Univerzita Hradec Králové
Filozofická fakulta

E-learningový kurz

Modern quantitative methods and shape analysis in archaeology

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Tento materiál vznikl v rámci realizace projektu Strategický rozvoj Univerzity Hradec Králové, reg. č. CZ.02.2.69/0.0/0.0/16_015/0002427.

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2D landmark analyses

Analyses of 2D landmarks

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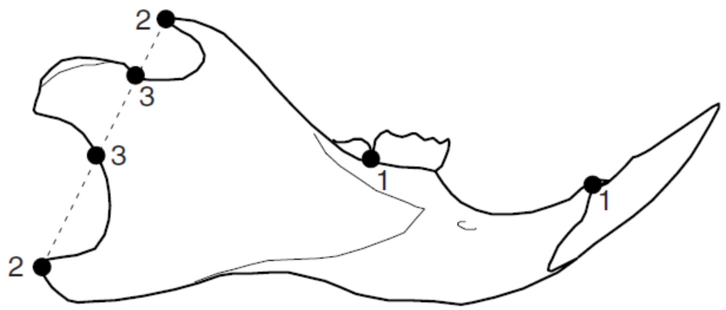
Landmarks

“Discrete anatomical loci that can be recognized as the same loci in all speciemens in the study” (Zelditch et al. 2004)

“A landmark is a point of correspondence on each object that matches between and within populations” (Dryden and Mardia 1988)

Landmark types (Bookstein 1991)
Type I: intersection
Type II: minimum/maximum of curvature
Type III (not a landmark): extreme points, geometric constructions, centroids, etc.

Configuration of landmarks: all landmarks on one object



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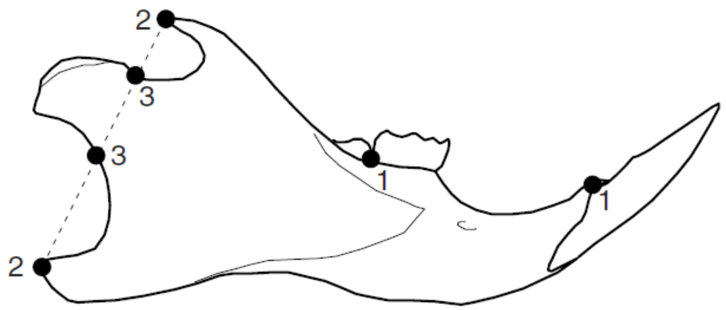
Landmarks

Criteria for choosing landmarks

- should be homologous anatomical loci
- should not alter typological positions relative to other landmarks
- should provide adequate coverage of the morphology
- should be found repeatedly and reliably
- should lie within the same plane
- should be plotted in the same order



Intuitive example from archaeology

Original

Copy

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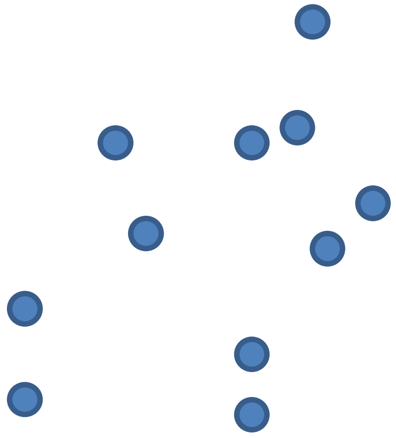
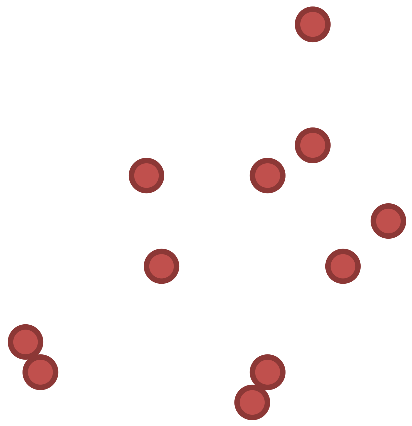
Landmarks

Intuitive example from archaeology



Original



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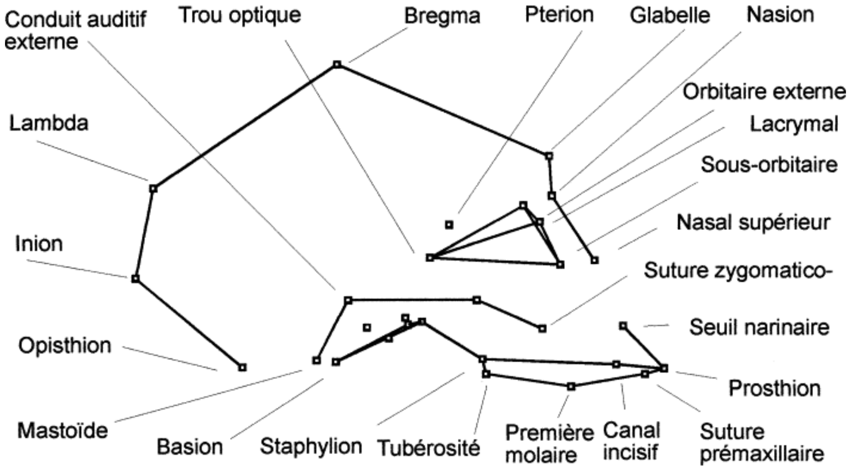
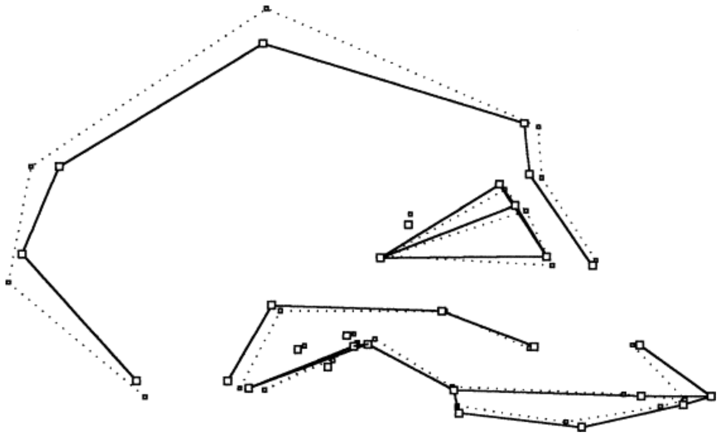
Landmarks

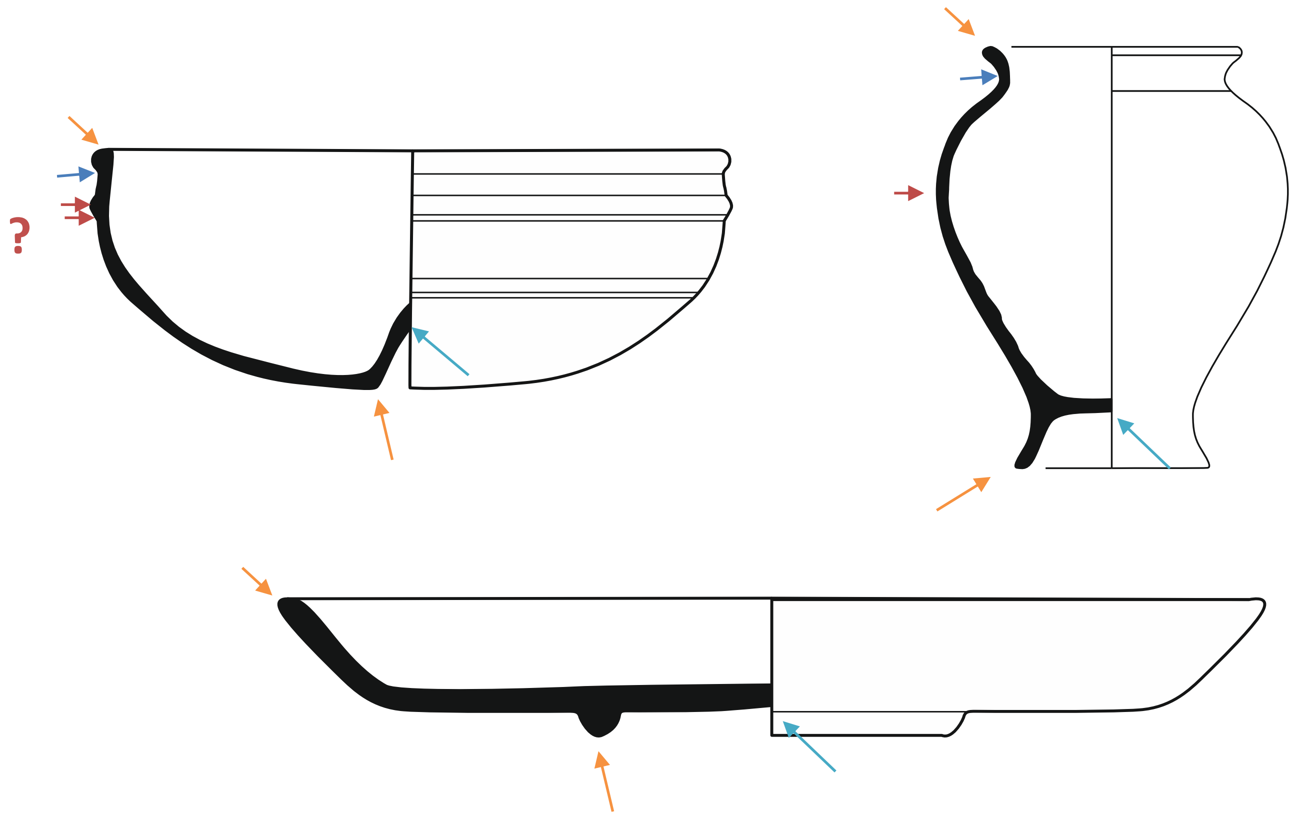
Landmarks in biology



juvenil in dots
Adult in line



Landmarks in archaeology…



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Landmarks

Other limitations?

