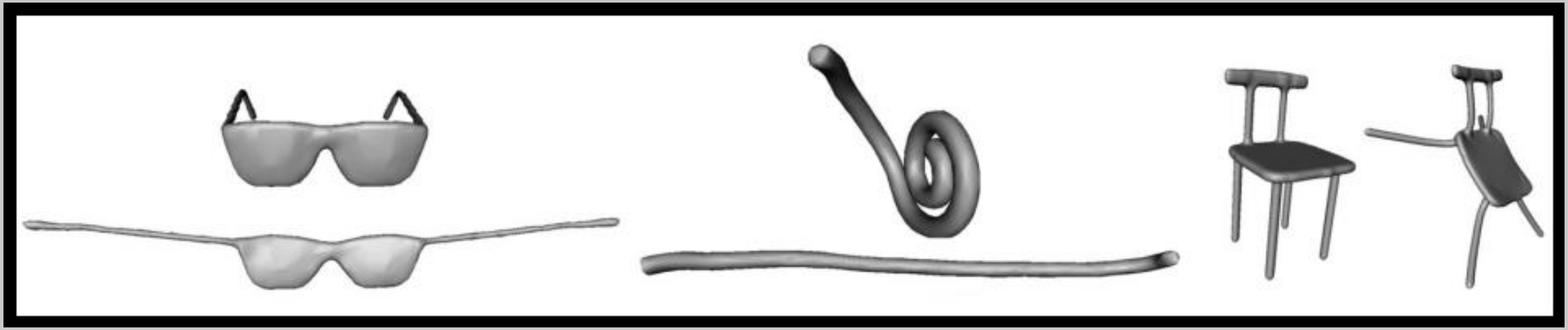
Detail-Preserving Mesh Unfolding for Nonrigid Shape Retrieval



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SIGGRAPH 2016

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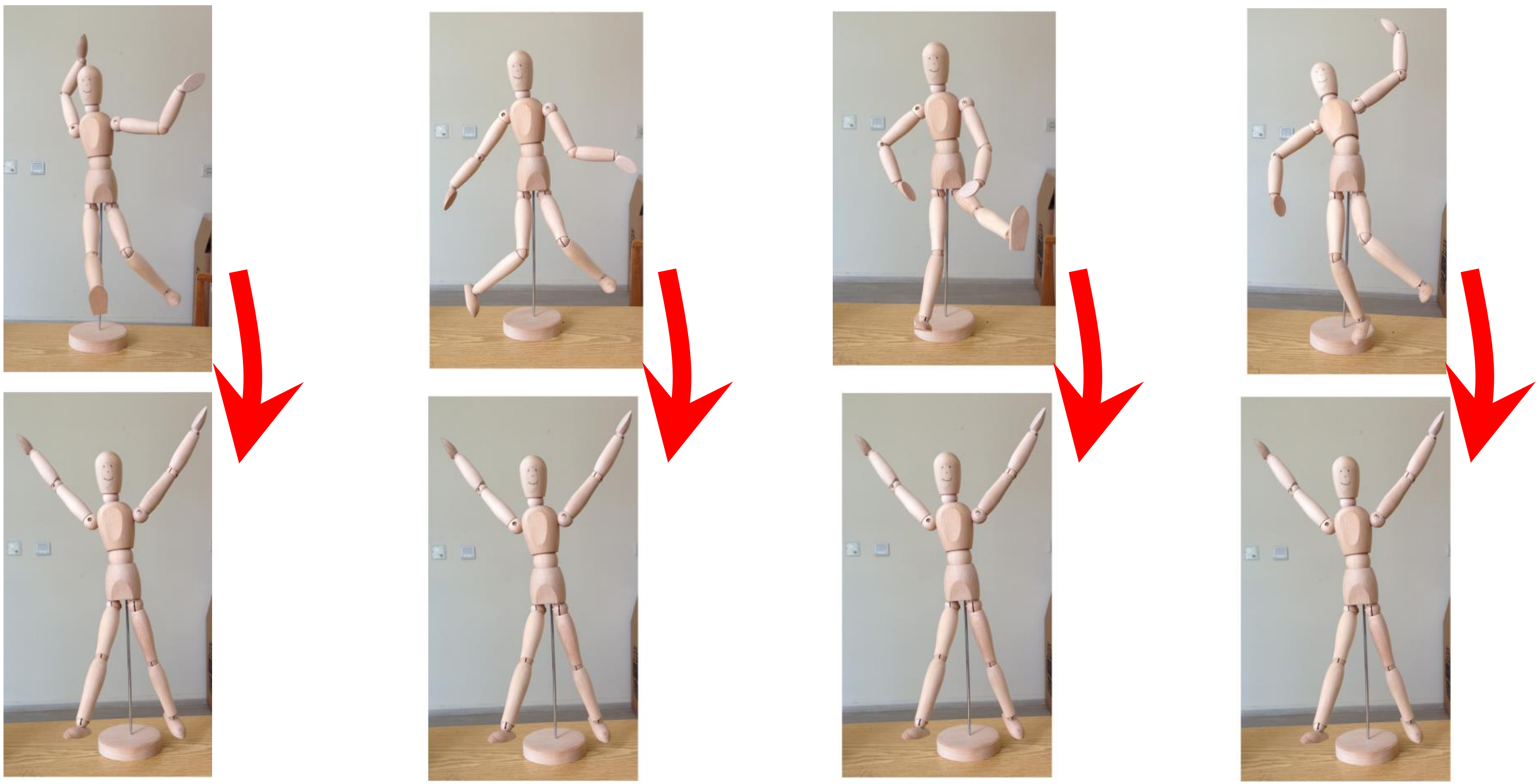
Problem Definition

Goal: Bring a 3D shape into a canonical pose that is invariant to nonrigid transformations.



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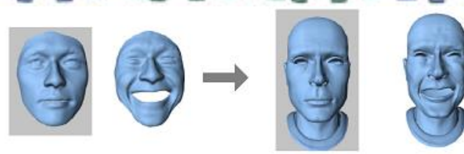
Applications

Given a mesh in canonical form, we'd be able to do:

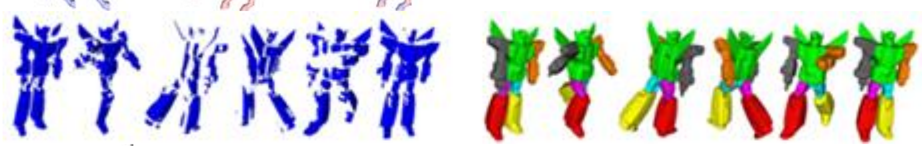
- ✓ Shape interpolation.

- ✓ Attribute transfer.

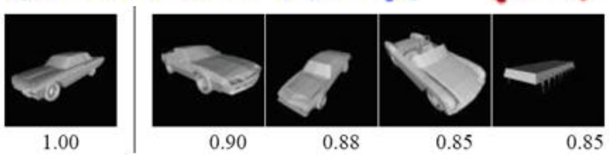


- ✓ Shape registration.

- ✓ Time-varying recon.



- ✓ Shape retrieval.



- ✓ Statistical shape analysis.

