**Supplementary Information for: A method for mapping morphological convergence on three-dimensional digital models: the case of the mammalian saber-tooth**

Melchionna M.1, Profico A.2, Castiglione S.1, Serio C.3, Mondanaro A.4, Modafferi, M. 1, Tamagnini, D.5, Maiorano, L.5, Raia P.1\*, Witmer L.M.6, Wroe S.7, Sansalone G.7

1 *Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse. Università di Napoli Federico II, 80126, Napoli, Italy*

2 *PalaeoHub, Department of Archaeology and Hull York Medical School University of York, Heslington, UK*

3 *Research Centre in Evolutionary Anthropology and Palaeoecology, School of Biological and Environmental Sciences, Liverpool John Moores University, Liverpool, England*

4 *Dipartimento di Scienze della Terra. Università degli studi di Firenze, 50121 Firenze, Italy*

*5* *Department of Biology and Biotechnologies “Charles Darwin”, University of Rome “La Sapienza”, viale dell’Università 32, 00185 Roma.*

*6* *Department of Biomedical Sciences, Ohio University Heritage College of Osteopathic Medicine, Ohio Center for Ecology and Evolutionary Studies, Athens, OH 45701, USA*

7 *Function, Evolution & Anatomy Research Lab, Zoology Division, School of Environmental and Rural Science, University of New England, NSW, 2351, Armidale, Australia*

**Corresponding author:** Pasquale Raia, email: [pasquale.raia@unina.it](mailto:pasquale.raia@unina.it). Address: DiSTAR, Via Cinthia, 21 - 80126, Monte Sant’Angelo, Napoli, Università di Napoli Federico II

**SUPPLEMENTARY MATERIAL AND METHODS**

*Phylogenetic tree in Newick format*

((Thylacosmilus\_atrox:105.7,(Thylacoleo\_carnifex:61.9536,(Thylacinus\_cynocephalus:39.9999,(Dasyurus\_hallucatus:5.3,(Dasyurus\_maculatus:4,Sarcophilus\_harrisii:4):4):32):22):47):50,(Barbourofelis\_fricki:25,(((((((((Felis\_chaus:3.5,(Felis\_margarita:2.8,(Felis\_silvestris:2.5,Felis\_bieti:2.5):0.3):0.7):6,(Otocolobus\_manul:5.9,(Prionailurus\_planiceps:3,((Prionailurus\_bengalensis:2,Mayailurus\_iriomotensis:2):0.5,Prionailurus\_viverrinus:2.5):0.5):2.9):3.6):0.5,(Acinonyx\_jubatus:5,(Herpailurus\_yaguaroundi:4.2,Puma\_concolor:4.2):0.8):5):0.5,(Lynx\_issiodorensis:4.5,(Lynx\_rufus:4.7,(Lynx\_canadensis:3.1,(Lynx\_lynx:3,Lynx\_pardinus:3):0.1):1.6):0.6):5.2):0.5,((Leopardus\_pardalis:1.6,Leopardus\_wiedii:1.6):3.4,(((Leopardus\_colocolo:1.5,Leopardus\_pajeros:1.5):0.5,Leopardus\_jacobita:2):0.5,(Leopardus\_tigrinus:1,Leopardus\_geoffroyi:1):1.5):2.5):6):0.5,(Leptailurus\_serval:6,(Caracal\_caracal:4.2,Caracal\_aurata:4.2):1.8):5.5):1,(Pardofelis\_marmorata:6,Catopuma\_temminckii:6):6.5):1.5,((Neofelis\_nebulosa:1.5,Neofelis\_diardi:1.5):7,((Panthera\_uncia:6.4,Panthera\_tigris:6.4):0.6,(Panthera\_onca:4.2,(Panthera\_pardus:4,(Panthera\_leo:2,(Panthera\_spelaea:1.886,Panthera\_atrox:1.89):0.1):2):0.2):2.8):1.5):5.5):8,(Homotherium\_serum:13.99,((Smilodon\_fatalis:2,Smilodon\_californicus:2):10.99,Yoshi\_garevskii:7.7):1):8):10):127);

The felids tree was taken from Castiglione *et al.* (2019; available in the RRphylo R package), modified, and integrated by adding the following species: *Felis bieti* (Mattucci *et al.,* 2019*), Homotherium serum* (as sister to *Homotherium latidens*), *Leopardus jacobita* (Cuff *et al.,* 2015), *Leopardus pajeros* (close to *Leopardus colocolo*), *Mayailurus iriomotensis* (Masuda & Yoshida, 1995), *Smilodon californicus* (sister to *Smilodon fatalis*), *Yoshi garevskii* (sister to *Yoshi minor*). Phylogenetic relationships of metatherians were taken from Wroe *et al.* (2000), and Roberts *et al.* (2001).

