Hasler et al. 2010]

Our Approach

- Iterative Rigging Strategy (multi-pass)



Our Approach

- Objective Function

$$\min \quad E = E_D + \omega E_S + \lambda E_J$$

$$\text{Where: } E_D = \frac{1}{NF} \sum_{i=1}^{N} \sum_{f=1}^{F} \left\| \sum_{j=1}^{B} w_{ij} [R_j^f | T_j^f] \begin{bmatrix} u_i \\ 1 \end{bmatrix} - v_i^f \right\|_2^2$$

Data Term

$$E_S = \sum_{j=1}^{B} w_j{}^{\mathsf{T}} L w_j$$

Weights Smoothness

$$E_J = \frac{1}{F} \sum_{(j,k)\in\mathbb{S}} \sum_{f=1}^{F} \left\| \left([R_j^f | T_j^f] - [R_k^f | T_k^f] \right) \begin{bmatrix} C_{jk} \\ 1 \end{bmatrix} \right\|_2^2$$

Joint Constraints

Objective Function

$$\min \quad E = \boxed{E_D} + \omega E_S + \lambda E_J$$

- Data Term [Le and Deng 2012]
  - Minimizing reconstruction error w.r.t. Weights & Bone transformations
  - No skeletal structure

$$E_D = \frac{1}{NF} \sum_{i=1}^{N} \sum_{f=1}^{F} \left\| \sum_{j=1}^{B} w_{ij} [R_j^f | T_j^f] \begin{bmatrix} u_i \\ 1 \end{bmatrix} - v_i^f \right\|_2^2$$

Objective Function

$$\min \quad E = E_D + \omega \boxed{E_S} + \lambda E_J$$

- Skinning Weight Regularization Term
  - No regularization: Fracture due to weights sparseness constraint or noisy input data
  - Our rigidness Laplacian regularization: Smooth, deformation sensitive

No Regularization | **Rigidness Laplacian Regularization**

$\omega = 0$ | $\omega = 10^{-3}$ | $\omega = 10^{-2}$

$$E_S = \sum_{j=1}^{B} w_j{}^{\mathsf{T}} L w_j$$

$$L_{ik} = \begin{cases} 1 & \text{if } k = i \\ -\frac{d_{ik}}{\sum_{h \in \mathcal{N}(i)} d_{ih}} & \text{if } k \in \mathcal{N}(i) \\ 0 & \text{otherwise.} \end{cases}$$

Where: $\mathcal{N}(i)$ denotes all the 1-ring neighbors of vertex i

Evaluated on all example poses ($f = 1..F$) →

$$d_{ik} = \frac{1}{\sqrt{\frac{1}{F}\sum_{f=1}^{F}\left(\left\|v_i^f - v_k^f\right\|_2 - \left\|u_i - u_k\right\|_2\right)^2}}$$

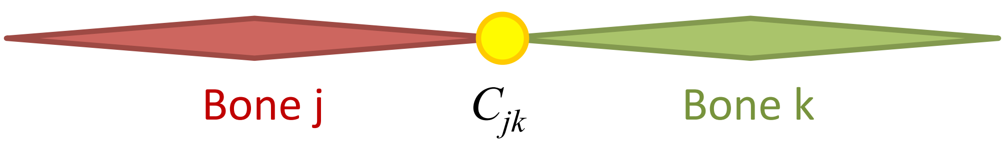
Objective Function

$$\min \; E = E_D + \omega E_S + \lambda E_J$$

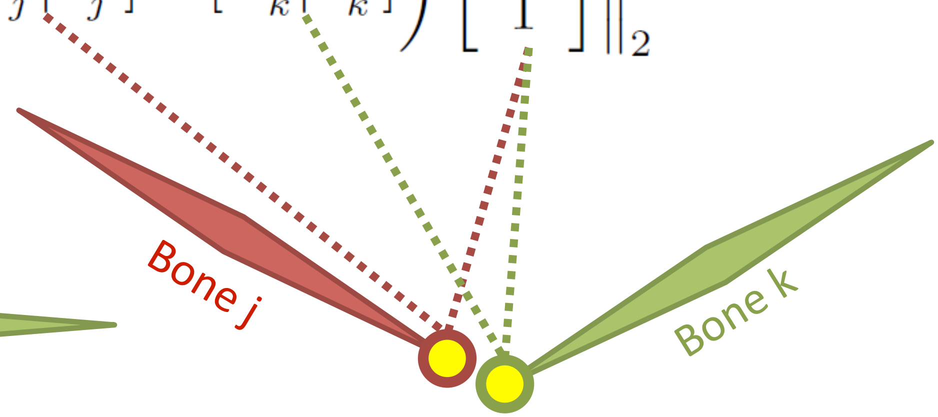
- Joint Constraint Term
  - Minimizing deviations of the joint locations after applying bone transformations

$$E_J = \frac{1}{F} \sum_{(j,k)\in\mathbb{S}} \sum_{f=1}^{F} \left\| \left([R_j^f | T_j^f] - [R_k^f | T_k^f] \right) \begin{bmatrix} C_{jk} \\ 1 \end{bmatrix} \right\|_2^2$$

