Stretchable and Twistable Bones for Skeletal Shape Deformation

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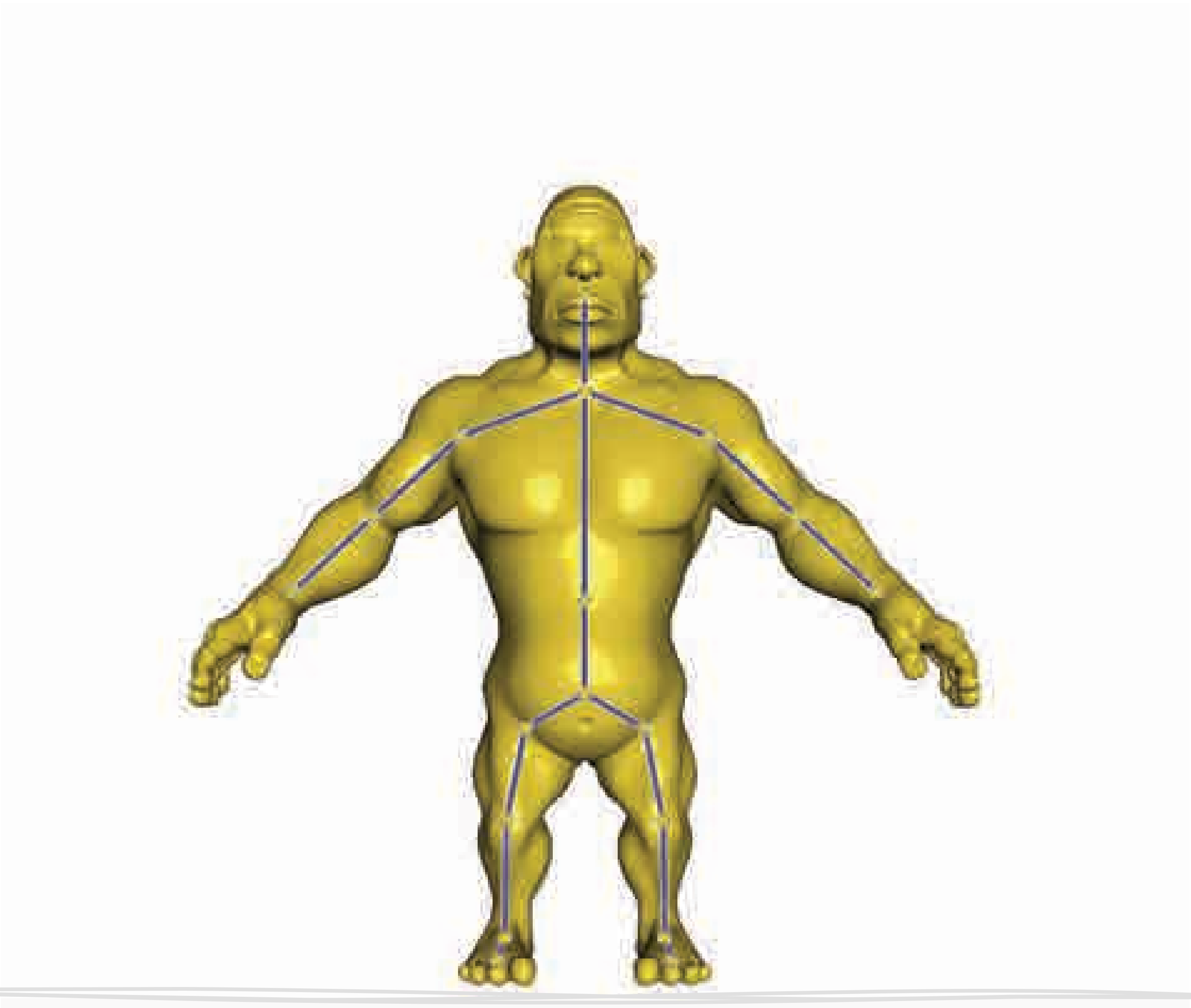
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Skeleton-based skinning provides direct metaphor for character animation



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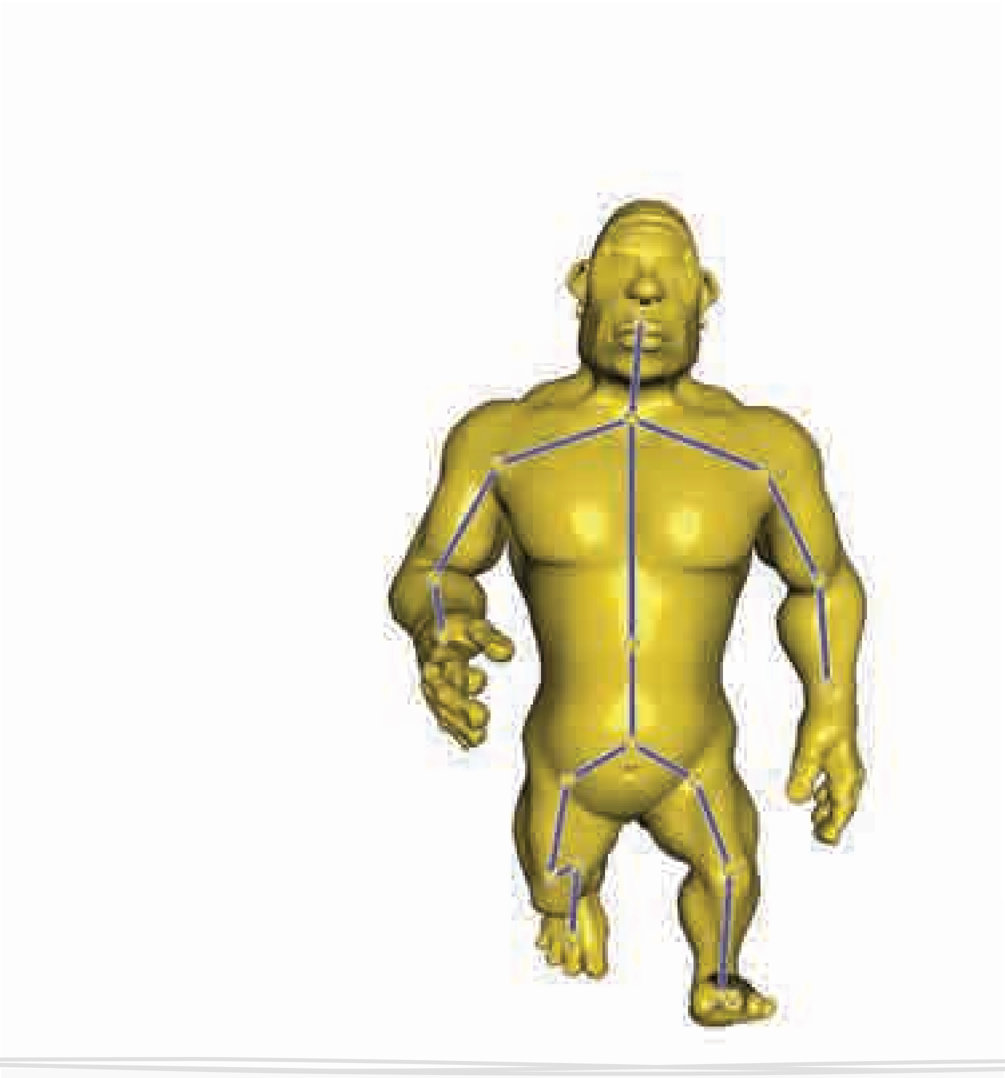
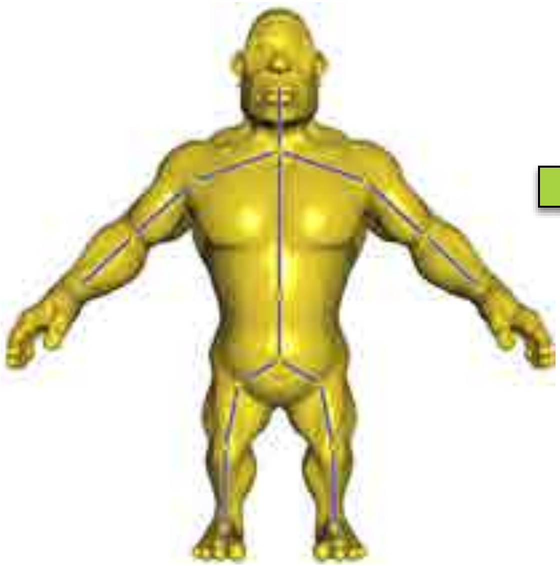


Linear Blend Skinning remains standard due to simplicity and efficiency



place skeleton in shape

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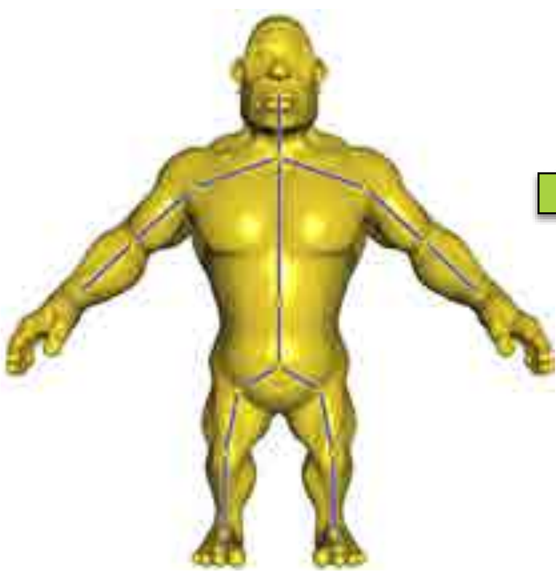

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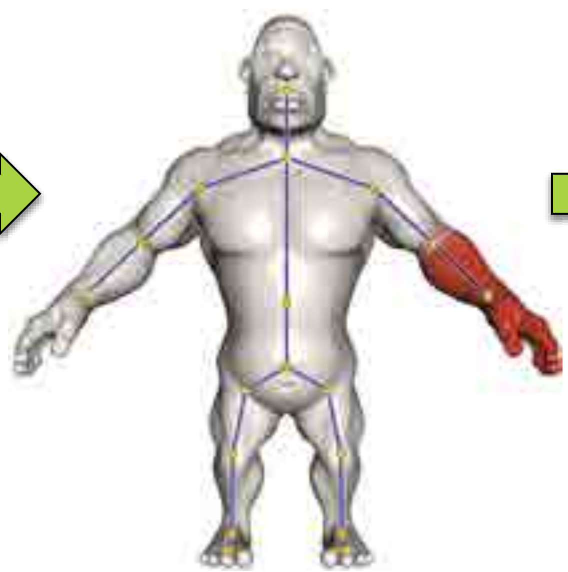

compute/paint weights

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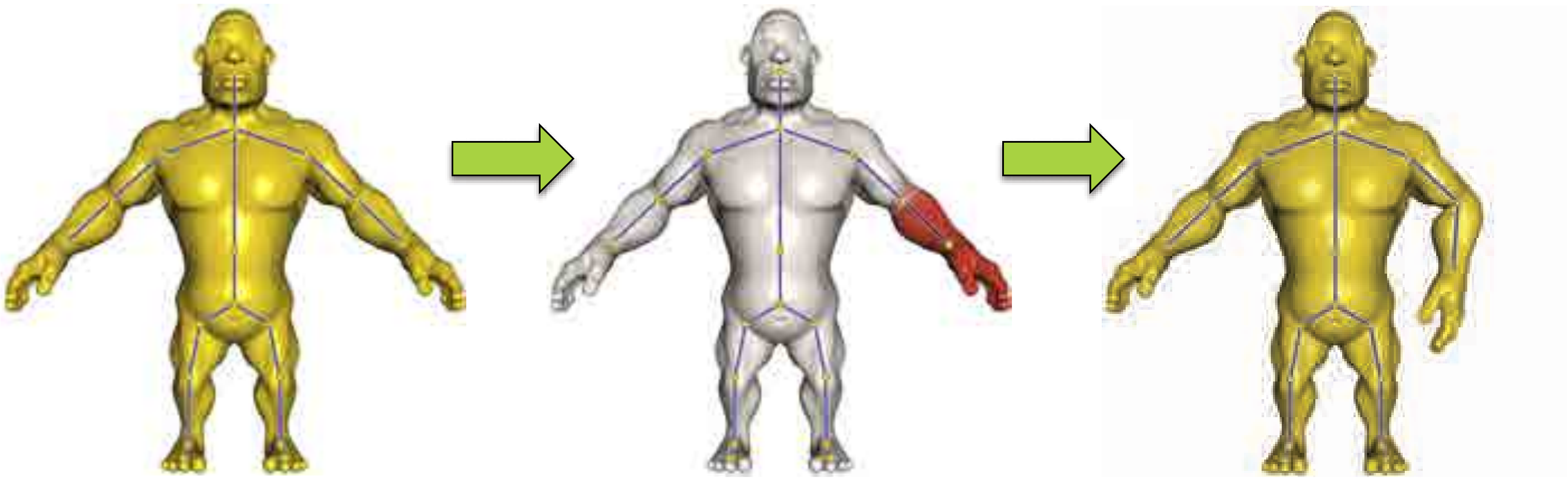

place skeleton in shape   compute/paint weights   deform bones

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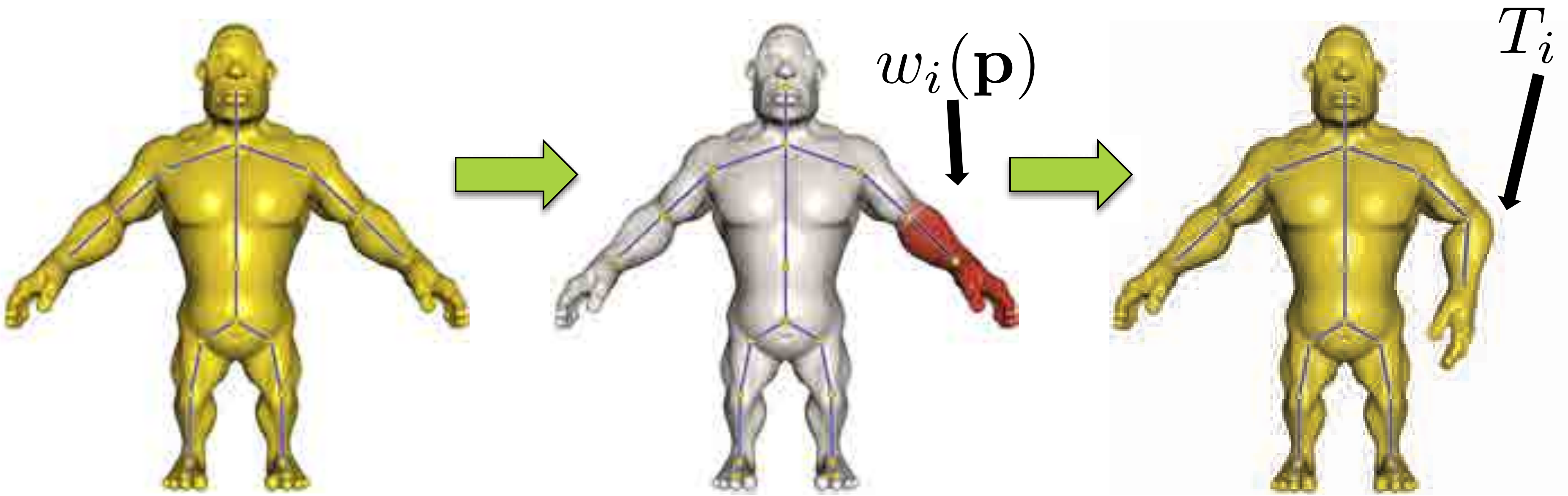
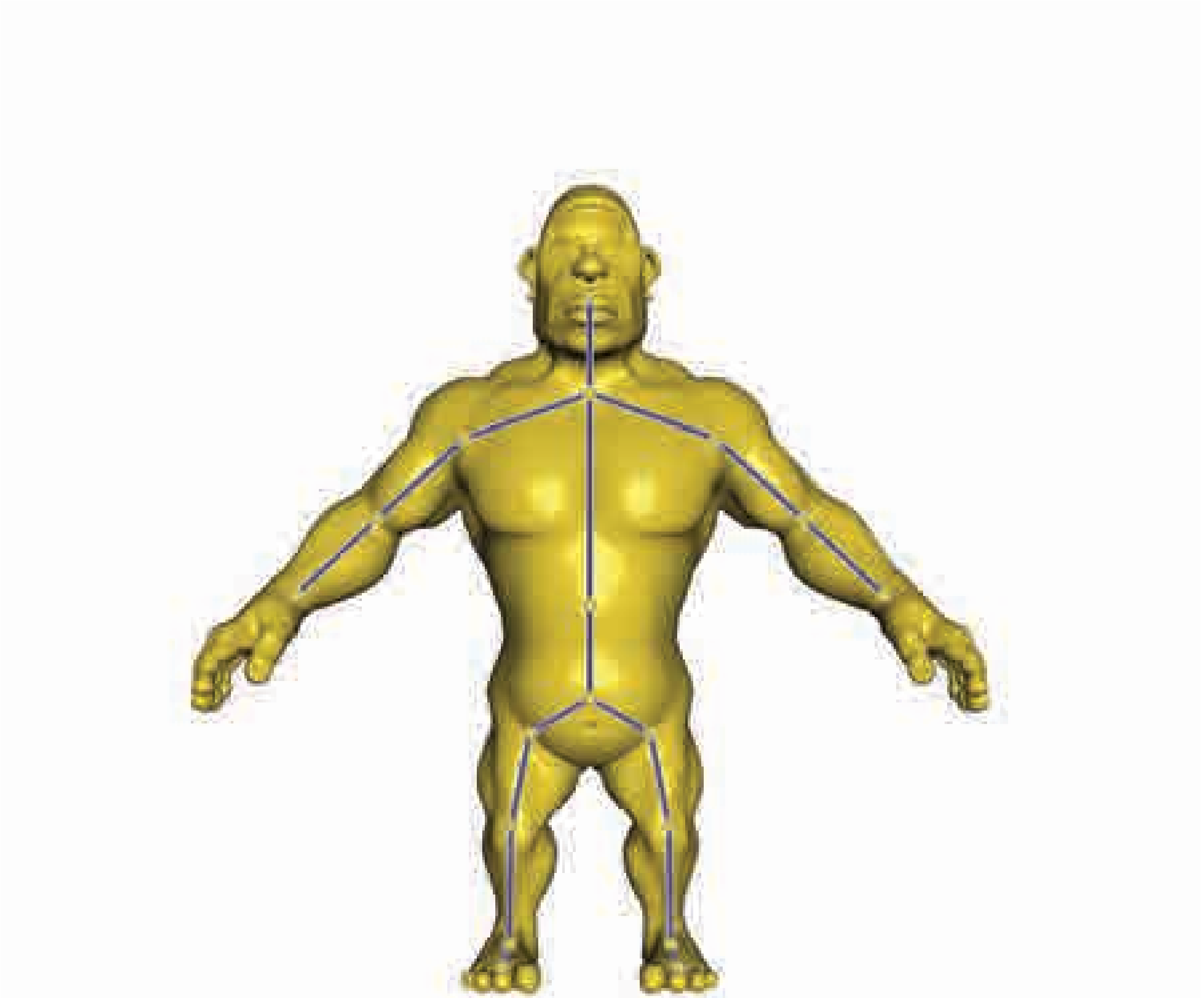


place skeleton in shape | compute/paint weights | deform bones

But stretching results in shape explosion…



LBS [Magnenat-Thalmann et al. 1988]

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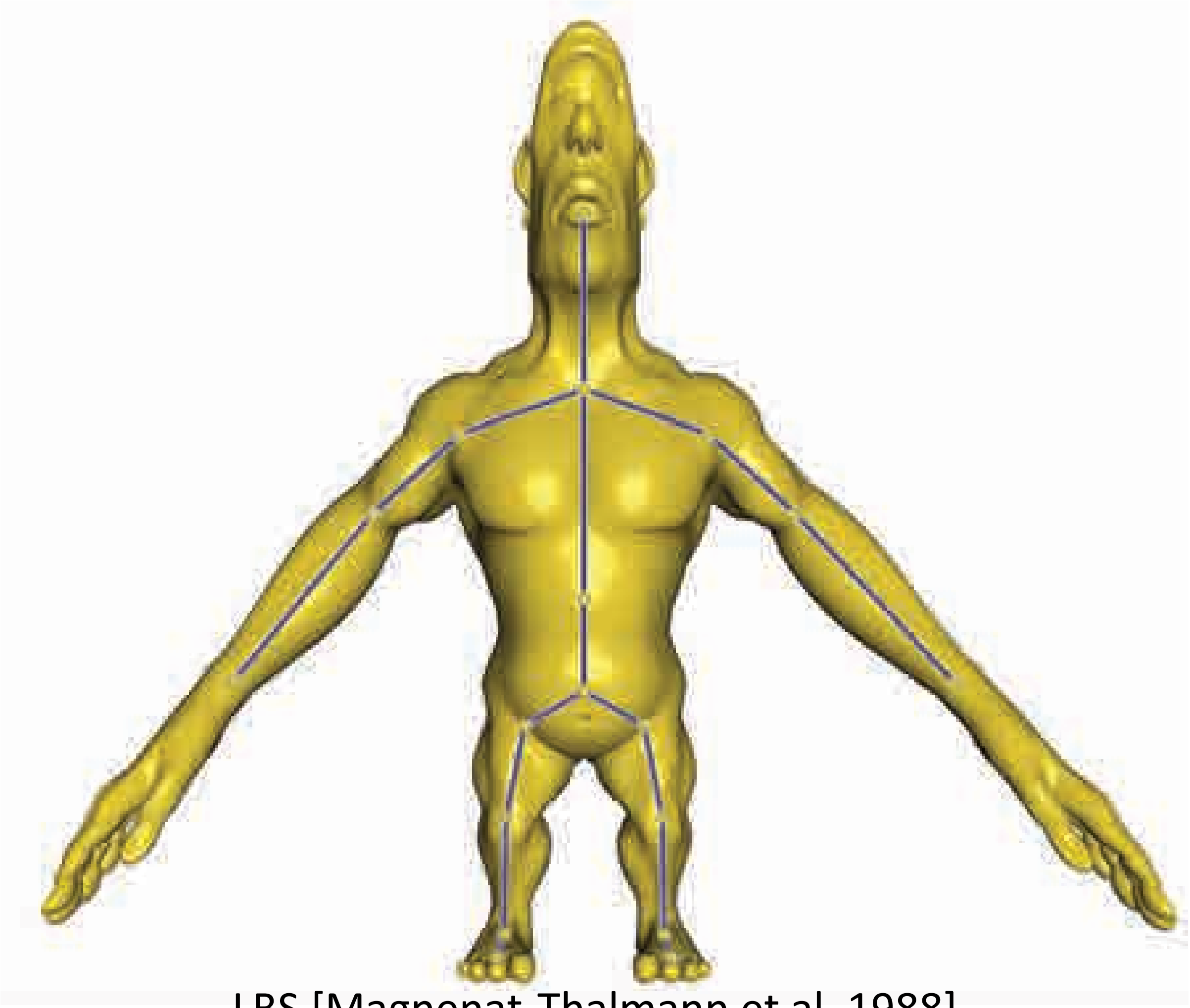
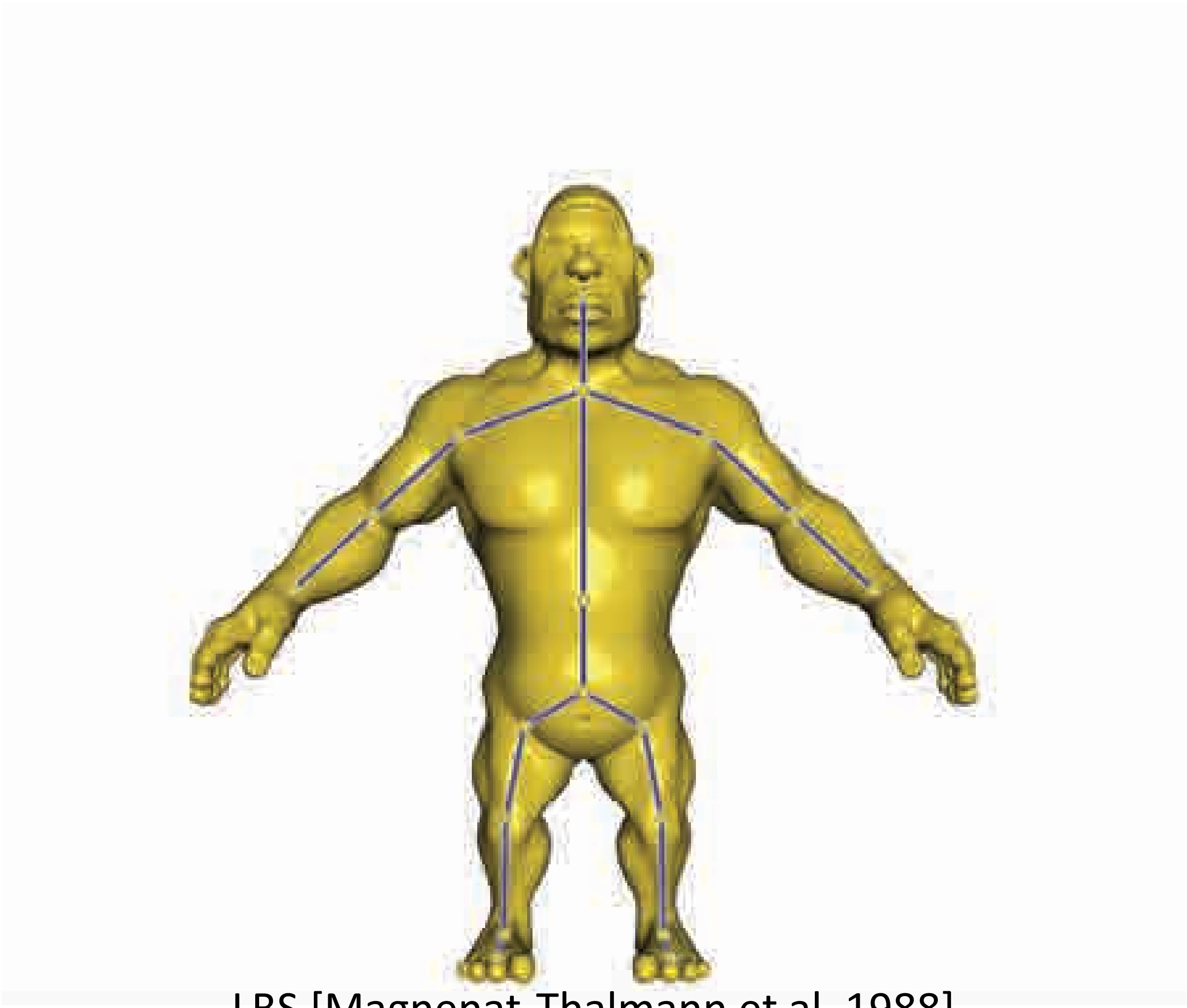


LBS [Magnenat-Thalmann et al. 1988]