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Workflow

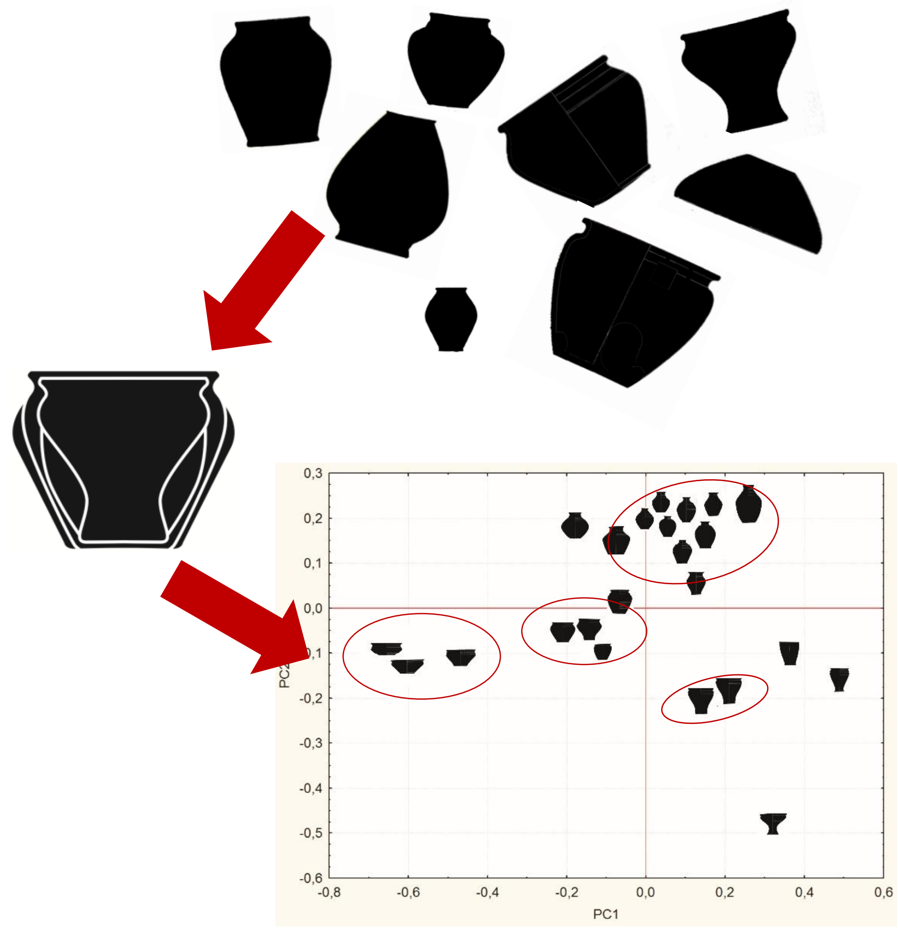
1) Data collection

2) Standardisation

(position, size and orientation)

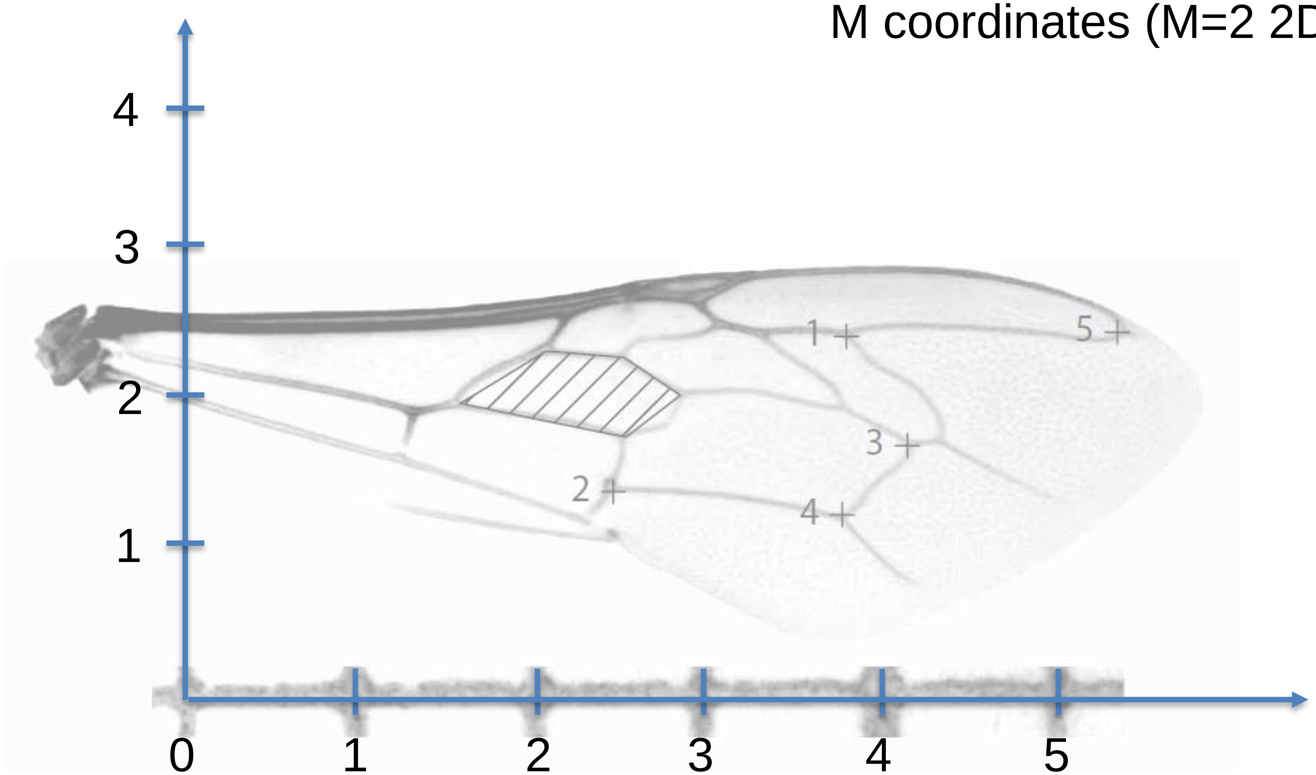
3) Calculation of shape variables

4) Data treatment and visualisation



Data collection

K landmarks
M coordinates (M=2 2D; M=3 for 3D)



configuration

$$X = \begin{bmatrix} 3.9 & 2.5 \\ 2.3 & 1.3 \\ 4.2 & 1.7 \\ 3.8 & 1.2 \\ 5.4 & 2.3 \end{bmatrix}$$

Claude 2008

What we can actually do?

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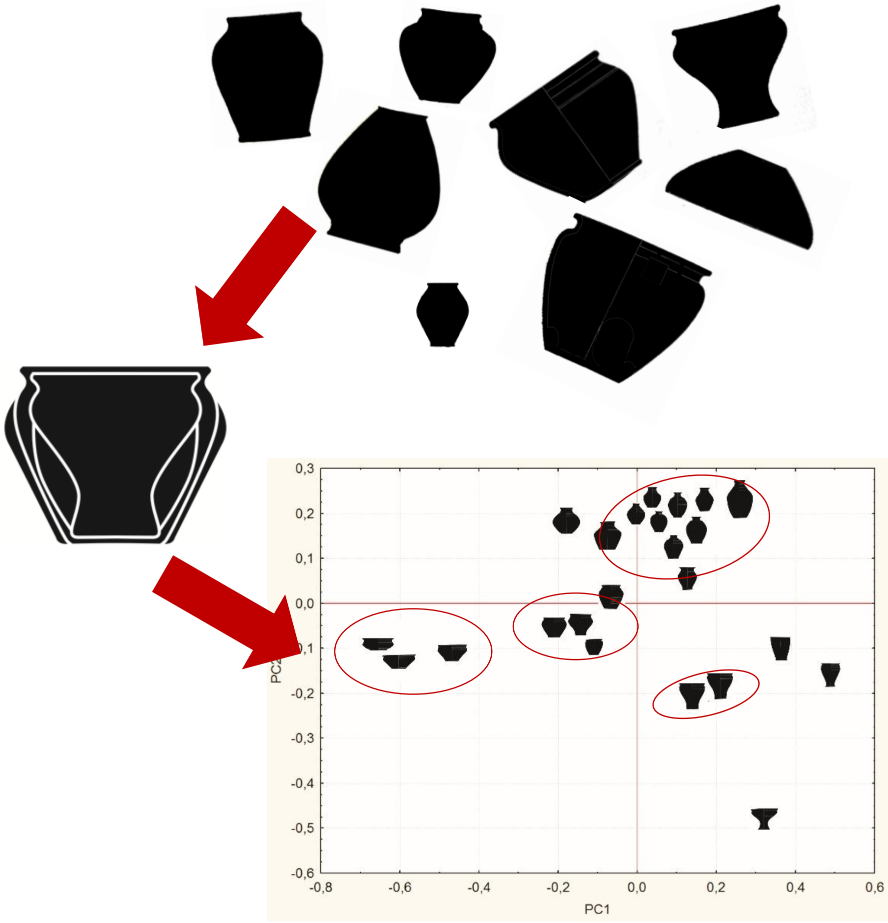
1) Data collection