C_{jk} is the joint position in the rest pose



Rest Pose



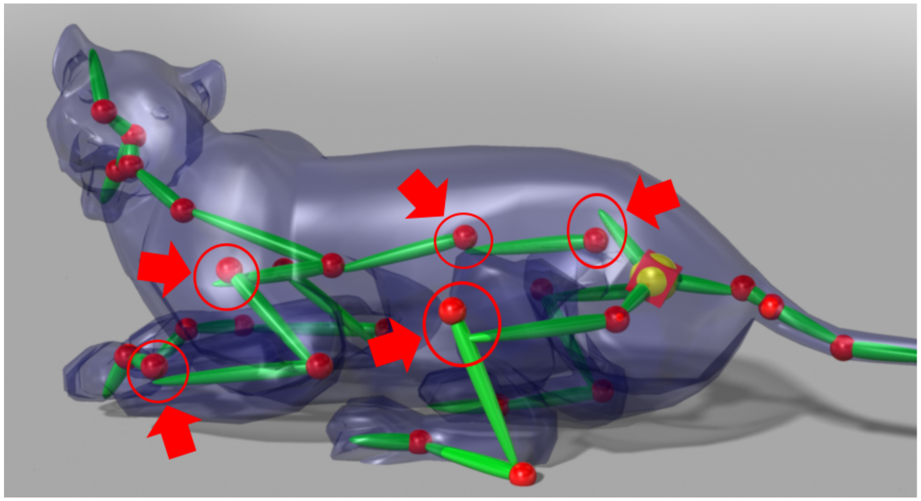
Example Pose f

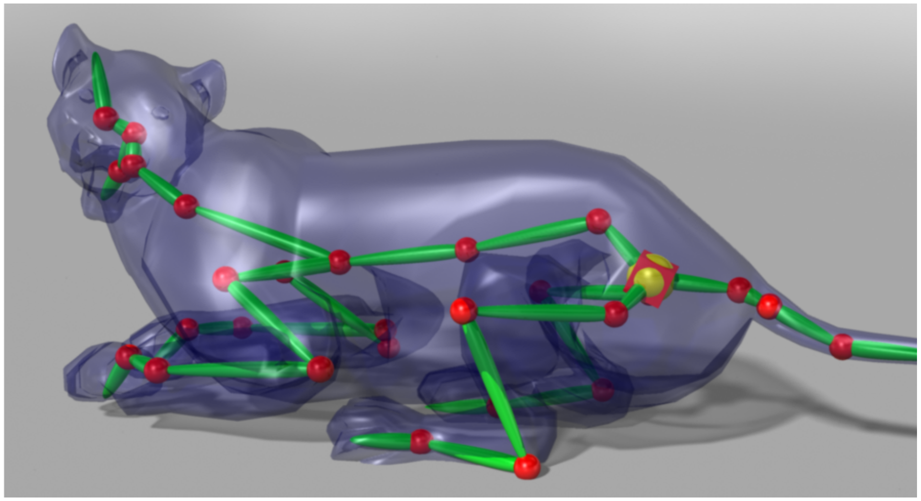
Recovering articulated object models from 3D range data [Anguelov et al. 2004]

Objective Function

$$\min \quad E = E_D + \omega E_S + \lambda \boxed{E_J}$$

- Joint Constraint Term
  - Minimizing deviations of the joint locations after applying bone transformations

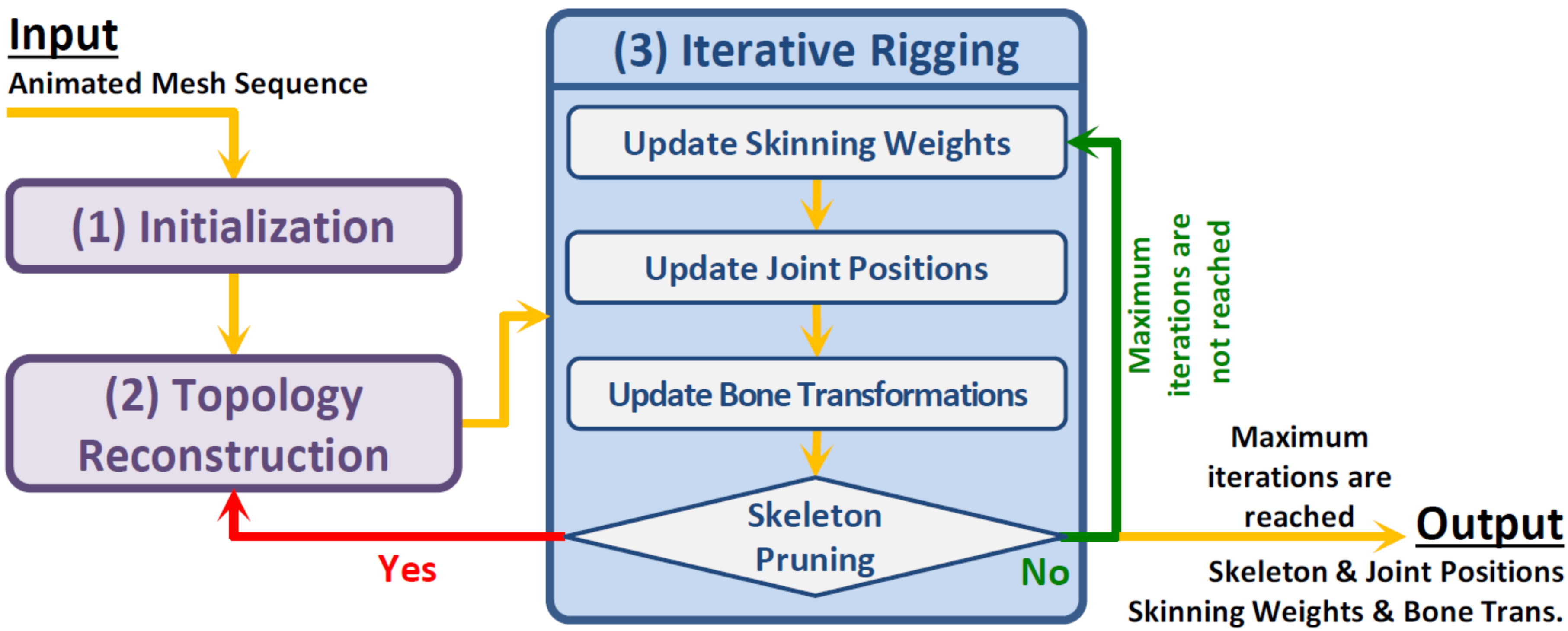




No Joint Constraint **With Joint Constraints**

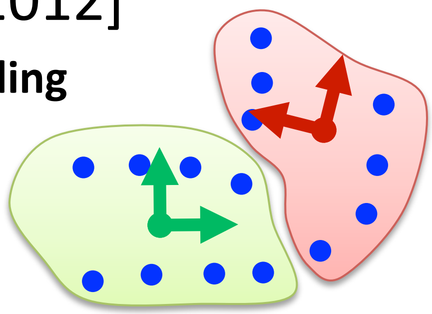
Our Approach

- Optimization Pipeline

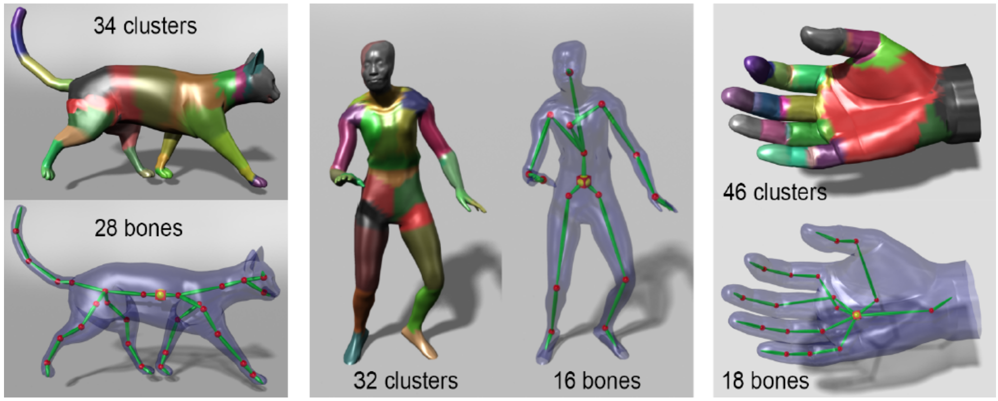


Initialization

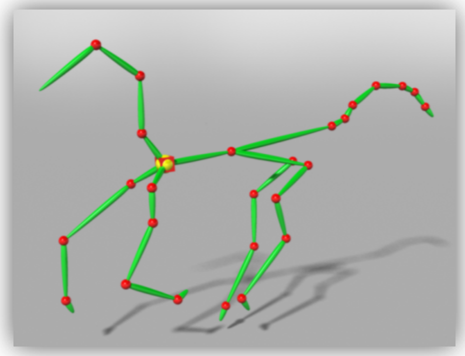
- Motion-driven vertex clustering [Le and Deng 2012]
  - Cluster vertices with similar rigid transformation, **no blending**
  - 1 bone transformation per cluster, **no connectivity**
  - Linde–Buzo–Gray algorithm, similar to K-means