… and twisting must be packed at joints



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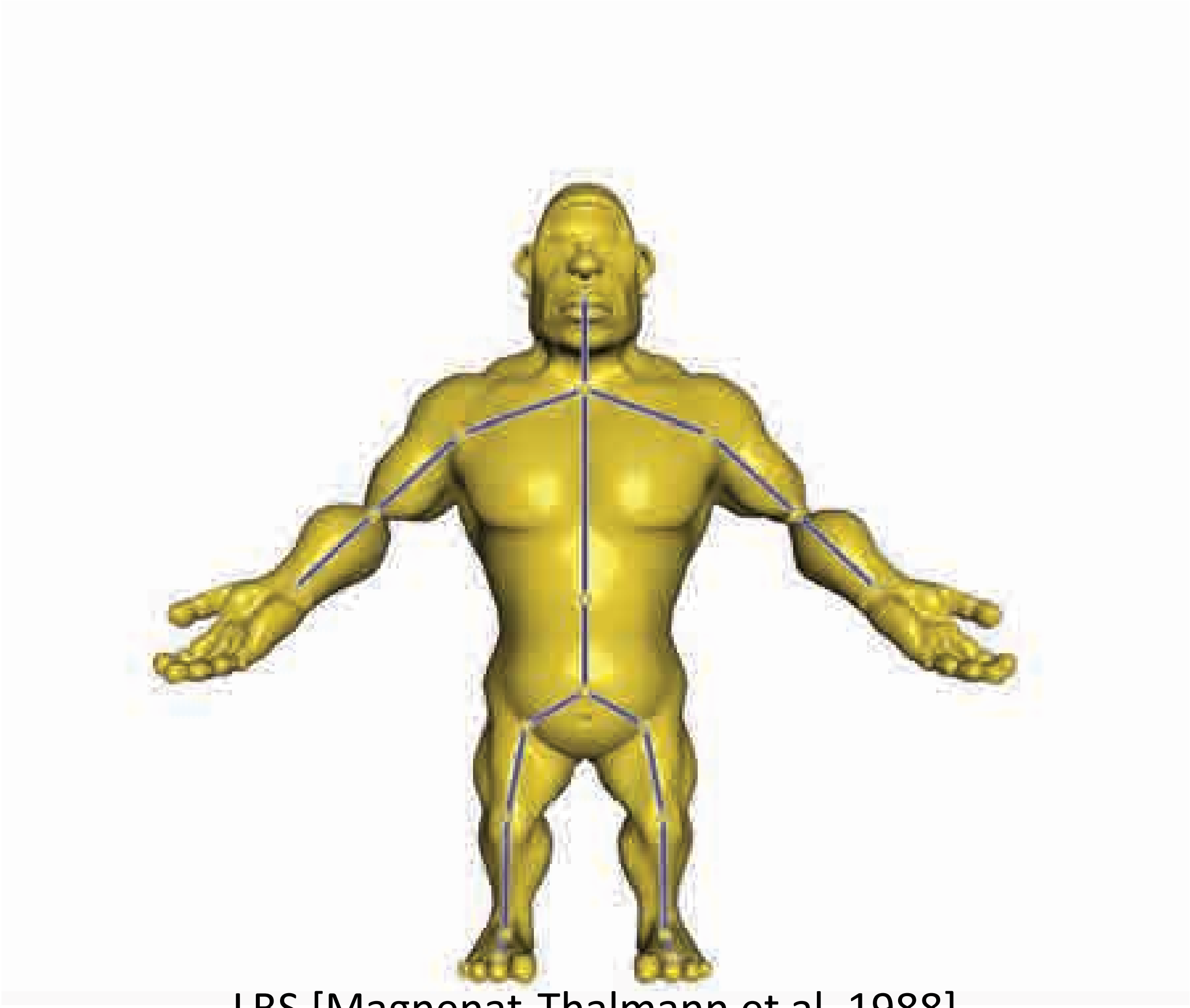
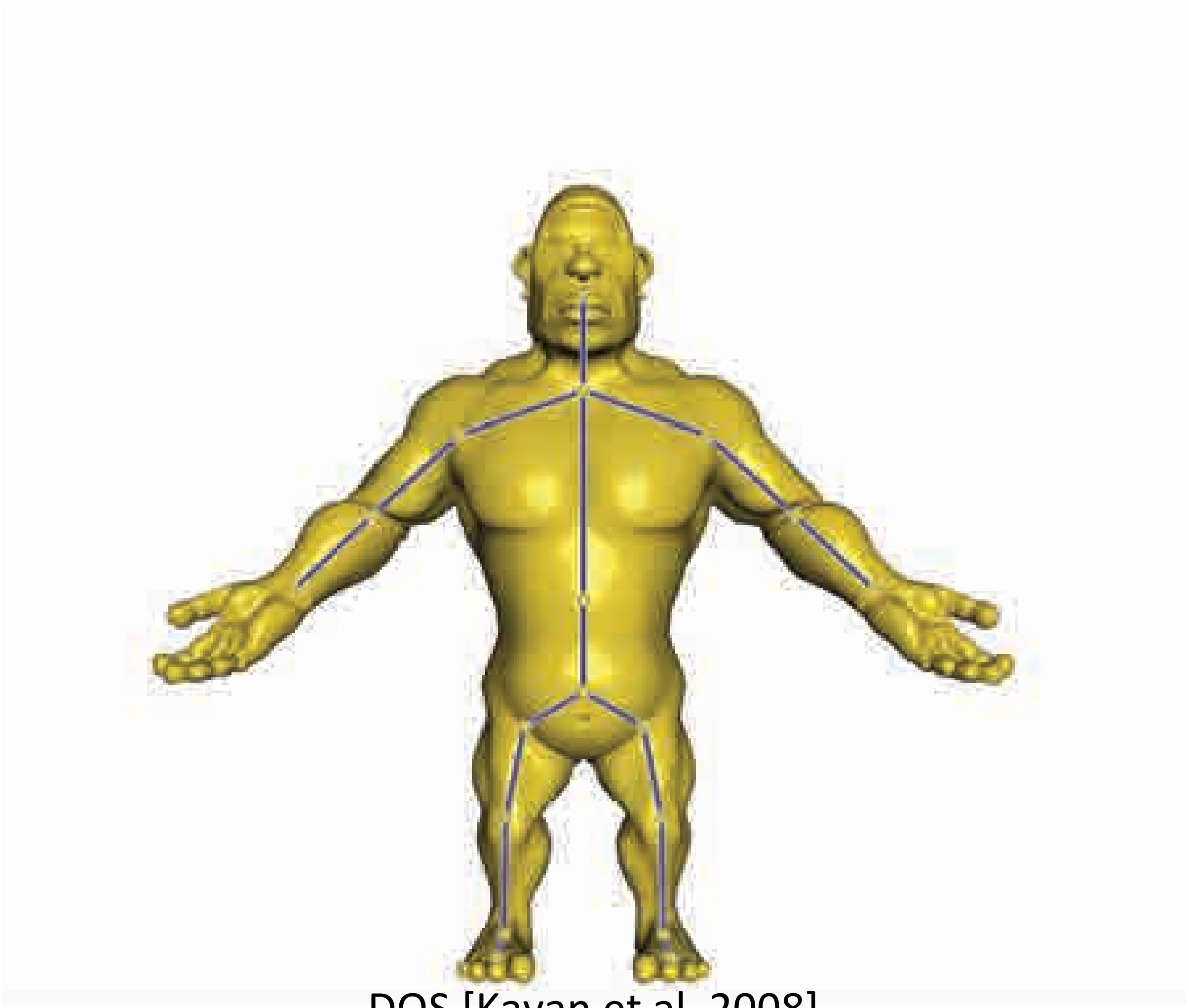


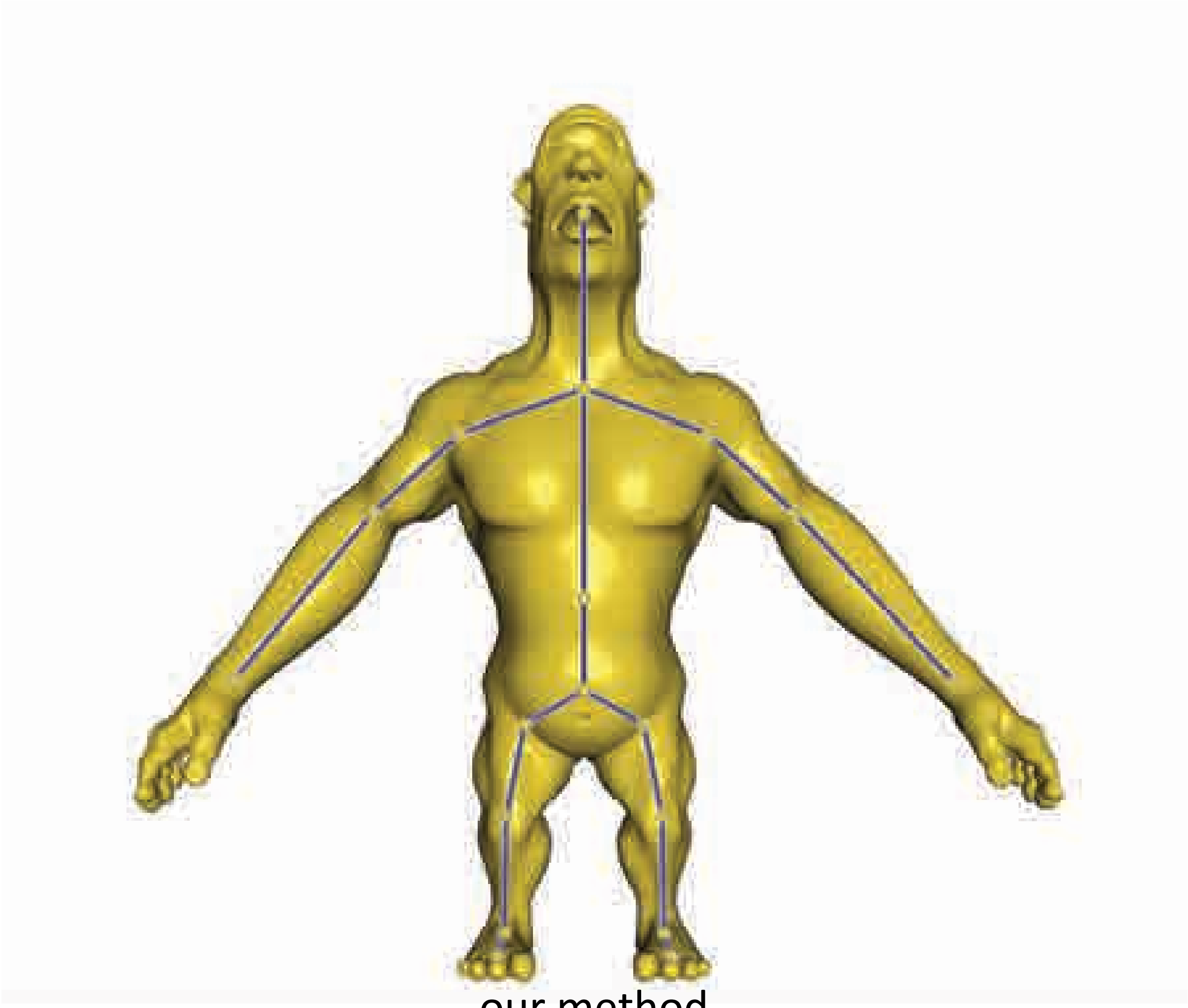
LBS [Magnenat-Thalmann et al. 1988]

Fixing candy-wrapper effect is not enough



DQS [Kavan et al. 2008]

We expand deformation space to include stretching and twisting



our method

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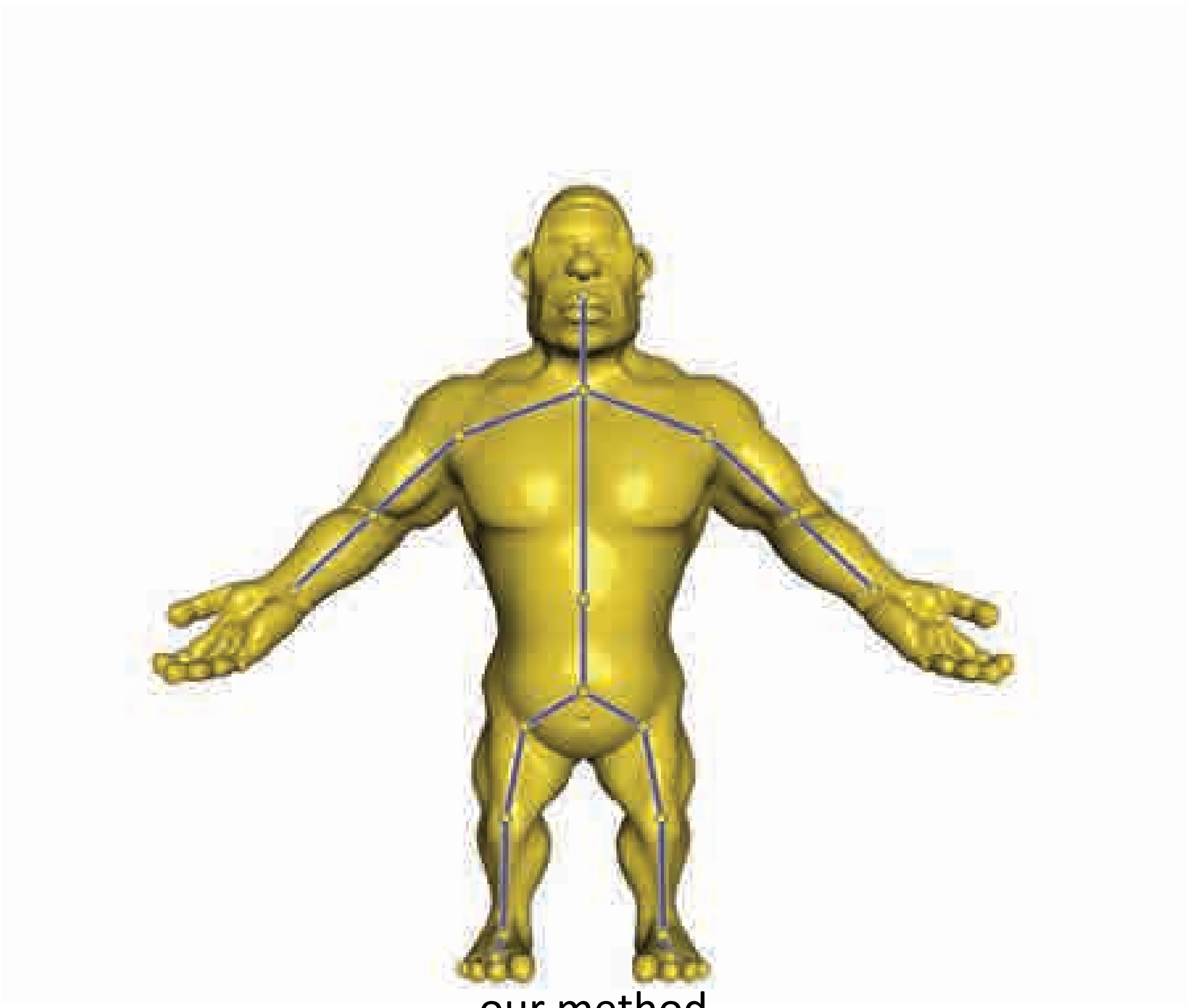
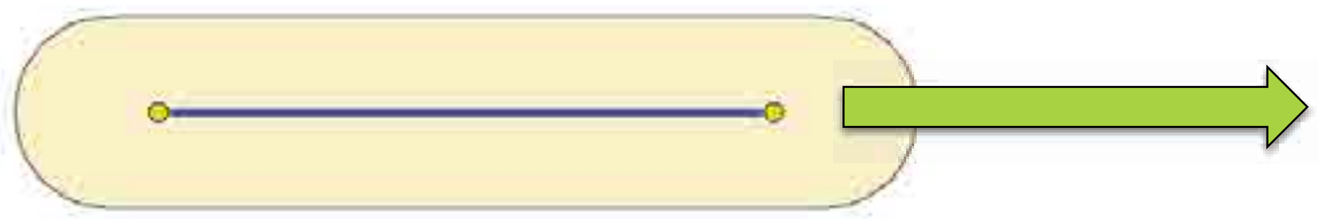


our method

Stretchable bones statue at Ten Thousand Buddhas Monastery in Hong Kong

LBS cannot properly handle stretching...



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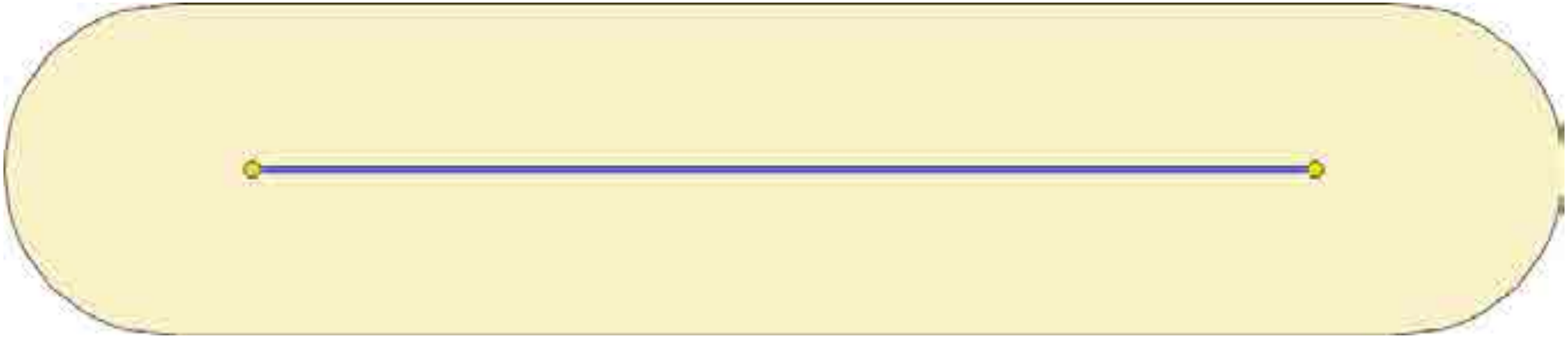
LBS cannot properly handle stretching...

uniform scaling



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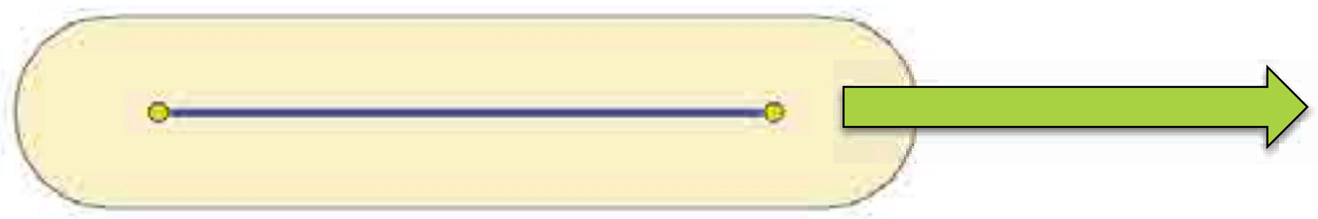

LBS cannot properly handle stretching

anisotropic scaling

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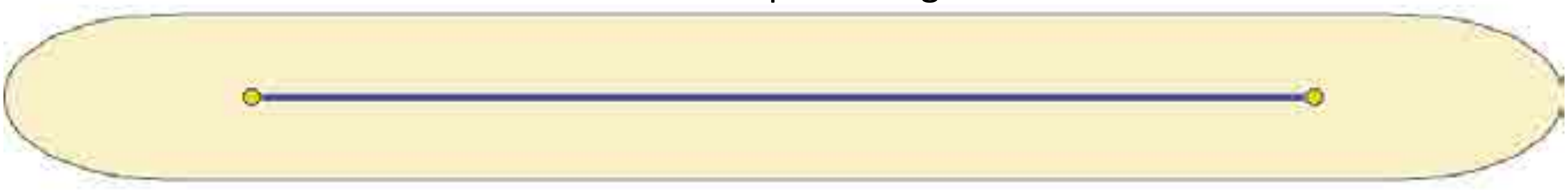
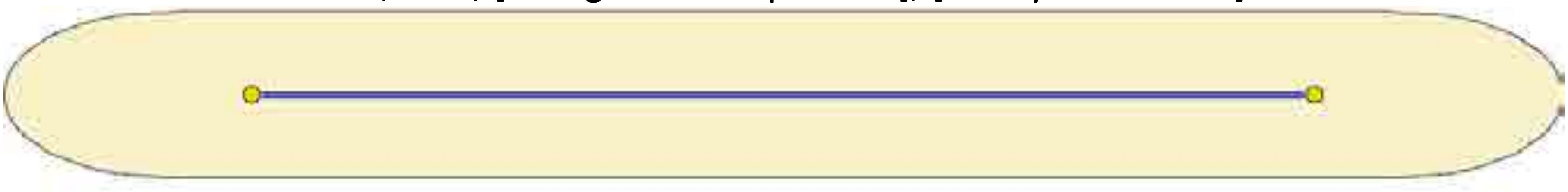


our method

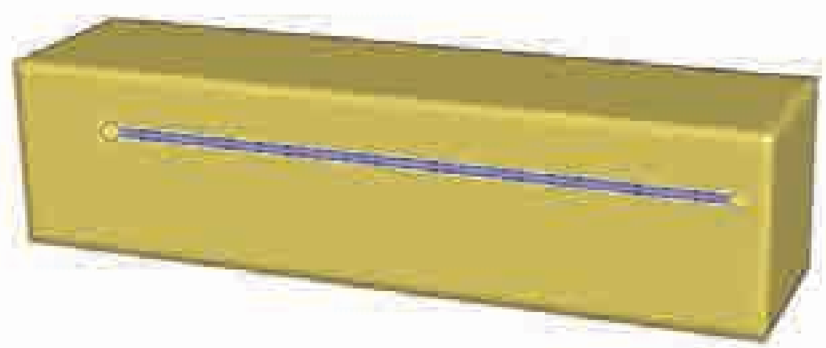
Previous methods with extra weights did not solve stretching problem

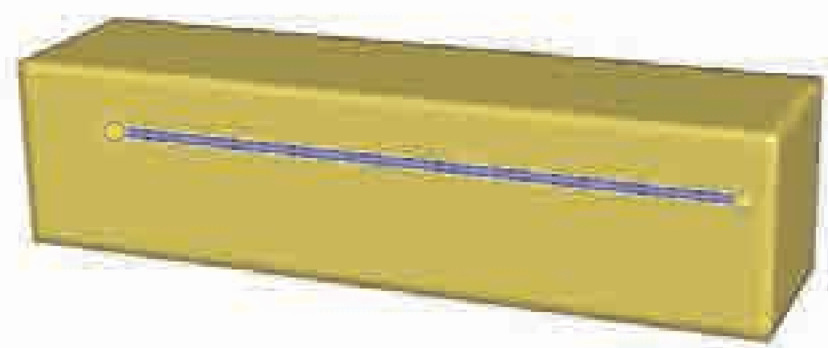
LBS, DQS, [Wang and Phillips 2002], [Merry et al. 2006]



our method

LBS and previous improvements cannot twist along bone lengths





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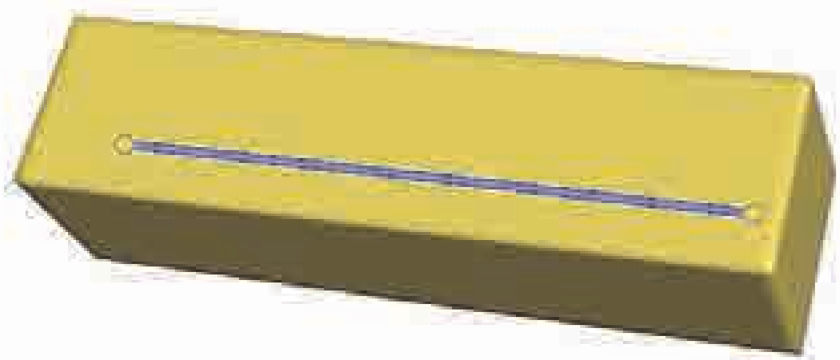

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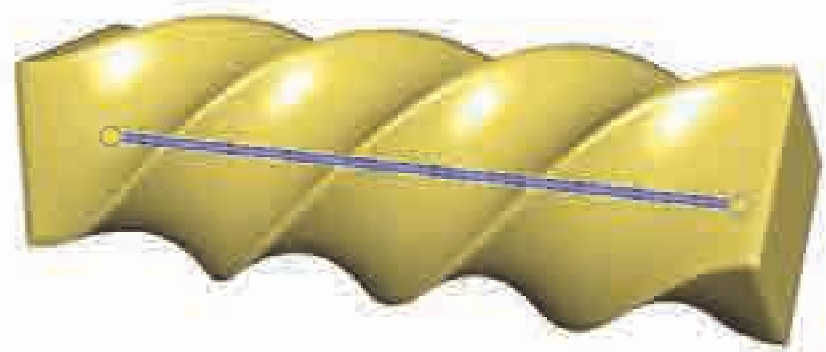

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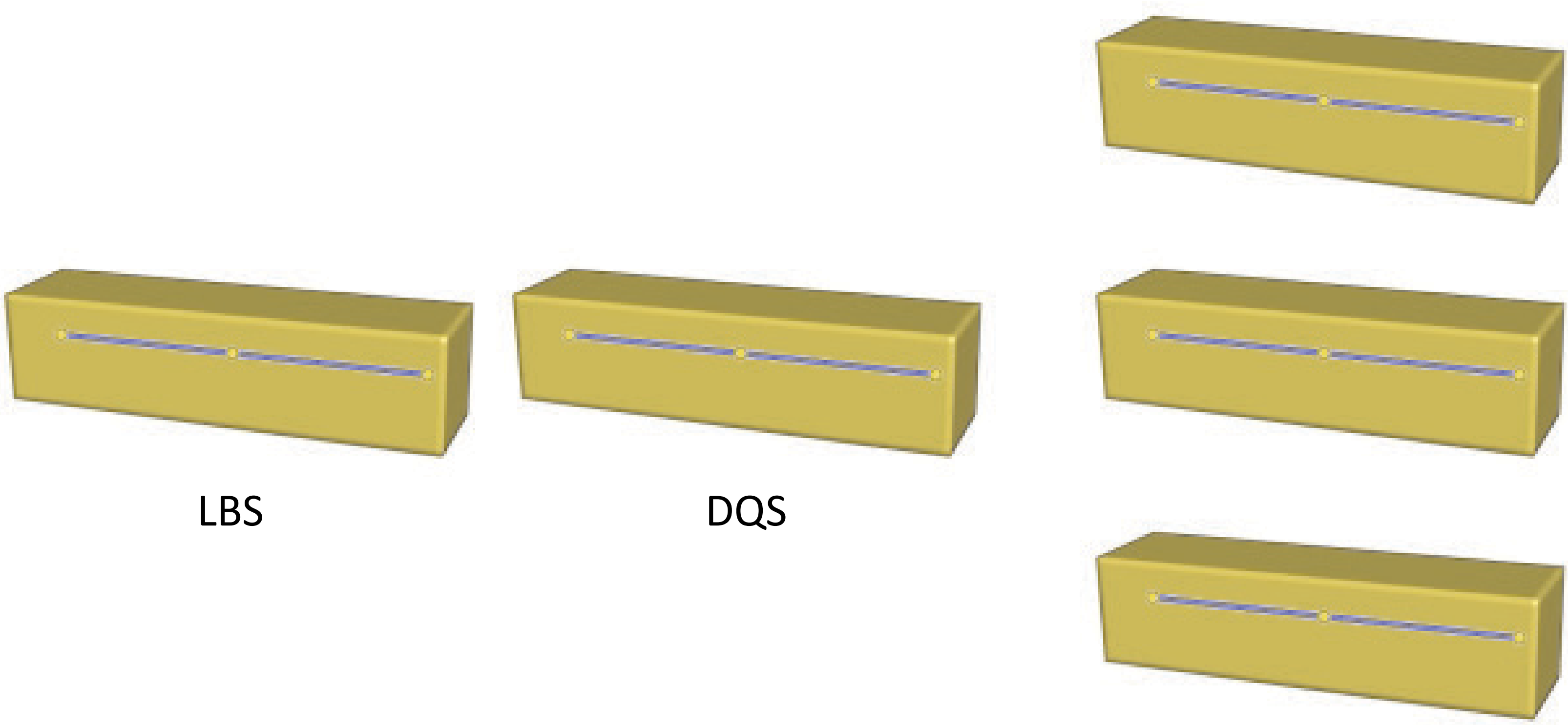

LBS

DQS

our method

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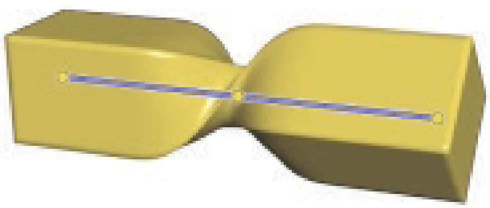
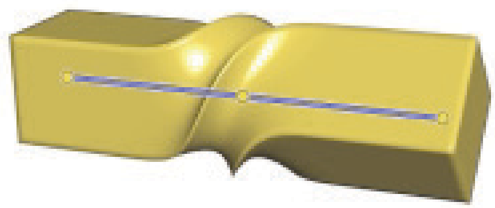