- ✓ Texture mapping, geodesic distance approximation, ……

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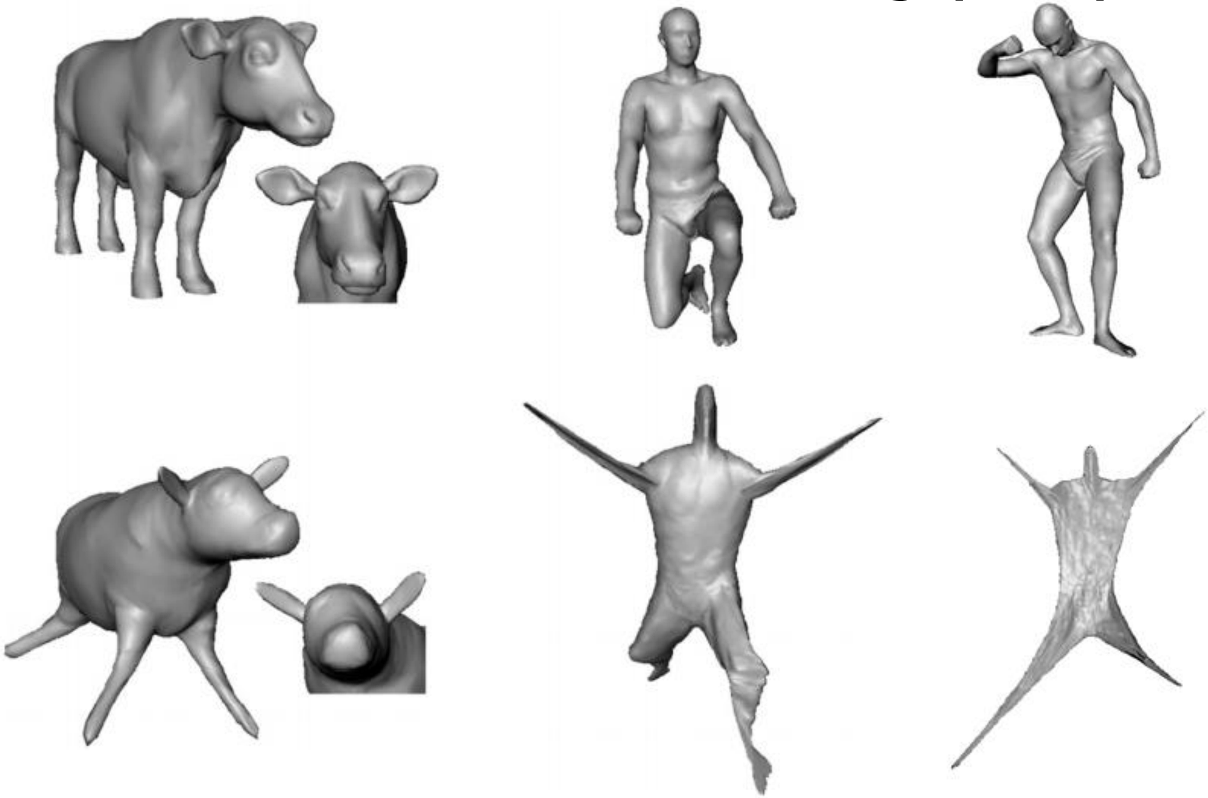
Contributions

✓ Avoid geometric distortion that is introduced by classical approaches such as multidimensional scaling (MDS).

Euclidean embedding (e.g., MDS)



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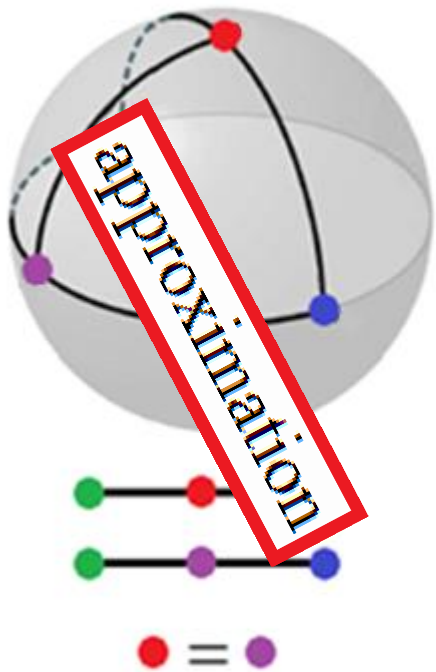

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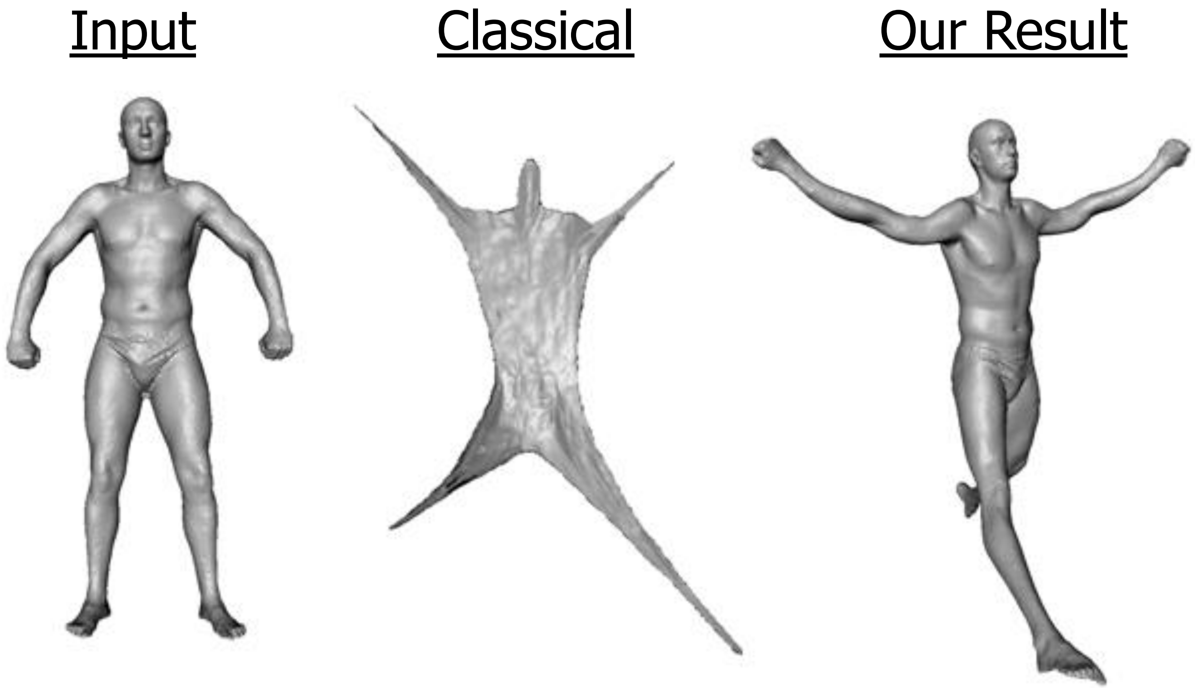
Contributions

- ✓ While you are at it, put additional constraints in the minimization procedure to preserve details.
  - ✓ This leads to a better post-processing (in, e.g., shape retrieval).



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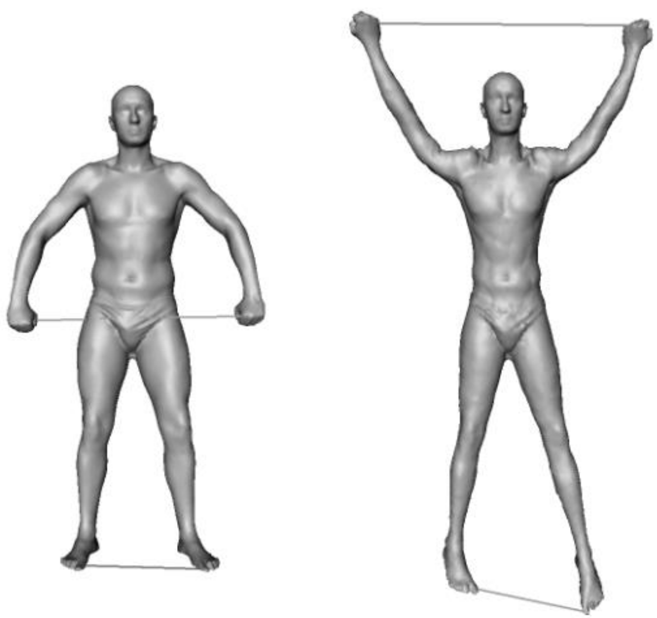
Contributions

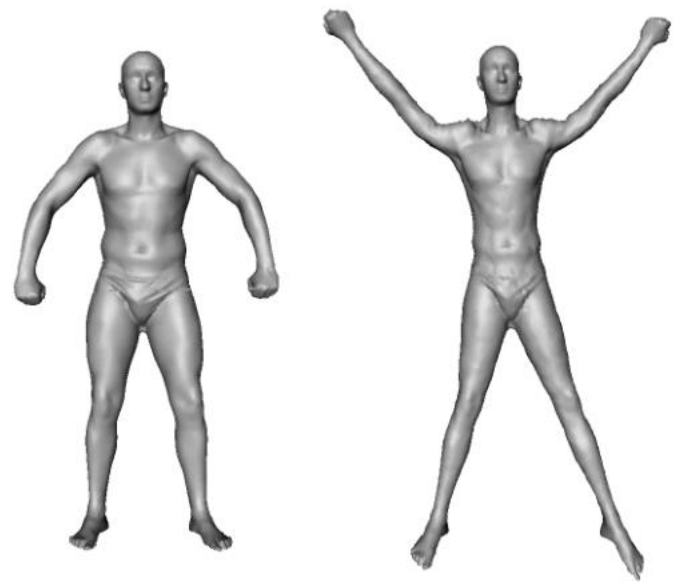
- ✓ Insensitivity to topological noise, as the 2nd contribution.
  - ✓ No topology-sensitive geodesic distance in our framework.