Table S1. List of used specimens with ID code, sex and museum location. F = female, M = male, U = unknown.

|  |  |  |  |
| --- | --- | --- | --- |
| **ID** | **Species** | **Sex** | **Museum** |
| MZUF-1831 | *Acinonyx jubatus* | F | Museo di storia naturale "La Specola" (Florence) |
| MZUF-2135 | *Acinonyx jubatus* | M | Museo di storia naturale "La Specola" (Florence) |
|  | *Barbourofelis fricki* | U | courtesy of Jorge Morales |
| MNHN.CG1939.687 | *Caracal aurata* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1940-1213 | *Caracal aurata* | M | Muséum National d'Histoire Naturelle (Paris) |
| MZUF-1752 | *Caracal caracal* | M | Museo di storia naturale "La Specola" (Florence) |
| MNHN.CG1939.2152 | *Catopuma temminckii* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1962-2927 | *Catopuma temminckii* | M | Muséum National d'Histoire Naturelle (Paris) |
| TMM M-6921 | *Dasyurus hallucatus* | U | Digimorph |
| UNSW\_Z20 | *Dasyurus maculatus* | U | University of New South Wales (Sydney) |
| MNHN.CG1893-151 | *Felis bieti* | U | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG2015-1302 | *Felis chaus* | F | Muséum National d'Histoire Naturelle (Paris) |
| IMNH.R-938 | *Felis margarita* | U | Idaho Museum of Natural History (Pocatello) |
| MNHN.CG1995-448 | *Felis silverstris* | F | Muséum National d'Histoire Naturelle (Paris) |
| SAP.ZOO.84 | *Felis silvestris* | M | Museum of Zoology, Sapienza University of Rome |
| ha0066 | *Felis silvestris* | U | Museum of Comparative Anatomy, Sapienza University of Rome |
| MNHN.CG2001-1292 | *Herpailurus yaguaroundi* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1966-7 | *Herpailurus yaguaroundi* | M | Muséum National d'Histoire Naturelle (Paris) |
| TMM.933-3444 | *Homotherium serum* | U | Texas Memorial Museum (Austin) |
| MNHN.CG1897-1261 | *Leopardus colocolo* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1912-748 | *Leopardus geoffroyi* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG2006-546 | *Leopardus jacobita* | U | Muséum National d'Histoire Naturelle (Paris) |
| MLP.1913 | *Leopardus pajeros* | U | Museo de Ciencias Naturales (La Plata) |
| MNHN.CG1998-1866 | *Leopardus pardalis* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CH1902-50 | *Leopardus pardalis* | M | Muséum National d'Histoire Naturelle (Paris) |
| SAP.ZOO.Aula\_A | *Leopardus pardalis* | U | Museum of Zoology, Sapienza University of Rome |
| MNHN.CG2006-542 | *Leopardus tigrinus* | F | Museo di storia naturale "La Specola" (Florence) |
| IMNH.R-601 | *Leopardus wiedii* | F | Museo di storia naturale "La Specola" (Florence) |
| ac0141 | *Leptailurus serval* | U | Museum of Comparative Anatomy, Sapienza University of Rome |
| MNHN.CG1995-452 | *Leptailurus serval* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1958-164 | *Leptailurus serval* | M | Muséum National d'Histoire Naturelle (Paris) |
| IMNH.R-213 | *Lynx canadensis* | F | Idaho Museum of Natural History (Pocatello) |
| UWBM80612 | *Lynx canadensis* | M | Burke Museum of Natural History and Culture (Seattle) |
| MNCN63887 | *Lynx issiodorensis* | U | Museo Nacional Ciencias Naturales (Madrid) |
| MG-2-2013\_852 | *Lynx lynx* | F | Museo di storia naturale "La Specola" (Florence) |
| MG-2-2013\_839 | *Lynx lynx* | M | Museo di storia naturale "La Specola" (Florence) |
| MNCN16784 | *Lynx pardinus* | U | Museo Nacional Ciencias Naturales (Madrid) |
| MNHN.CG2012-1024 | *Lynx rufus* | F | Muséum National d'Histoire Naturelle (Paris) |
| UV.155 | *Lynx rufus* | M | Museum of the University of Victoria Biology department |
| UWBM32046 | *Lynx rufus* | M | Burke Museum of Natural History and Culture (Seattle) |
| IMNH.R-115 | *Lynx rufus* | U | Idaho Museum of Natural History (Pocatello) |
| Z-774 | *Mayailurus iriomotensis* | M | Digital Morphology Museum, KUPRI |
| MNHN.CG1879-2133 | *Neofelis diardi* | M | Muséum National d'Histoire Naturelle (Paris) |
| 030608\_UNSW | *Neofelis nebulosa* | U | University of New South Wales (Sydney) |