- Over-completed clustering
  - Redundant bones will be pruned
  - Easy parameter tuning
  - Robust initialization (good coverage)



Skeletal Topology Reconstruction



→Minimum Spanning Tree problem

[Kirk et al. 2005; Schaefer and Yuksel 2007;
de Aguiar et al. 2008; Hasler et al. 2010]

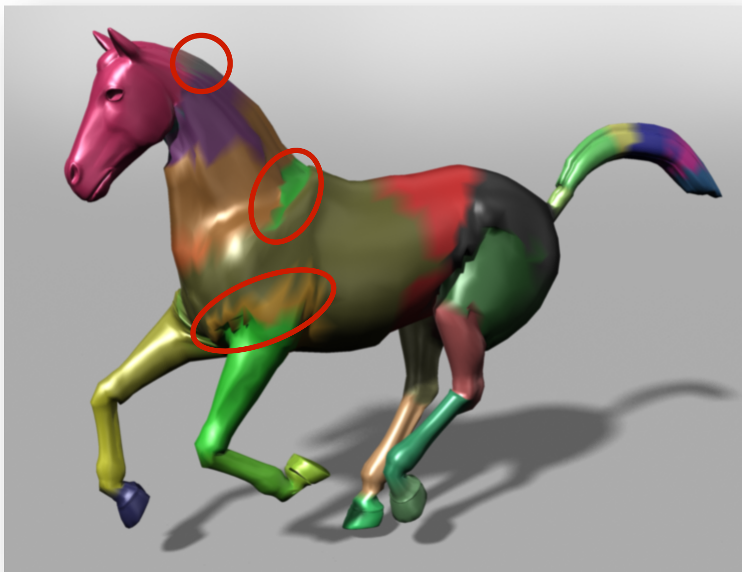
– Cost of edge *(j, k)*

$$g(j,k) = \frac{\sum_{f=1}^{F} \left\| \left([R_j^f | T_j^f] - [R_k^f | T_k^f] \right) \begin{bmatrix} C_{jk} \\ 1 \end{bmatrix} \right\|_2^2}{\sum_{i=1}^{N} w_{ij} w_{ik}}$$

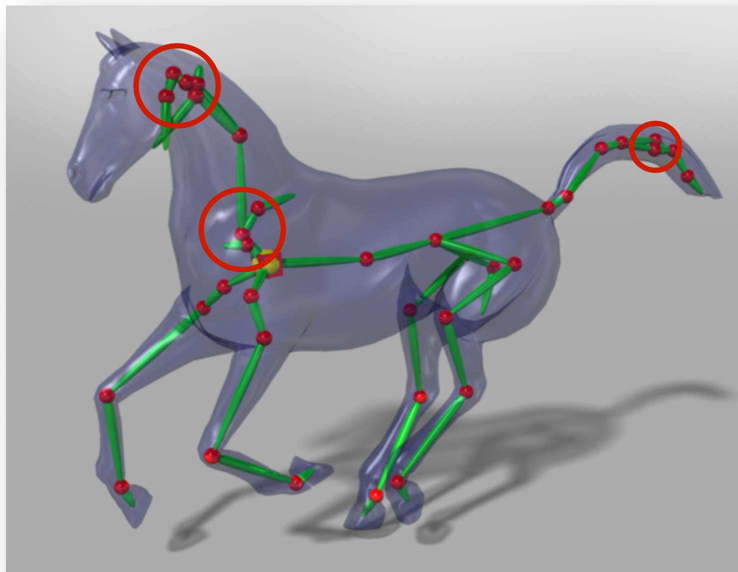
Numerator: Joint constraint value
Denominator: Weight blending of 2 bones