Input — Our Result



close to the noise-free execution at right ➔

Input — Our Result



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Algorithm

- ✓ Pre-processing.
  - ✓ For more realistic results, use volumetric elasticity, which requires tetrahedralizing the volume of the input mesh [Jacobson et al.].
- ✓ Our deformation algorithm seeks optimal vertex positions:

$$\mathbf{v}^* = \arg\min_{\mathbf{v}} E(\mathbf{v})$$

Algorithm

- ✓ Search space is reduced by exploiting the fact that $\mathbf{v}^*$ for a bending-free pose
  - ✓ move every vertex as far away from each other,
  - ✓ while keeping the mesh in good shape with original details.

$$\mathbf{v}^* = \arg\min_{\mathbf{v}} E(\mathbf{v})$$

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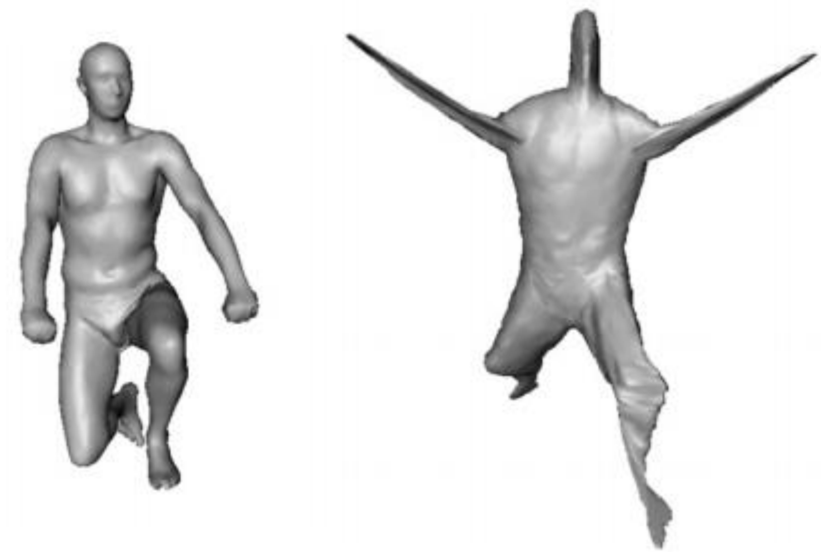
Algorithm

- ✓ Consider $E(\mathbf{v}) = \sum_{i<j} (||\mathbf{v}_i - \mathbf{v}_j|| - g(i, j))^2$
  - ✓ move every vertex as far away from each other,
  - ✓ ~~while keeping the mesh in good shape with original details.~~



  - ✓ This mass-spring system = least-squares MDS [Elad & Kimmel 03].

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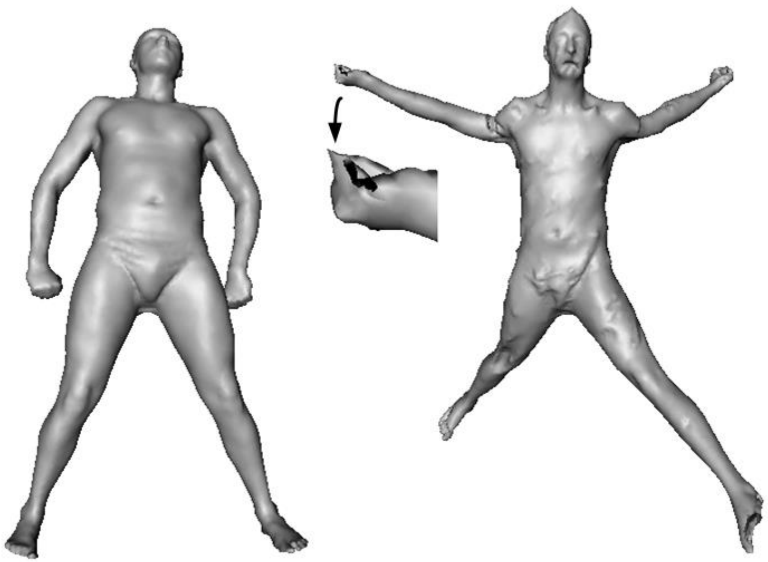
Algorithm

- ✓ Consider $E(\mathbf{v}) = \frac{1}{2}\sum_{(i,j)\in\mathcal{G}\cup\mathcal{E}} k_{ij}(||\mathbf{v}_i - \mathbf{v}_j|| - r_{ij})^2$
  - ✓ move every vertex as far away from each other,
  - ✓ while keeping the mesh in good shape with original details.



  - ✓ Alleviates detail problem but has serious issues.

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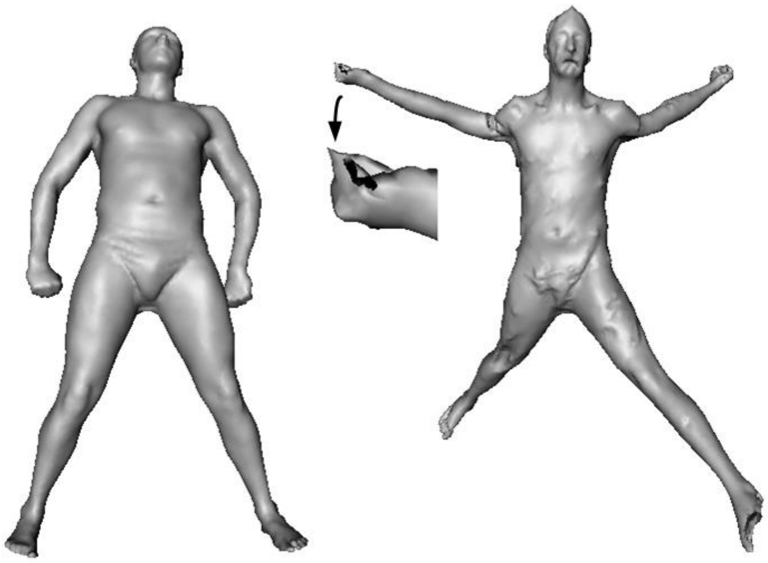
Algorithm

- ✓ Consider $E(\mathbf{v}) = \frac{1}{2} \sum_{(i,j) \in \mathcal{G} \cup \mathcal{E}} k_{ij} (||\mathbf{v}_i - \mathbf{v}_j|| - r_{ij})^2$
  - ✓ Rest length r_{ij} takes the value of geodesic distance (for $\mathcal{G}$) or original edge length (for edge springs $\mathcal{E}$).
  - ✓ Issues:
    - ✓ Geodesic distance dependence.
    - ✓ Pure spring-based approach to capture volumetric elasticity.