LBS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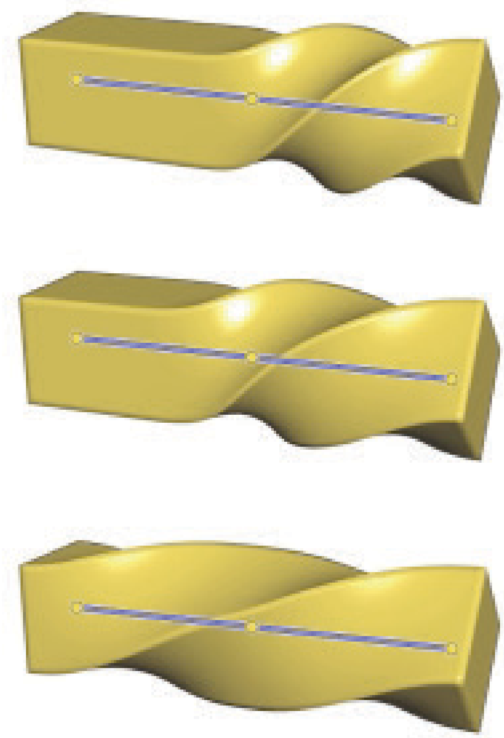
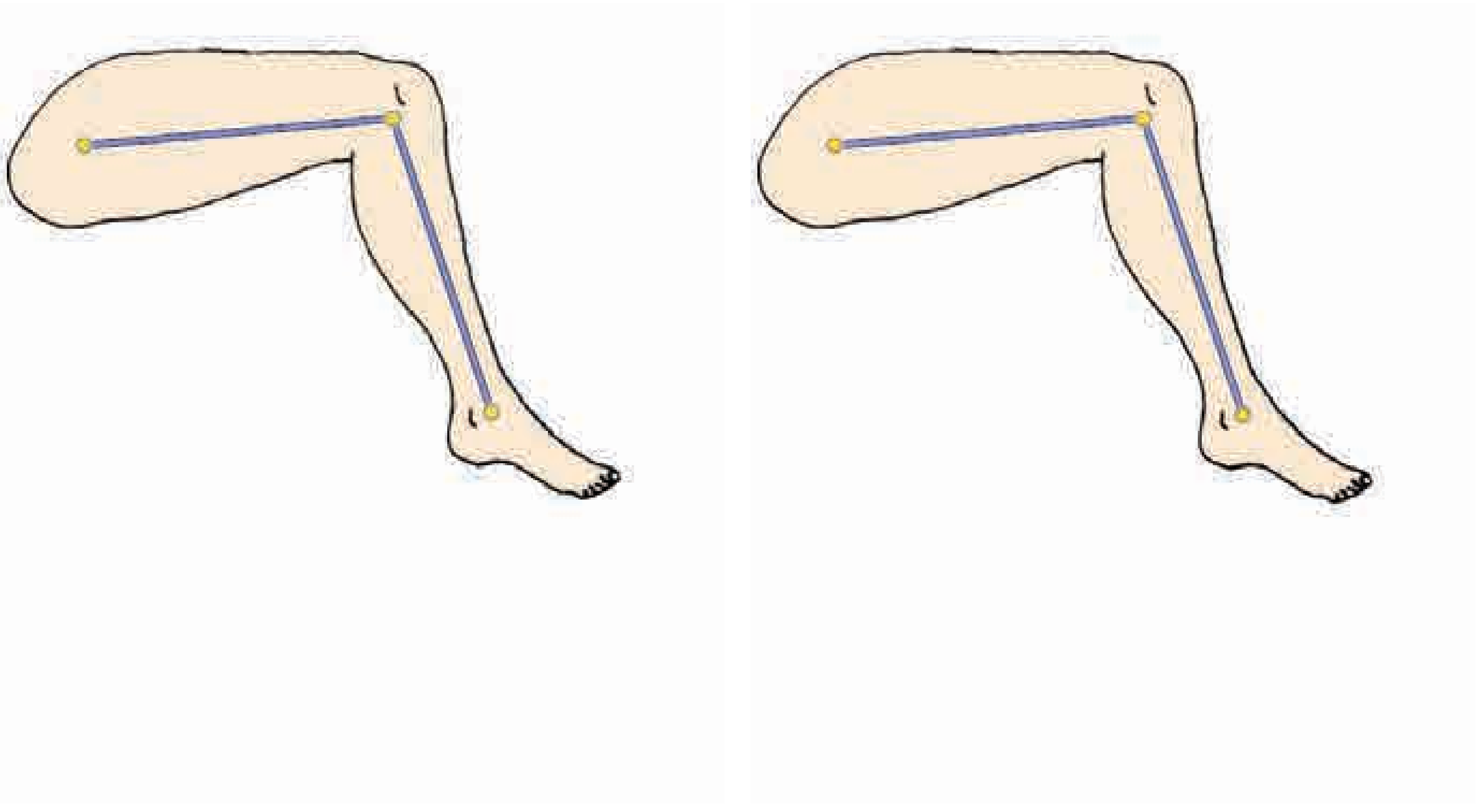

our method

Other improvements change too much or rely on examples

- Automatic extra bones [Mohr and Gleicher 2003]
  - Anatomically incorrect
  - Needs example poses
- Curve or spline skeletons [Fortsmann and Ohya 2006; Yang et al. 2006; Fortsmann et al. 2007]
  - Extra weights ignore input shape
  - Rigging tools and controls inconsistent with existing pipeline

Bone weights capture rigid parts well…



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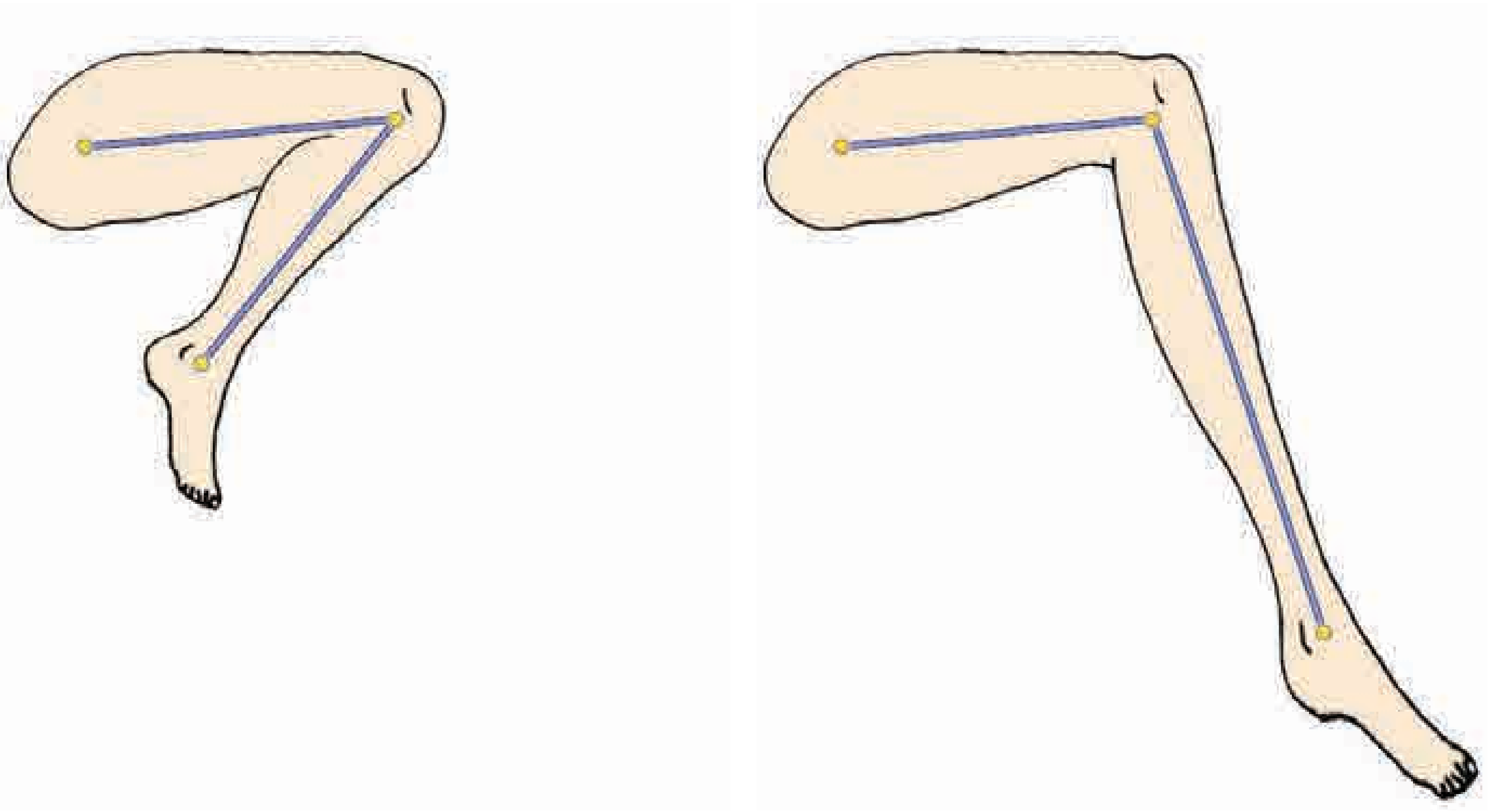
… but fail to control along bone lengths



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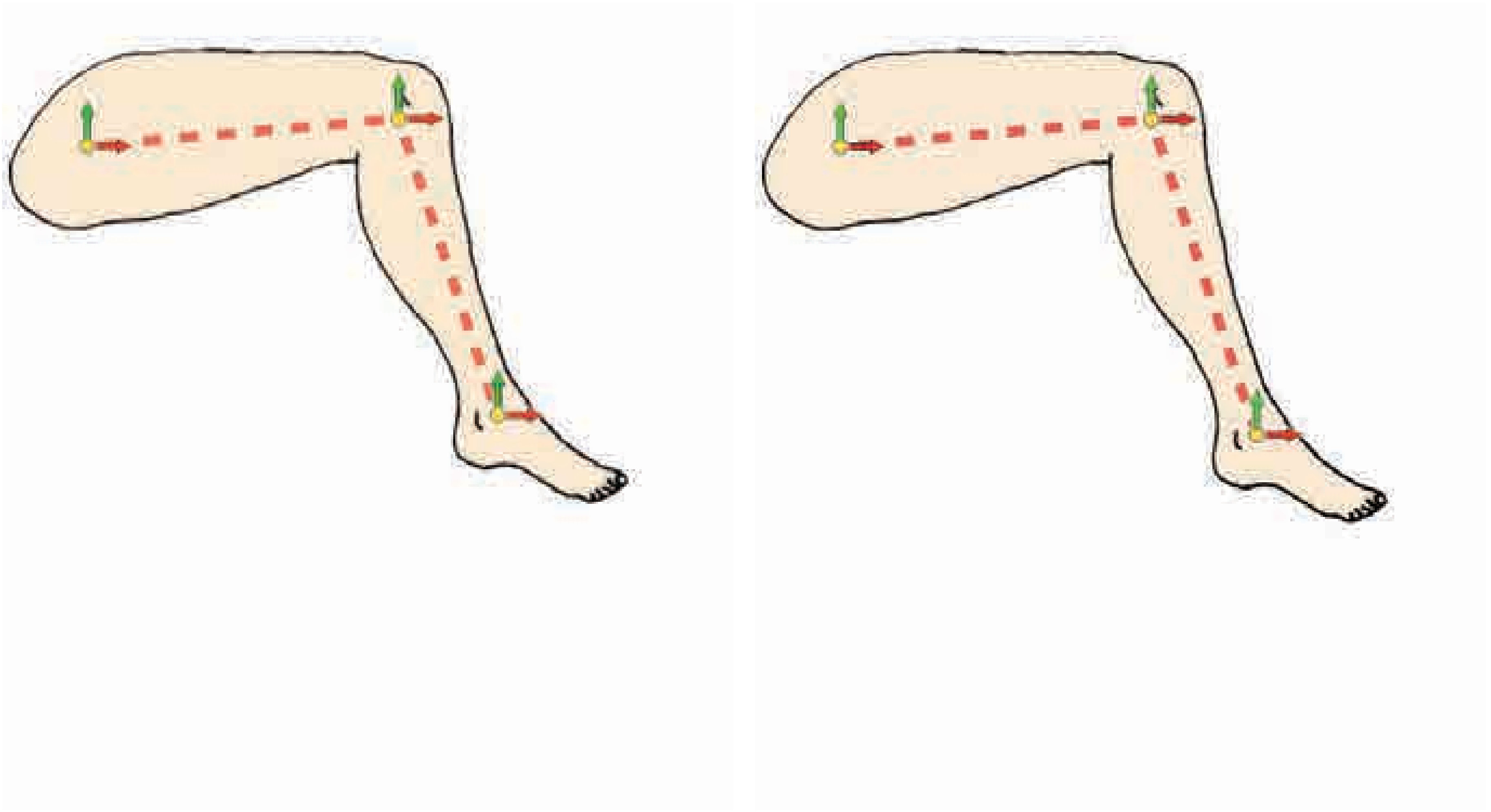
Point weights stretch correctly …



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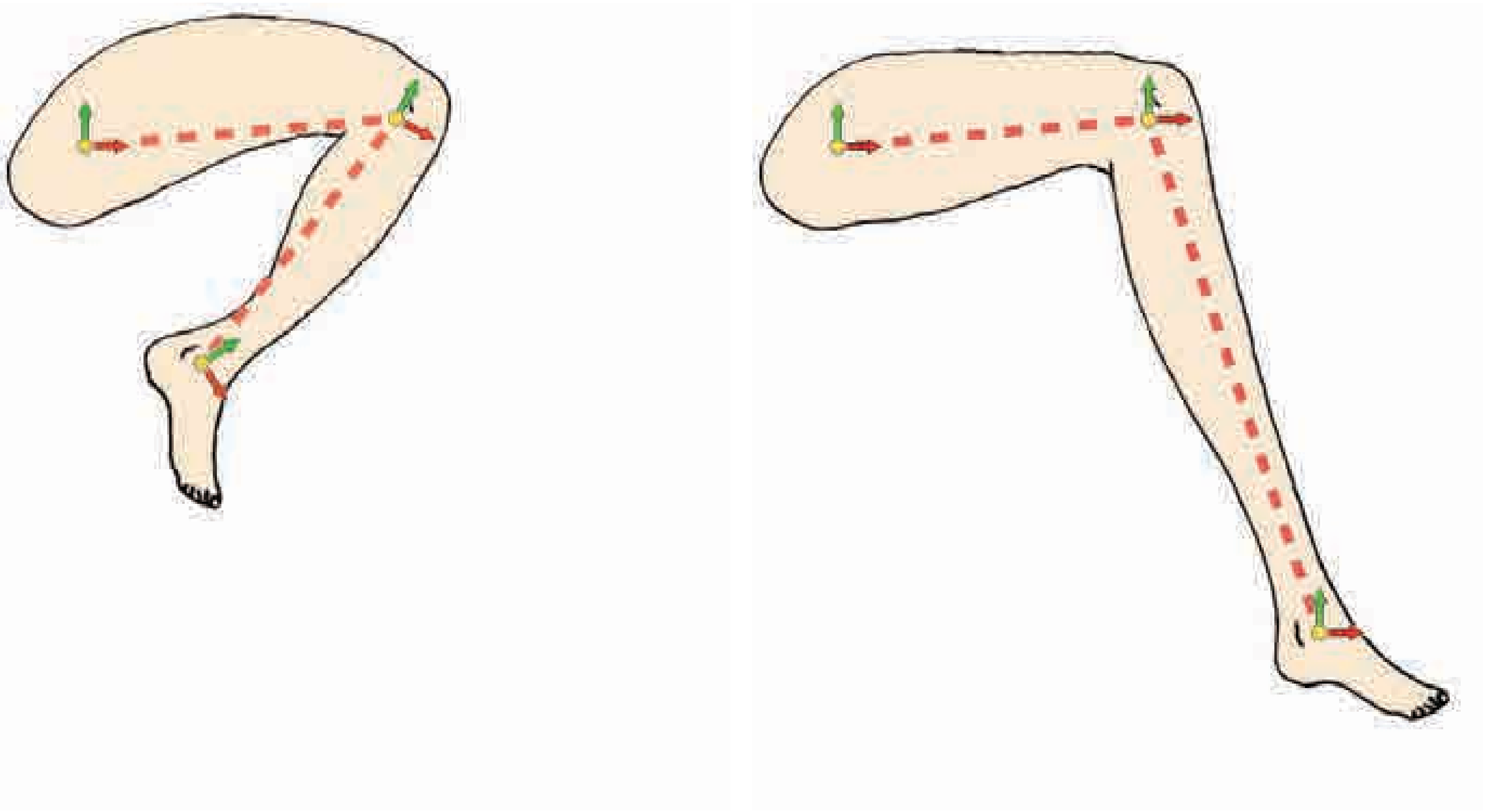
... but cannot bend like bone joints



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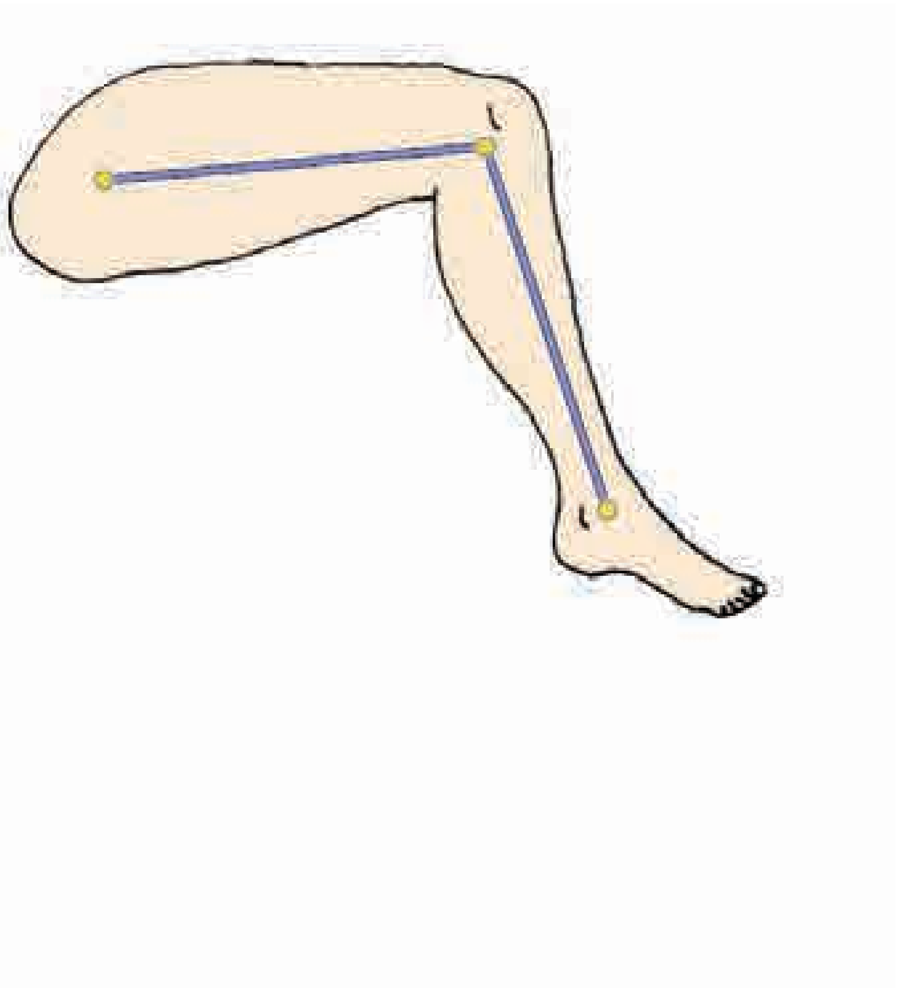
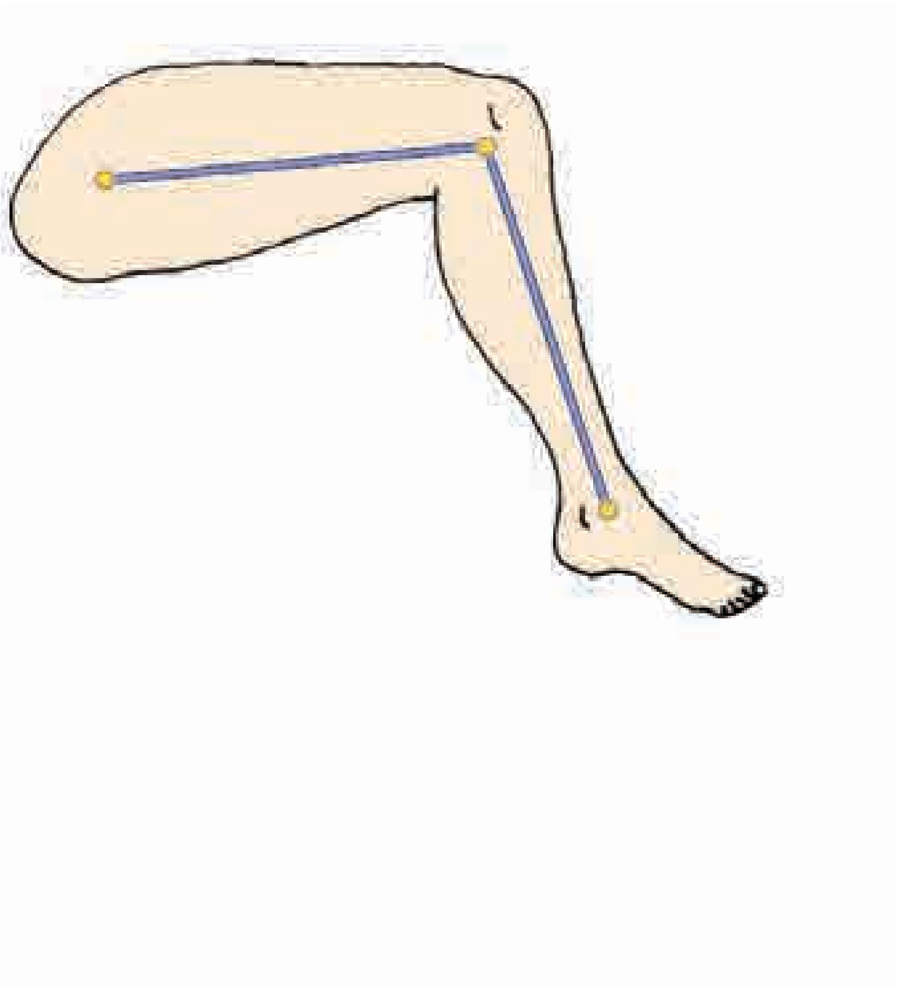
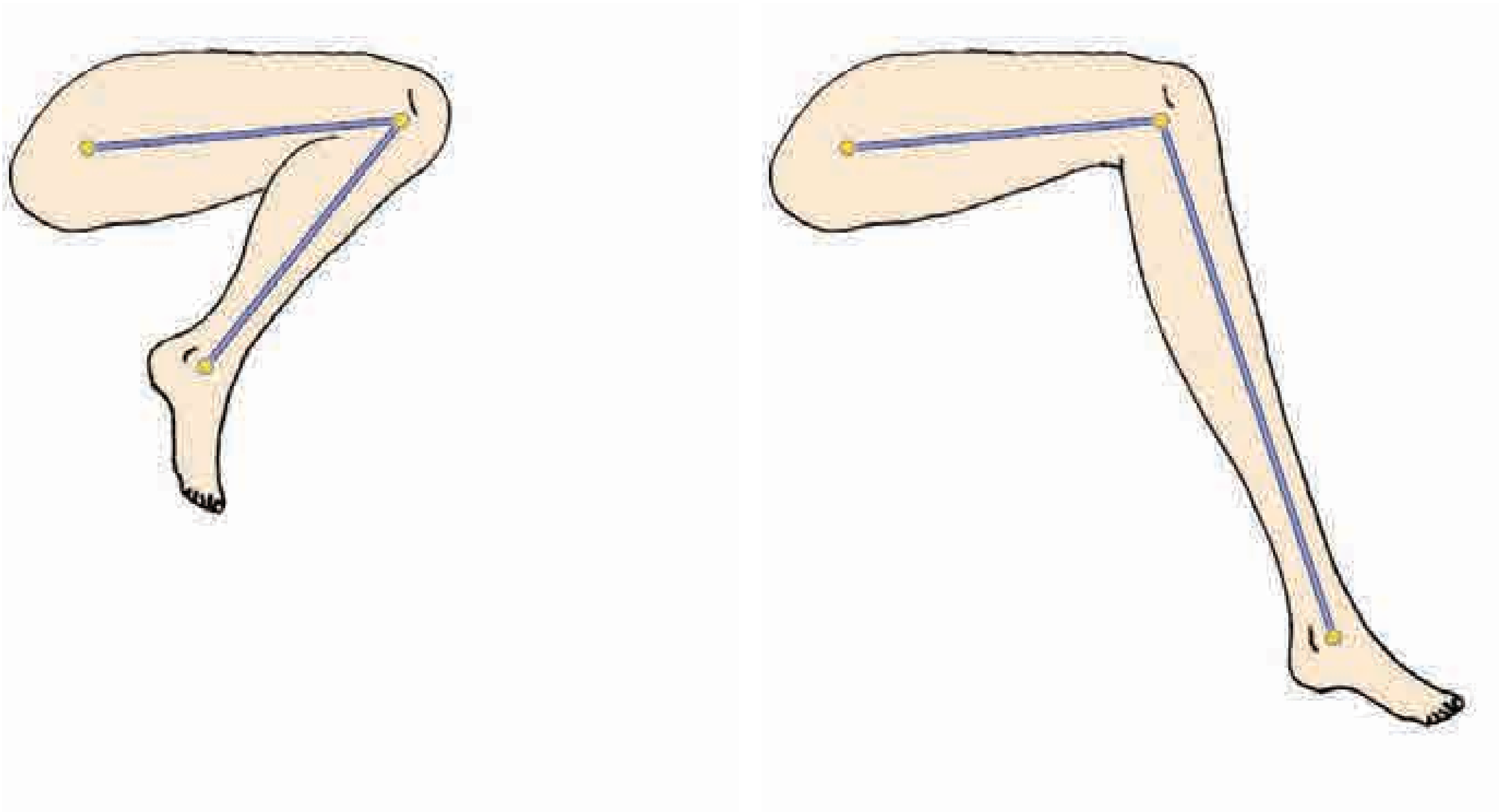
Utilizing bone weights and point weights allows bending like bones …