Skeleton Pruning

- Redundant Bones



Initialization



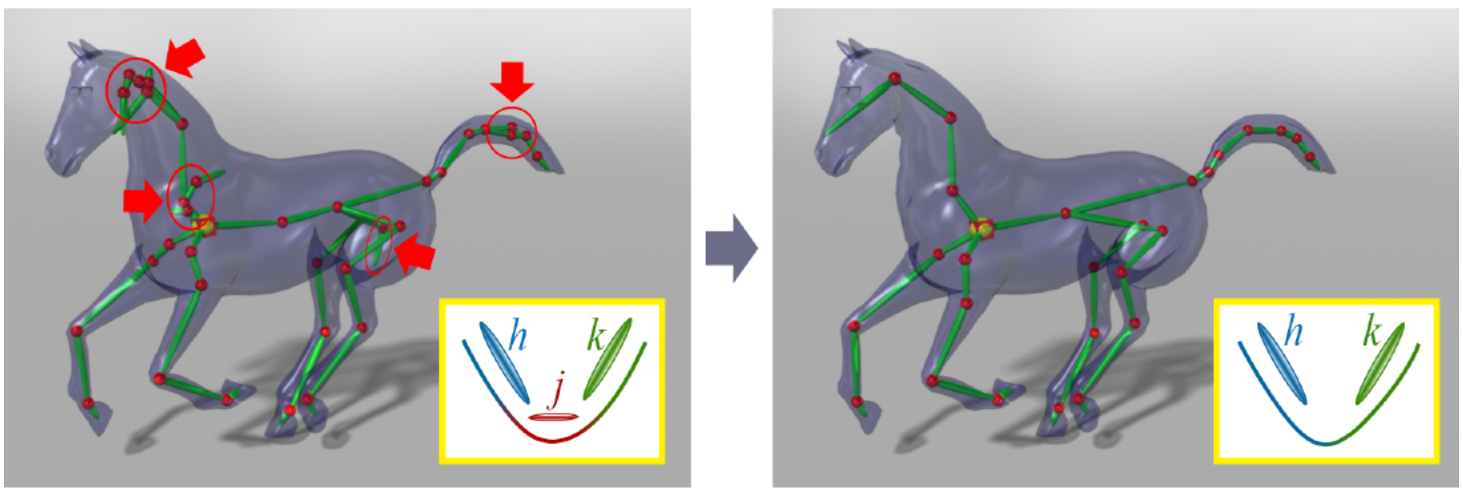
Skeleton

Skeleton Pruning

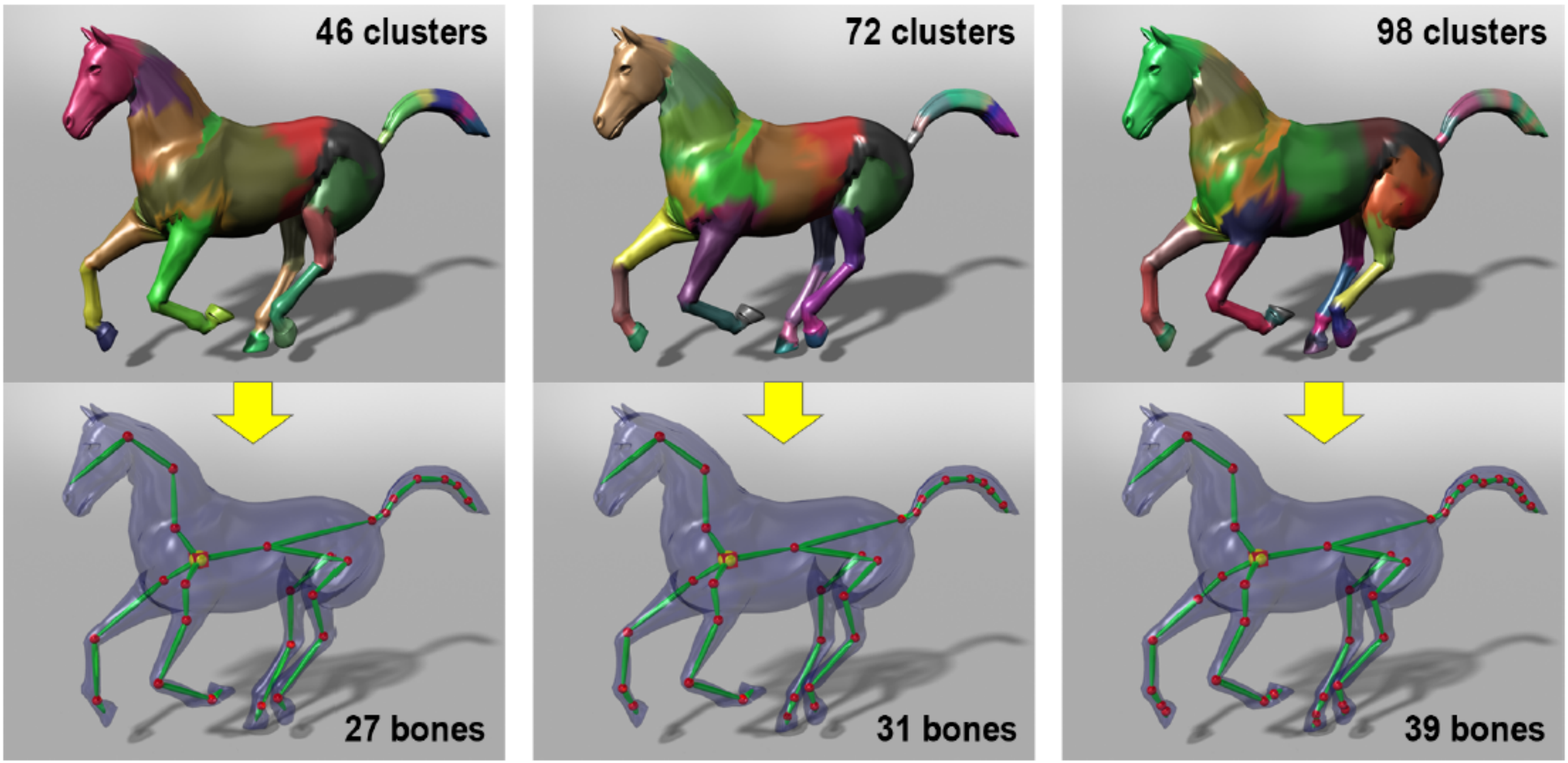
With weights smoothness regularization

Remove bone j if $\sum_{i=1}^{N} {w_{ij}}^2 < 10^{-2} M.$

where: $M = \max_k \left\{ \sum_{i=1}^{N} {w_{ik}}^2 \right\}.$

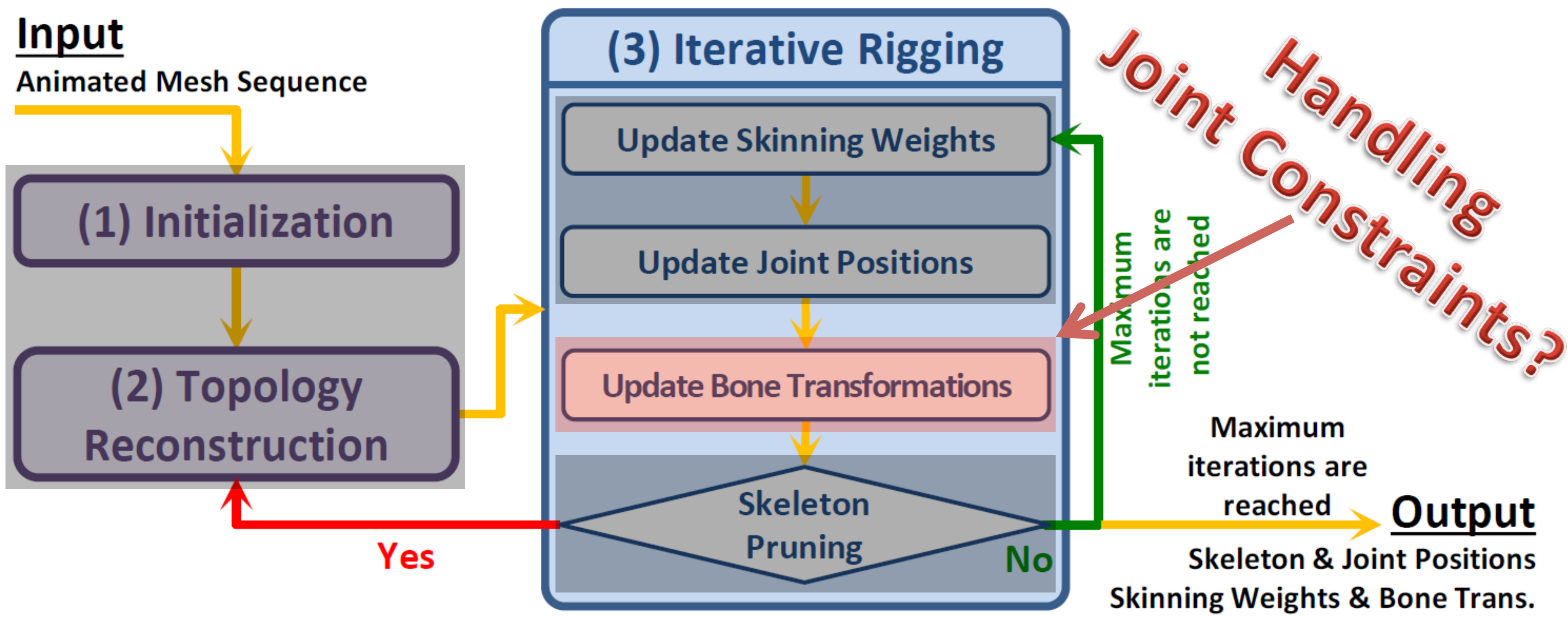


Skeleton Pruning



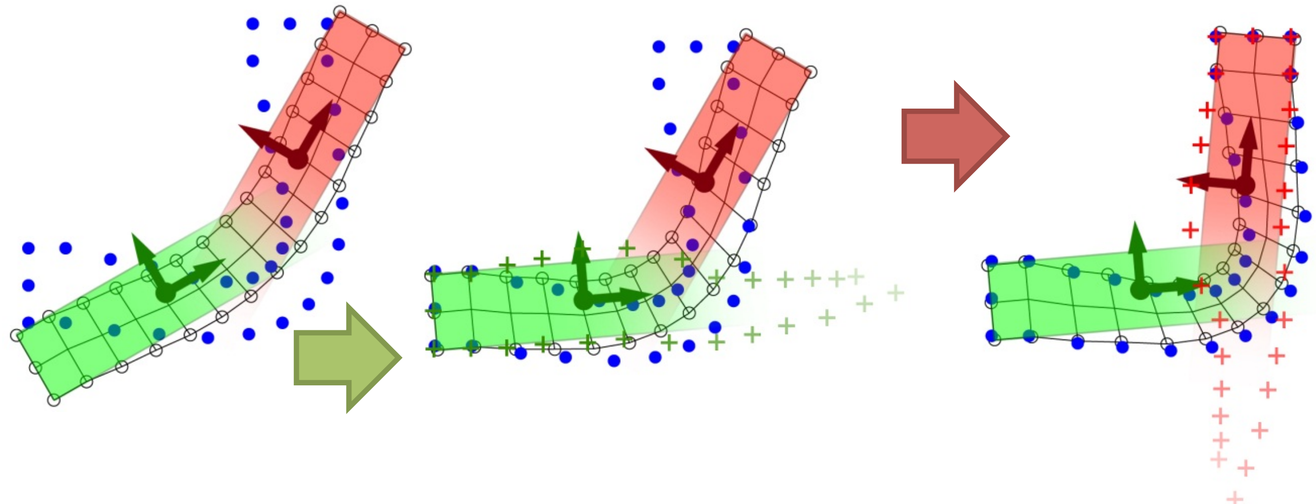
Our Approach

- Optimization Pipeline



Bone Transformations Update

- No Joint [Le and Deng 2012]



Remove Translation

$$\overline{p}_i = u_i - p_*;$$

$$\overline{q}_i^f = q_i^f - w_{i\hat{j}} q_*^f;$$

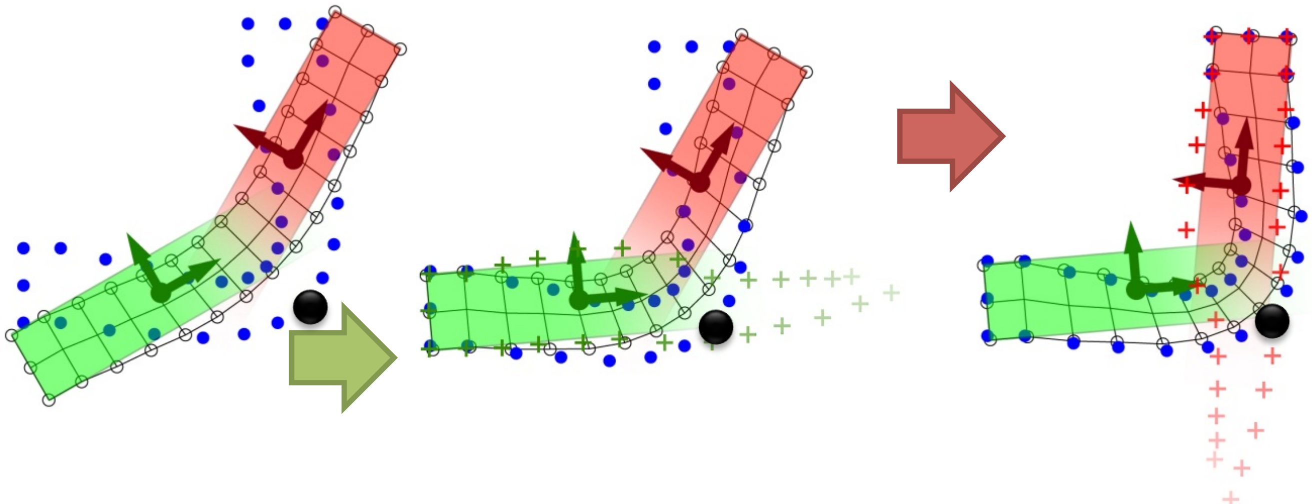
Centers of Rotation