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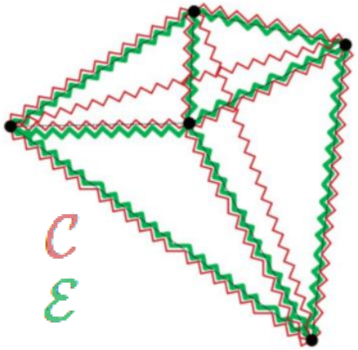
Algorithm

- ✓ Proposed energy functional:

$$E(\mathbf{v}) = \frac{1}{2}\left(\sum_{(i,j)\in\mathcal{C}} -k_{ij}||\mathbf{v}_i - \mathbf{v}_j||^2 + \alpha \sum_{(i,j)\in\mathcal{E}} k_{ij}(||\mathbf{v}_i - \mathbf{v}_j|| - r_{ij})^2 \right)$$

Move every vertex as far away from each other using charge springs ($\mathcal{C}$). Here, r_{ij} = 0.

Keep mesh in good shape with original details using edge springs ($\mathcal{E}$). Here, r_{ij} = original edge len.



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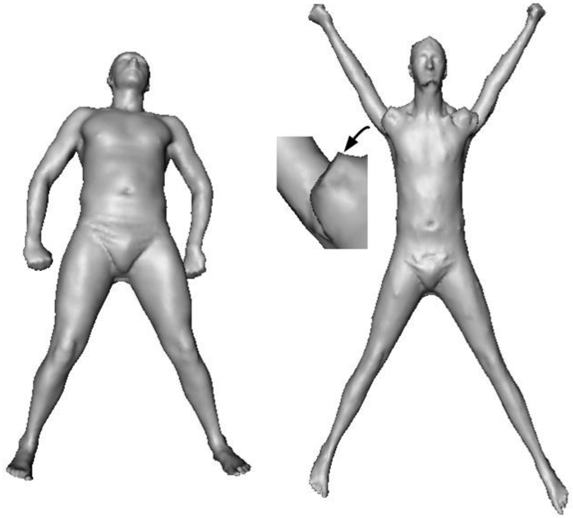
✓ Without any FE constraints, this energy is still not perfect.



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Algorithm

- ✓ Proposed FE regularization constraints:
  - ✓ Preserve local volume in the neighborhood of each vertex:

$$c_i(\mathbf{v}) : \sum_{t \in \eta(i)} \mathrm{vol}(t) = l_i \quad \forall i \in V$$

  - ✓ Prevent inversions:

$$c_t(\mathbf{v}) : \mathrm{vol}(t) > \epsilon \quad \forall t \in T$$

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Algorithm

✓ Final nonlinear constrained optimization problem:

$$\underset{\mathbf{v}}{\text{minimize}} \quad E(\mathbf{v})$$

$$\text{subject to} \quad c_i(\mathbf{v}),\ \forall i \in V \quad \text{and} \quad c_t(\mathbf{v}),\ \forall t \in T$$

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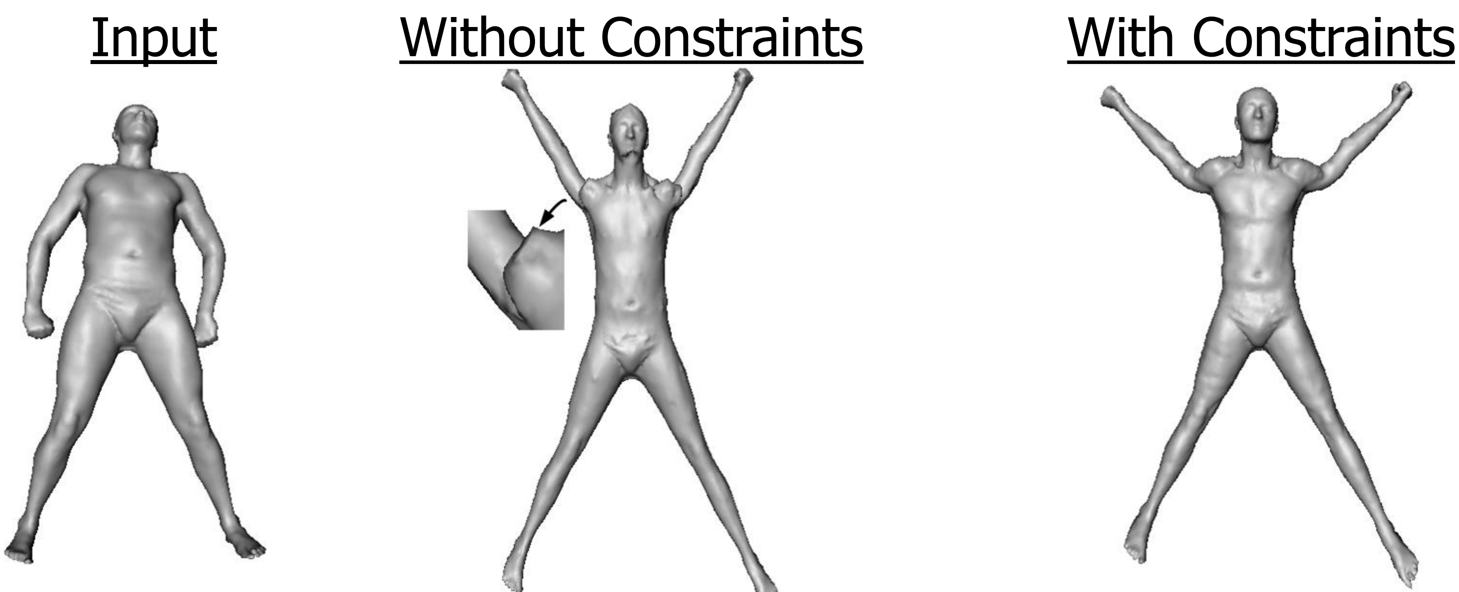

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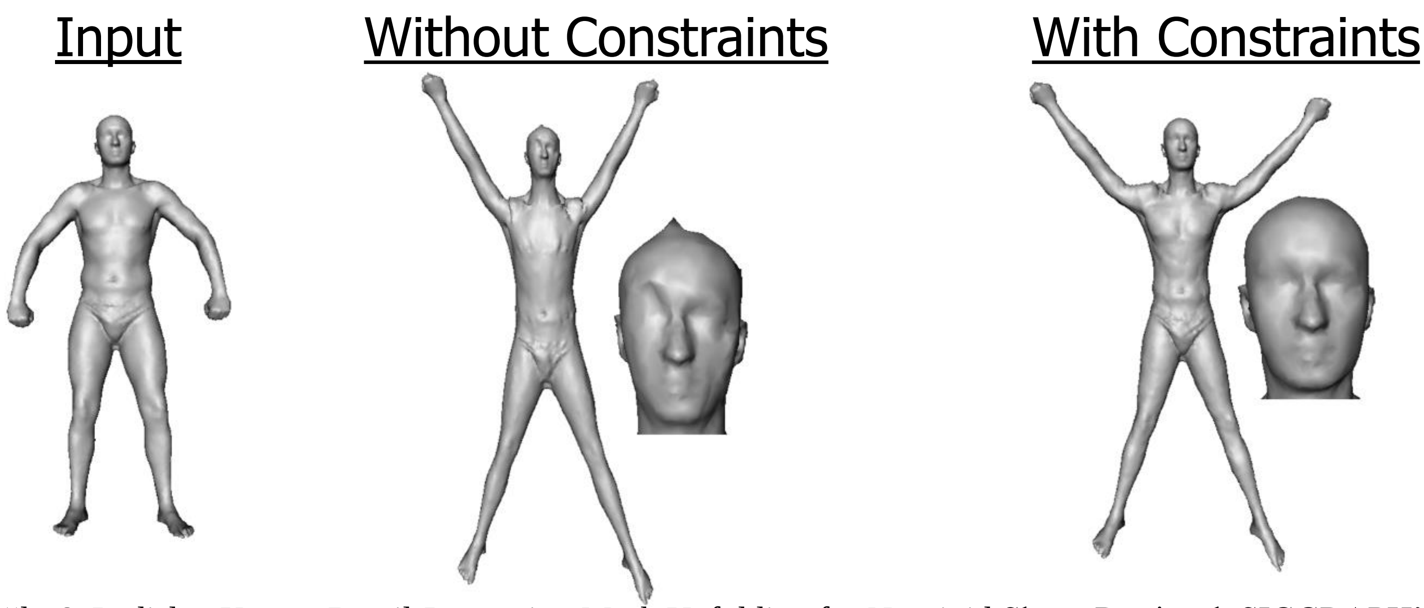