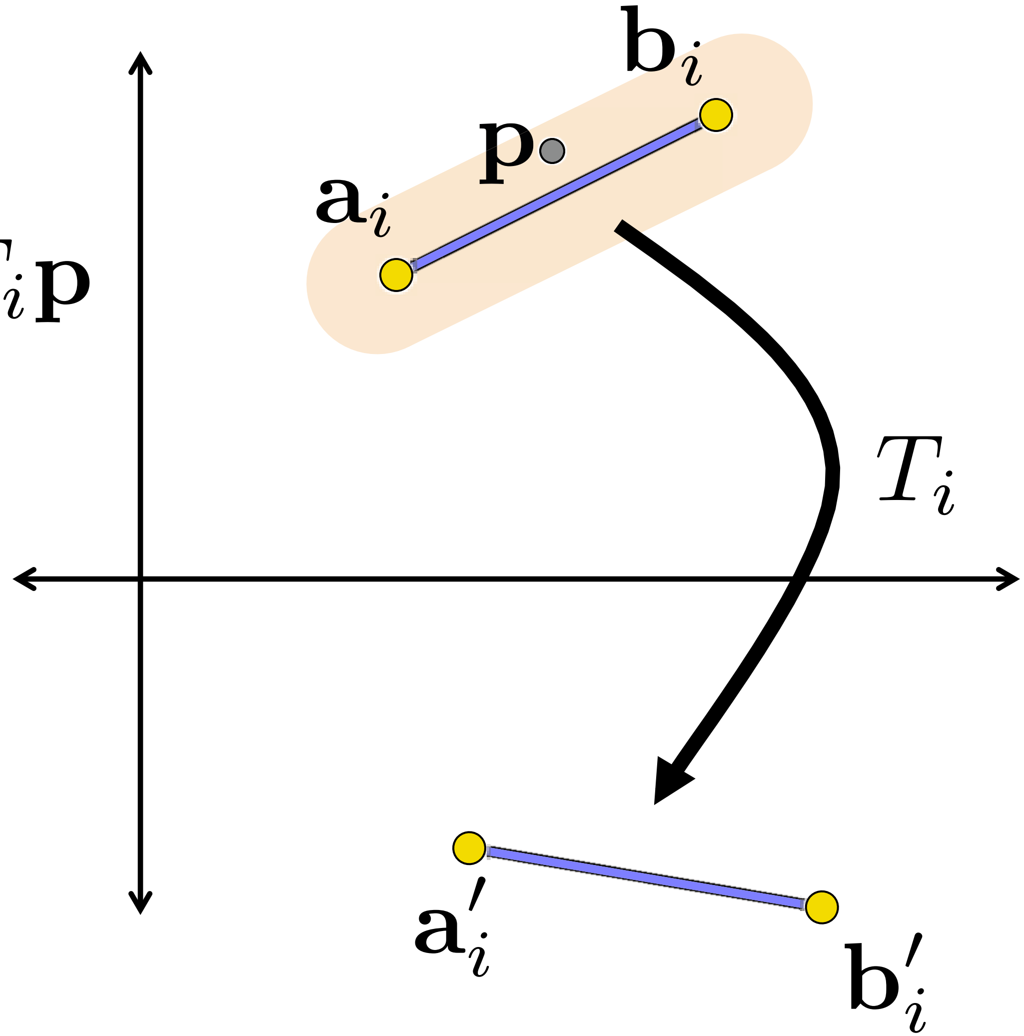


… and stretching like points



Decomposing Linear Blend Skinning exposes constant terms

$$\mathbf{p}' = \sum_{i \in B} w_i(\mathbf{p}) T_i \mathbf{p}$$



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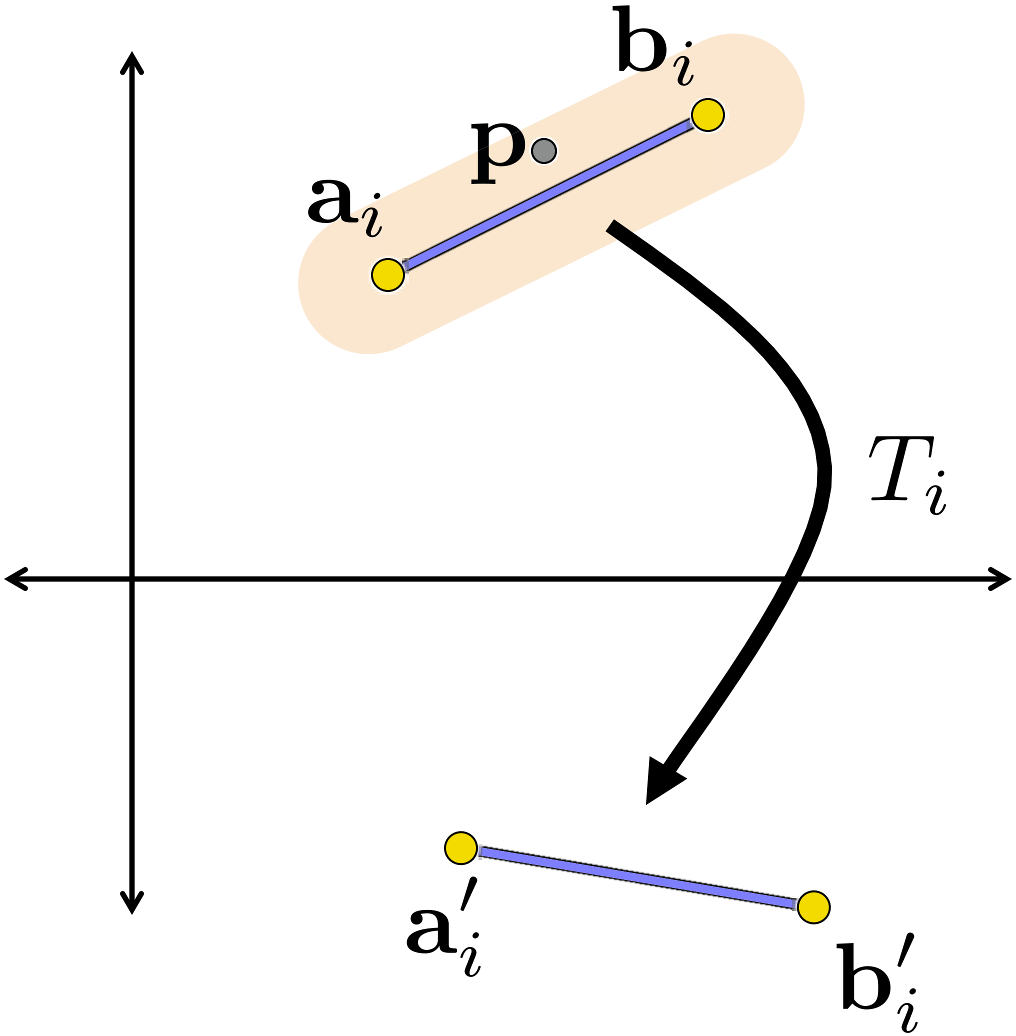
$T_i \mathbf{p}$



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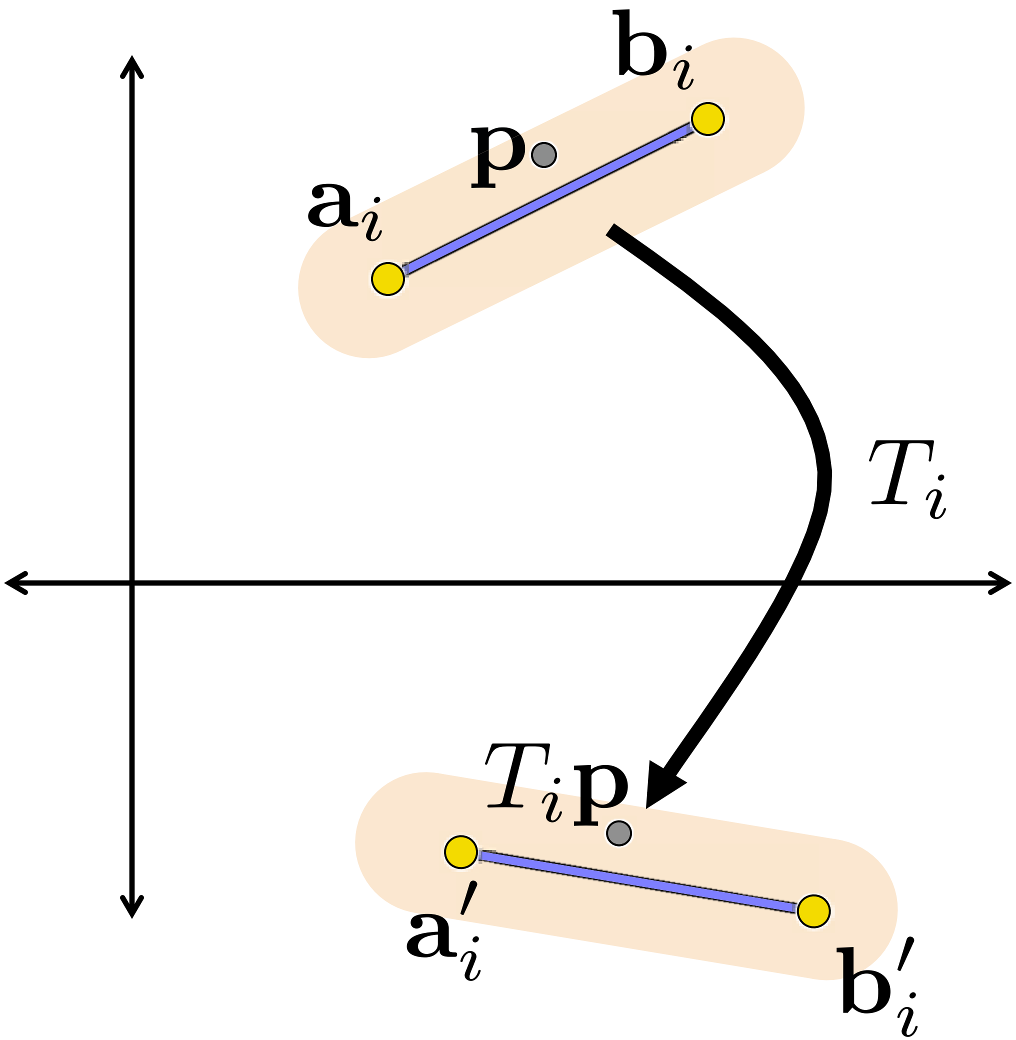
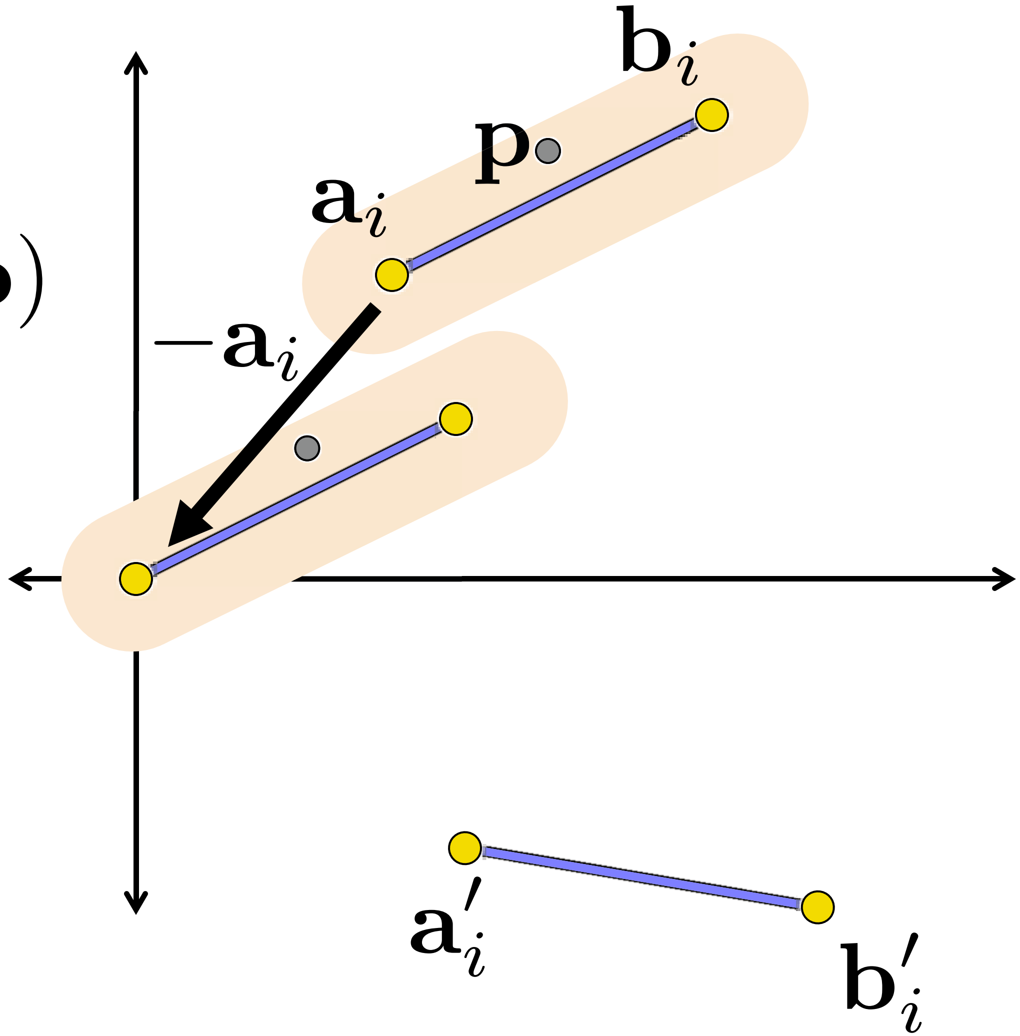


Decomposing Linear Blend Skinning exposes constant terms

$$\mathbf{a}_i' + R_i(-\mathbf{a}_i + \mathbf{p})$$



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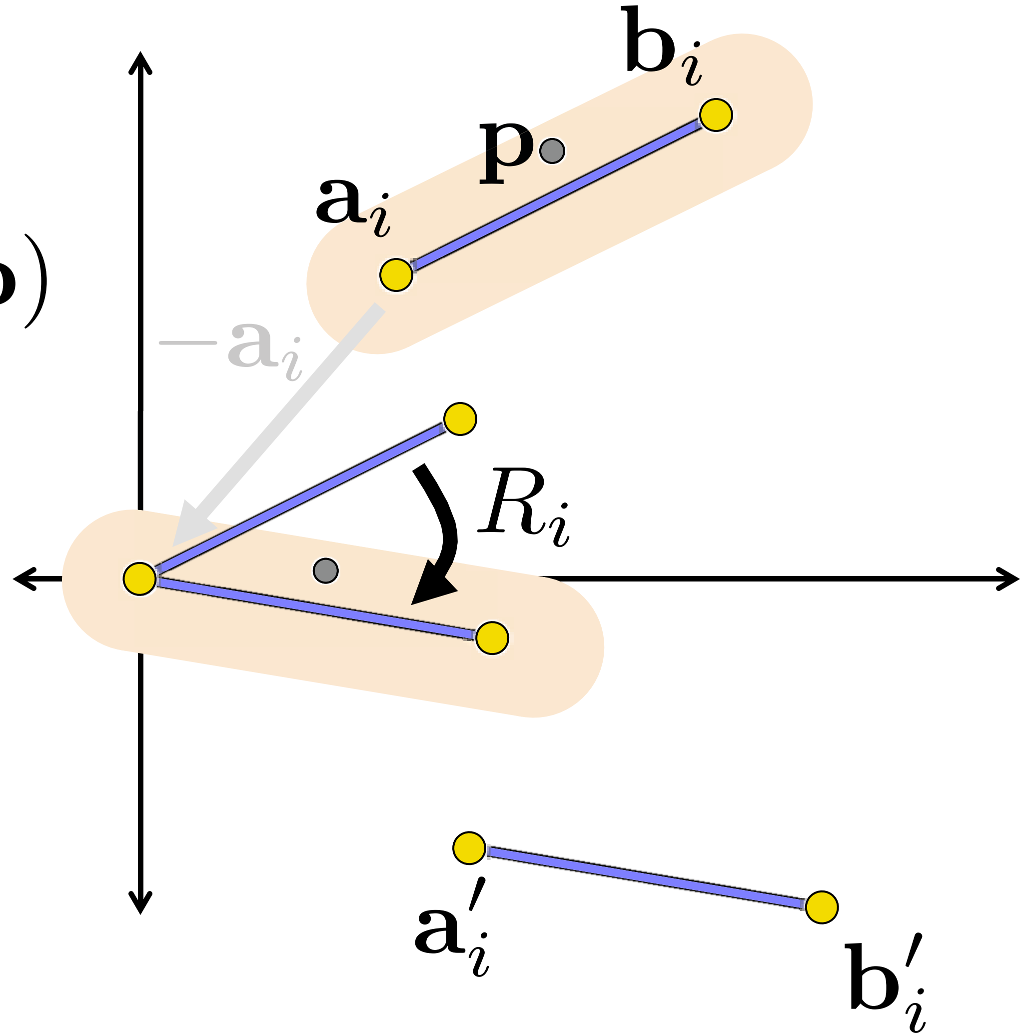

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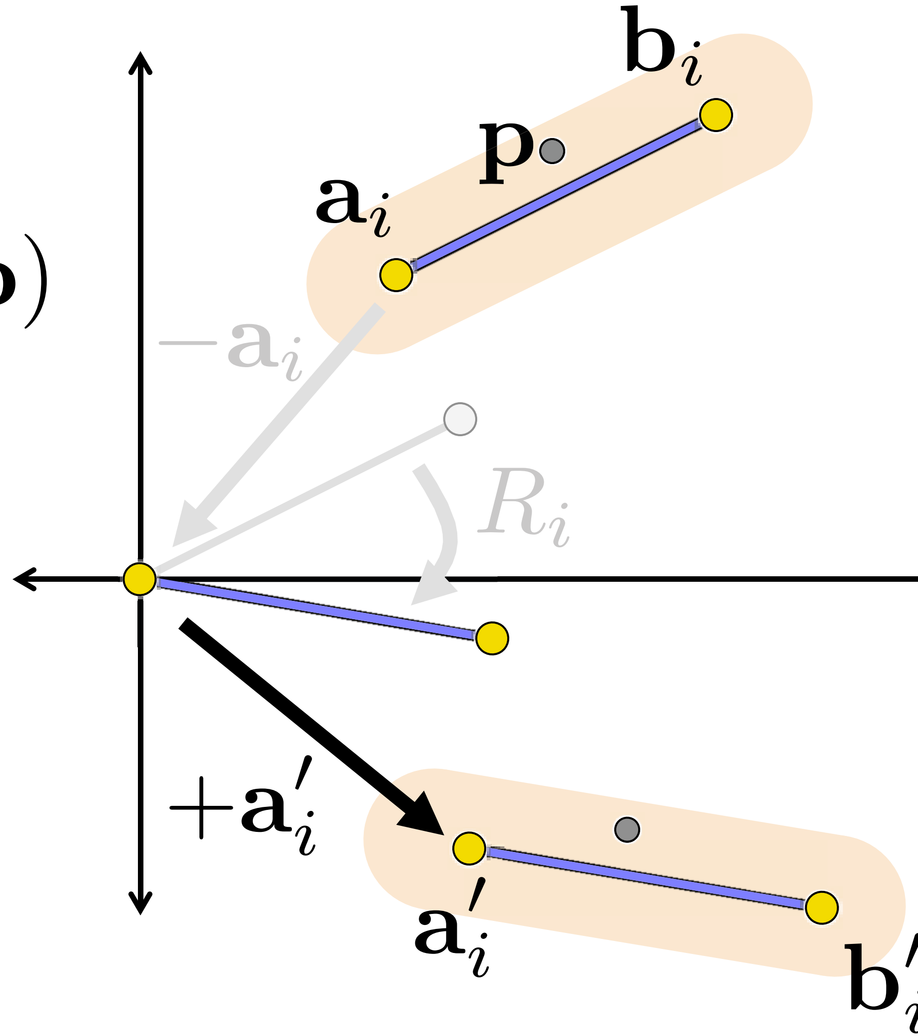

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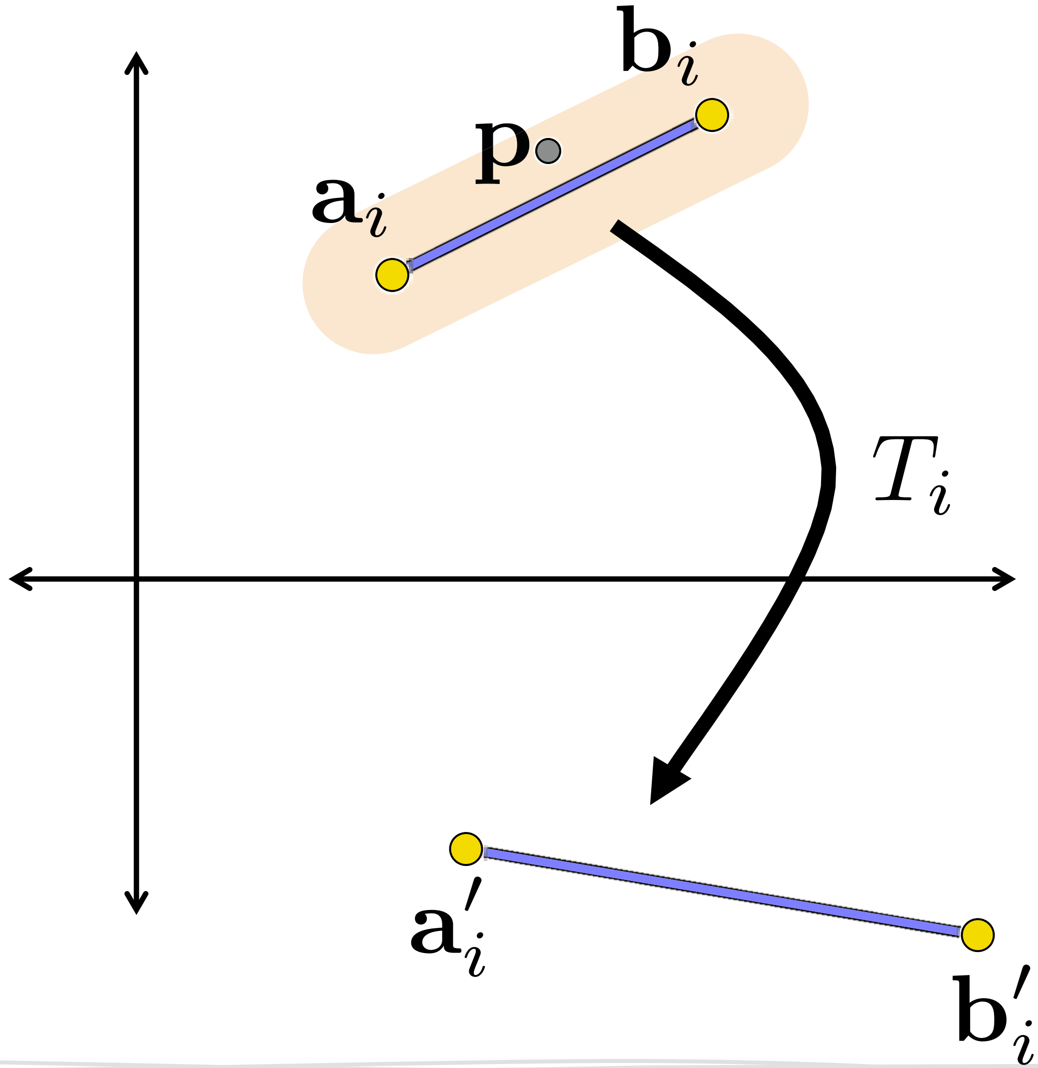
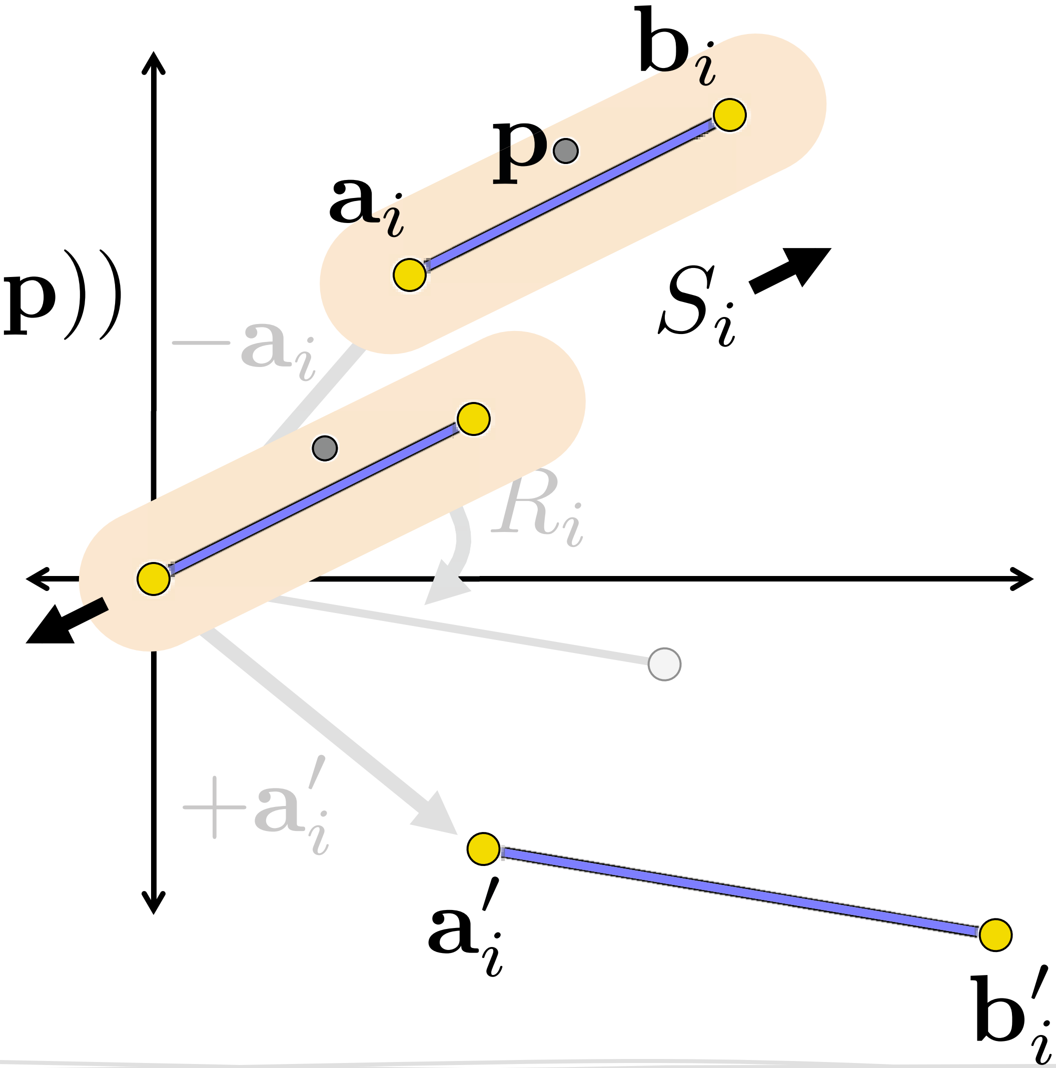


Anisotropic scaling term is constant for each bone weight

$$\mathbf{a}_i' + R_i(S_i(-\mathbf{a}_i + \mathbf{p}))$$



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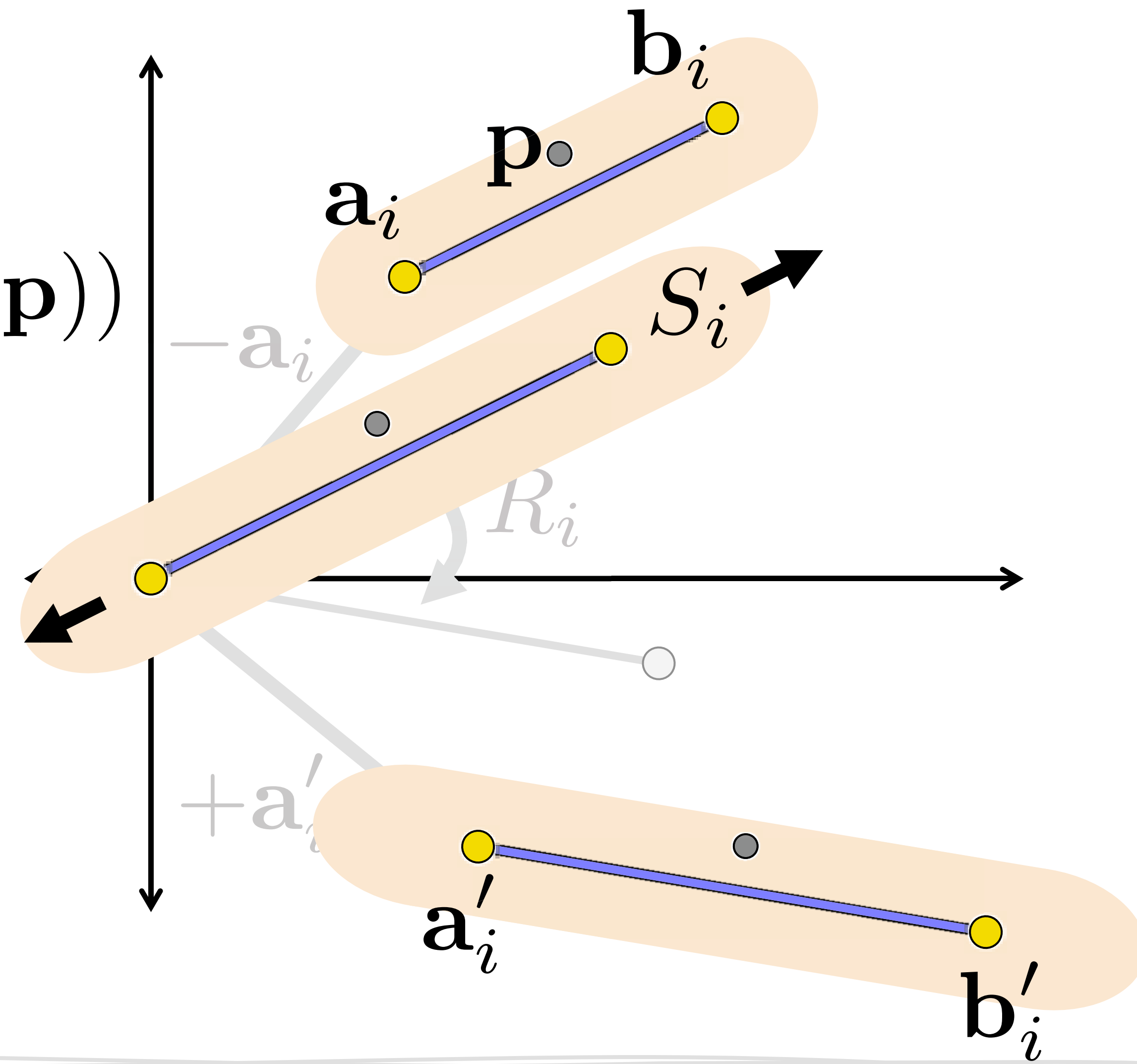