$$p_* = \frac{\frac{1}{N}\sum_{i=1}^{N} w_{i\hat{j}}^2 u_i}{\frac{1}{N}\sum_{i=1}^{N} w_{i\hat{j}}^2}$$

$$q_*^f = \frac{\frac{1}{N}\sum_{i=1}^{N} w_{i\hat{j}} q_i^f}{\frac{1}{N}\sum_{i=1}^{N} w_{i\hat{j}}^2}$$

Bone Transformations Update

- With Joints: Joint = Regular point with weight λ → +∞



Remove Translation

$$\overline{p}_i = u_i - p_*;$$

$$\overline{q}_i^f = q_i^f - w_{i\hat{j}} q_*^f;$$

$$\overline{C}_{\hat{j}k} = C_{\hat{j}k} - p_*$$

$$\overline{\Psi}_k^f(C_{\hat{j}k}) = \Psi_k^f(C_{\hat{j}k}) - q_*^f$$

Centers of Rotation

$$p_* = \frac{\frac{1}{N}\sum_{i=1}^{N} w_{i\hat{j}}^2 u_i + \lambda \sum_{(\hat{j},k)\in\mathbb{S}} C_{\hat{j}k}}{\frac{1}{N}\sum_{i=1}^{N} w_{i\hat{j}}^2 + \lambda \left|(\hat{j},k)\in\mathbb{S}\right|}$$