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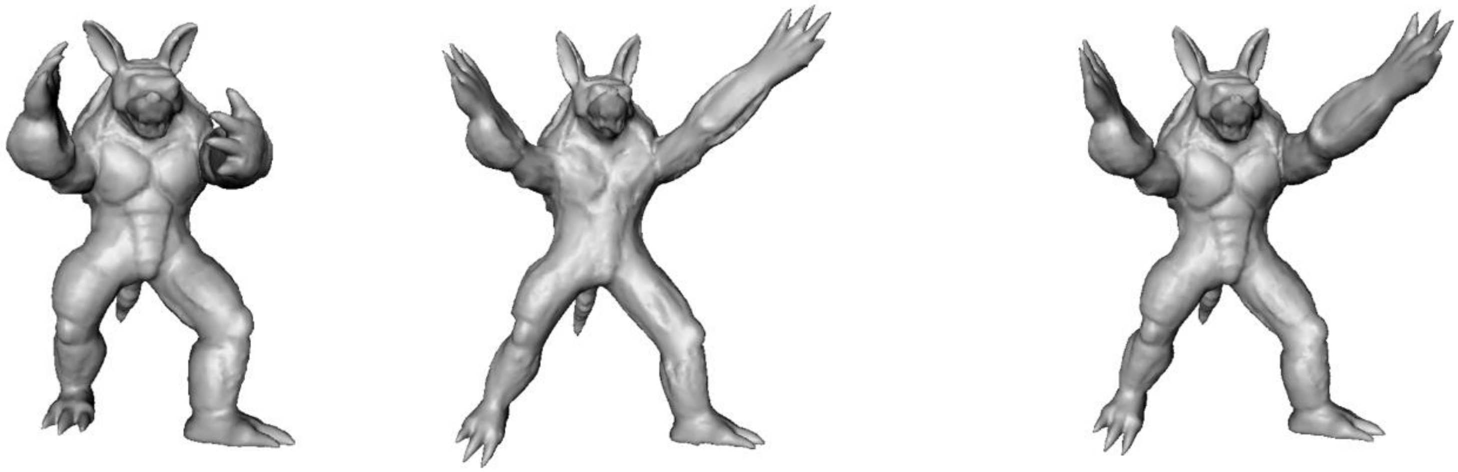
<u>Input</u> <u>Without Constraints</u> <u>With Constraints</u>



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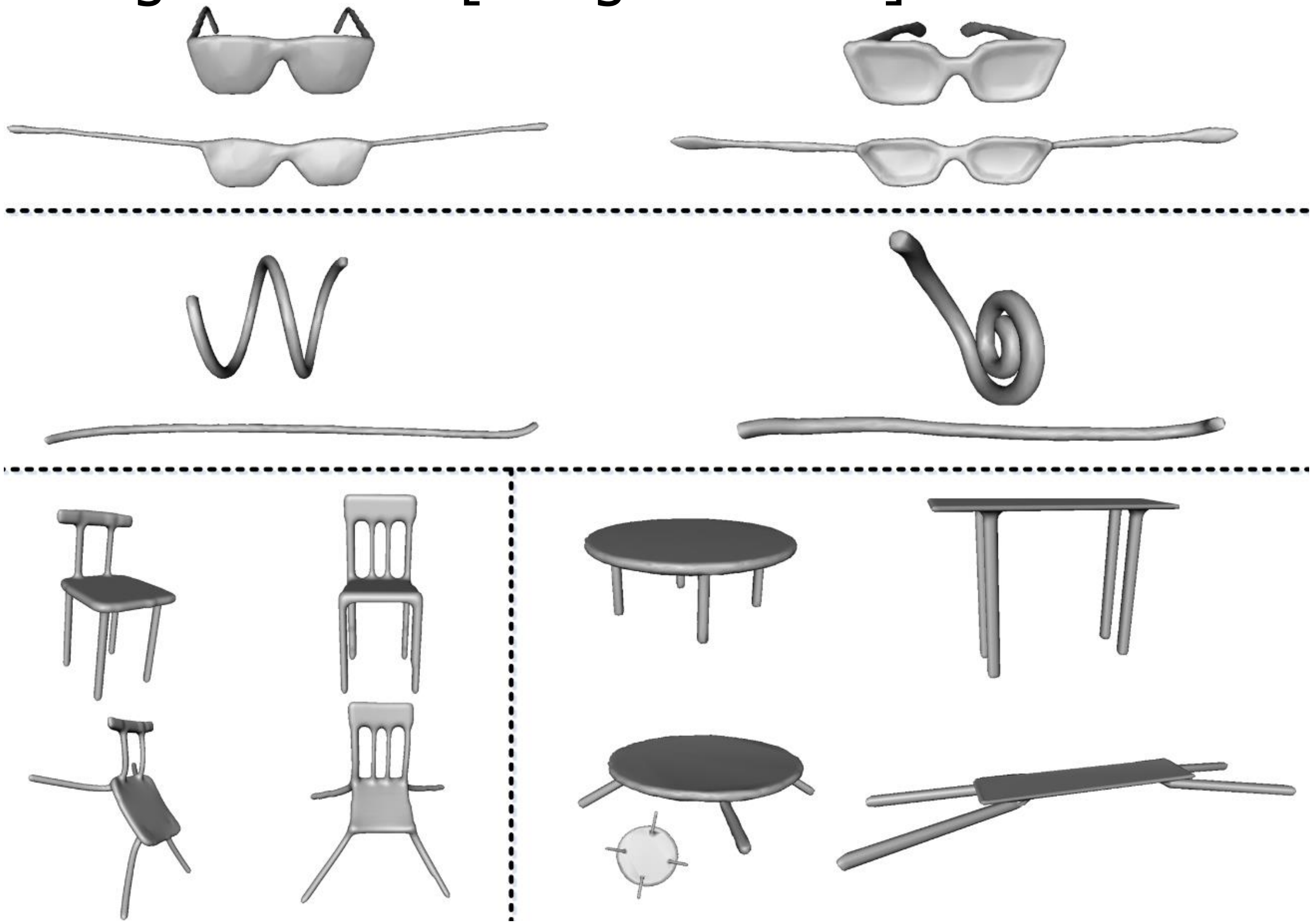
Experimental Results

✓ Watertight dataset [Giorgi et al. 07].