2) Standardisation

(position, size and orientation)

3) Calculation of shape variables

4) Data treatment and visualisation



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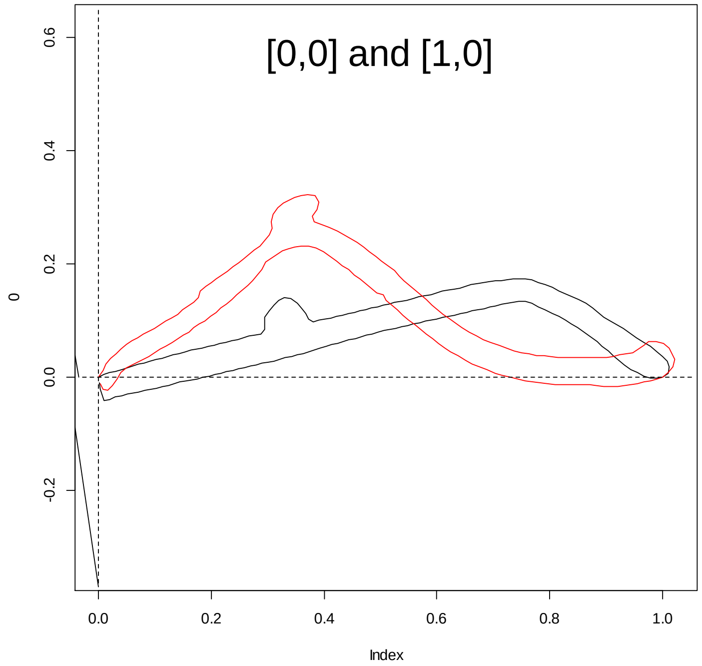
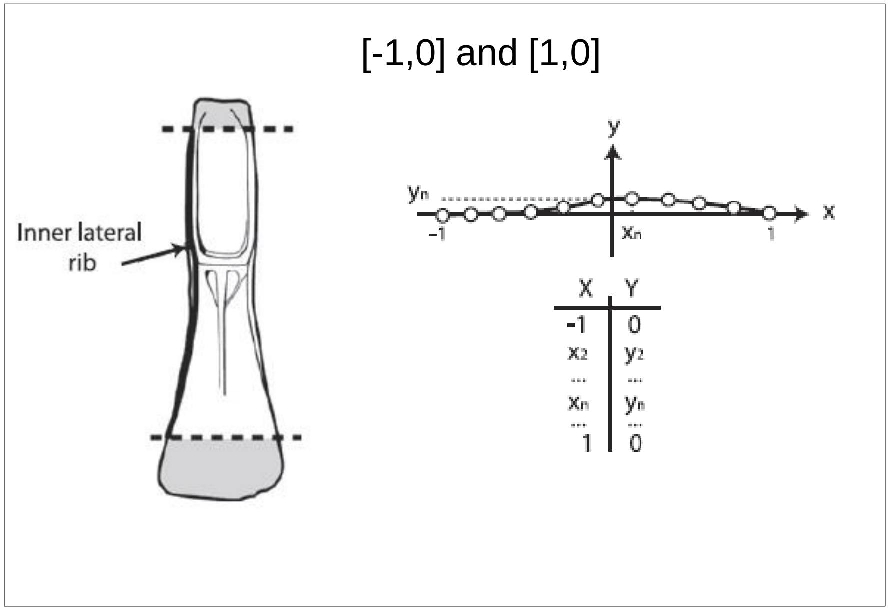
Fixation of two selected coordinates

ceramics



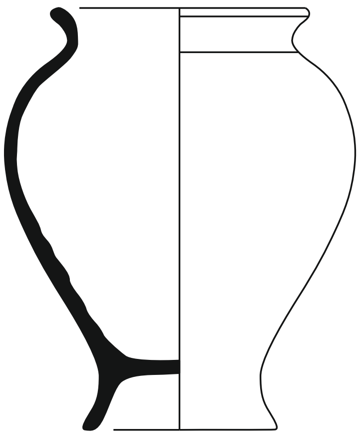
axe

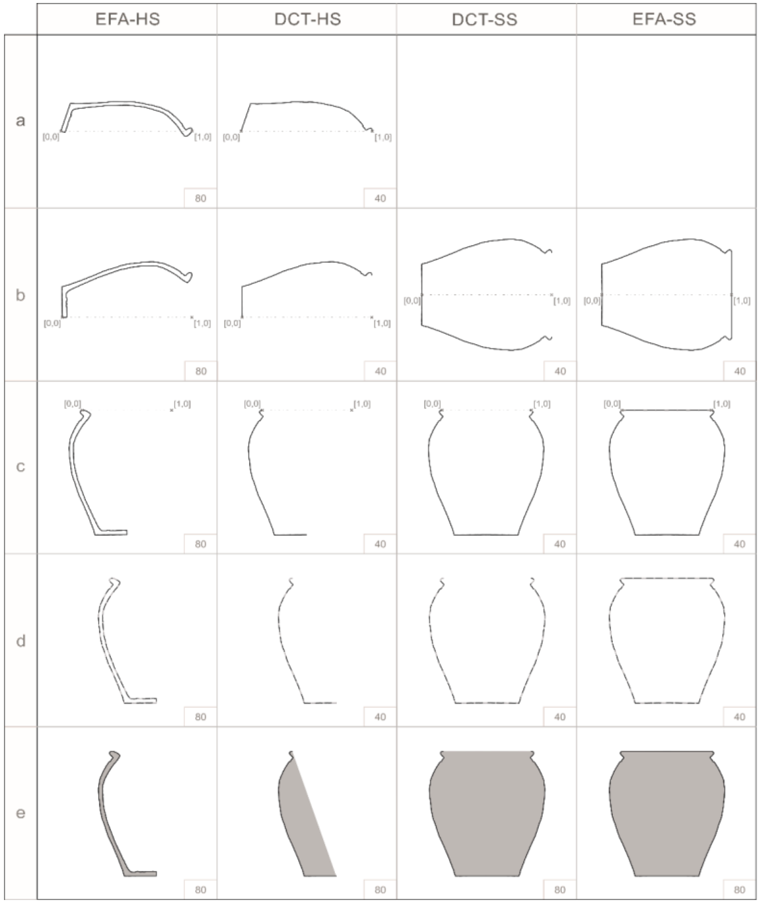


Forel et al., 2009

Baseline/Bookstein registration

Fixation of two selected coordinates
Surface standardisation





Wilczek et al. 2014

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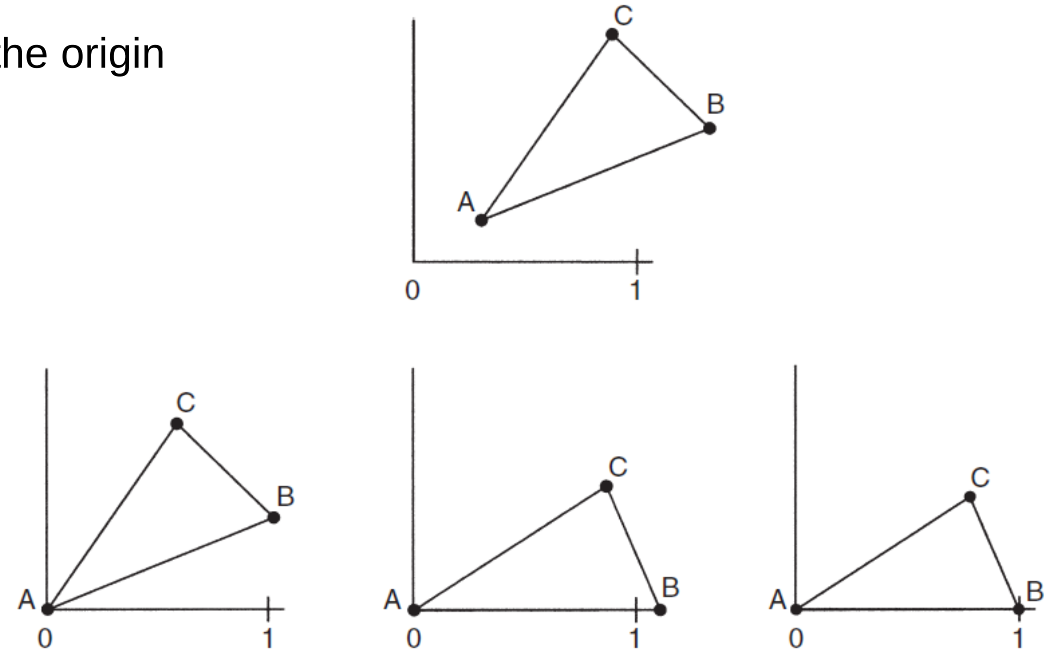
Fixation of two selected coordinates