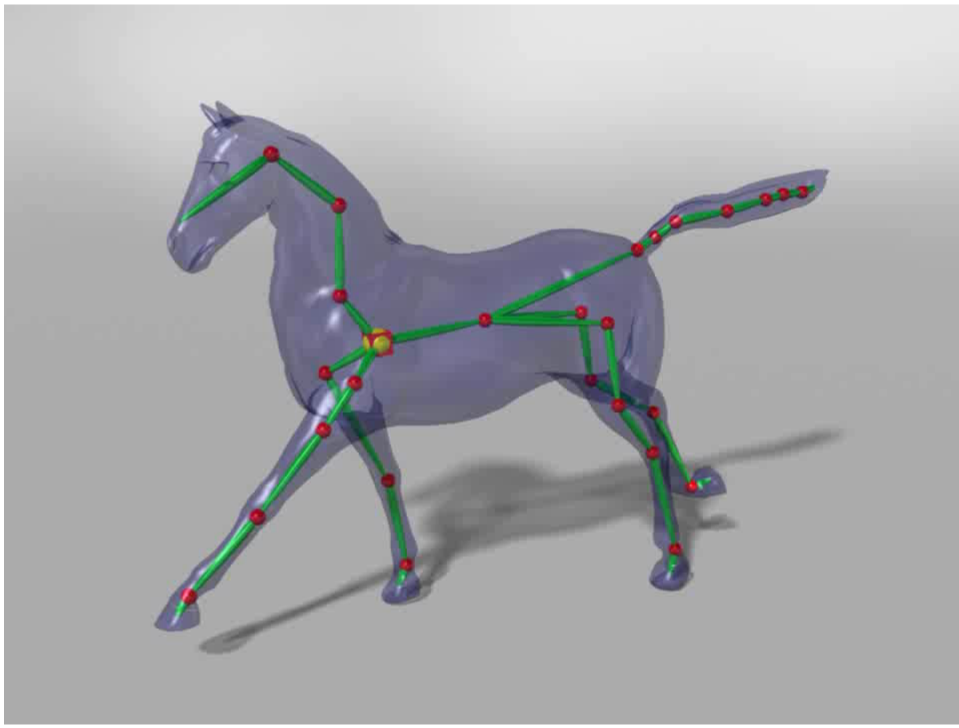
$$q_*^f = \frac{\frac{1}{N}\sum_{i=1}^{N} w_{i\hat{j}} q_i^f + \lambda \sum_{(\hat{j},k)\in\mathbb{S}} \Psi_k^f(C_{\hat{j}k})}{\frac{1}{N}\sum_{i=1}^{N} w_{i\hat{j}}^2 + \lambda \left|(\hat{j},k)\in\mathbb{S}\right|}$$