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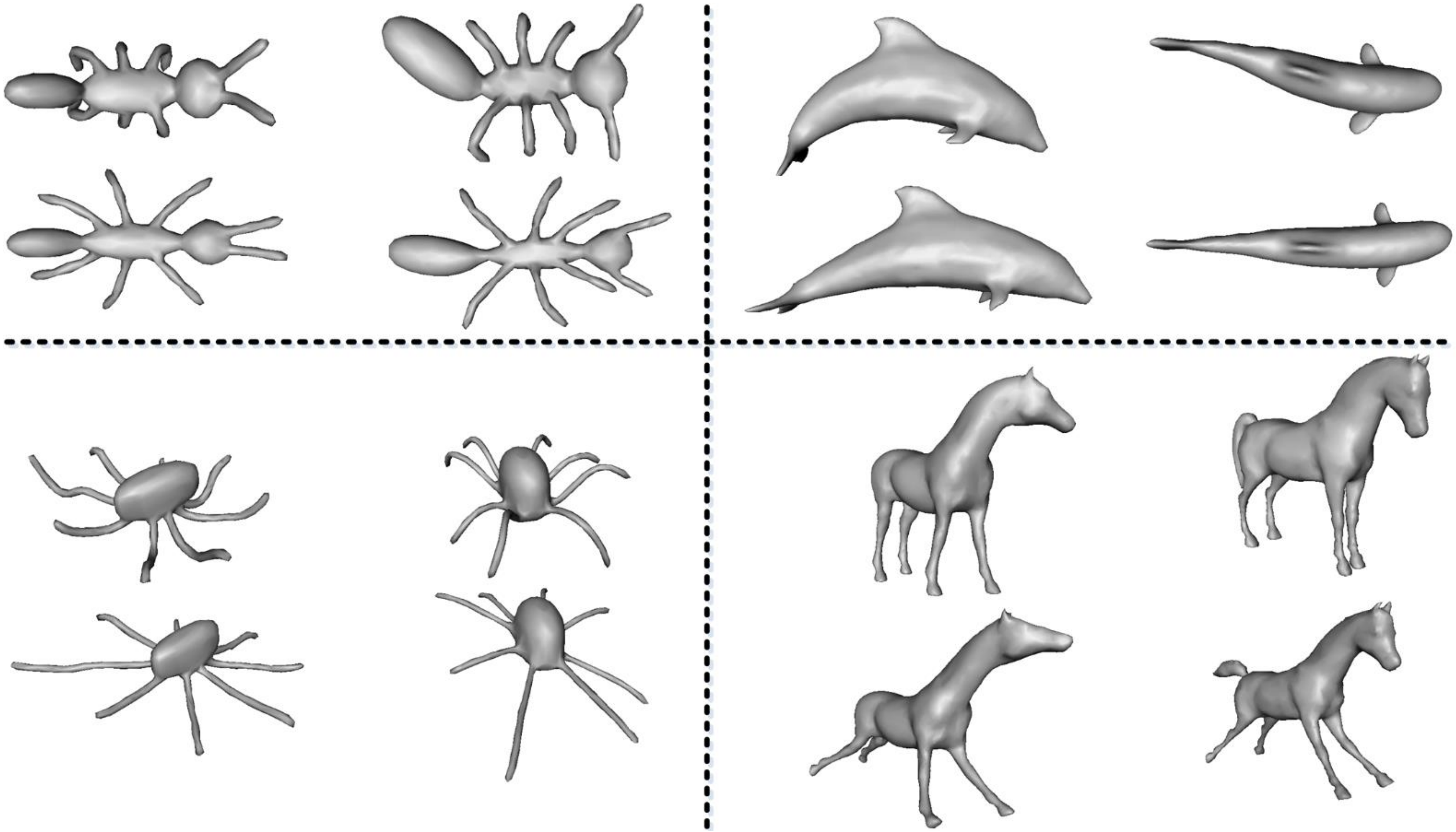

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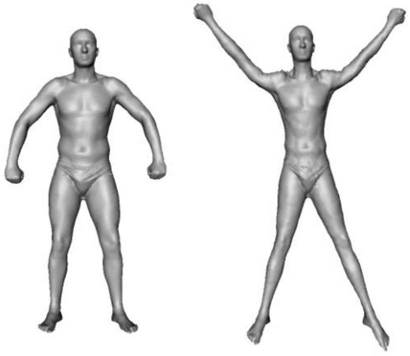
Experimental Results

- ✓ Watertight dataset [Giorgi et al. 07].
- ✓ Timing on a 2.53GHz PC.
  - ✓ # of tets: 35K, 20K, 9K, 3K.
  - ✓ # of secs: 575, 280, 21, 4.

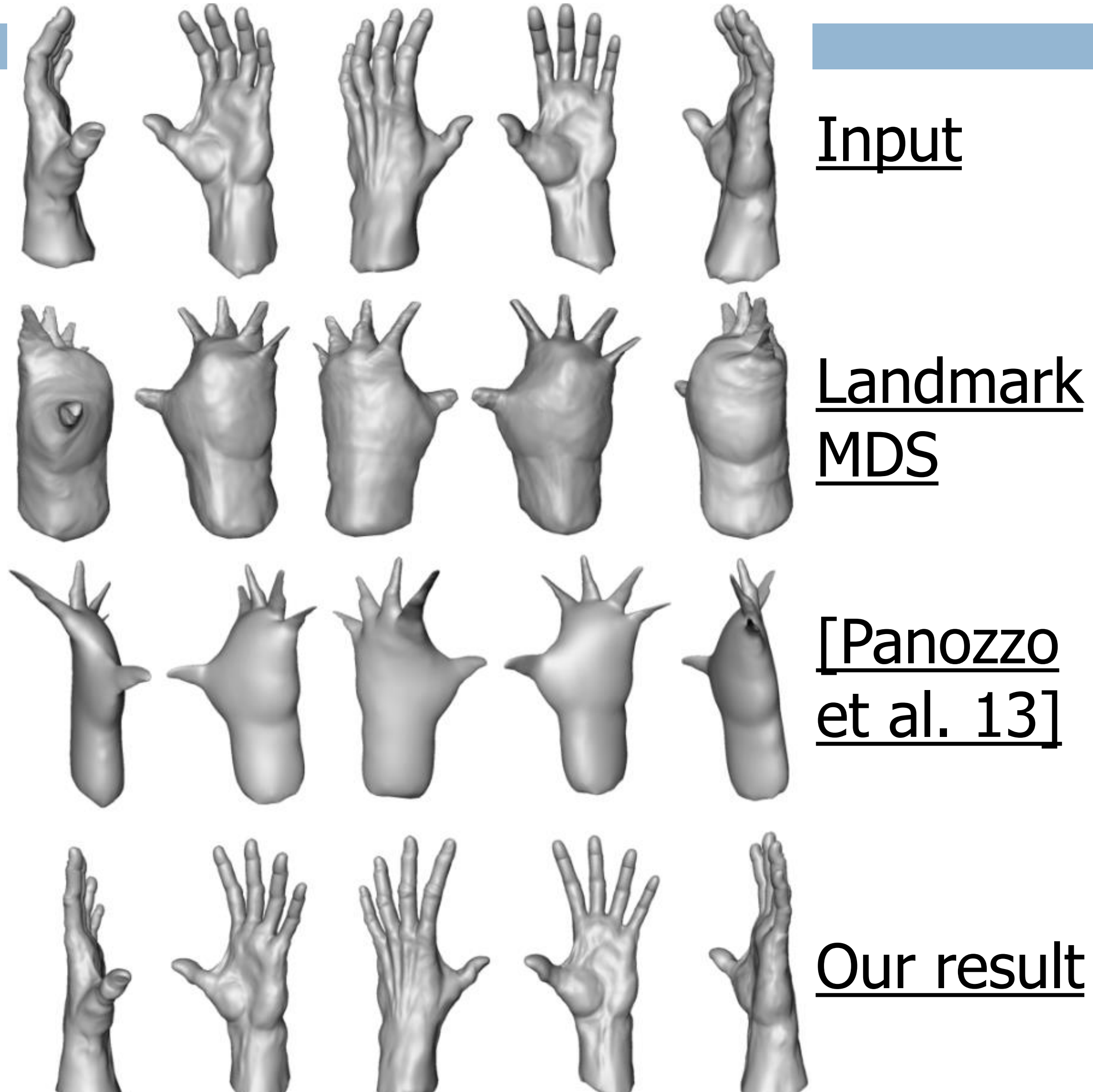
- ✓ Timing for SCAPE models (45K tets).
  - ✓ 985 seconds.
  - ✓ [Anguelov et al. 2005]



- ✓ Timing for Hand model (51K tets).
  - ✓ 1684 seconds.
  - ✓ [Panozzo et al. 2013]

Experimental Results

✓ Hand model [Panozzo et al. 13].