Procedure

- Translation of the first point to the origin
- Rotation
- Rescaling

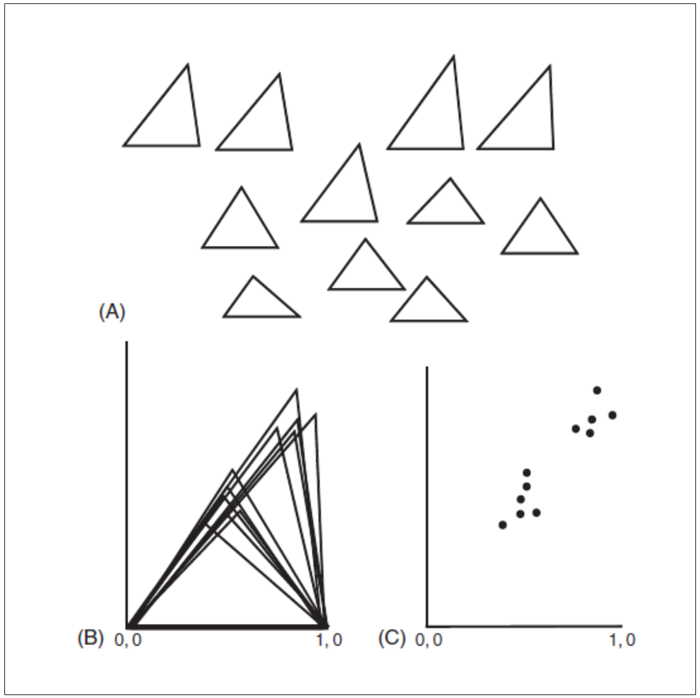


Zelditch et al., 2004

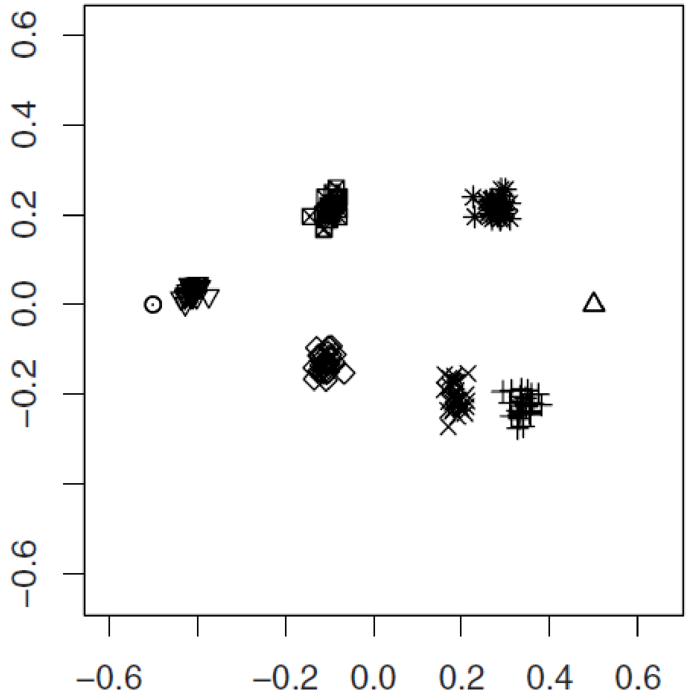
Baseline/Bookstein registration

Fixation of two selected coordinates

11 triangles



30 female gorillas



Zelditch et al., 2004

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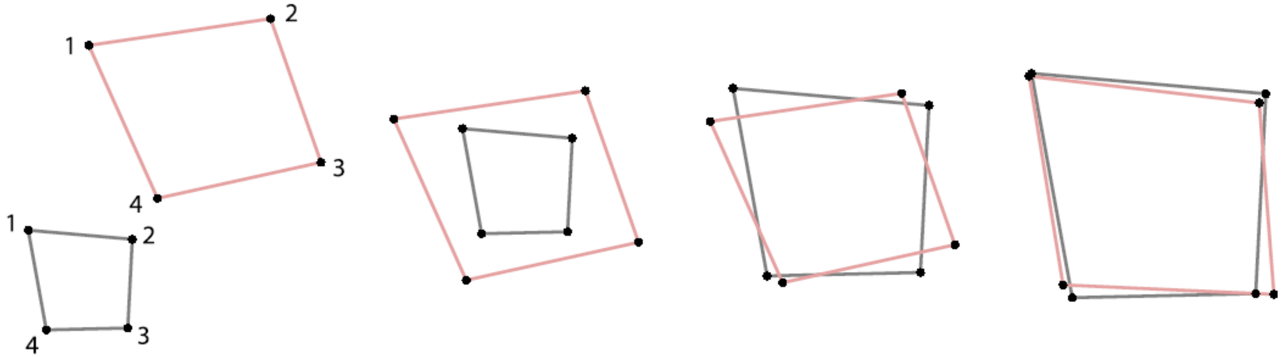
Procrustes superimposition

Take out the effect of the <u>position</u>, <u>size</u> and <u>rotation</u>

Position – move to the common origin
Size – scale to the same (unit) centroid size
Rotation – rotate until (squared) distances between landmarks are minimal



raw landmarks | centered landmarks | centered and scaled landmarks | centered, scaled, and rotated lms

Mitteroecker and Gunz, 2009

Take out the effect of the position, size and rotation

$$A = \begin{bmatrix} -1 & -1 \\ 1 & -1 \\ 0 & 1 \end{bmatrix} \qquad B = \begin{bmatrix} 1.07 & -1.64 \\ 3.10 & -0.72 \\ 1.55 & 0.82 \end{bmatrix}$$

Position – move to the common origin

(1) Calculate centroid coordinates of each configuration: $X_{centroid} = \left[\frac{1}{K}\sum_{j=1}^{K} X_j \quad \frac{1}{K}\sum_{j=1}^{K} Y_j\right]$

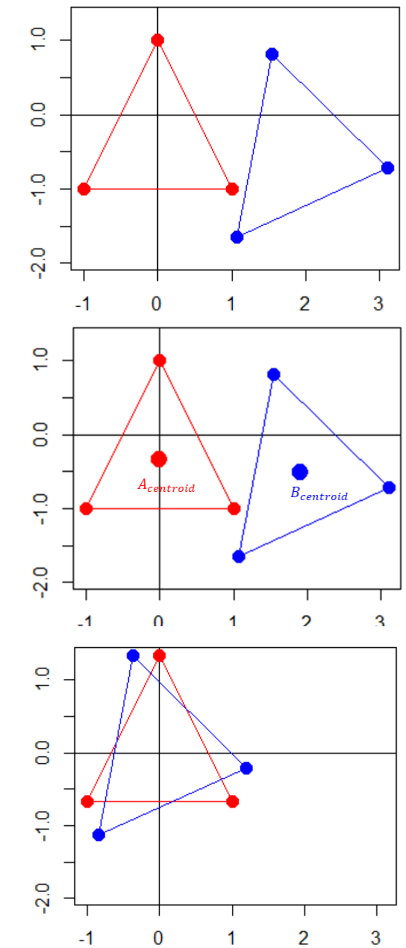
$A_{centroid} = [0 \quad -0.333]$ $\qquad B_{centroid} = [1.907 \quad -0.513]$

(2) Subtract centroid coordinates from each landmark

$$A_{centered} = \begin{bmatrix} -1 & -1 \\ 1 & -1 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & -0.333 \\ 0 & -0.333 \\ 0 & -0.333 \end{bmatrix} = \begin{bmatrix} -1 & -0.667 \\ 1 & -0.667 \\ 0 & 1.333 \end{bmatrix}$$

$$B_{centered} = \begin{bmatrix} 1.07 & -1.64 \\ 3.10 & -0.72 \\ 1.55 & 0.82 \end{bmatrix} - \begin{bmatrix} 1.907 & -0.513 \\ 1.907 & -0.513 \\ 1.907 & -0.513 \end{bmatrix} = \begin{bmatrix} -0.837 & -1.127 \\ 1.193 & -0.207 \\ -0.357 & 1.333 \end{bmatrix}$$