| MNHN.CG1971-86 | *Neofelis nebulosa* | F | Muséum National d'Histoire Naturelle (Paris) |
| MZUF-1024 | *Neofelis nebulosa* | M | Museo di storia naturale "La Specola" (Florence) |
| MNHN.CG2009.251 | *Otocolobus manul* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG2010-646 | *Otocolobus manul* | M | Muséum National d'Histoire Naturelle (Paris) |
| CB2900-3 | *Panthera atrox* | U | Natural History Museum of Los Angeles County (L.A.) |
| MVZ-117849 | *Panthera leo* | U | Digimorph |
| MNHN.A12259 | *Panthera leo* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1938-632 | *Panthera leo* | M | Muséum National d'Histoire Naturelle (Paris) |
| ab0030 | *Panthera leo* | U | Museum of Comparative Anatomy, Sapienza University of Rome |
| ab0031 | *Panthera leo* | U | Museum of Comparative Anatomy, Sapienza University of Rome |
| DUNUC2021 | *Panthera leo* | U | D’Arcy Thompson Zoology Museum (Dundee) |
| MVZ.117849 | *Panthera leo* | U | University of California Museum of Vertebrate Zoology (Berkeley) |
| PRIZ2078 | *Panthera leo* | U | Primate Research Institute, Kyoto University |
| SAP.ZOO.Sala\_lettura | *Panthera leo* | U | Museum of Zoology, Sapienza University of Rome |
| MNHN.CG1962-2880 | *Panthera onca* | F | Muséum National d'Histoire Naturelle (Paris) |
| MZUF-501 | *Panthera onca* | M | Museo di storia naturale "La Specola" (Florence) |
| D.2-1.11.1853 | *Panthera onca* | U | Museu de Ciències Naturals (Barcelona) |
| MZB2003-1528 | *Panthera onca* | U | Primate Research Institute, Kyoto University |
| PRIZ890 | *Panthera onca* | U | World Museum (Liverpool) |
| LACM-11704 | *Panthera pardus* | M | Digimorph |
| MNHN.CG1998-1249 | *Panthera pardus* | M | Muséum National d'Histoire Naturelle (Paris) |
| 18.5.97.4 | *Panthera pardus* | U | World Museum (Liverpool) |
| IMNH.### | *Panthera spelaea* | U | Idaho Museum of Natural History (Pocatello) |
| MNHN.CG1895-355 | *Panthera tigris* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1985-1860 | *Panthera tigris* | M | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG2016-1664 | *Panthera uncia* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1998-1248 | *Panthera uncia* | M | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1886-25 | *Pardofelis marmorata* | U | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1954-293 | *Prionailurus bengalensis* | F | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG1873-228 | *Prionailurus planiceps* | U | Muséum National d'Histoire Naturelle (Paris) |
| MNHN.CG2015-1300 | *Prionailurus viverrinus* | F | Muséum National d'Histoire Naturelle (Paris) |
| ab0037 | *Puma concolor* | U | Museum of Comparative Anatomy, Sapienza University of Rome |
| UV.4117 | *Puma concolor* | F | Museum of the University of Victoria Biology department |
| LACM-87430 | *Puma concolor* | M | Digimorph |
| MNHN.CG1926-250 | *Puma concolor* | M | Muséum National d'Histoire Naturelle (Paris) |
| IMNH.R-27 | *Puma concolor* | U | Idaho Museum of Natural History (Pocatello) |
| ISM.ZOO.693928 | *Puma concolor* | U | Illinois State Museum (Springfield) |
| MZB2003-1534 | *Puma concolor* | U | Museu de Ciències Naturals (Barcelona) |
| PRIZ891 | *Puma concolor* | U | Digital Morphology Museum, KUPRI |
| AM10756 | *Sarcophilus harrisii* | U | Australian Museum (Sydney) |
| ZD 2003.331 | *Sarcophilus harrisii* | U | Morphosource |
| BCGD27000 | *Smilodon californicus* | U | Beloit College Museum (Winsconsin) |
| F.AM.14349 | *Smilodon fatalis* | U | American Museum of Natural History (New York) |
| AM1821 | *Thylacinus cynocephalus* | U | Australian Museum (Sydney) |
| ZE\_1963\_8\_30\_1 | *Thylacinus cynocephalus* | U | Morphosource |
| AM F52398-1 | *Thylacoleo carnifex* | U | Australian Musem (Sydney) |
| UCLA-VP 366 | *Thylacosmilus atrox* | U | Natural History Museum of Los Angeles County (Los Angeles, California, USA) |
| MMNH-Sk-69 | *Yoshi garevskii* | U | Macedonian Museum of Natural History (Skopje) |