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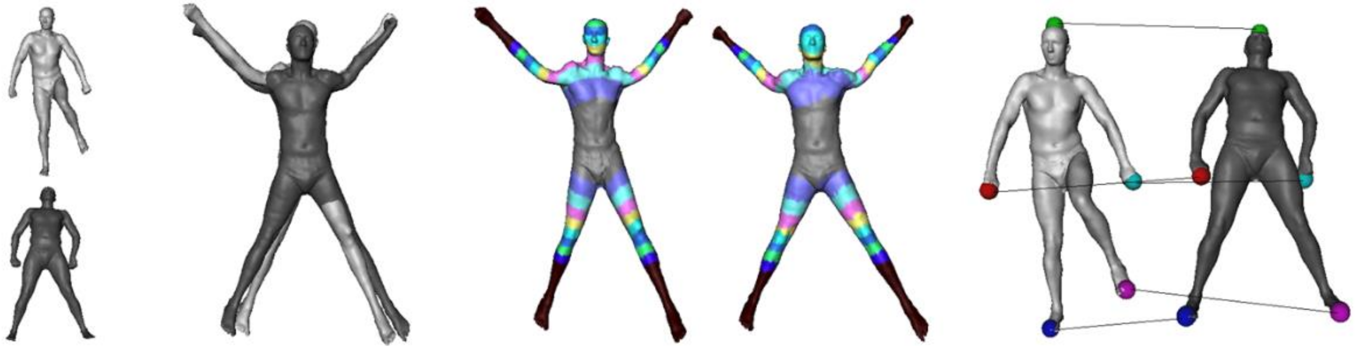
Experimental Results

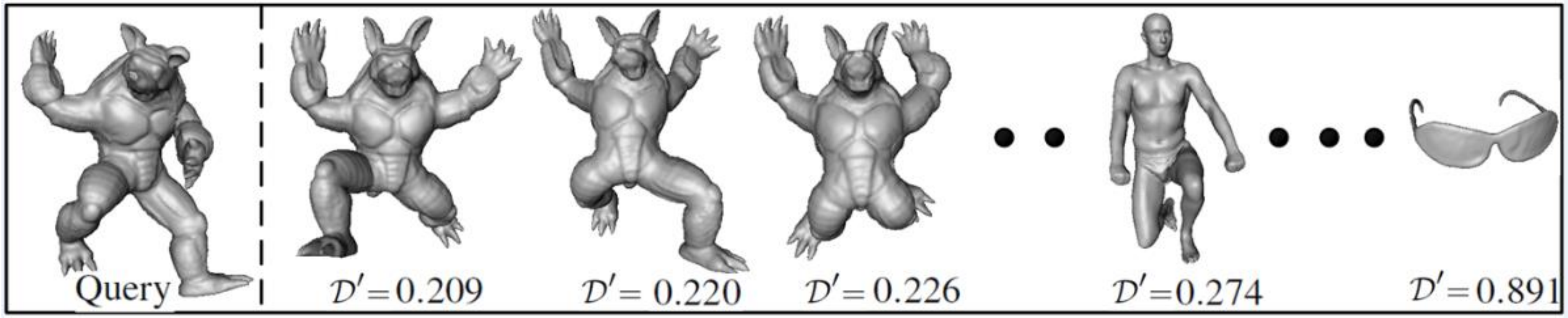
- ✓ Nonrigid shape retrieval.
- ✓ Canonical poses computed by our algo are
  - ✓ rigidly aligned (PCA followed by ICP),
  - ✓ matched by the closest points in the aligned config, and

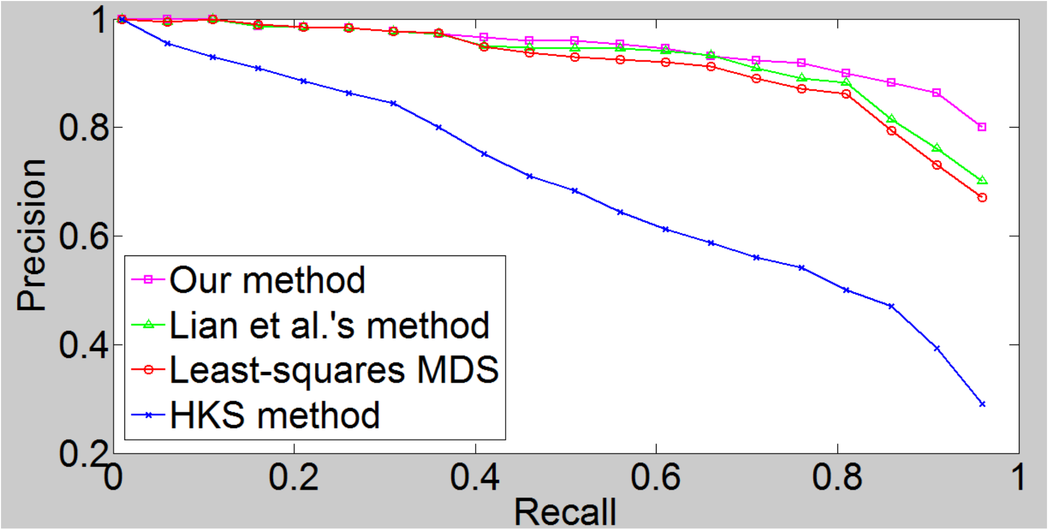


  - ✓ exposed to the following similarity measure: $\mathcal{D}'(\phi) = \frac{1}{|\phi|} \sum_{(i,j)\in\phi} ||\mathbf{v}_i - \mathbf{v}_j||$

Experimental Results

✓ Nonrigid shape retrieval.





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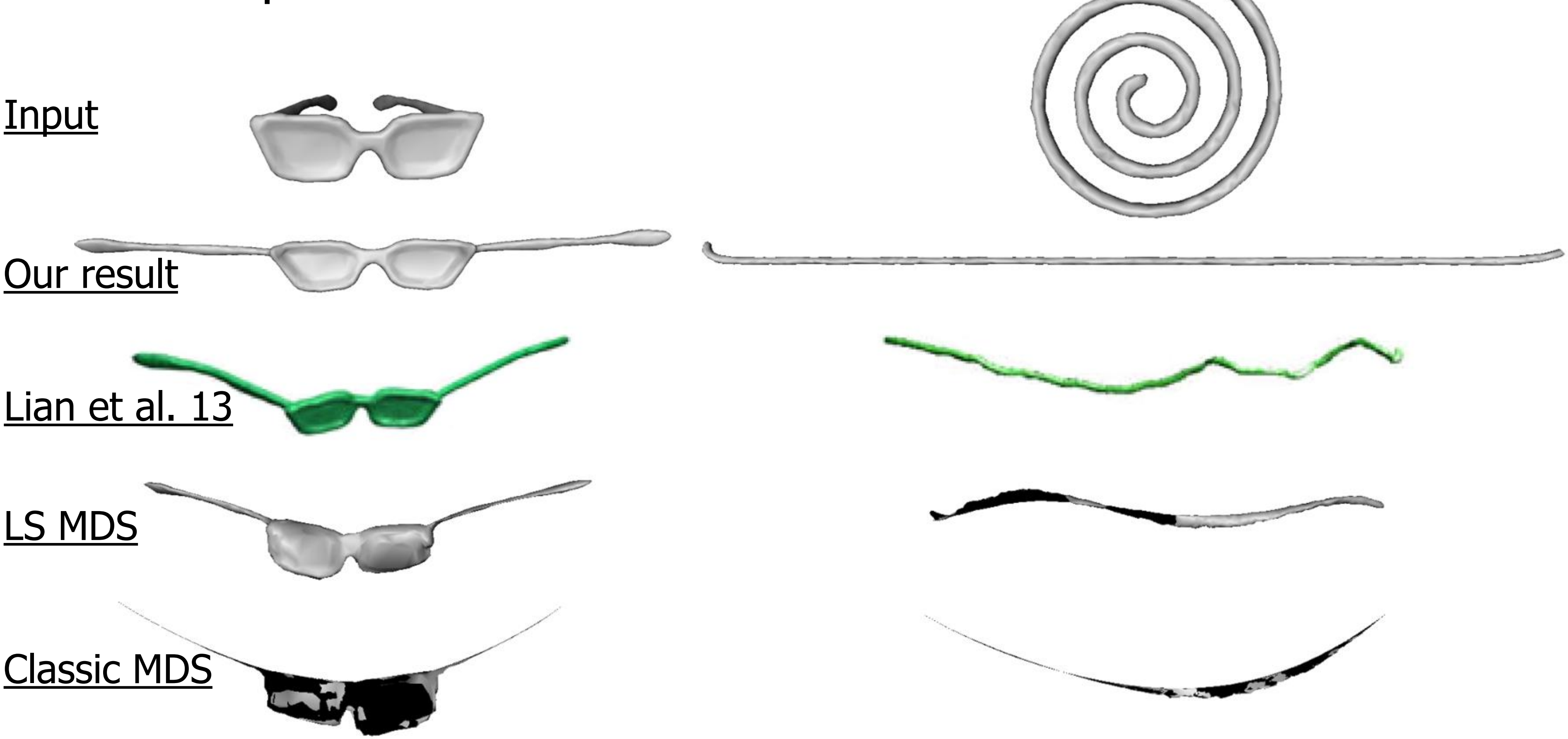
Experimental Results

- ✓ Comparisons.