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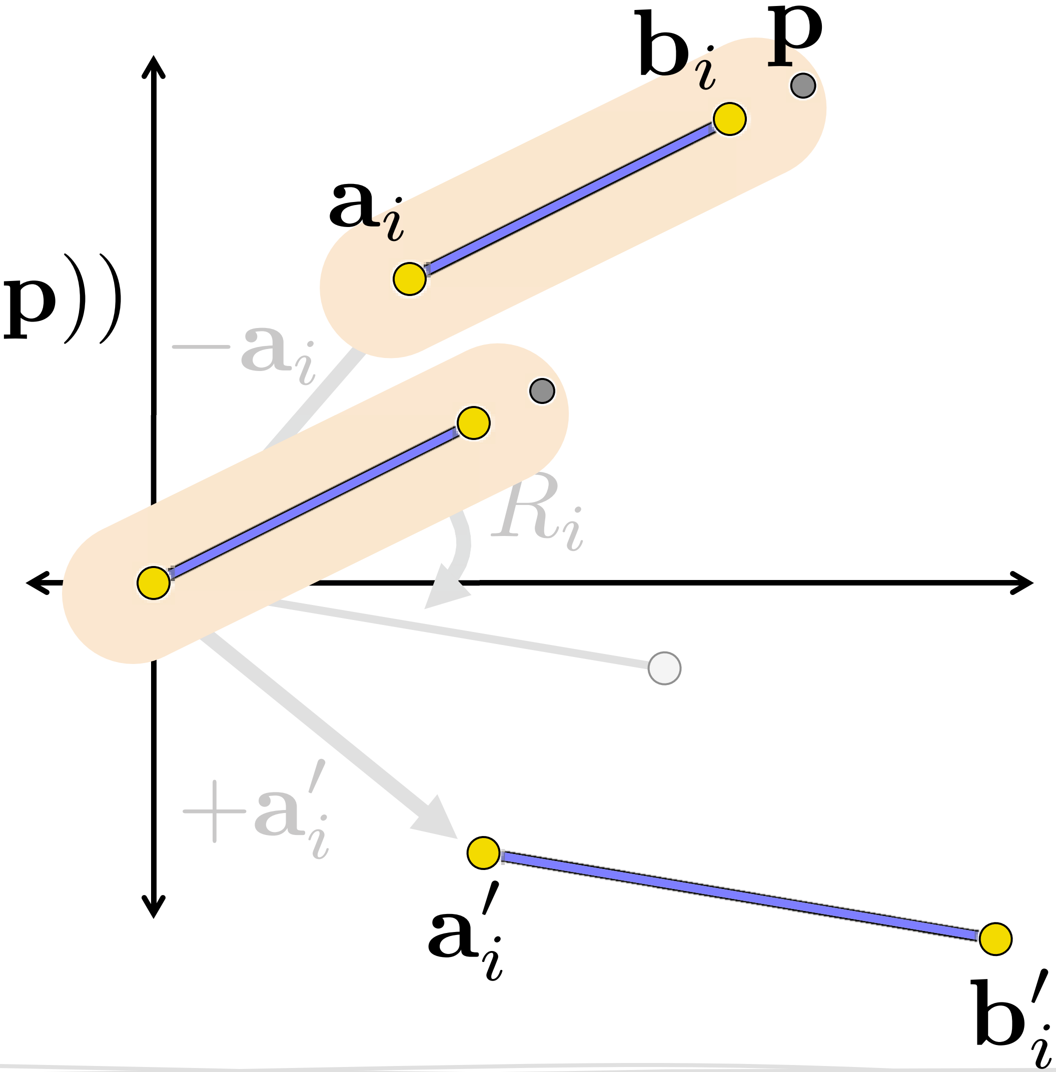

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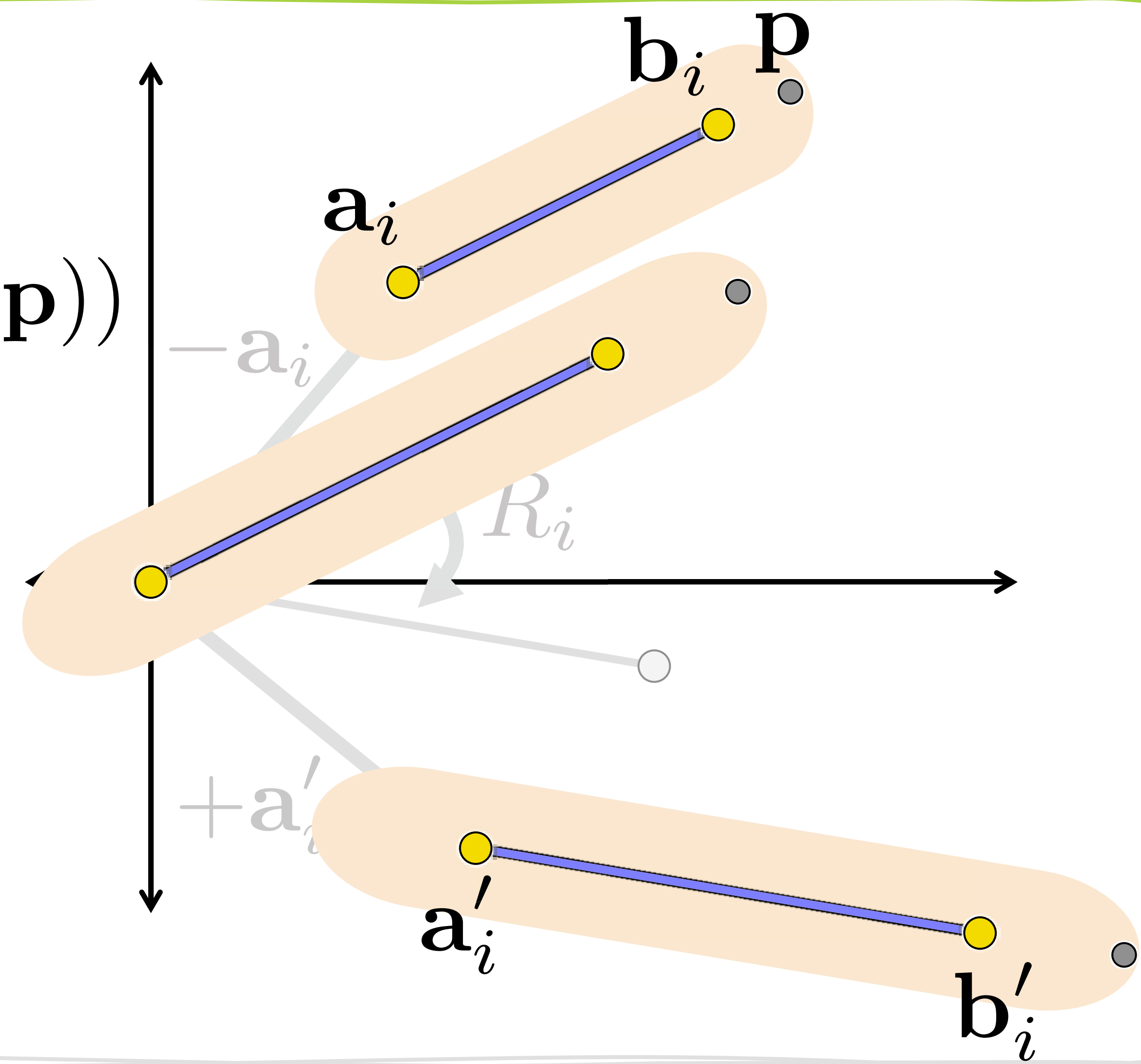

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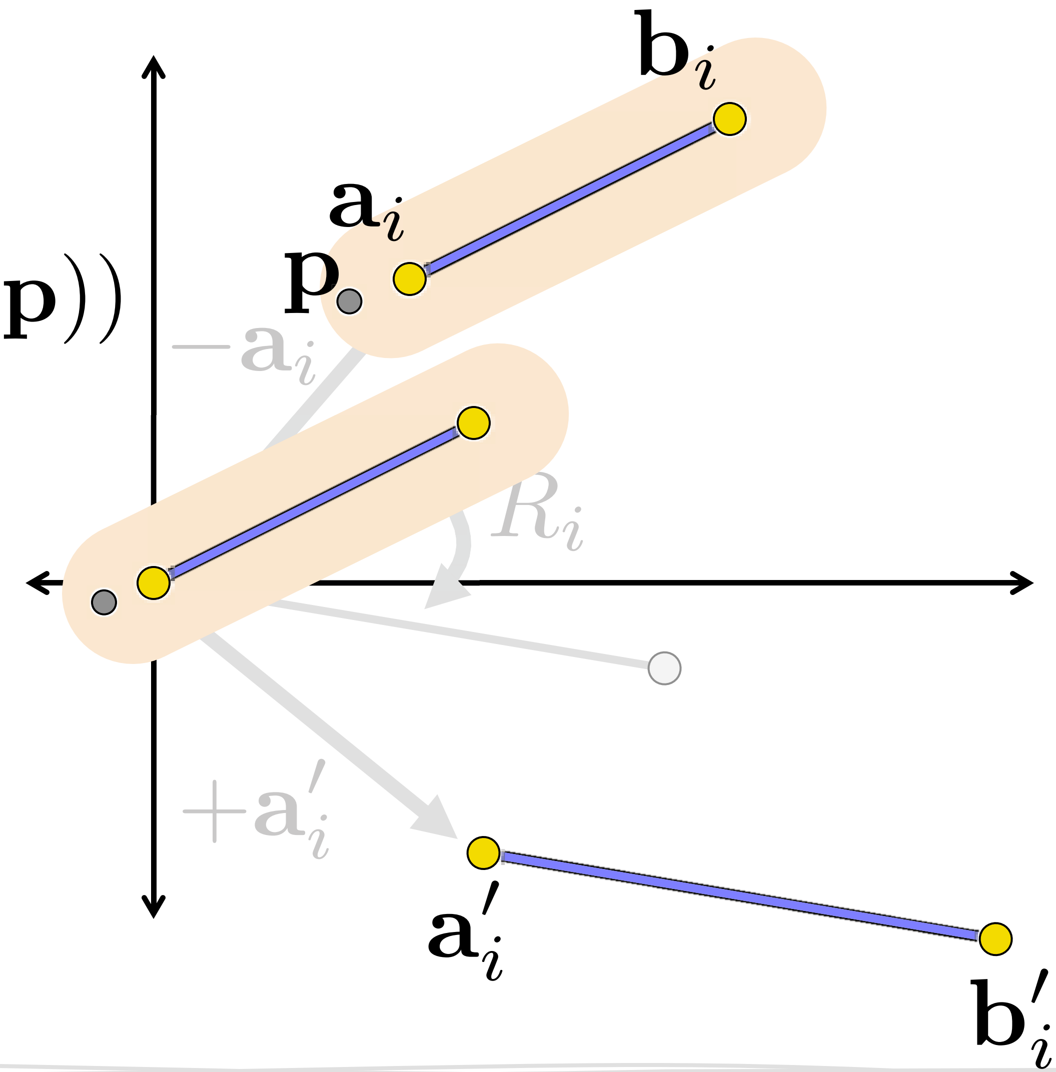
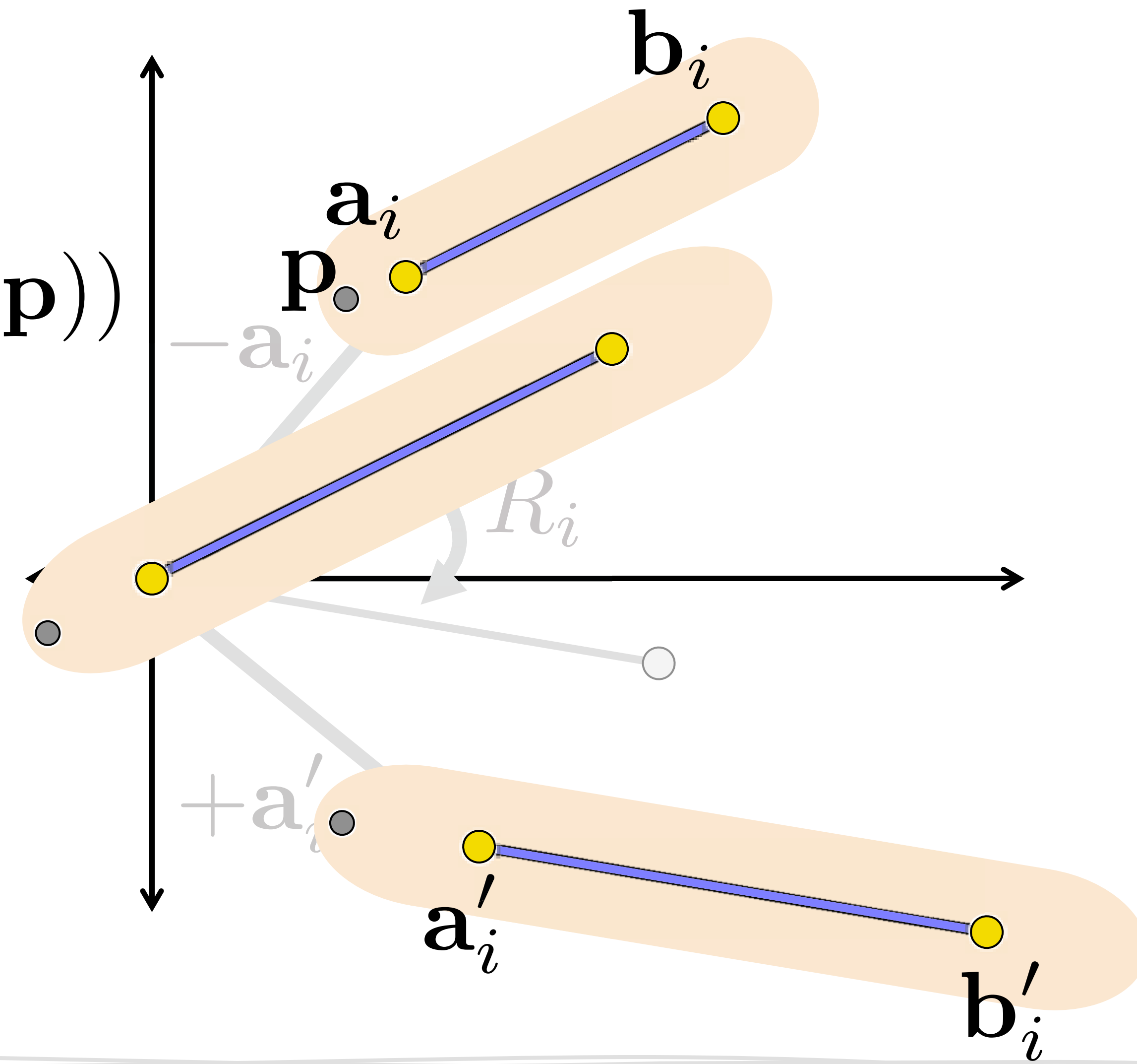


Anisotropic scaling term is constant for each bone weight

$$\mathbf{a}'_i + R_i(S_i(-\mathbf{a}_i + \mathbf{p}))$$



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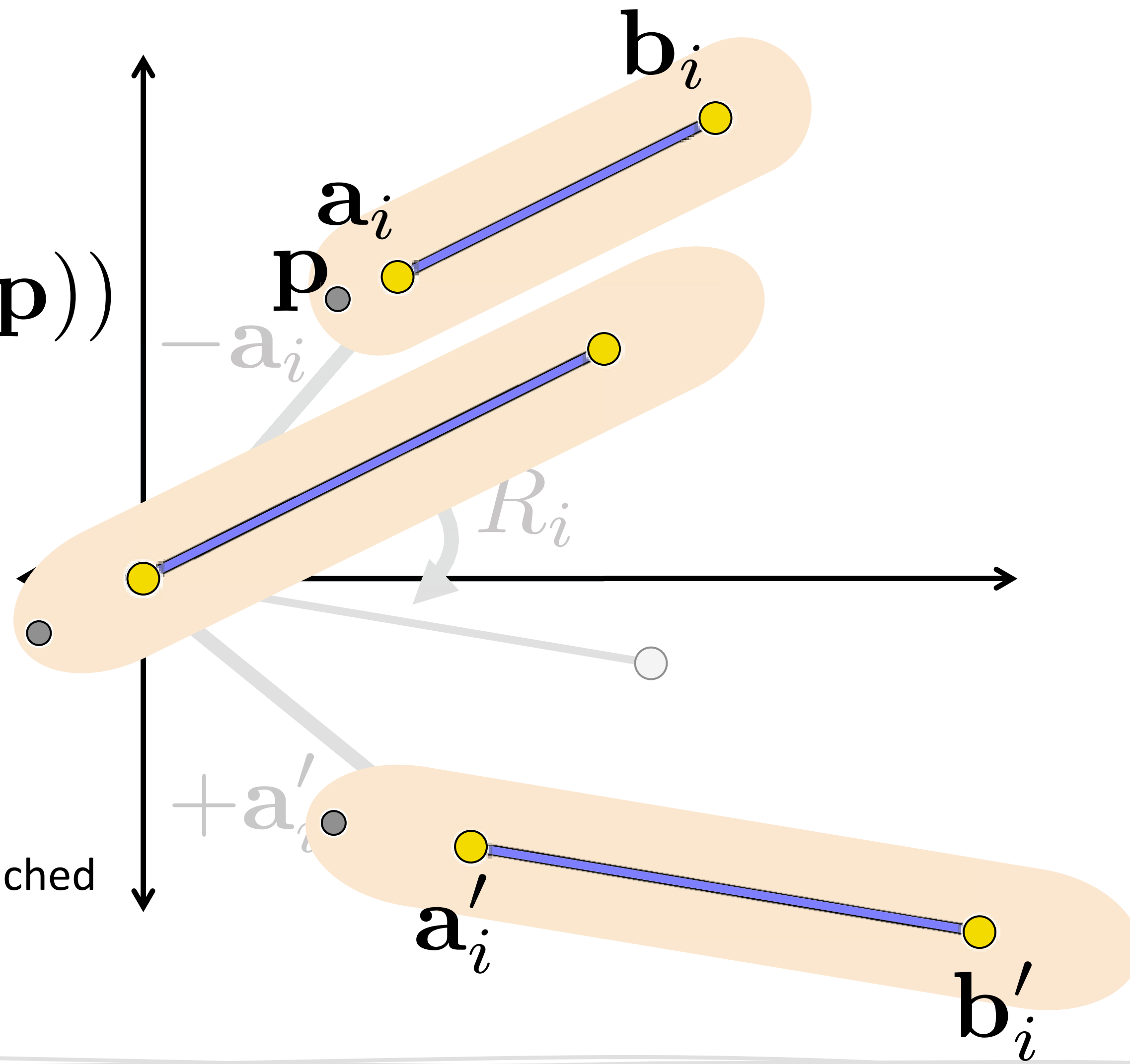
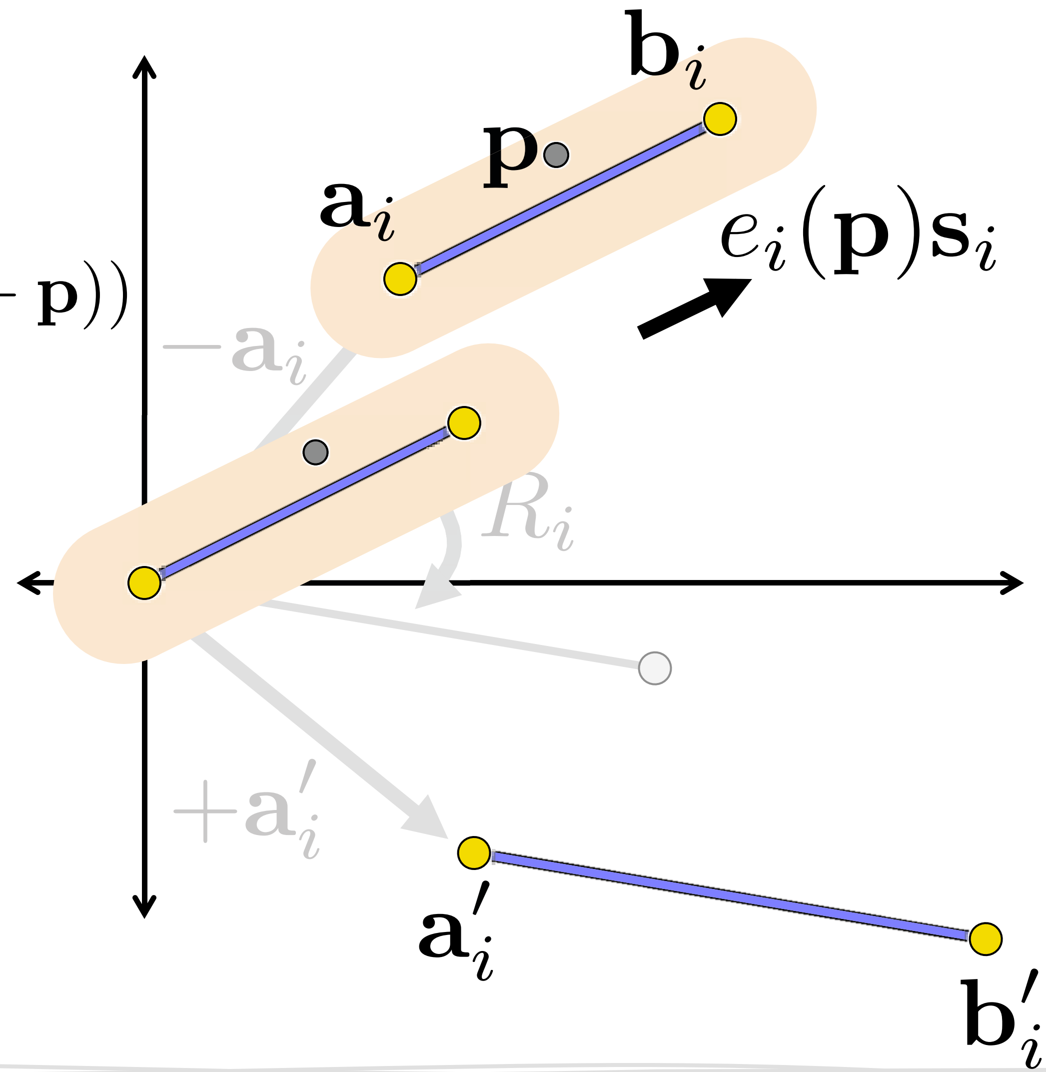


Missing information: where is **p** attached to the bone?

Replace constant scaling term with translation varied by *endpoint weights*

$$\mathbf{a}_i' + R_i\left(e_i(\mathbf{p})\mathbf{s}_i + (-\mathbf{a}_i + \mathbf{p})\right)$$



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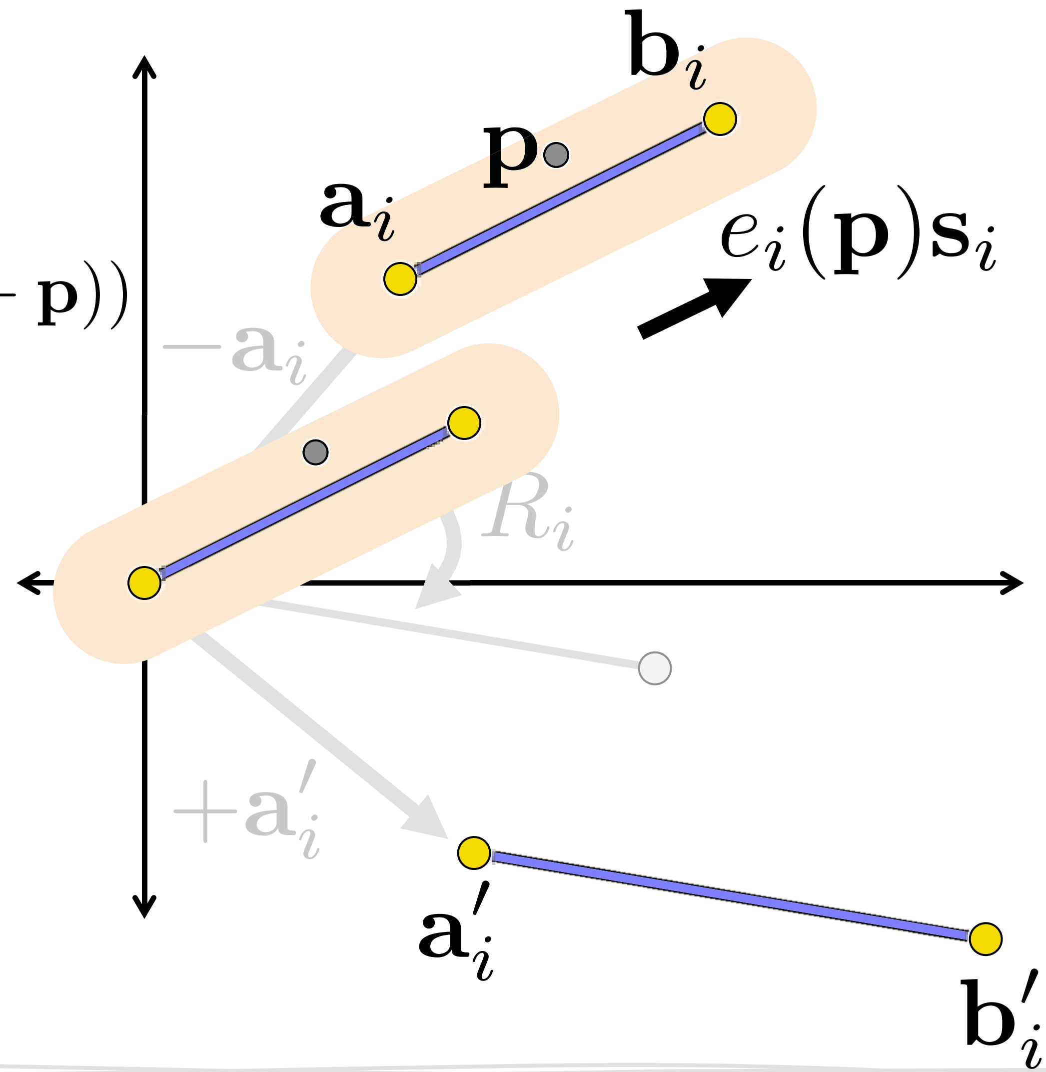
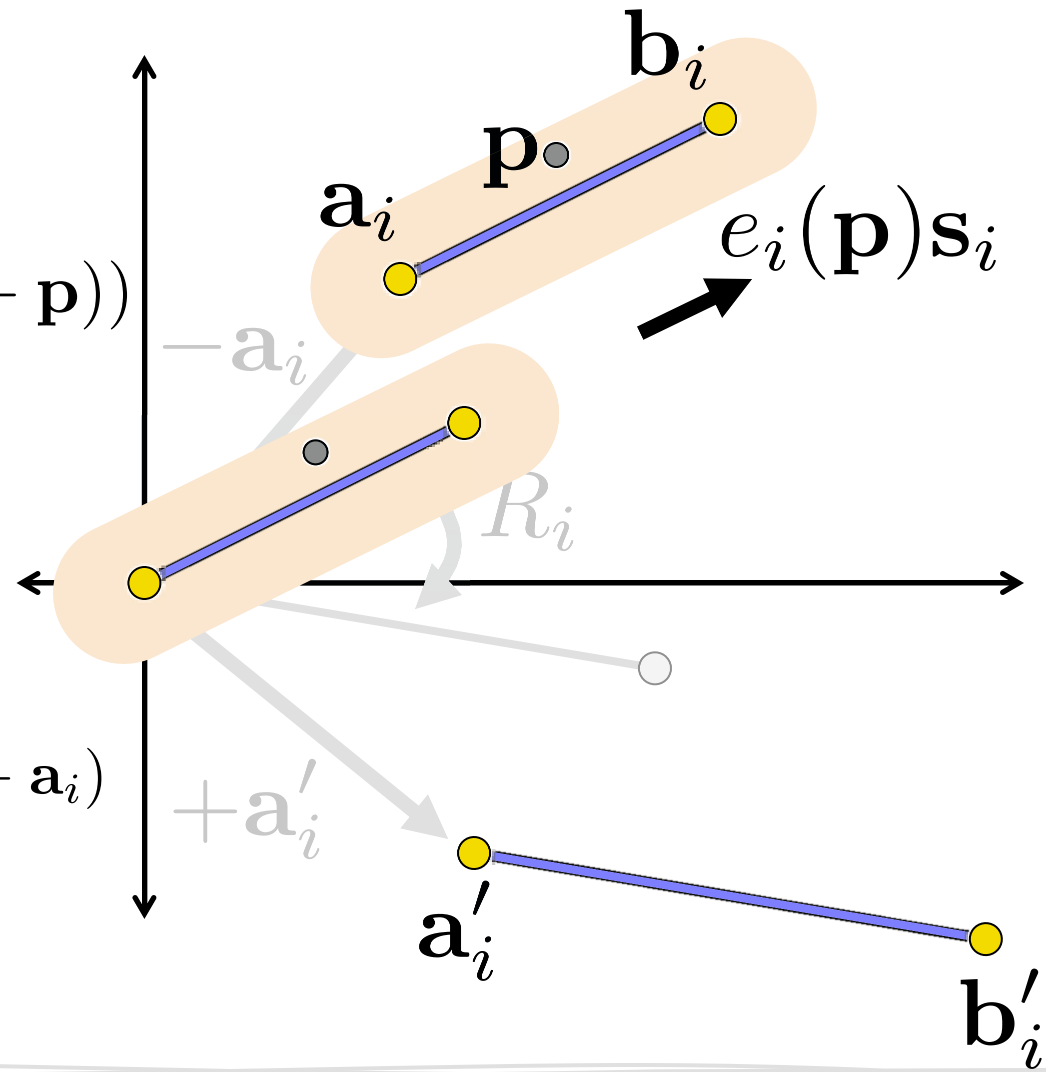