Table S2. Anatomical definition of sampled landmarks on each specimen.

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| --- | --- |
| **Number** | **Landmark definition** |
| 1 and 2 | Alveolar margin at the posterior aspect of the last incisor (right and left side) |
| 3 and 4 | Alveolar margin at the posterior aspect of the canine (right and left side) |
| 5 and 6 | Frontal zygomatic process (right and left side) |
| 7 and 8 | Post-orbital constriction (right and left side) |
| 9 and 10 | End of supraorbital margin (right and left side) |
| 11 and 12 | Margin of the nasal aperture (right and left side) |
| 13 and 14 | Infraorbital foramen (right and left side) |
| 15 and 16 | Alveolar margin at the posterior aspect of the last molar |
| 17 | Interpremaxillary suture at the alveolar margin |
| 18 | Anterior point of midline between nasals |
| 19 | Topmost point of the nuchal crest |
| 20 | Interpremaxillary suture at the inferior margin of the nasal aperture |
| 21 and 22 | Lacrimal-maxilla contact (right and left side) |
| 23 and 24 | Inferiormost point of the orbit (right and left side) |
| 25 and 26 | Root of the zygomatic arch (right and left side) |
| 27 and 28 | Mastoid process (right and left side) |
| 29 and 30 | Interparietal process (right and left side) |
| 31 and 32 | Point at occipital-parietal-temporal suture (right and left side) |

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Fig. S1. Landmark configuration (blue) and semilandmark patch (yellow) used in the analysis.

*Retrodeformation*

The specimen of *Barbourofelis fricki* suffers from latero-lateral distortions and compressions which altered the proportion of the specimen. To restore the specimen symmetry, we performed the retrodeformation procedure, as described in Schlager *et al.* (2018), by using 56 manually sampled bilateral landmarks. Even if the canines have not been aligned, the overall skull morphology appears symmetric and less compressed (Fig. S2).

The specimen of *Homotherium serum* shows a right dorso-left ventral flattening and loss of symmetry. To restore the specimen, we manually sampled 46 bilateral landmarks. The retrodeformation procedure successfully restored the sample symmetry (Fig. S3).

Fig. S2. The process of retrodeformation on *Barbourofelis fricki*. A-B, the specimen before and after the retrodeformation process. C, the original specimen showing the modified areas during the retrodeformation in terms of expansion (blue) and contraction (red).

Fig. S3. The process of retrodeformation on *Homotherium serum*. A-B, the specimen before and after the retrodeformation process. C, the original specimen showing the modified areas during the retrodeformation in terms of expansion (blue) and contraction (red).

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Fig. S4. Illustration of the workflow followed to perform *conv.map*. A. We first performed a Principal Component Analysis on the sample. B. We used the *search.conv* function (‘RRphylo’ R package) to identify convergent species. C. We performed a Relative Warp Analyses on the shape data, setting the alpha parameter to 1. The RW scores obtained by RWA were fed to conv.map to select the axes best-embodying convergence, by using the *ede* function (‘inflection’ R package). After the RW axes were selected, their scores were used to compute pairwise angle distances between species. D. *conv.map* plots highlighting the areas responsible for convergence (in blue).

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