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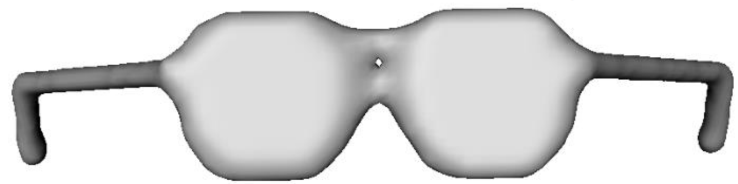
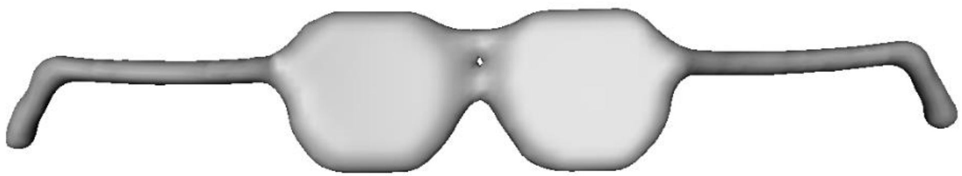
Experimental Results

- ✓ Regularization weight (α). $E(\mathbf{v}) = \frac{1}{2}\left(\sum_{(i,j)\in\mathcal{C}} -k_{ij}||\mathbf{v}_i - \mathbf{v}_j||^2 + \alpha \sum_{(i,j)\in\mathcal{E}} k_{ij}(||\mathbf{v}_i - \mathbf{v}_j|| - r_{ij})^2\right)$

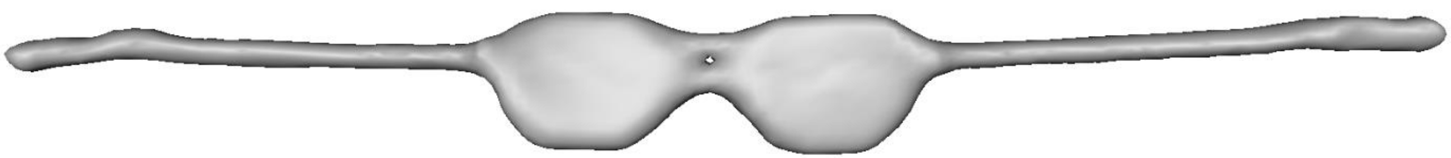
Input



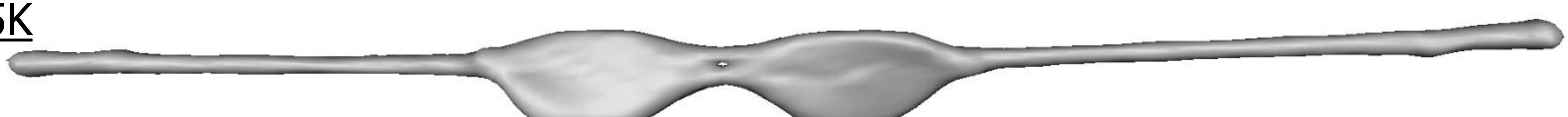
α = 100K



α = 20K



α = 5K



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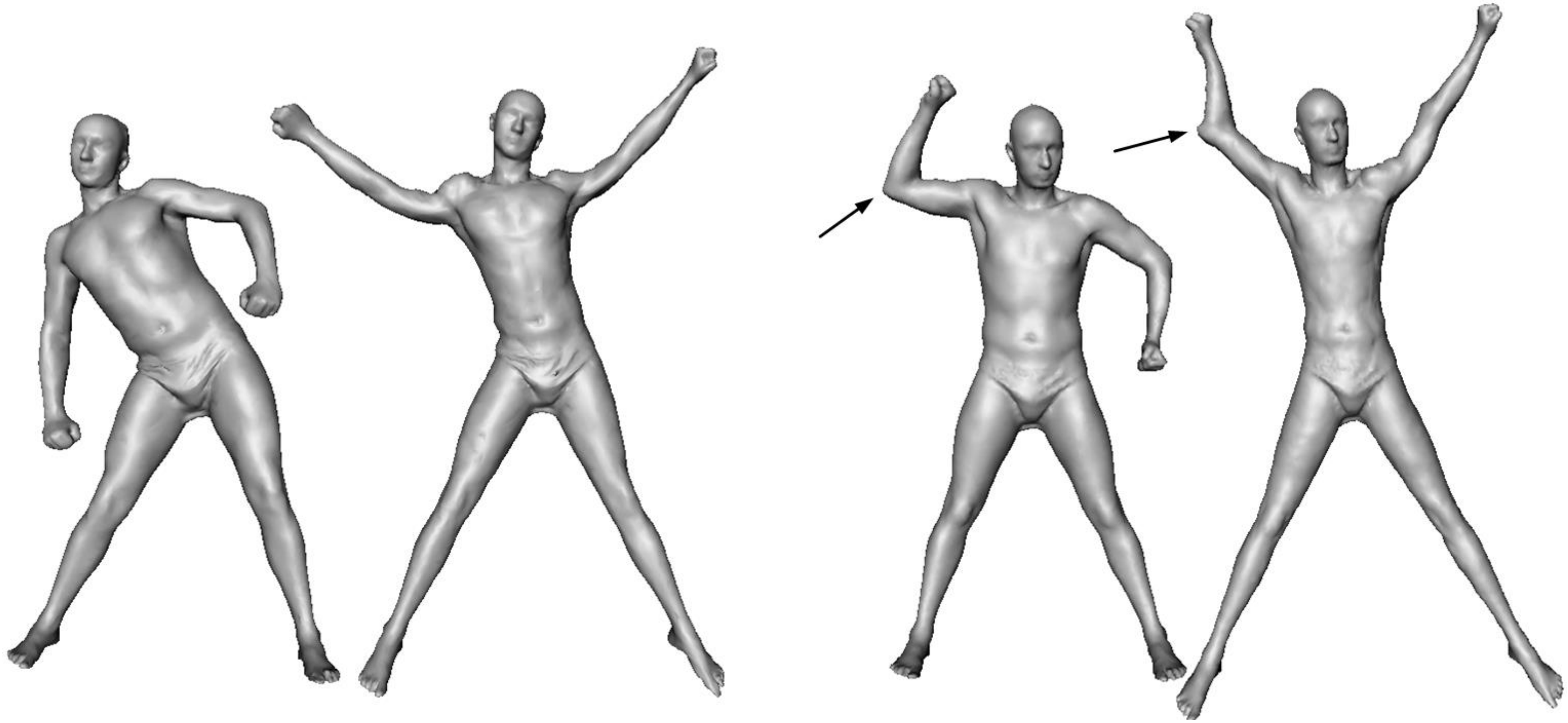
Limitations

- ✓ Regularization slightly sensitive to the original pose.
- ✓ Decreases shape correspondence performance.
  - ✓ Such a loose mapping still useful for nonrigid shape retrieval app.



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Conclusion

- ✓ A deformation algorithm that unfolds a 3D model without distorting its geometric details.
- ✓ This detail-preserving unfolding gives a canonical pose that is suitable especially for nonrigid shape retrieval.
- ✓ No geodesics, efficient, less topological noise sensitivity, arbitrary genus.
- ✓ Outperforms state-of-the-art retrieval applications.

- ✓ Future: Incorporate semantic parameters to create more specific poses, e.g., Vitruvian Man.

People

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Asst. Prof.

Ladislav Kavan,
Asst. Prof.