Replace constant scaling term with translation varied by *endpoint weights*

$$\mathbf{a}_i' + R_i\left(e_i(\mathbf{p})\mathbf{s}_i + (-\mathbf{a}_i + \mathbf{p})\right)$$

$$\mathbf{s}_i = \left(\frac{\|\mathbf{b}_i' - \mathbf{a}_i'\|}{\|\mathbf{b}_i - \mathbf{a}_i\|} - 1\right)(\mathbf{b}_i - \mathbf{a}_i)$$



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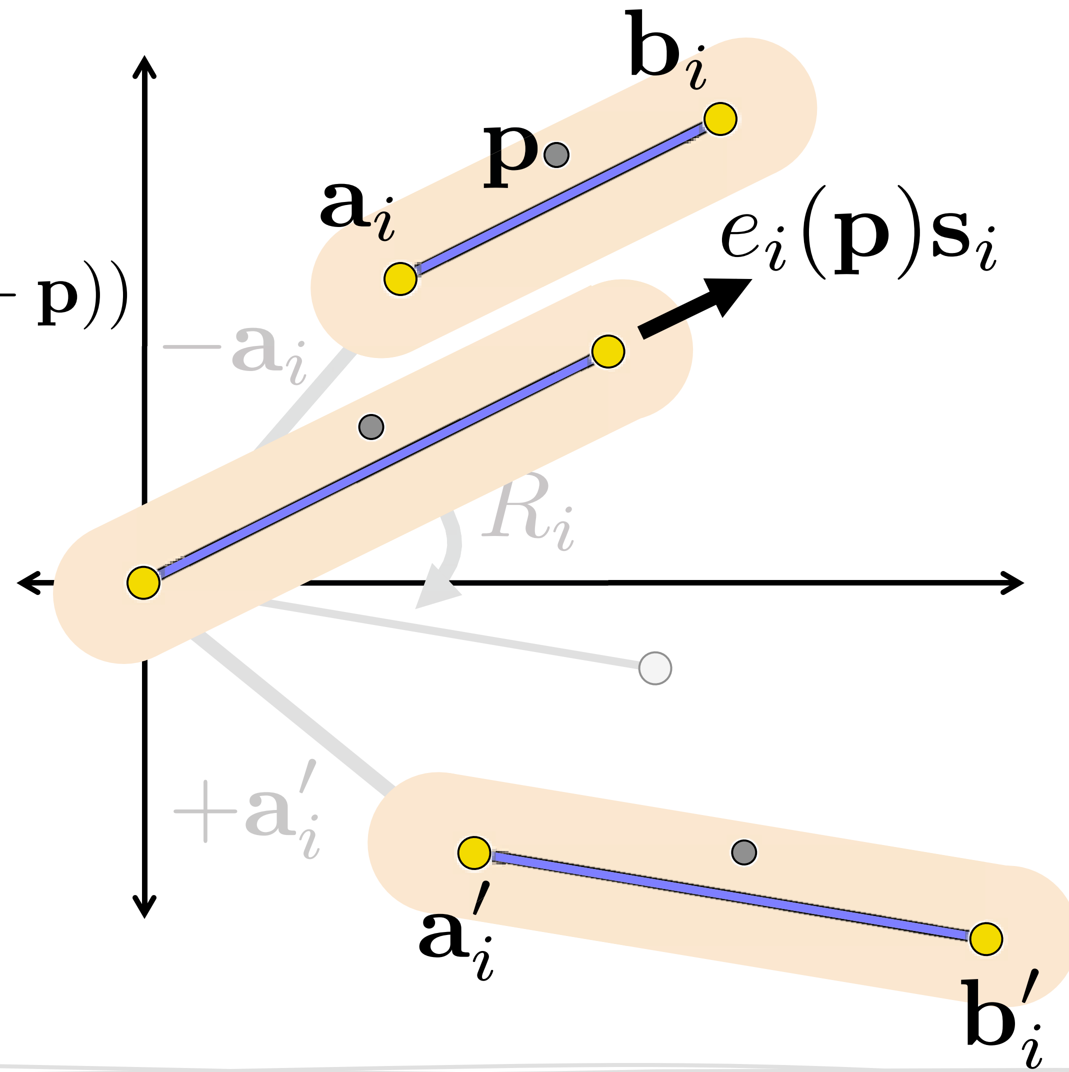
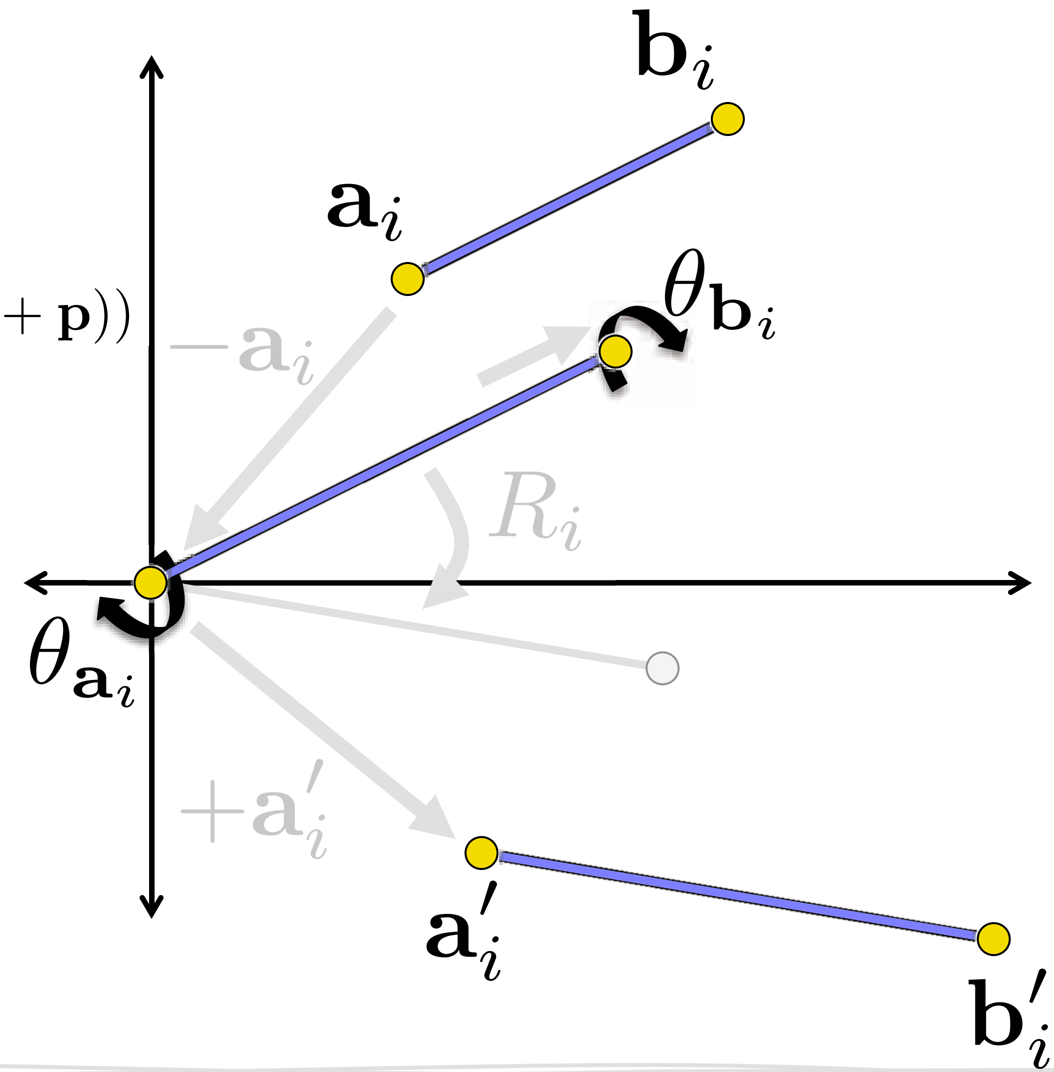


In 3D, use endpoint weights to blend additional twists at either endpoint

$$\mathbf{a}_i' + R_i K_i(e_i(\mathbf{p}))(e_i(\mathbf{p})\,\mathbf{s}_i + (-\mathbf{a}_i + \mathbf{p}))$$



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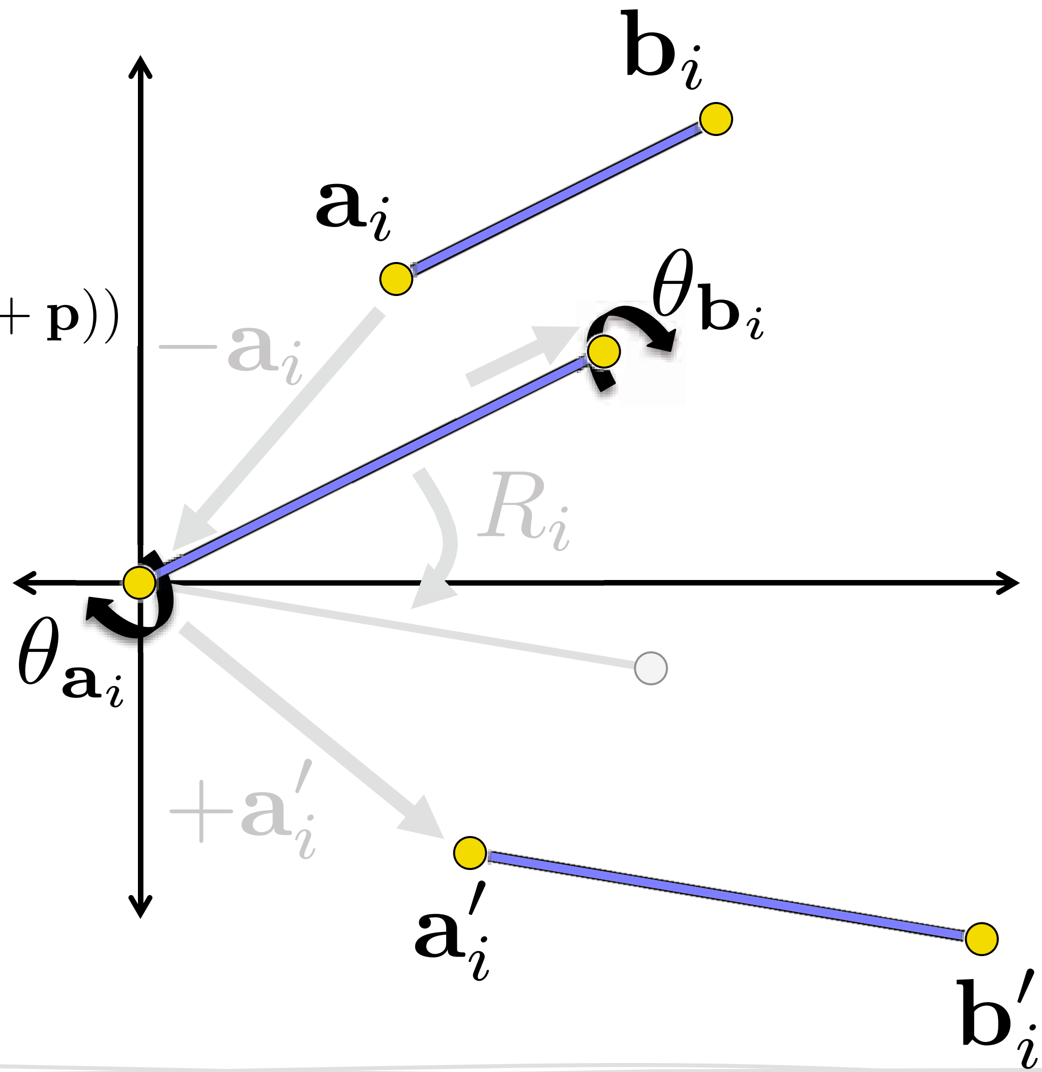
$$\mathbf{a}_i' + R_i K_i(e_i(\mathbf{p}))(e_i(\mathbf{p})\,\mathbf{s}_i + (-\mathbf{a}_i + \mathbf{p}))$$

$$K_i(t) = (1-t)\theta_{\mathbf{a}_i} + t\theta_{\mathbf{b}_i}$$



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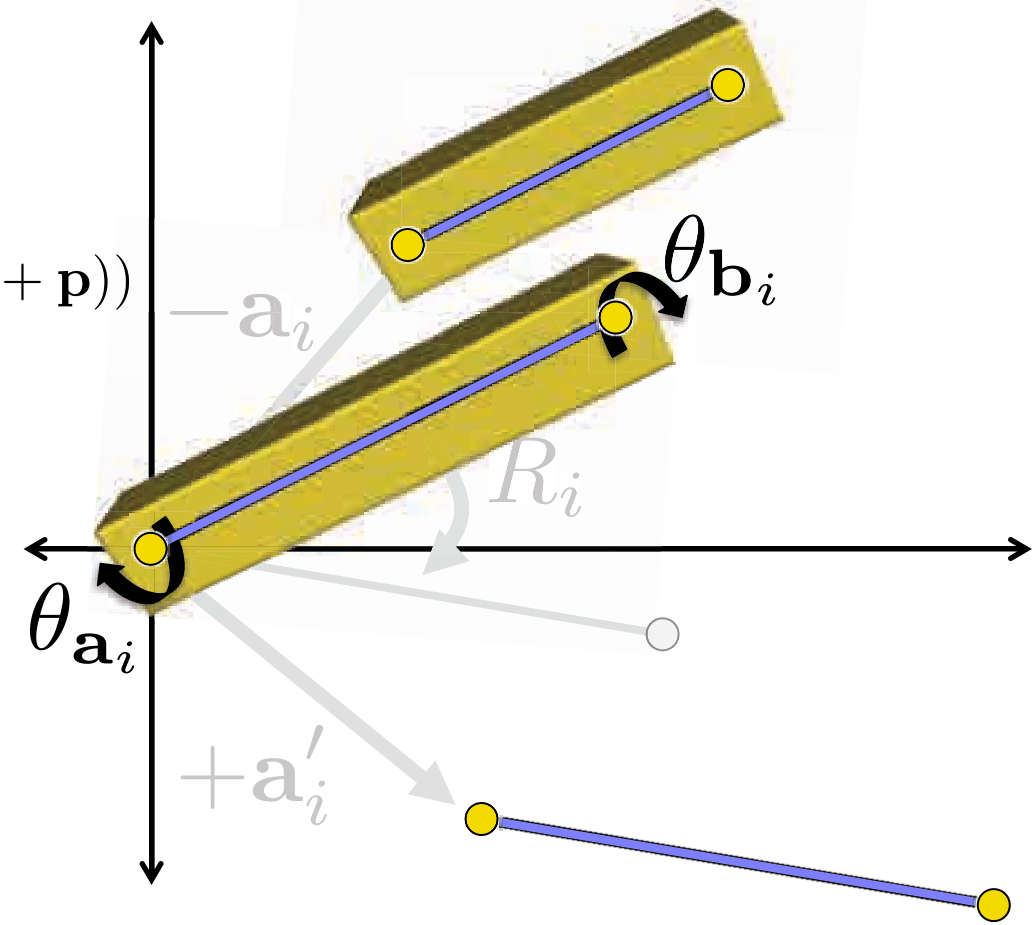

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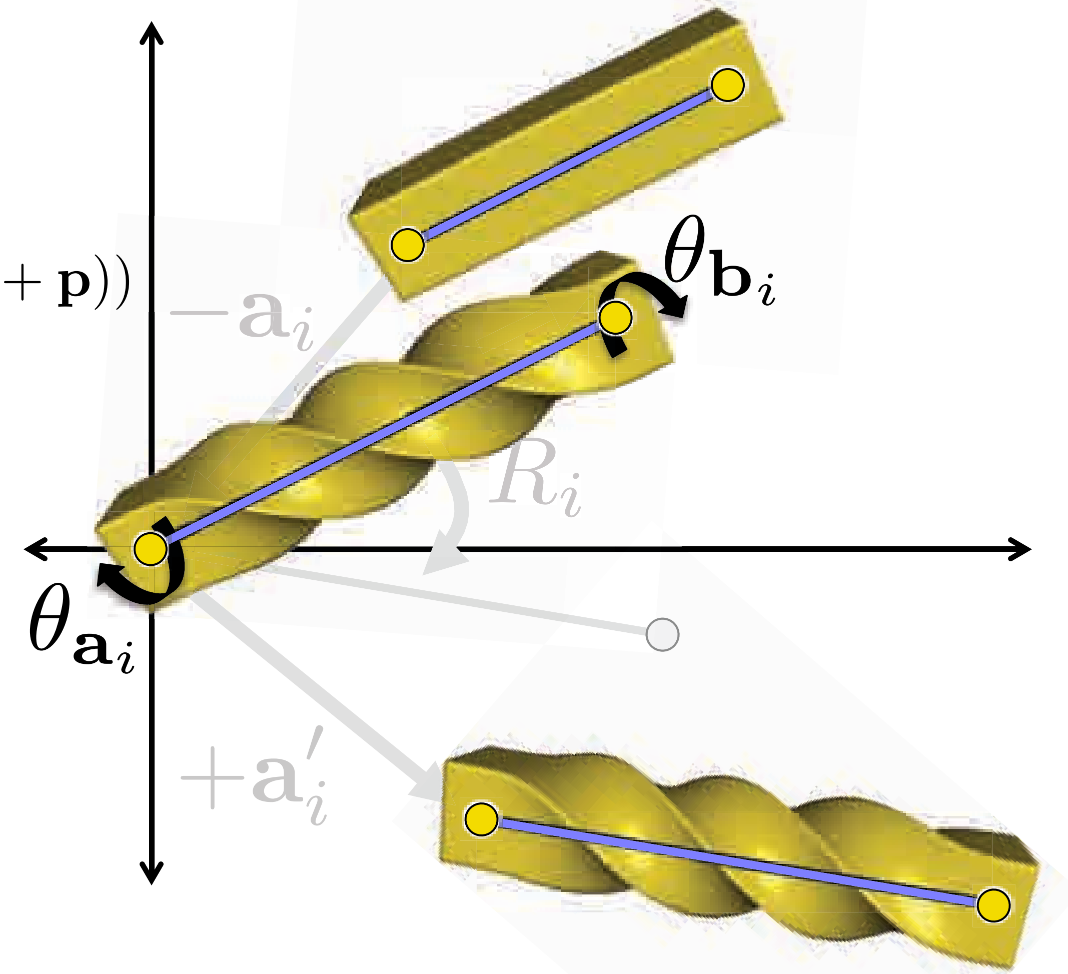


Per-vertex, per-bone transformations are non-constant, but still rigid

$$\mathbf{p}' = \sum_{i \in B} w_i(\mathbf{p})\{\mathbf{a}'_i +$$

$$R_i K_i(e_i(\mathbf{p}))(e_i(\mathbf{p})\,\mathbf{s}_i + (-\mathbf{a}_i + \mathbf{p}))\}$$

Per-vertex, per-bone transformations are non-constant, but still rigid

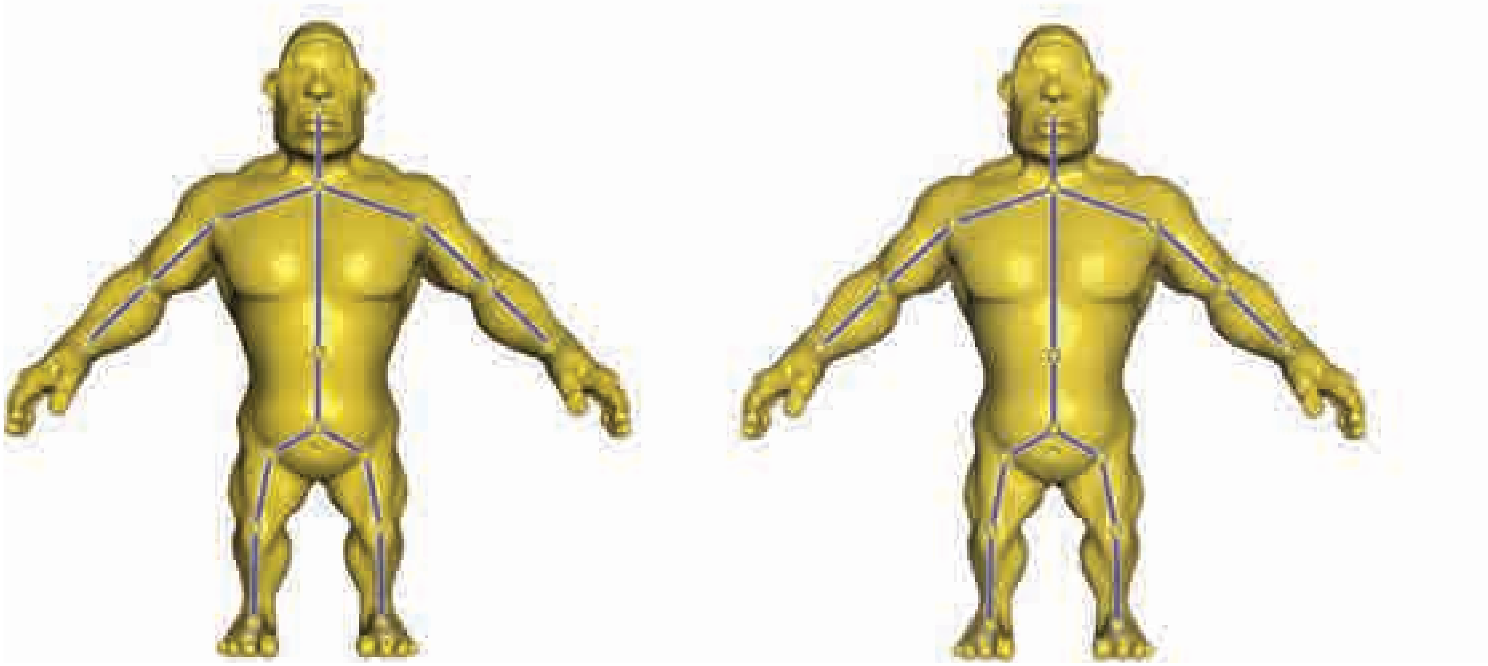
$$\mathbf{p}' = \sum_{i \in B} w_i(\mathbf{p}) \{ \mathcal{T}_i(e_i(\mathbf{p})) + \mathcal{R}_i(e_i(\mathbf{p}))\, \mathbf{p} \}$$

Per-vertex, per-bone rigid transformations may be blended as dual quaternions

$$\mathbf{p}' = \sum_{i \in B} w_i(\mathbf{p}) \{\mathcal{T}_i(e_i(\mathbf{p})) + \mathcal{R}_i(e_i(\mathbf{p}))\,\mathbf{p}\}$$

Instead of blending transformation matrix elements linearly, blend rigid transformations as dual quaternions

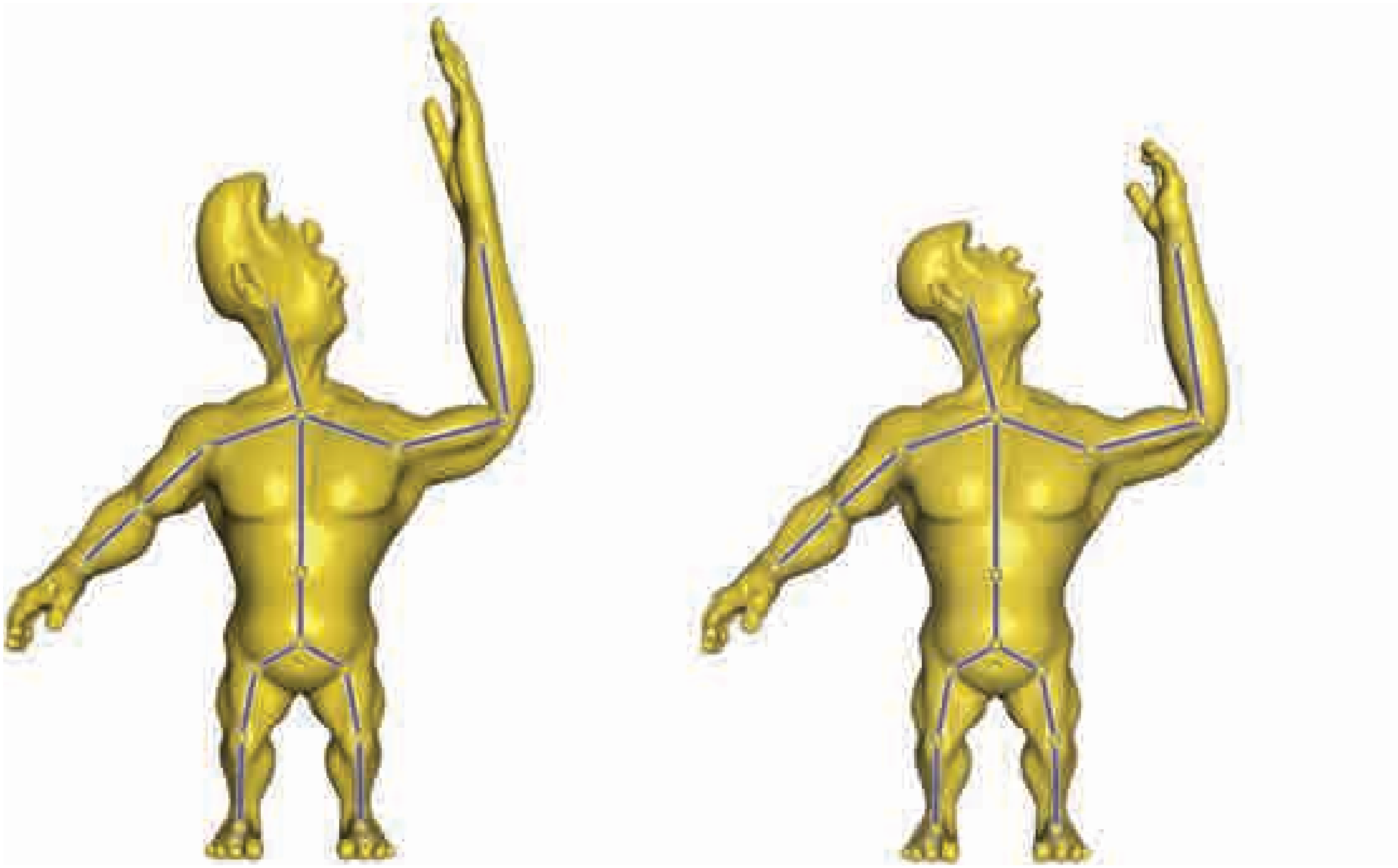
Simple modification leads to powerful expression