Results

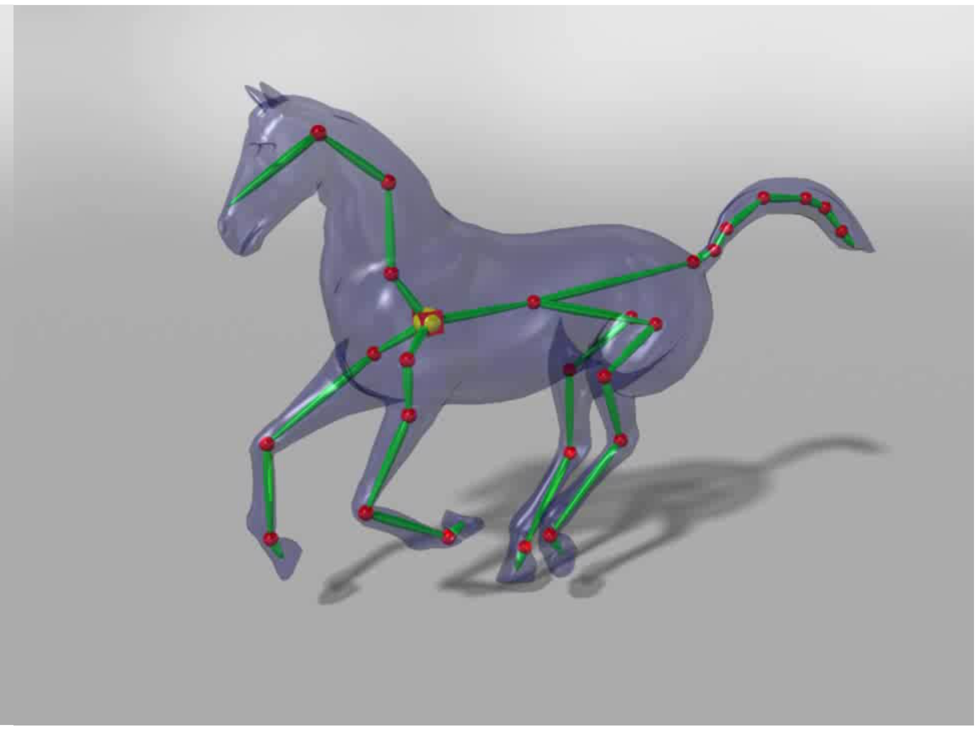
- Input: 48 example poses

Results

- Output: 27 bones



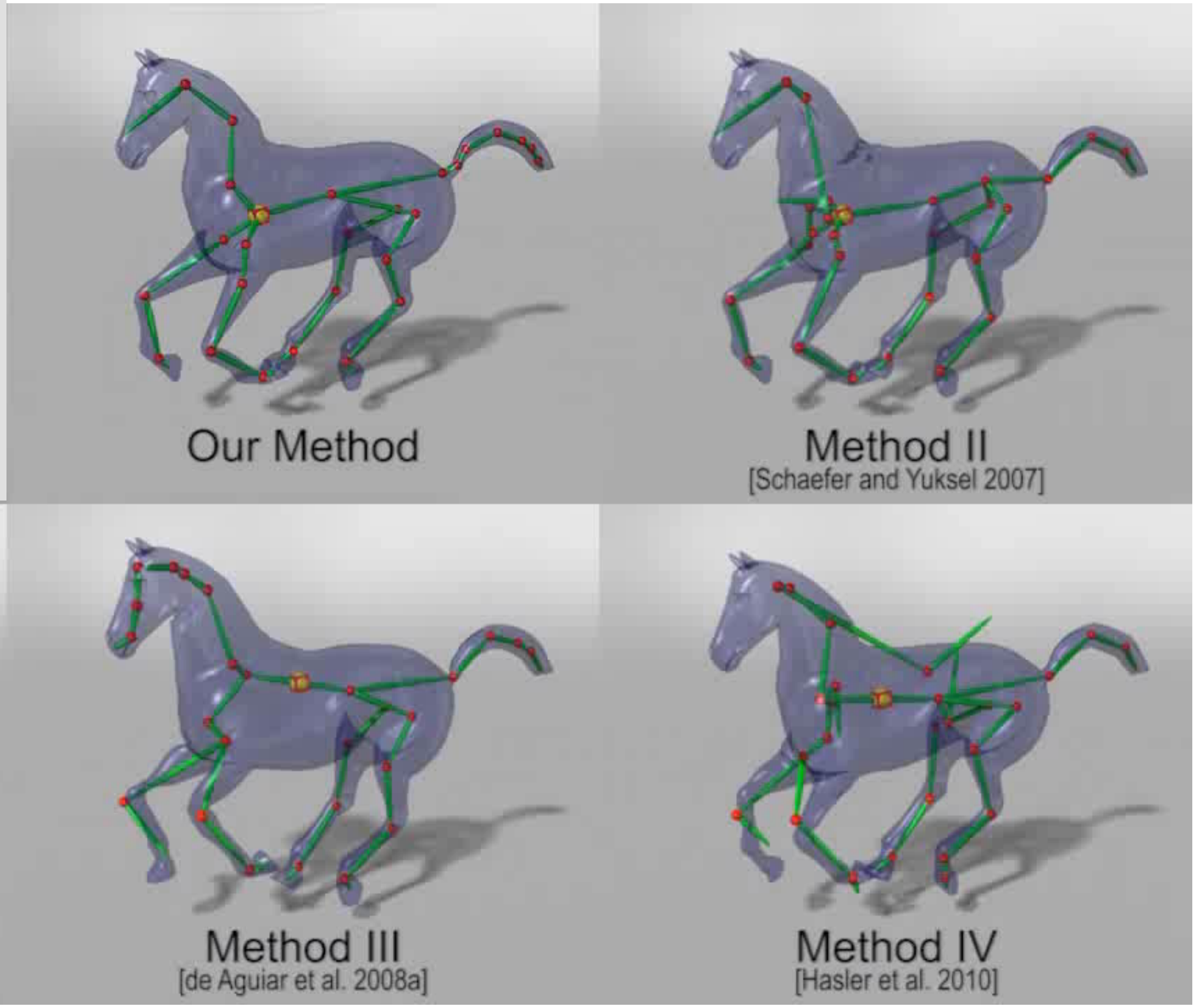
Skeleton



Skinning Weights

Comparisons

horse-gallop
8431 vertices
48 example poses
27 bones

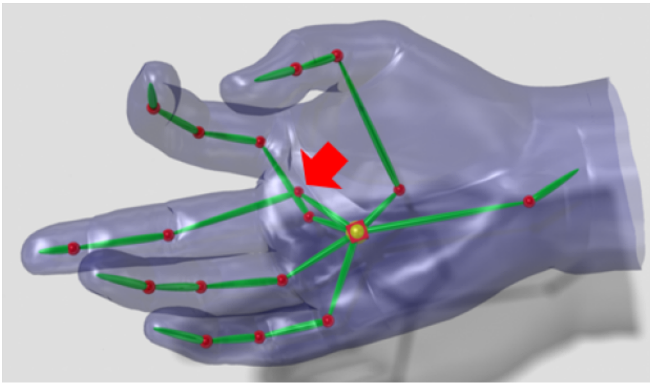


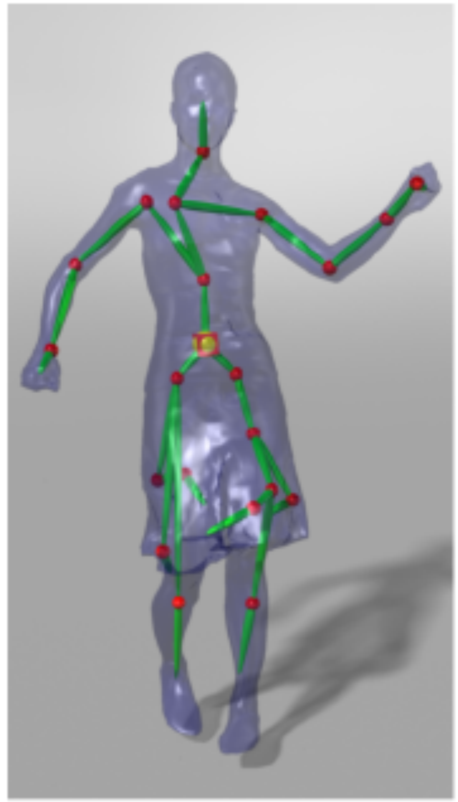
Comparisons

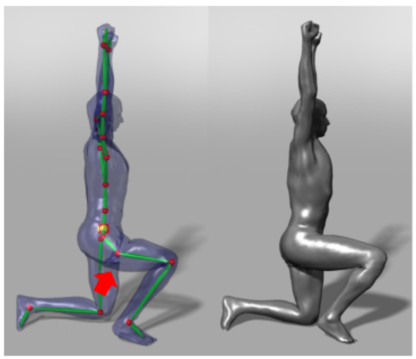
Dataset	N	F	B	Our method		Method II		Method III		Method IV	
				Time	RMSE	Time	RMSE	Time	RMSE	Time	RMSE
cat-poses	7207	9	28	5.8	**0.25**	0.1	0.68	6.9	1.04	17.2	0.63
horse-poses	8431	10	27	7.7	**0.21**	0.2	0.54	6.2	1.24	20.0	0.75
lion-poses	5000	9	30	4.1	**0.27**	0.1	0.83	4.0	1.62	11.7	1.14
horse-gallop	8431	48	27	41.9	**0.22**	0.8	0.44	33.3	1.10	80.3	0.88
hand	7997	43	18	65.1	**0.18**	0.6	0.23	20.0	0.42	41.9	**0.18**
dance	7061	201	16	148.7	**0.22**	2.5	0.76	61.8	0.78	168.0	0.53
scape	12500	70	23	252.1	**0.42**	1.7	1.03	60.7	1.18	410.4	1.24
samba	9971	175	22	348.2	**0.56**	3.3	1.29	95.1	1.57	296.0	1.79
cow	2904	204	11	72.3	**1.52**	1.0	5.41	16.0	5.61	47.9	5.58