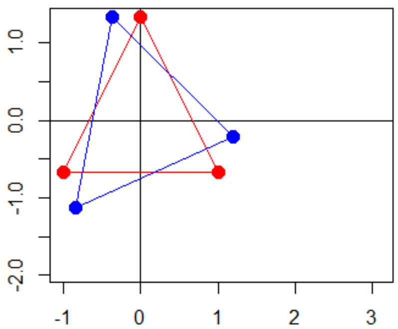
We have lost 2 degrees of freedom (configurations do not differ by the x and y position of their centroid)



Procrustes superimposition

Take out the effect of the position, size and rotation

$$A_{centered} = \begin{bmatrix} -1 & -0.667 \\ 1 & -0.667 \\ 0 & 1.333 \end{bmatrix} \qquad B_{centered} = \begin{bmatrix} 1.07 & -1.64 \\ 3.10 & -0.72 \\ 1.55 & 0.82 \end{bmatrix}$$



Size – scale to the same (unit) centroid size

(1) Calculate centroid size of each configuration as the square root of the sum of the squared distances of the landmarks from the centroid: $CS(X) = \sqrt{\sum_{i=1}^{K}\sum_{j=1}^{M}(X_{ij} - C_j)^2}$

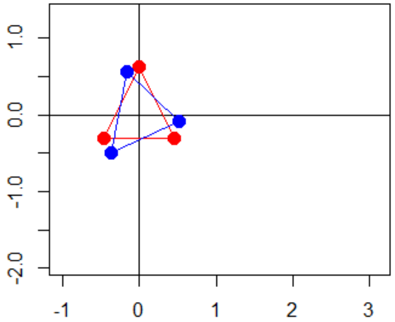
$$CS(A_{centered}) = \sqrt{(-1.0)^2 + (-0.667)^2 + (1.0)^2 + (-0.667)^2 + (0)^2 + (1.333)^2} = 2.160$$

$$CS(B_{centered}) = \sqrt{(-0.837)^2 + (1.127)^2 + (1.193)^2 + (0.207)^2 + (-0.357)^2 + (1.333)^2} = 2.311$$

(2) Divide each coordinate of the centered triangle by its centroid size

$$A_{centred-scaled} = \frac{1}{2.160}\begin{bmatrix} -1 & -0.667 \\ 1 & -0.667 \\ 0 & 1.333 \end{bmatrix} = \begin{bmatrix} -0.463 & -0.309 \\ 0.463 & -0.309 \\ 0.000 & 0.617 \end{bmatrix}$$

$$B_{centered-scaled} = \frac{1}{2.311}\begin{bmatrix} -0.837 & -1.127 \\ 1.193 & -0.207 \\ -0.357 & 1.333 \end{bmatrix} = \begin{bmatrix} -0.362 & -0.488 \\ 0.516 & -0.089 \\ -0.154 & 0.557 \end{bmatrix}$$



We have lost 1 degree of freedom (configurations do not differ by their size)

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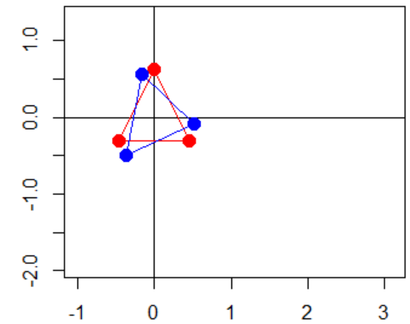
Procrustes superimposition

Take out the effect of the position, size and rotation

$$A_{centred-scaled} \begin{bmatrix} -0.463 & -0.309 \\ 0.463 & -0.309 \\ 0.000 & 0.617 \end{bmatrix} \quad B_{centered-scaled} = \begin{bmatrix} -0.362 & -0.488 \\ 0.516 & -0.089 \\ -0.154 & 0.557 \end{bmatrix}$$



Rotation – rotate until distances between landmarks are minimal

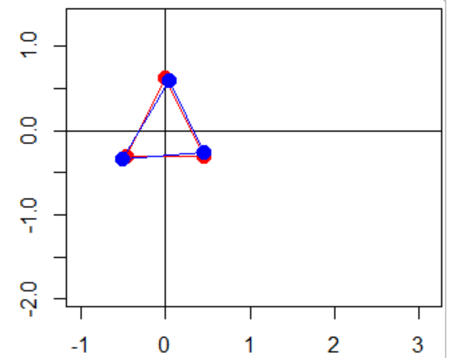
(1) Fix one configuration (here A) and rotate the second (B) until distances between landmarks are minimal, get angle of the rotation. (this step is calculated by computer)

$\theta = -19.2^{o}$

(2) Rotate the second configuration by the angle theta

$$B_{centered-scaled-rotated} = \begin{bmatrix} (-0.362\cos\theta) - (-0.488\sin\theta) & (-0.362\sin\theta) + (-0.488\cos\theta) \\ (0.516\cos\theta) - (-0.089\sin\theta) & (0.516\sin\theta) + (-0.089\cos\theta) \\ (-0.154\cos\theta) - (0.577\sin\theta) & (-0.154\sin\theta) + (0.577\cos\theta) \end{bmatrix}$$

$$= \begin{bmatrix} -0.502 & -0.341 \\ 0.458 & -0.254 \\ 0.044 & 0.596 \end{bmatrix}$$



We have lost 1 degree of freedom (configurations do not differ by their rotation)

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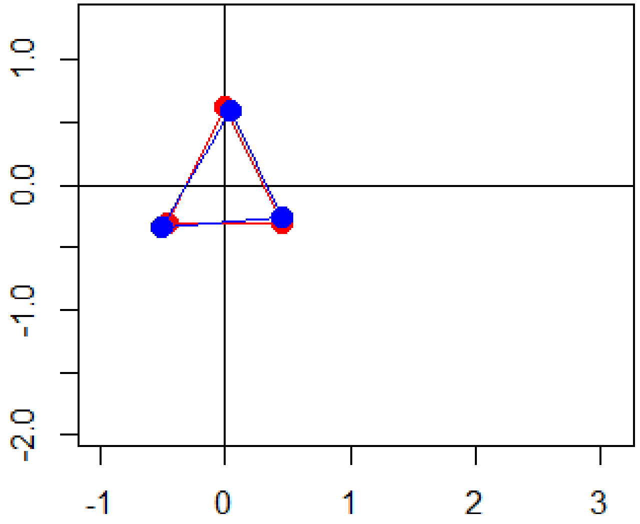
Procrustes superimposition

Take out the effect of the position, size and rotation

$$A_{centred-scaled}\begin{bmatrix}-0.463 & -0.309\\ 0.463 & -0.309\\ 0.000 & 0.617\end{bmatrix} \quad B_{centered-scaled-rotated}=\begin{bmatrix}-0.502 & -0.341\\ 0.458 & -0.254\\ 0.044 & 0.596\end{bmatrix}$$

Distance between configurations is the **Partial Procrustes Distance**

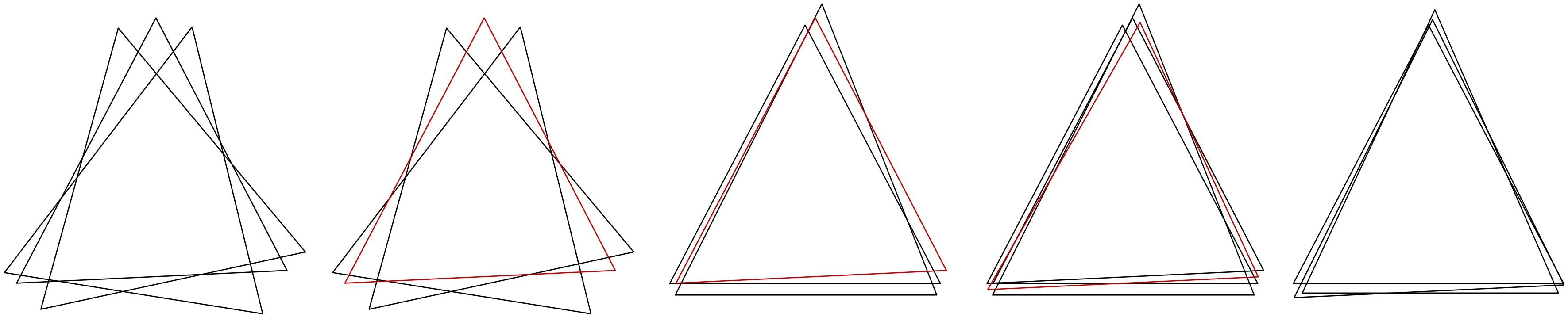
$$D_p=\sqrt{\begin{matrix}(-0.502-(-0.463))^2+(-0.341-(-0.309))^2+(0.458-0.463)^2\\ +(-0.254-(-0.309))^2+(0.044-0)^2+(0.596-617)^2\end{matrix}}$$
$$=0.089$$



General Procrustes Analysis (GPA)

Principles with more then 2 configurations

(1) Shift to origin
(2) Scale to CS=1
(3) Choose one configuration as Template form
(4) Rotate all configurations to minimize distances with Template form
(5) Calculate mean-shape and set is as Template form
(6) Iterate steps (4) to (5) until convergence.