LBS

our method extending LBS

Simple modification leads to powerful expression



LBS

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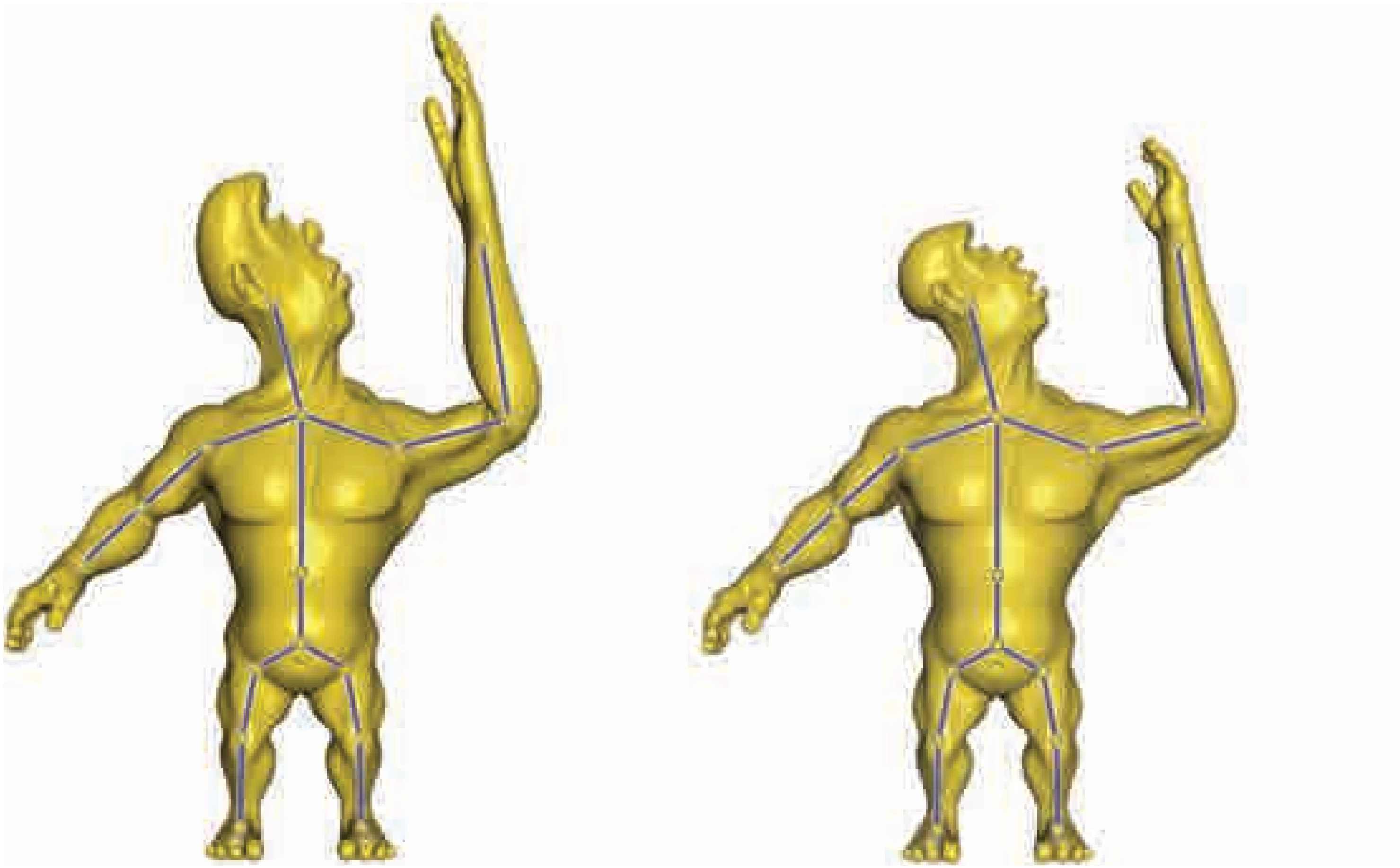
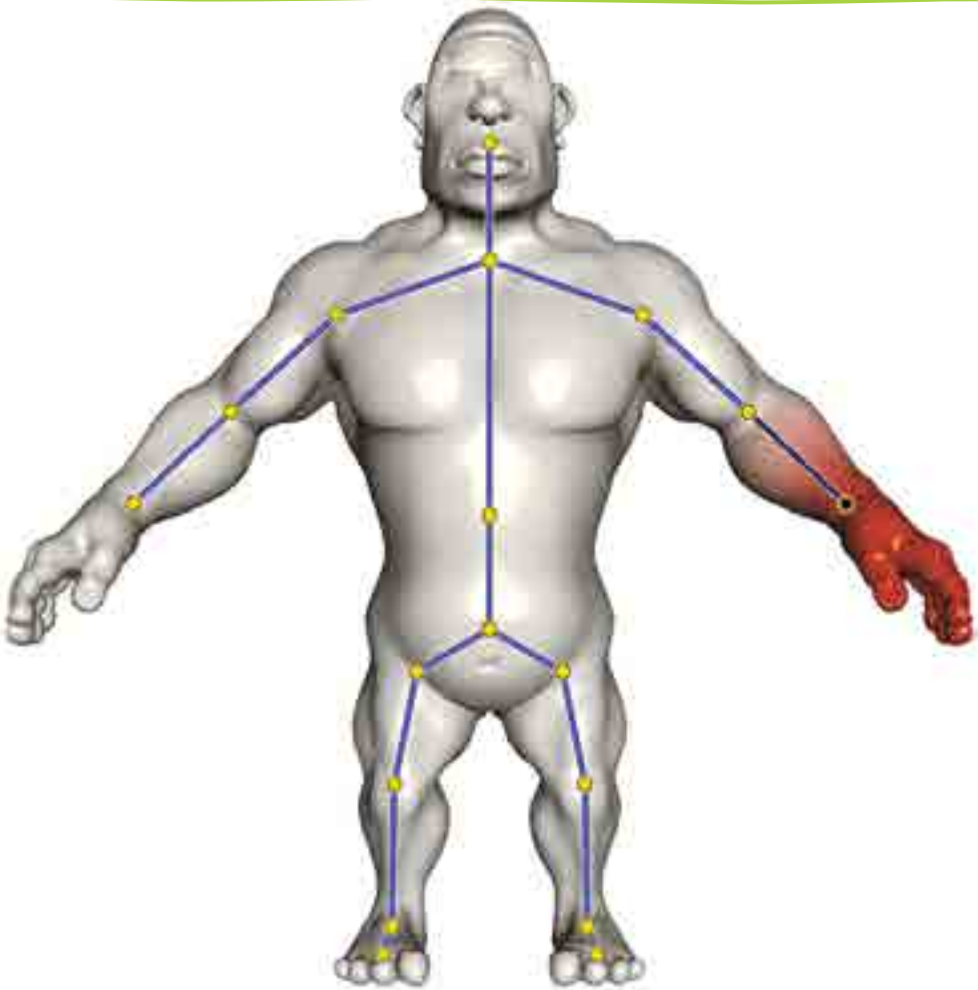
Simple modification leads to powerful expression



DQS

our method extending DQS

Endpoint weights have a clear geometric meaning



Feasibly painted manually, or design automatic methods without relying on examples

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Good endpoint weights maintain desirable properties

- Smooth
- Local, shape-aware
- Bound between 0 and 1
- Interpolate endpoints
- In 2D, vary linearly along bone

Endpoint weights are independent of bone weights and other endpoint weights

$$1 = \sum_{i \in B} e_i(\mathbf{p})$$

$$1 = \sum_{i \in B} w_i(\mathbf{p}) + e_i(\mathbf{p})$$

Endpoint weights may be conveniently defined in terms of point weights at joints

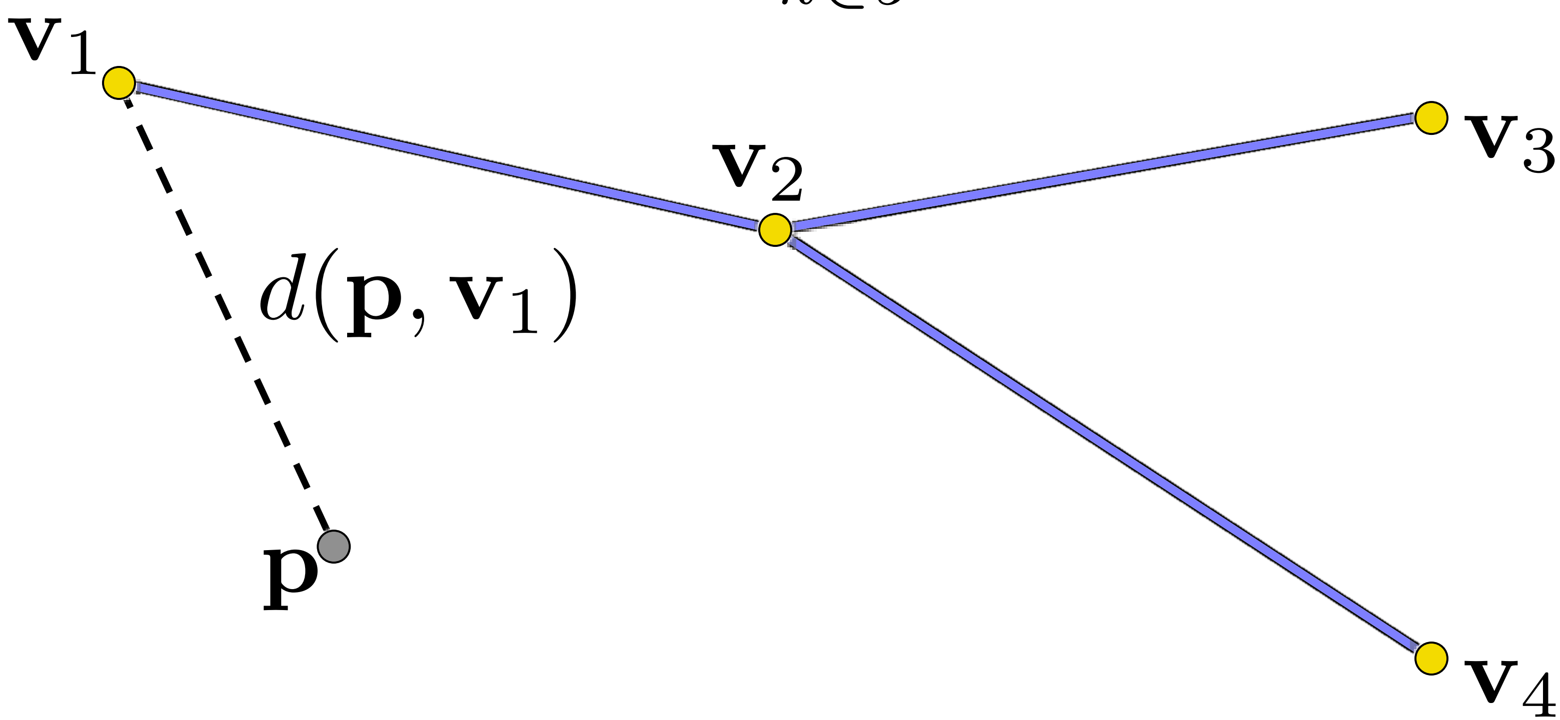
$$e_i = \frac{1}{2}((1 - j_{\mathbf{a}_i}) + j_{\mathbf{b}_i})$$

Point weights defined at $\mathbf{a}_i$

Point weights defined at $\mathbf{b}_i$

Naïve endpoint weights lack many qualities

$$j_{\mathrm{IEDW}_i}(\mathbf{p}) = \frac{d(\mathbf{p}, \mathbf{v}_i)^{-\alpha}}{\sum_{k \in J} d(\mathbf{p}, \mathbf{v}_k)^{-\alpha}}$$



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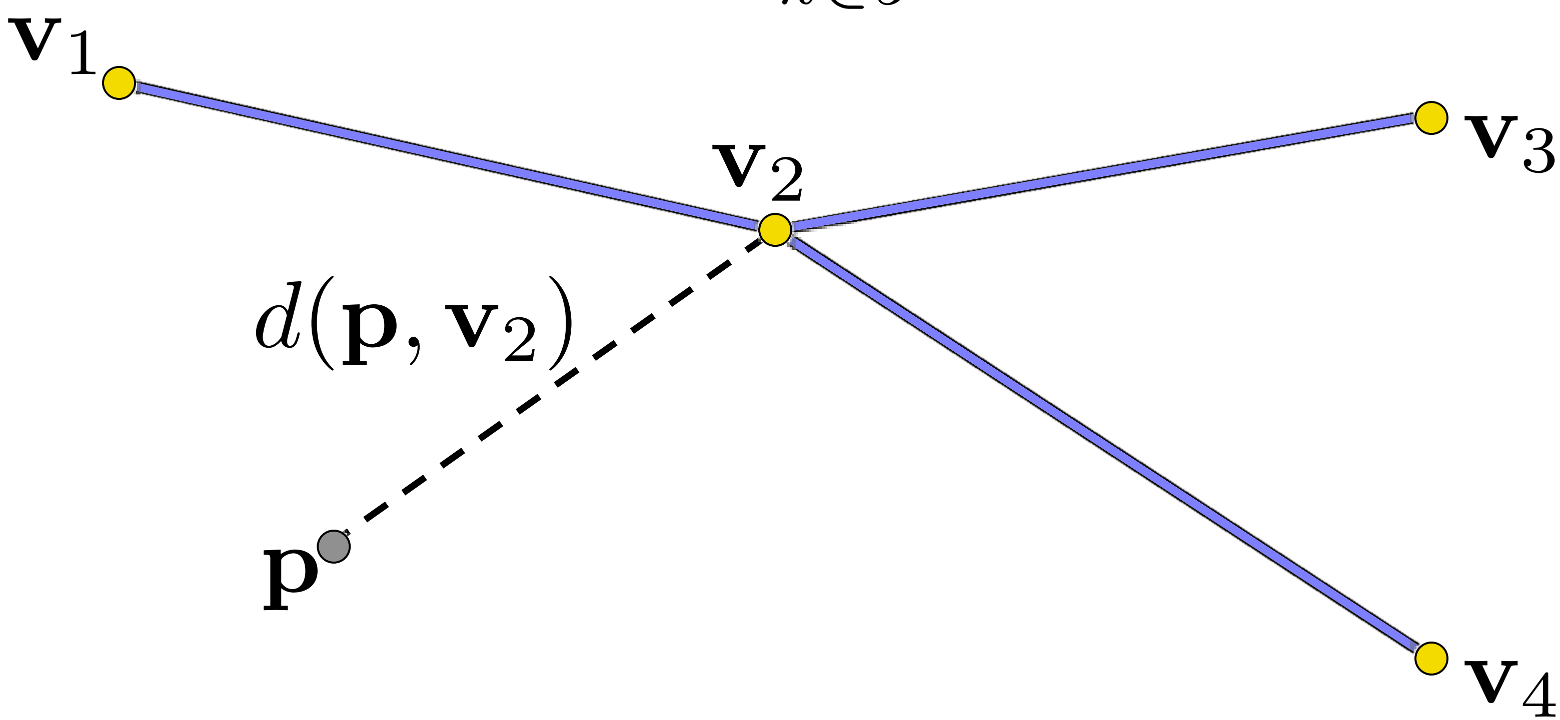

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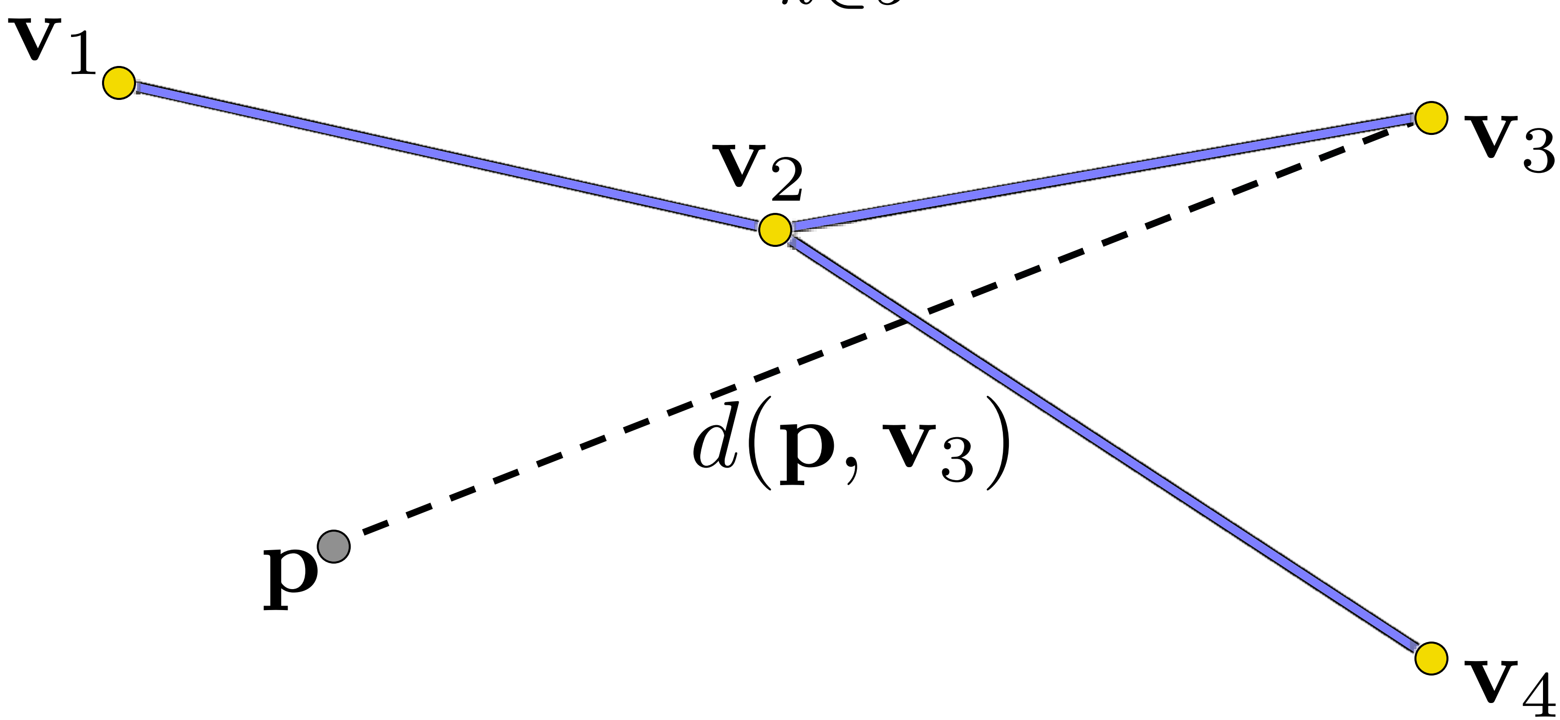

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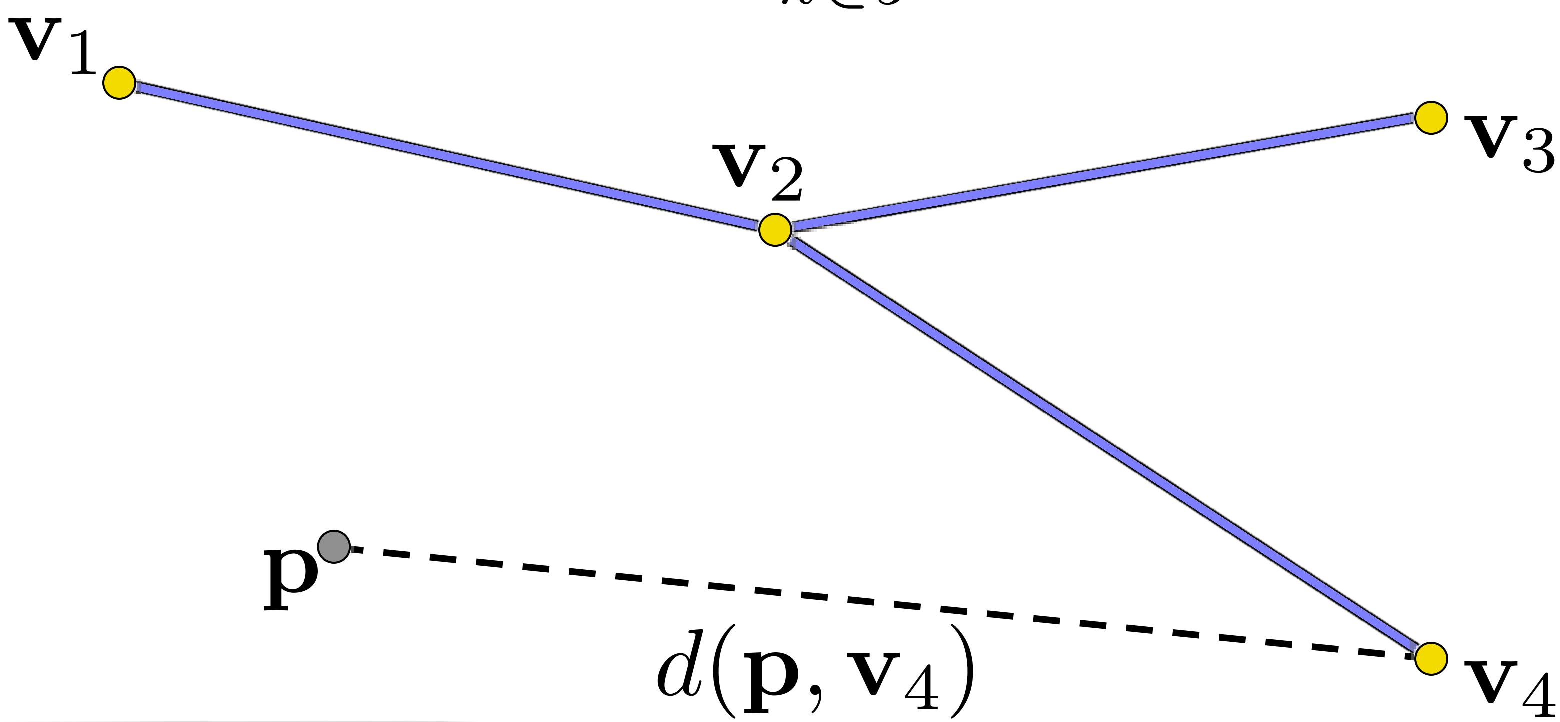
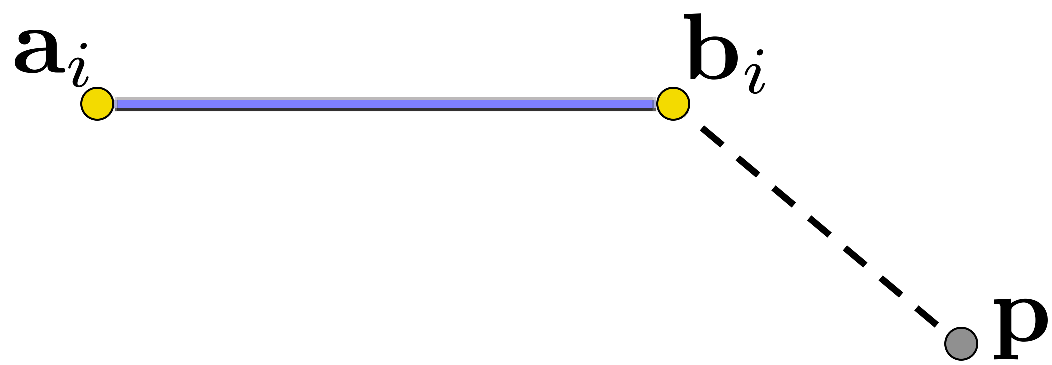


Naïve endpoint weights lack many qualities

$$e_{\text{proj}_i}(\mathbf{p}) = \frac{\|\text{proj}_i(\mathbf{p}) - \mathbf{a}_i\|}{\|\mathbf{b}_i - \mathbf{a}_i\|}$$



$$e_{\text{proj}_i}(\mathbf{p}) = 1$$

Naïve endpoint weights lack many qualities

$$e_{\text{proj}_i}(\mathbf{p}) = \frac{\|\text{proj}_i(\mathbf{p}) - \mathbf{a}_i\|}{\|\mathbf{b}_i - \mathbf{a}_i\|}$$

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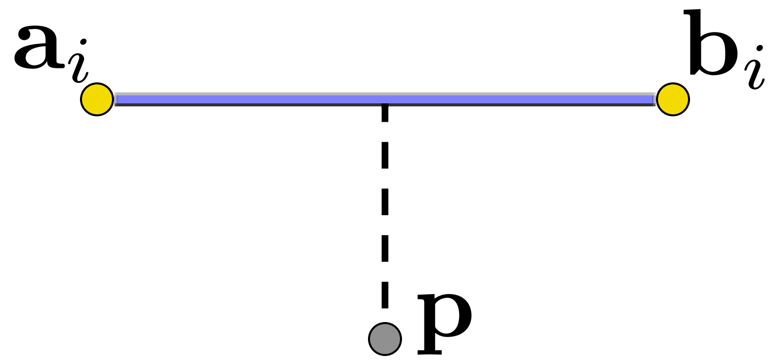
$$e_{\text{proj}_i}(\mathbf{p}) = \frac{\|\text{proj}_i(\mathbf{p}) - \mathbf{a}_i\|}{\|\mathbf{b}_i - \mathbf{a}_i\|}$$



$$e_{\text{proj}_i}(\mathbf{p}) = 0.5$$

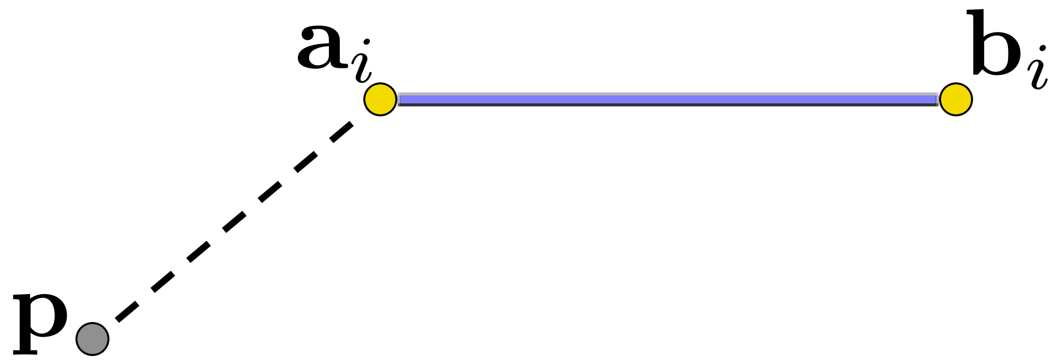
Naïve endpoint weights lack many qualities

$$e_{\text{proj}_i}(\mathbf{p}) = \frac{\|\text{proj}_i(\mathbf{p}) - \mathbf{a}_i\|}{\|\mathbf{b}_i - \mathbf{a}_i\|}$$

$$e_{\text{proj}_i}(\mathbf{p}) = 0$$

Naïve endpoint weights lack many qualities

$$e_{\mathrm{proj}_i}(\mathbf{p}) = \frac{\|\mathrm{proj}_i(\mathbf{p}) - \mathbf{a}_i\|}{\|\mathbf{b}_i - \mathbf{a}_i\|}$$



$$e_{\mathrm{proj}_i}(\mathbf{p}) = 0$$

Recent automatic methods produce high quality endpoint weights

- [Weber et al. 2007], [Wang et al. 2007]
  - rely on extra input
- Bone heat [Baran and Popović 2007]
  - requires visibility computation
- BBW [Jacobson et al. 2011]
  - requires meshing volume and quadratic programming