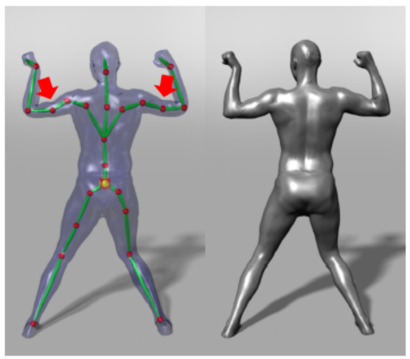
Lowest RMSE

Fun on Highly Deformable Models

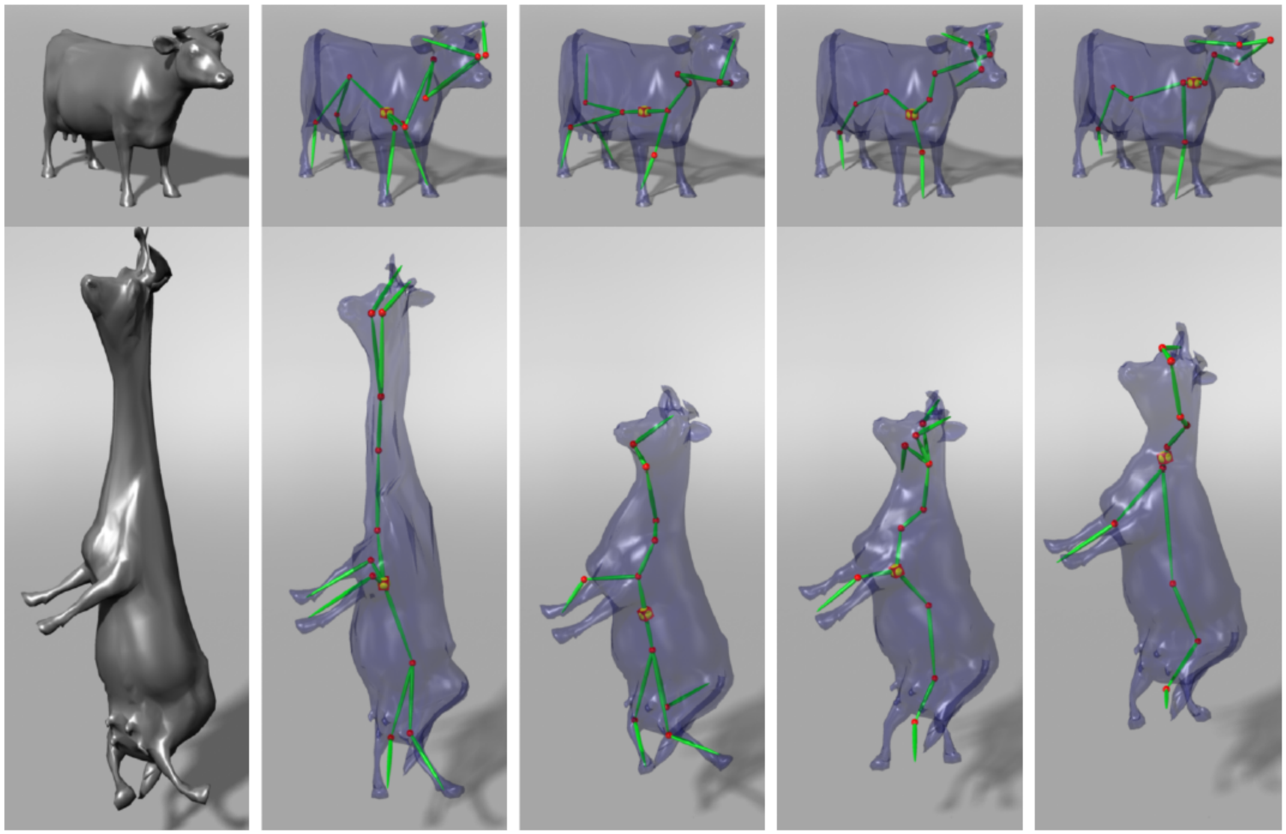






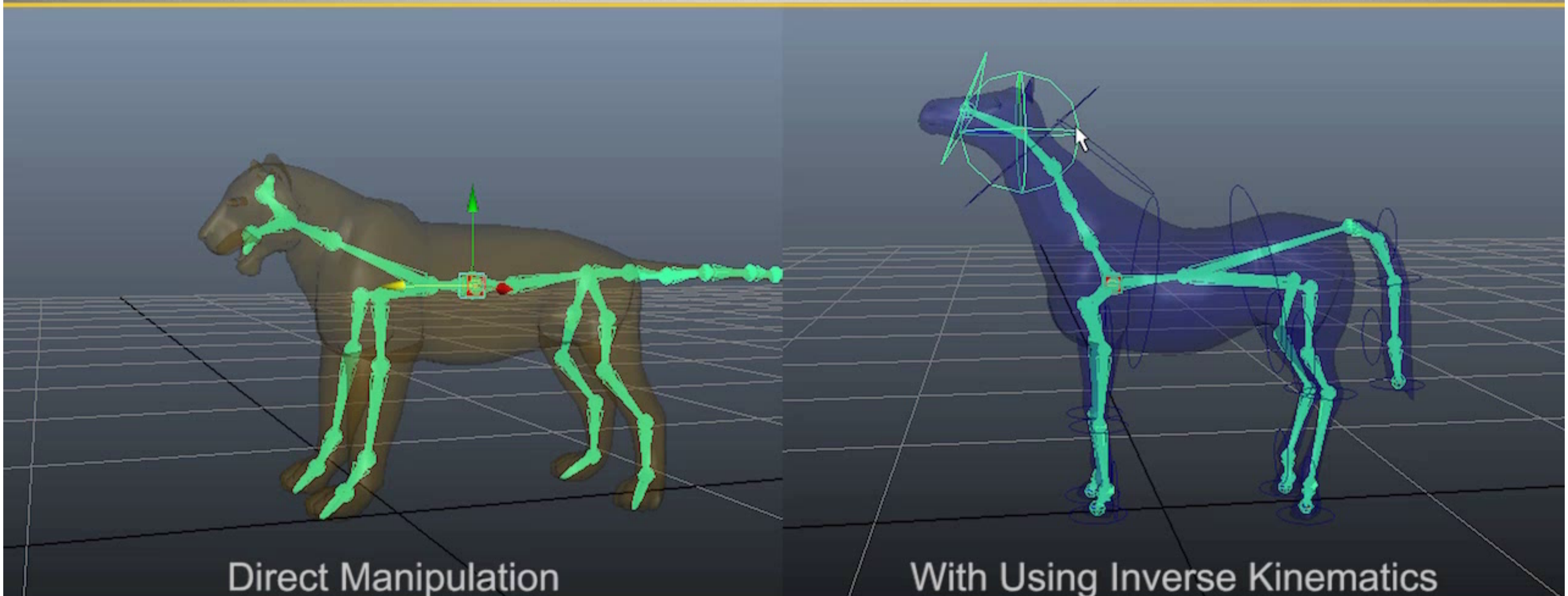


Fun on Highly Deformable Models



Ground Truth | Our Method | Method II [Schaefer and Yuksel 2007] | Method III [de Aguiar et al. 2008a] | Method IV [Hasler et al. 2010]

Skeleton-based Editing in MAYA



Rigged models are extracted from the LION mesh sequence
and the HORSE-POSES mesh sequence

Conclusions

- Input : Example poses
- Output: de-facto Skeleton-based linear blend skinning (LBS)
  (skeleton + skinning weights + bone transformations)

✓ Rigidness Laplacian regularizer for smooth weights & pruning
✓ Robust skeleton pruning for over-completed initialization
✓ Accurate solver for bone transformations with joint constraints

× Linear model (LBS)
× Data dependency
× Low computational efficiency

Acknowledgements

- NSF IIS-0914965 and NIH 1R21HD075048-01A1
- Daniel Vlasic, Jovan Popovic, James Davis, and Hugues Hoppe for providing mesh sequences
- JP Lewis and Omprakash Gnawali for proofreading help

http://graphics.cs.uh.edu/ble/papers/2014s-ske/

(execution file available)

Thank You