(2) **(3)** **(4)** **(5)** **final**

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What we can actually do?

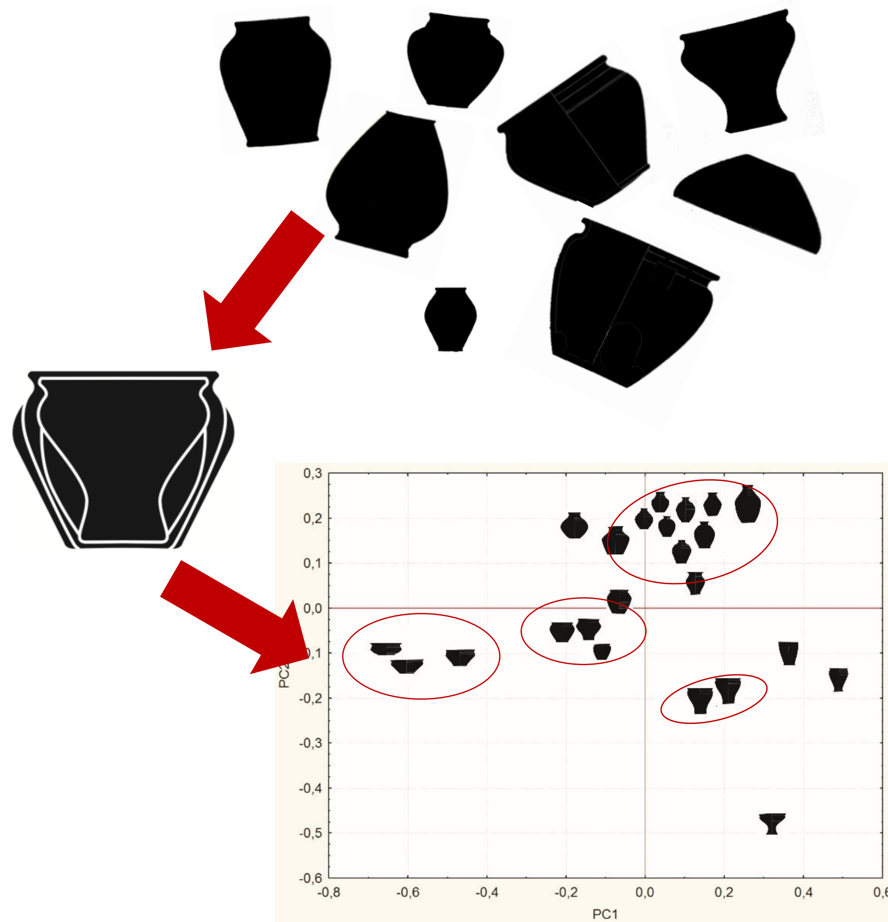
1) Data collection

2) Standardisation

(position, size and orientation)

3) Calculation of shape variables

4) Data treatment and visualisation



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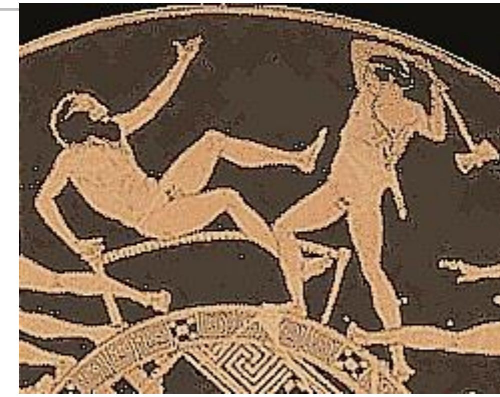
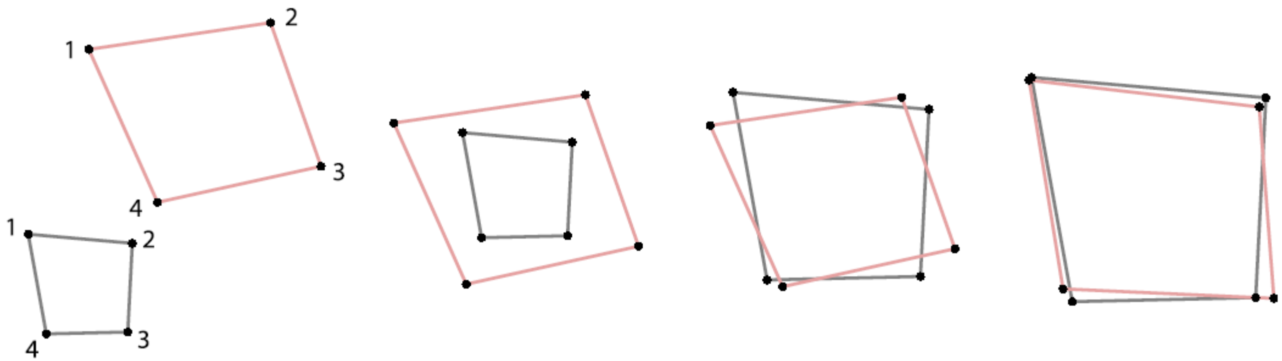
General Procrustes Analysis (GPA)



Procrustes coordinates
Partial Procrustes distances
Full Procrustes distances

We have lost 4 degrees of freedom
- 2 for translation, 1 for scaling, 1 for rotation
- Need adjustments in statistical tests !!!



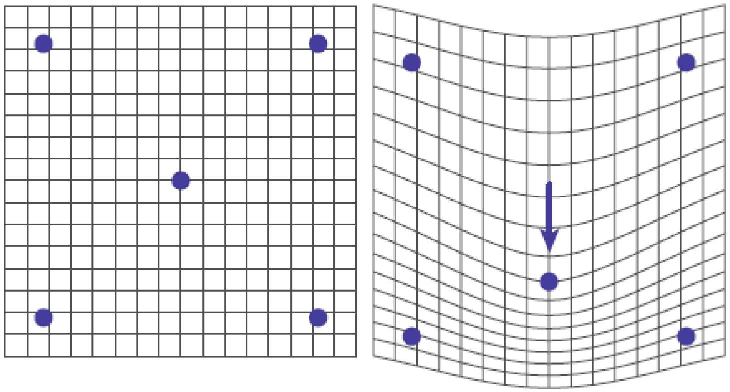
raw landmarks | centered landmarks | centered and scaled landmarks | centered, scaled, and rotated lms

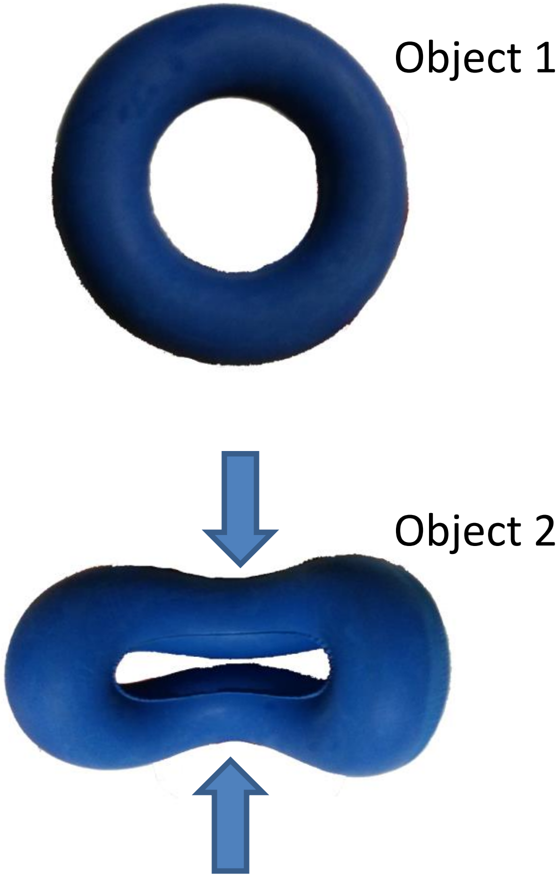
Mitteroecker and Gunz, 2009

Thin-Plate Splines (TPS)

The quantity and direction of energy required to deform one object to another can give information about their similarities

Transformation grid – invented by Albrecht Dürer and rediscovered by D'Arcy Thompson