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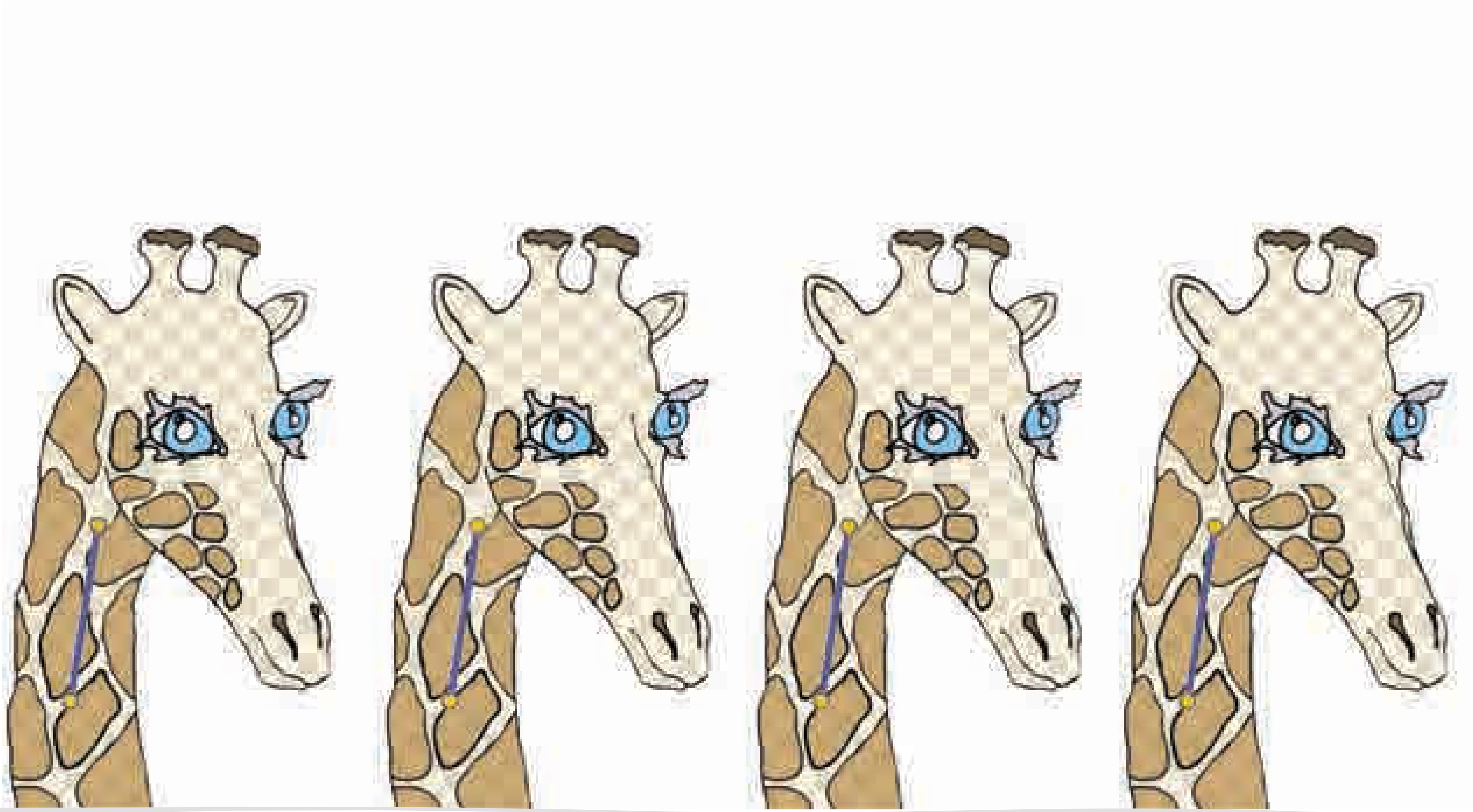
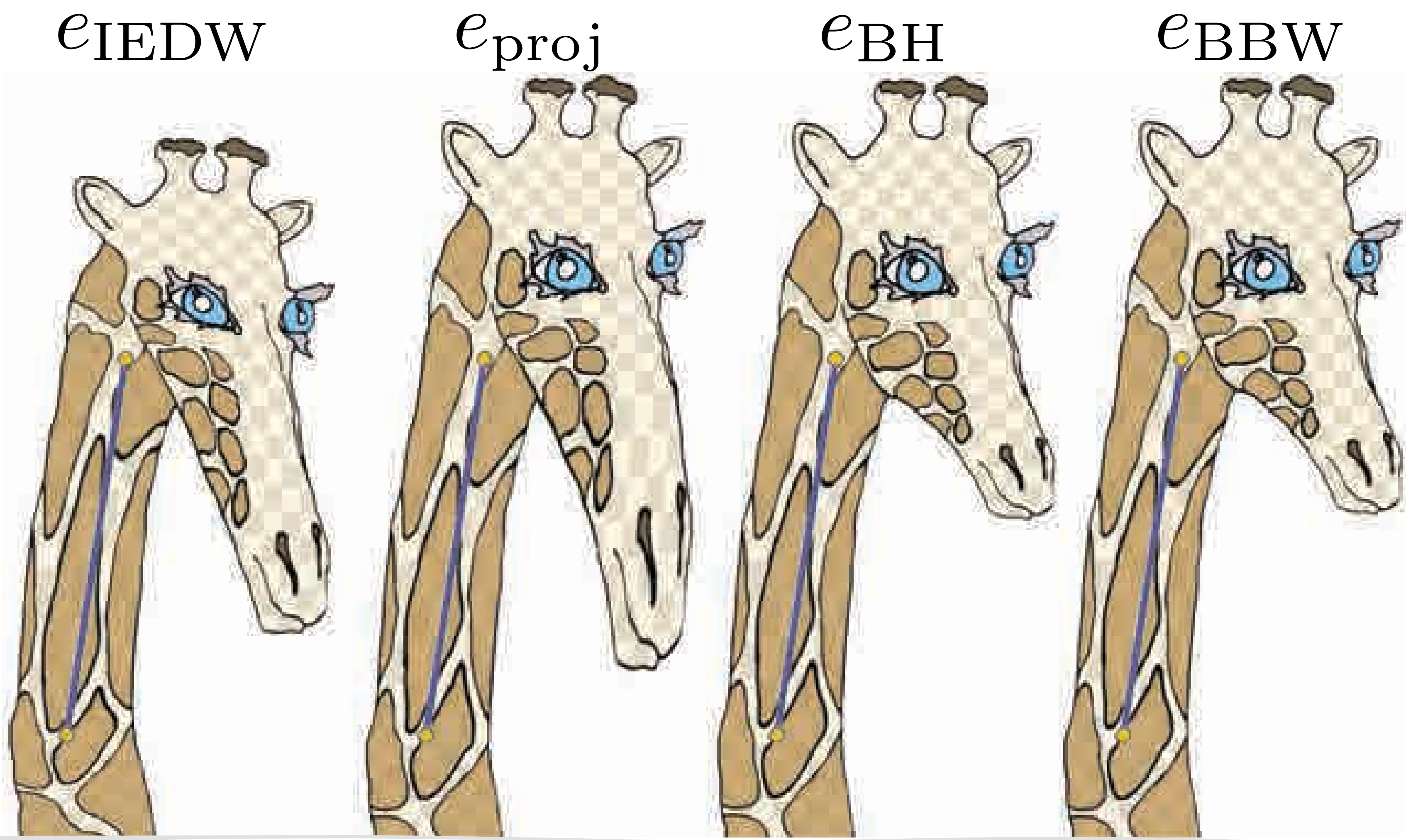
Advanced methods pay off in final quality

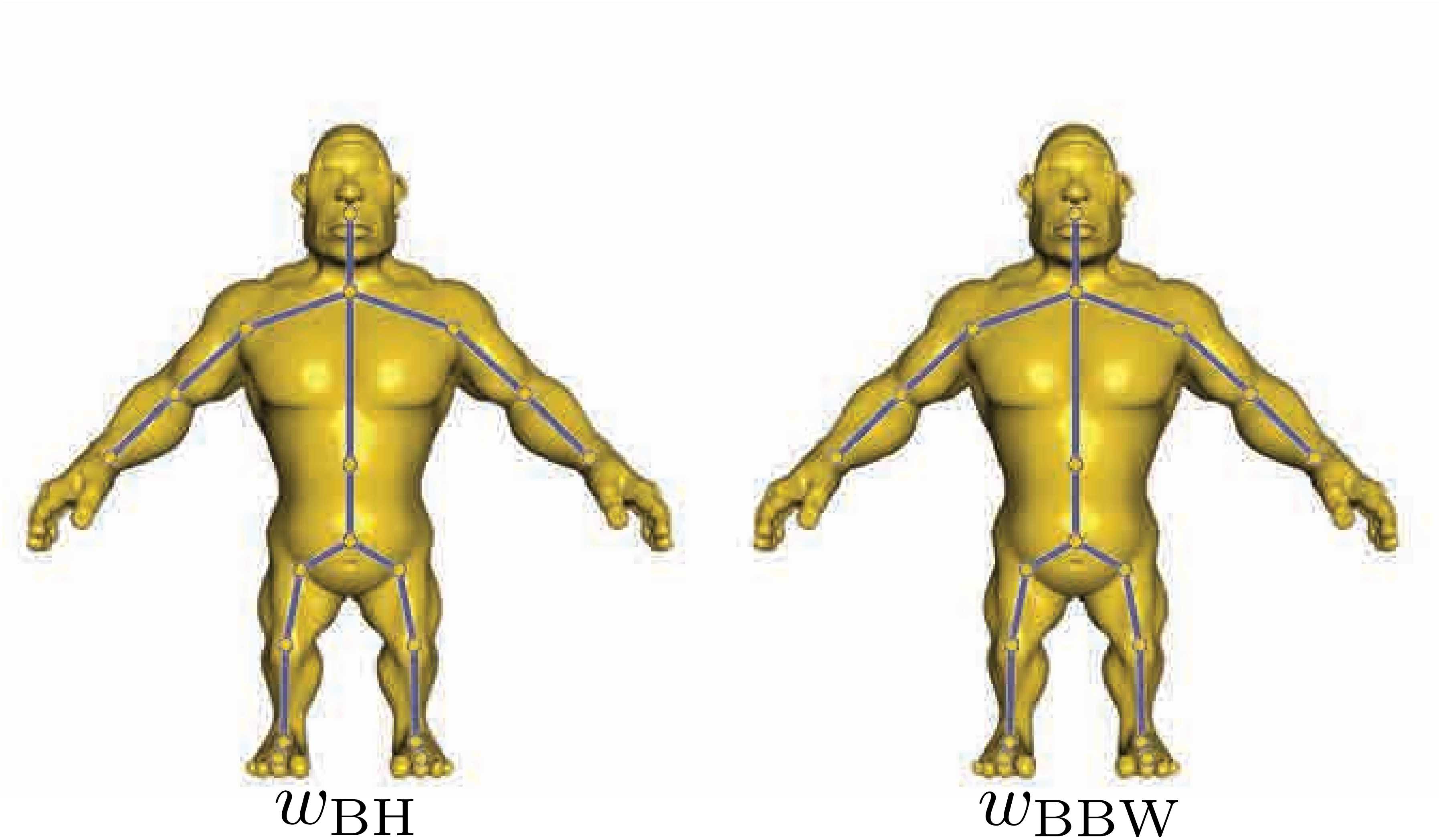
e_{IEDW} e_{proj} e_{BH} e_{BBW}



Advanced methods pay off in final quality



Good endpoint weights cannot save insufficient bone weights



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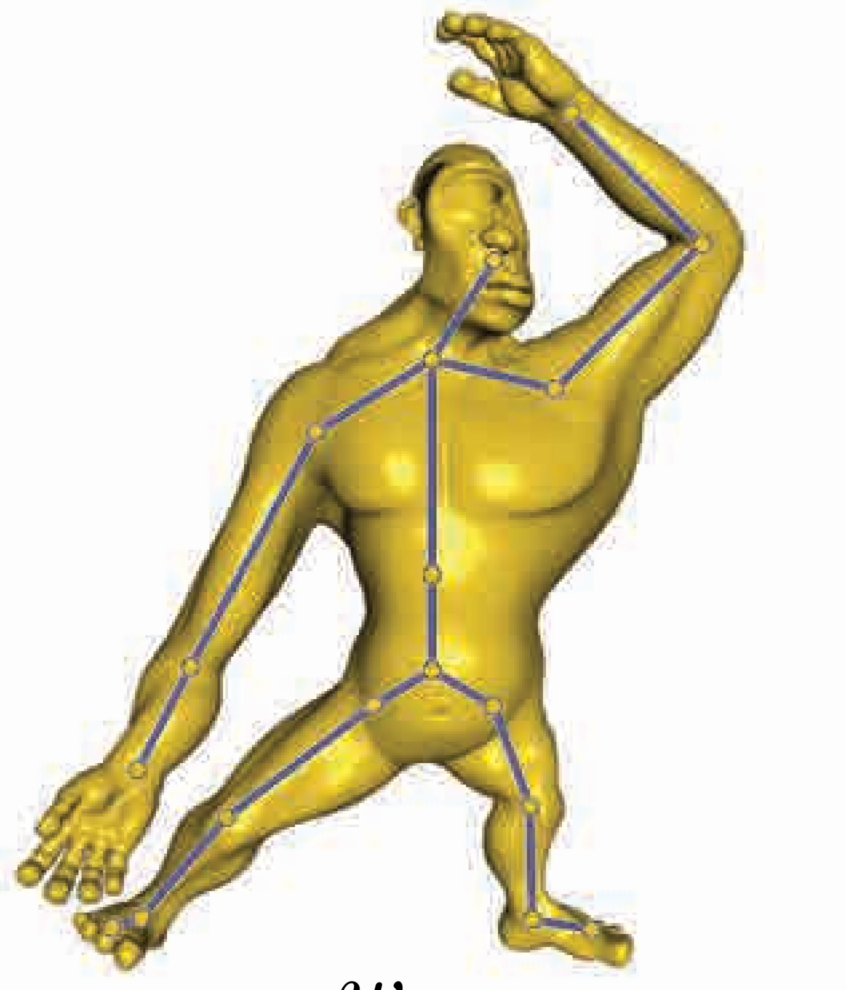

w_{BH}

w_{BBW}

Like LBS, runtime implementation is simple and efficient

- Once per session: load additional endpoint weights into memory
- Each update: pass bone transformations and extra twist parameters
- LBS or DQS form of:

$$\mathbf{p}' = \sum_{i \in B} w_i(\mathbf{p})\{\mathbf{a}_i' + R_i K_i(e_i(\mathbf{p}))(e_i(\mathbf{p})\,\mathbf{s}_i + (-\mathbf{a}_i + \mathbf{p}))\}$$

Stretching facilitates exaggeration, a basic principle of life-like animation

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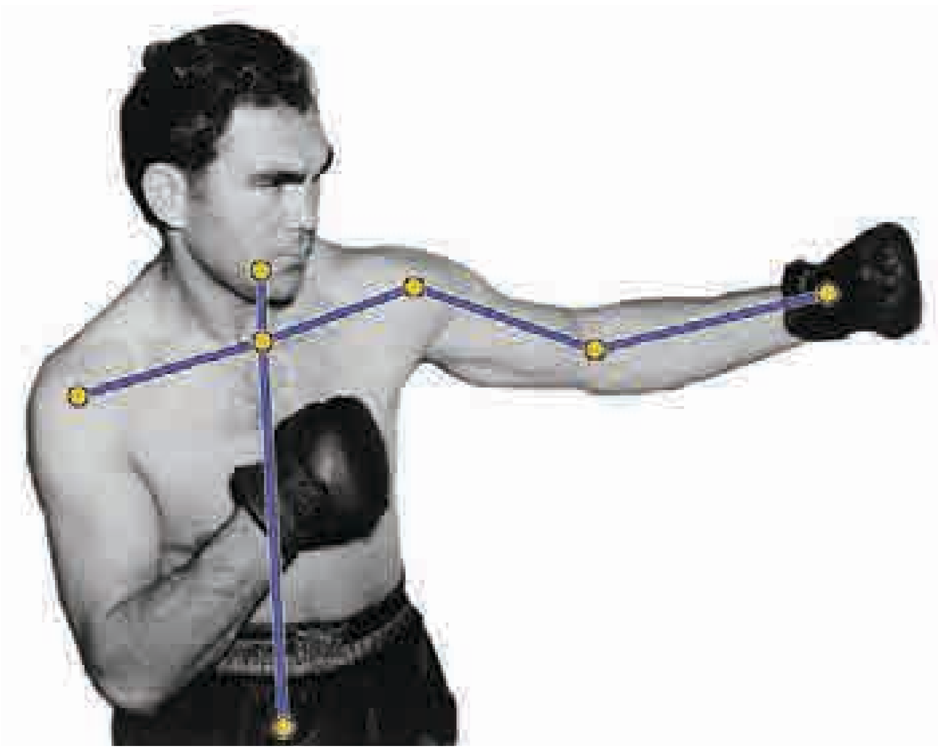
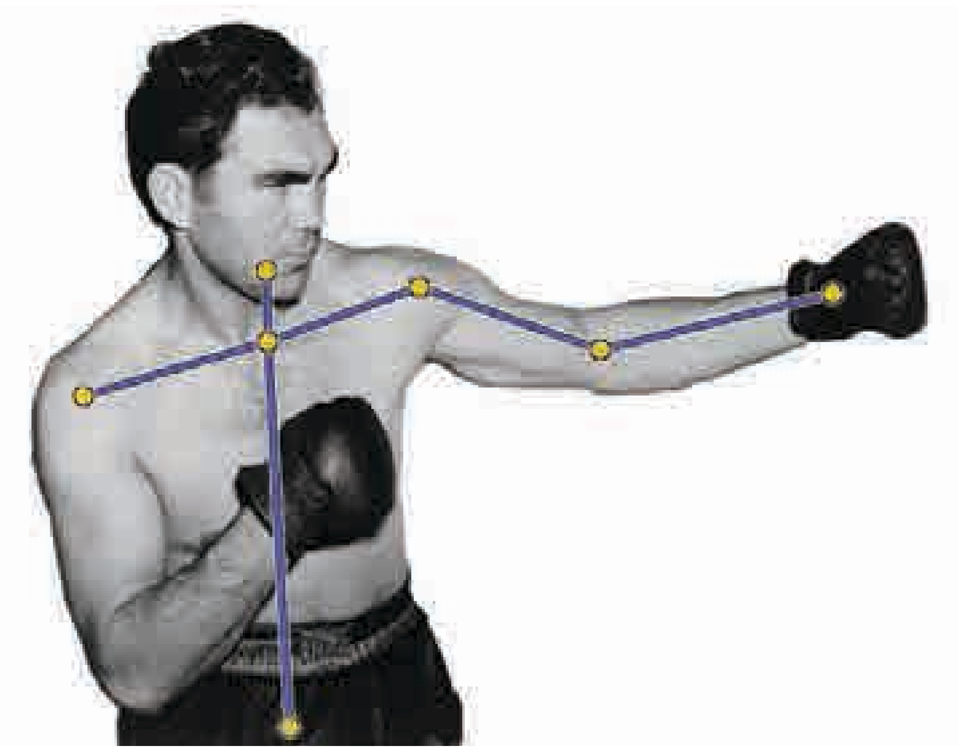
In 2D, stretching manipulates foreshortening



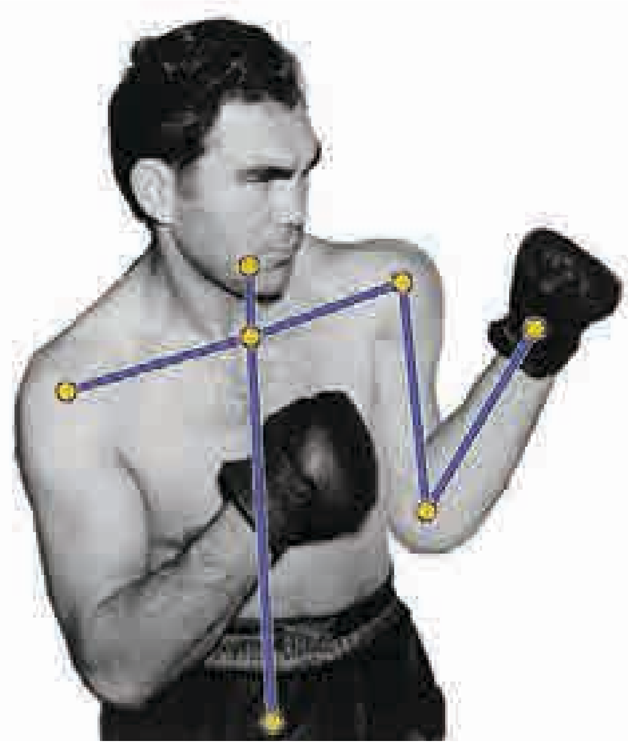
LBS without allow bones to change length



STBS with *stretchable* bones

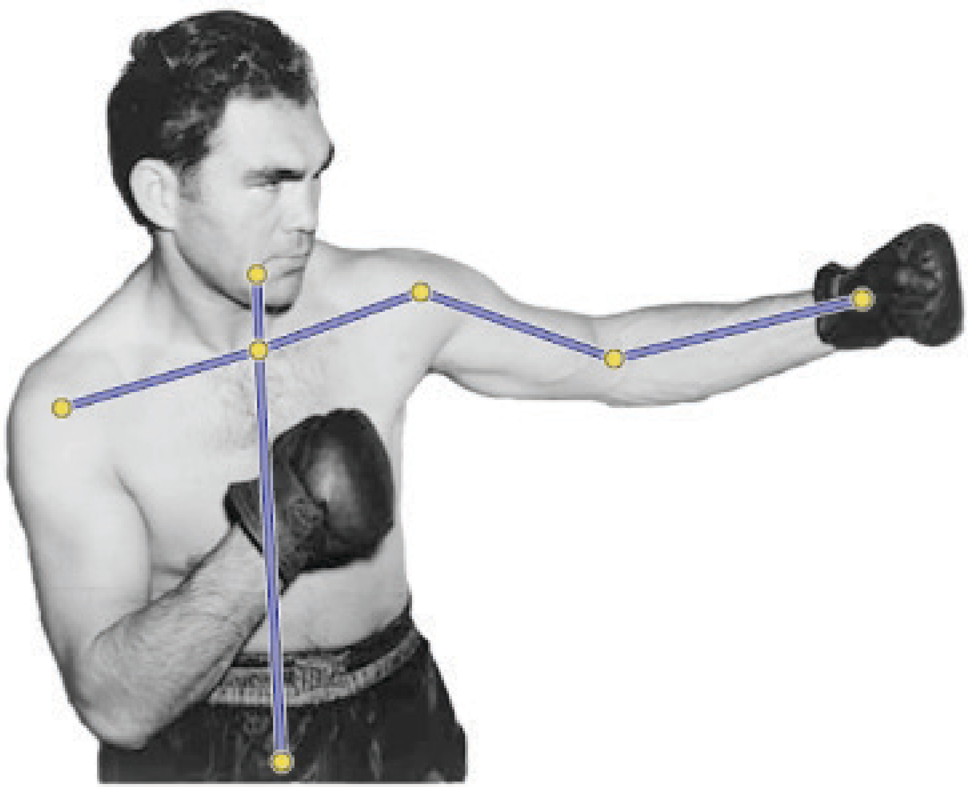
In 2D, stretching manipulates foreshortening

LBS without allow bones to change length

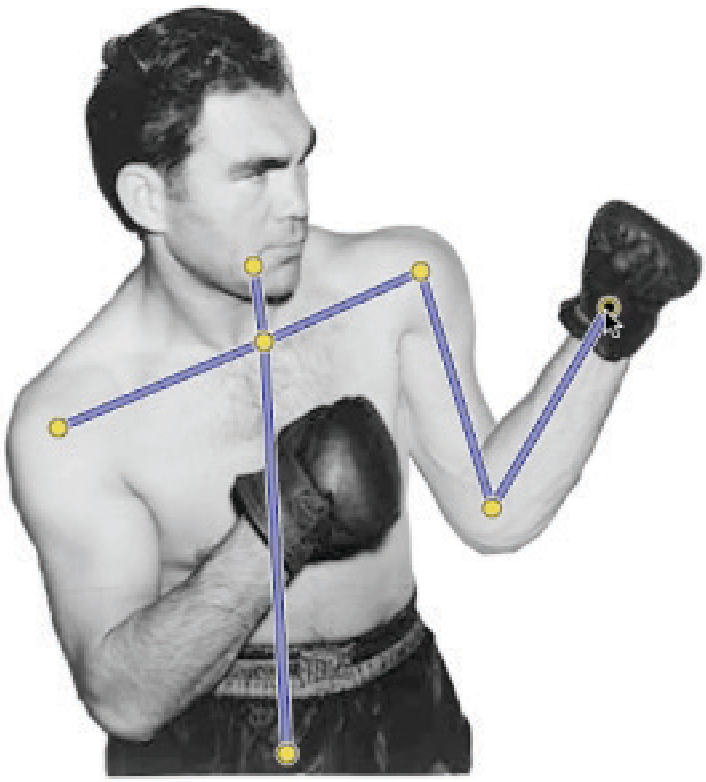


STBS with *stretchable* bones

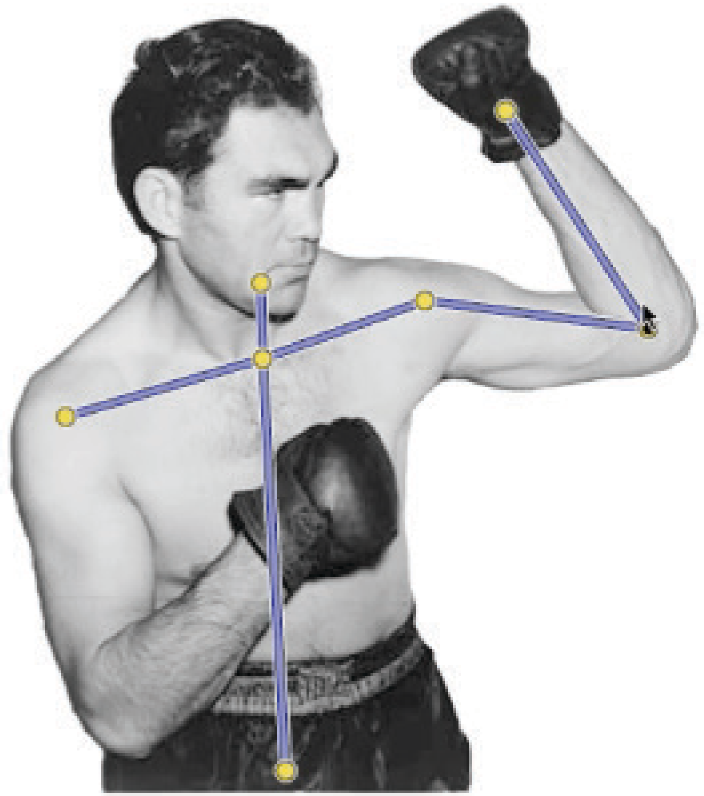
Dragable joints simplify user interface



Dragable joints simplify user interface



Dragable joints simplify user interface



Stretchable, Twistable Bones Skinning expands space of real-time deformations

- Real-time:
  - simple and embarrassingly parallel
- Extra endpoint weights have geometric meaning
  - May be painted manually
  - Or use recent automatic methods
- Existing rigs (skeletons and bone weights) are unmodified

Future work

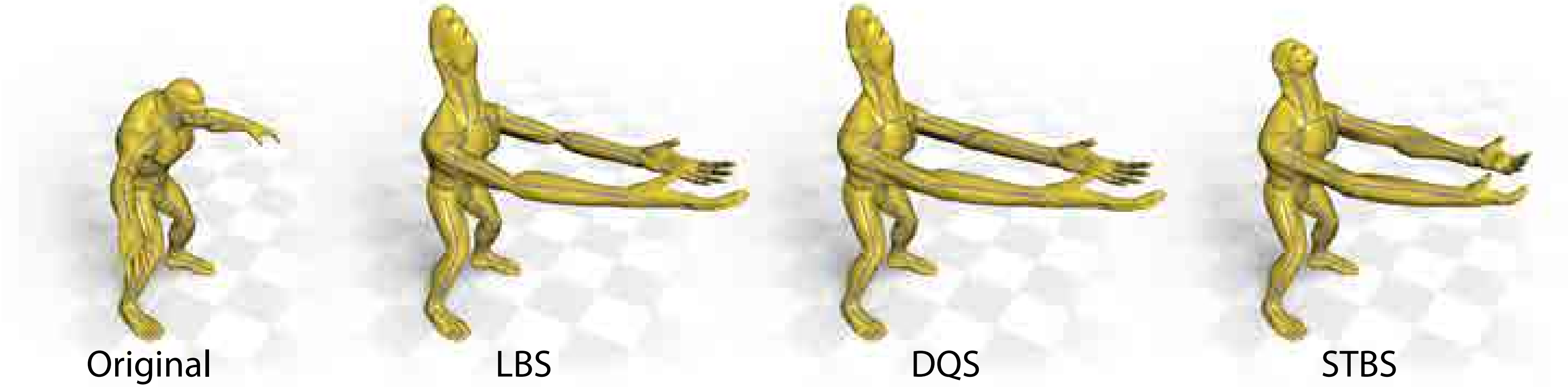
- Treat stretching and twisting separately
- Inverse Kinematics and procedural animation
- Fit existing mesh animations
- Explore other roles for endpoint weights
    - e.g. Muscle bulging via simple filters

Acknowledgements

We are grateful to Ofir Weber and Ilya Baran for illuminating discussions. We thank the United States Library of Congress for its collection of public domain photographs including the half-portrait of Max Schmeling. Special thanks to Felix Hornung for beautifying the teaser image.

Stretchable and Twistable Bones for Skeletal Shape Deformation

http://igl.ethz.ch/projects/skinning/stretchable-twistable-bones/



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August 13, 2012

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