Mitteroecker and Gunz, 2009

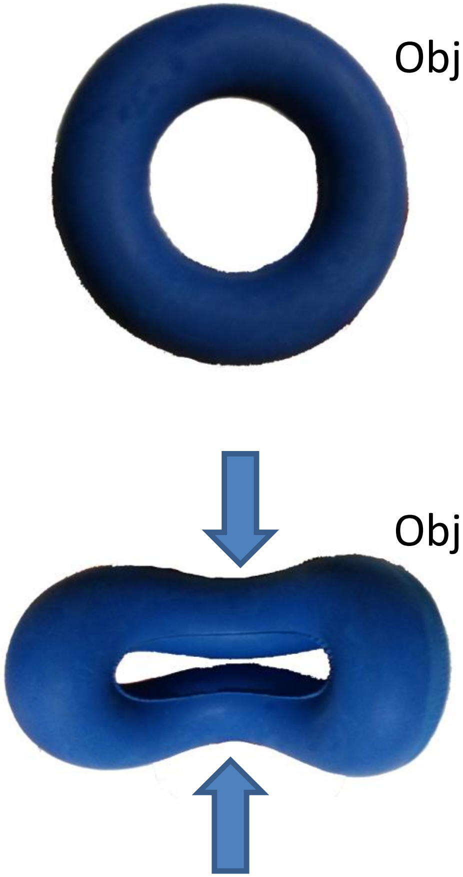
Thin-Plate Splines (TPS)

Advantages

- used in combination with Procrustes
- we can take into account what happens between landmarks
- coefficients of TPS (partial warp scores) can be used in conventual statistical test without adjustment of degrees of freedom

Not the best when

- landmarks are far from another
- when changes in shape are very local (mouse teeth)



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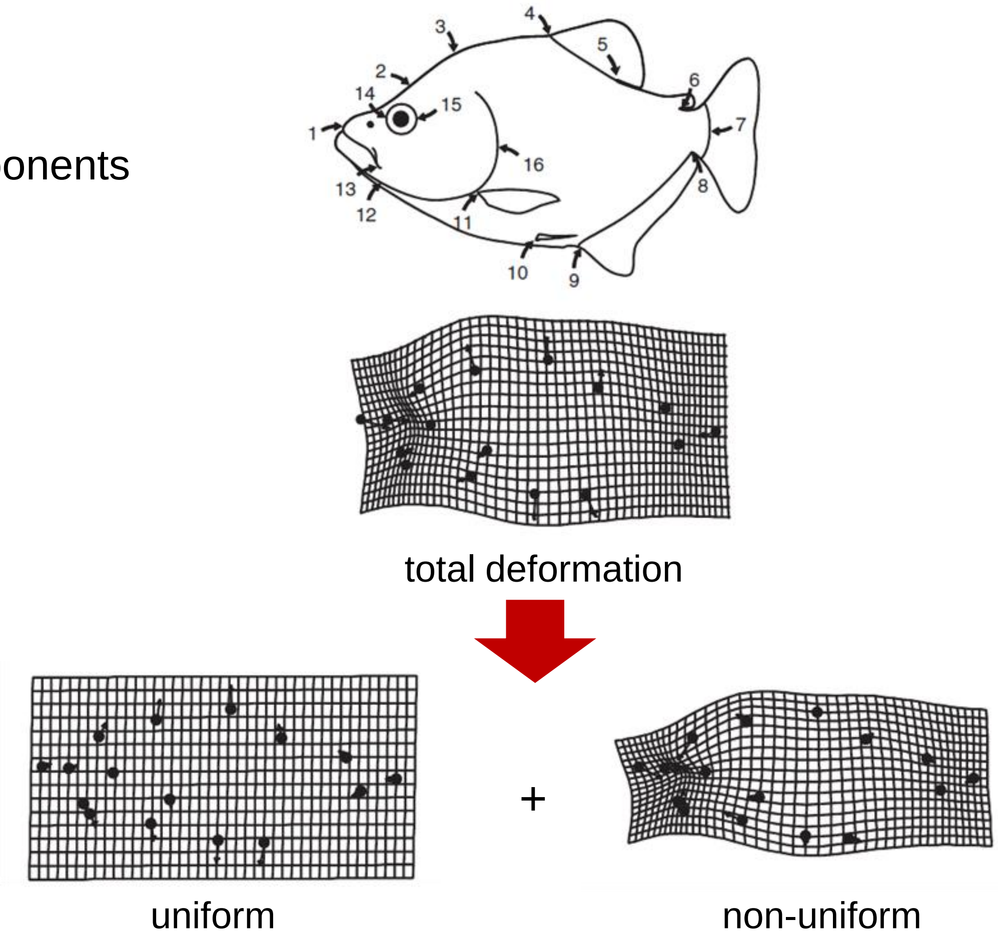
Thin-Plate Splines (TPS)

2 components of deformation

- Uniform (affine) and non-uniform
- Entire description requires all components



Zelditch et al., 2004

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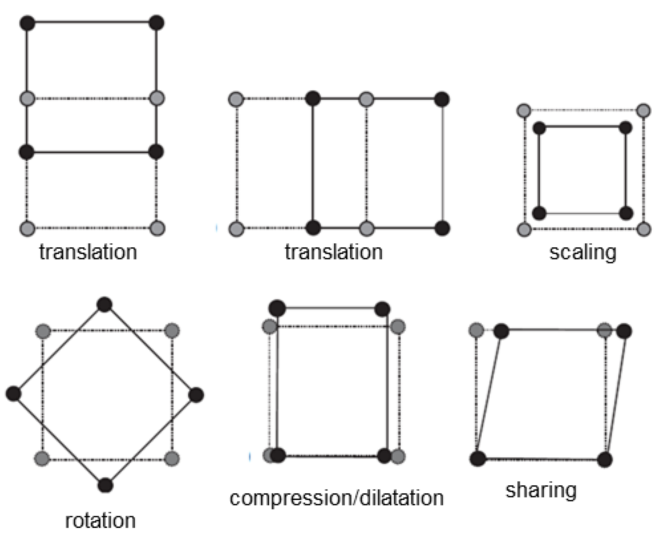
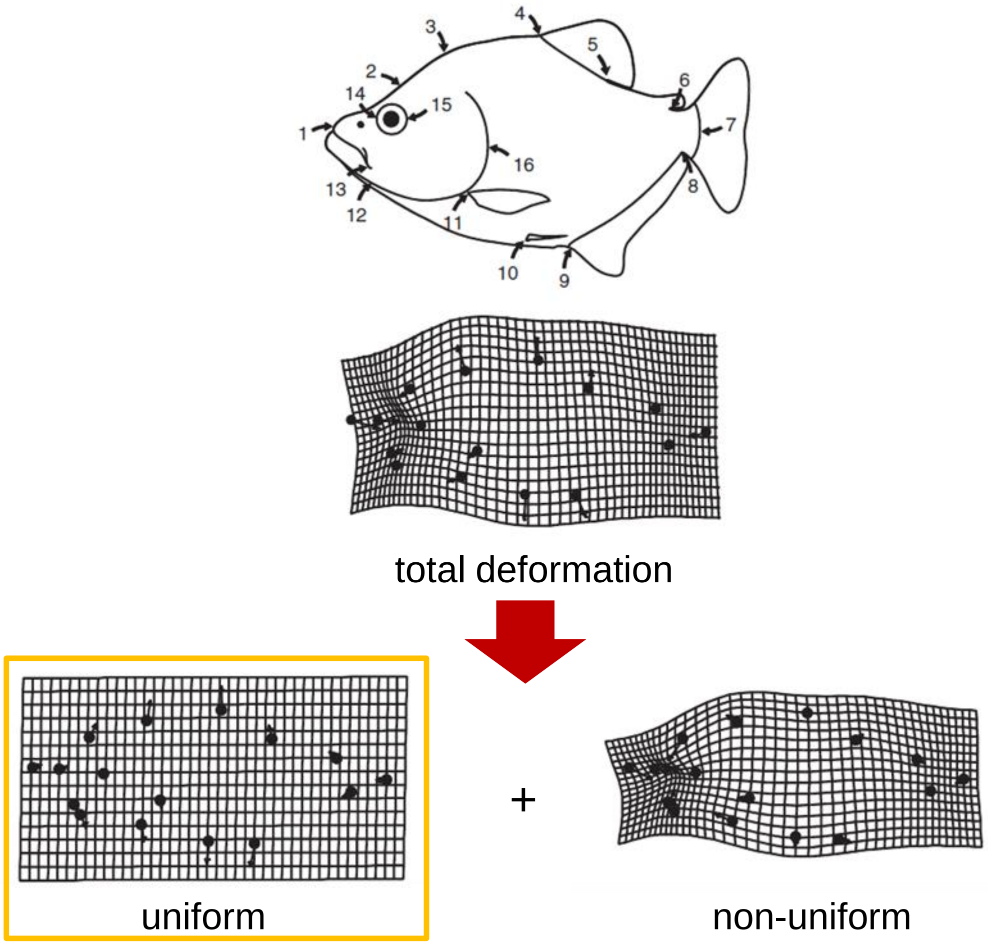
Thin-Plate Splines (TPS)

Uniform (affine) components
- let parallel lines parallel
- 6 types
- they are independent/orthogonal
- do not need bending energy
- 2 of them change the shape





Zelditch et al., 2004

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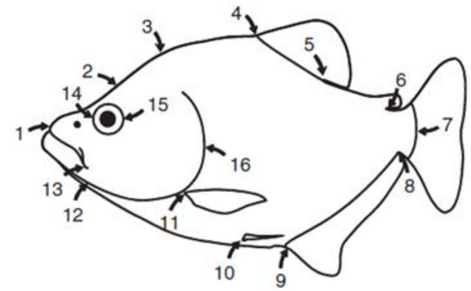
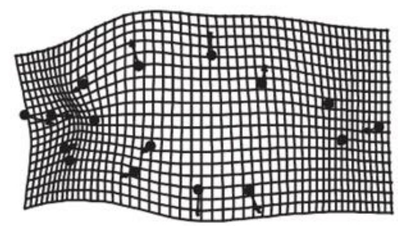
Thin-Plate Splines (TPS)

Non-uniform (non-affine) components

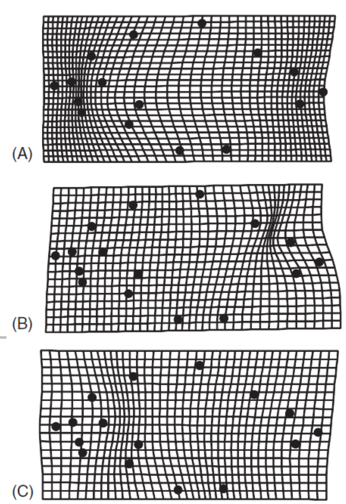
- do not let parallel lines parallel
- they are independent/orthogonal
- components are named **Partial warps (PW)**
- **each PW** is multiplied by a 2D vector **Partial warp scores**
- **Partial warp scores** express contribution of each Partial warp to the total deformation
- the combination of all Partial warps must be taken for description and interpretation

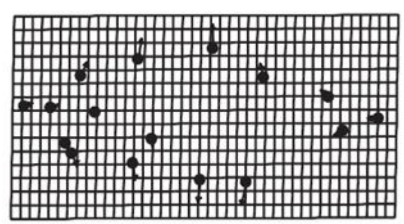




total deformation

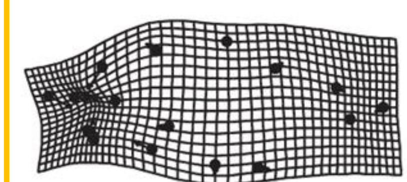
Example of 3 partial warps





uniform

+



non-uniform

Zelditch et al., 2004

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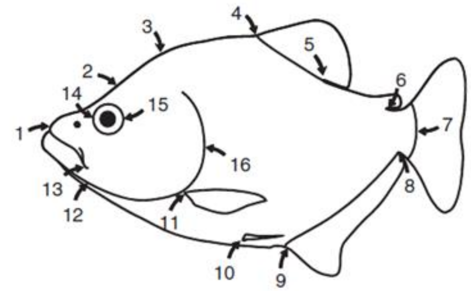
Thin-Plate Splines (TPS)

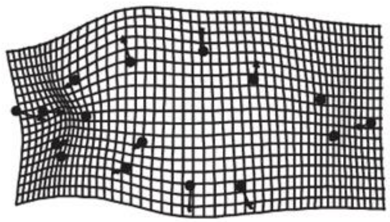
Using TPS

Combination of the uniform and non-uniform components completely describes any shape change

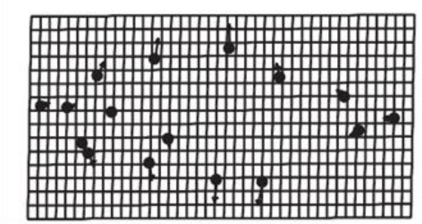
The set of Partial warp scores can be used in any conventional statistical analyses

Correct degrees of freedom => no need adjustment





total deformation



uniform

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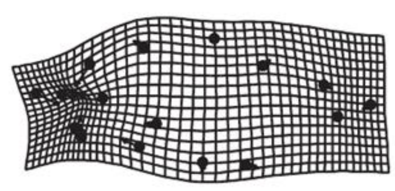


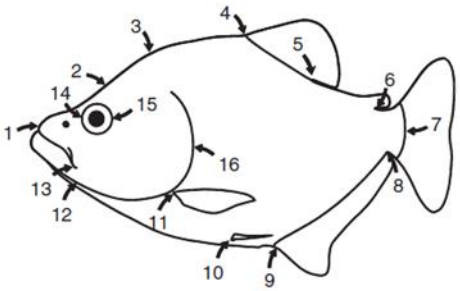
non-uniform

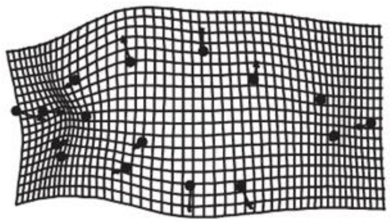
Zelditch et al., 2004

Using TPS

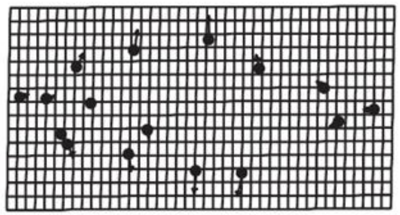
Relative warps analysis (RWA)

- Principal components of Partial Warp Scores, sometimes weighted to emphasize components of low or high bending energy
- key is the value alpha (α) which corresponds to a factor multiplying Partial Warp Scores
  - if $\alpha = 0$: PW are not weighted (RWA is PCA)
  - $\alpha > 0$: PW with lower bending energy are weighted highly
  - $\alpha < 0$: PW with greater bending energy are weighted highly
  - usually





total deformation



uniform

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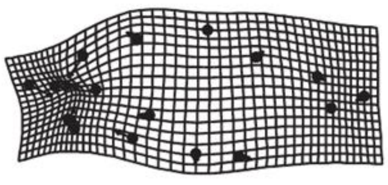

non-uniform

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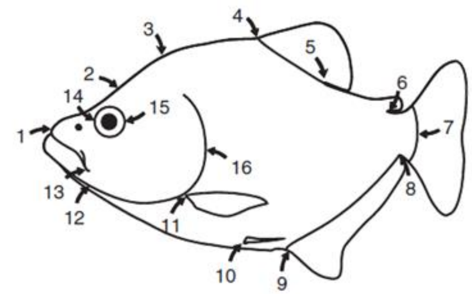
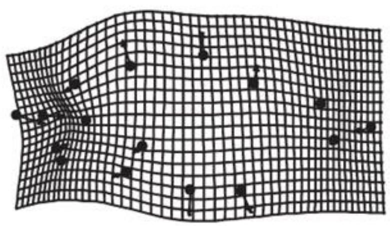
Thin-Plate Splines (TPS)

Interpreting changes by TPS

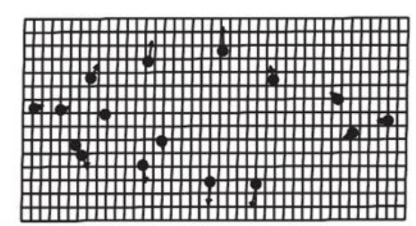
- Interpretations should be presented in terms of the total deformation (not by separating uniform and non-uniform components)

- Attention (!) changes depicted are based on an interpolation function – we do not actually know what occurs between landmarks





total deformation



uniform

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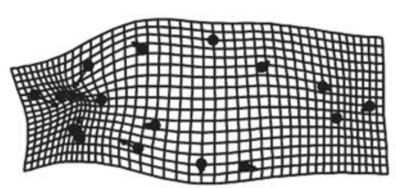

non-uniform

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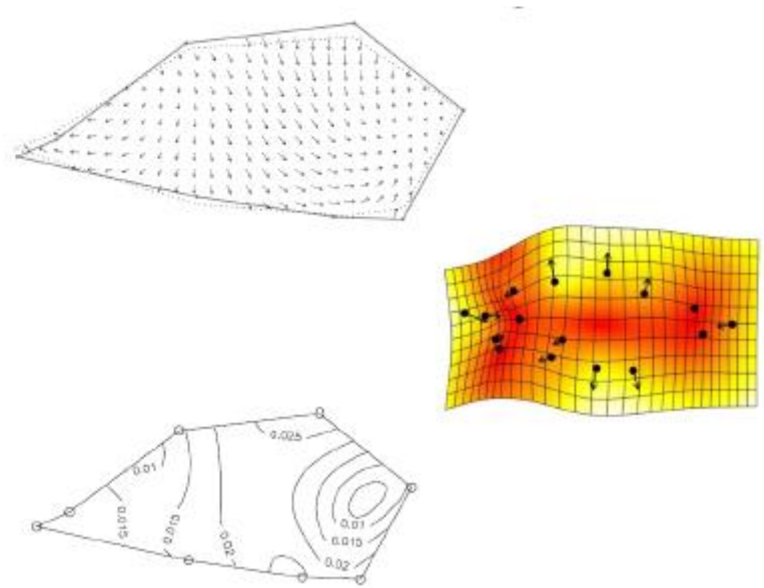
Thin-Plate Splines (TPS)

Visualisation of deformation

- Landmarks
- Arrows
- Lollipops
- Deformation grids
- Vector displacement
- Heat maps
- Isobars



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