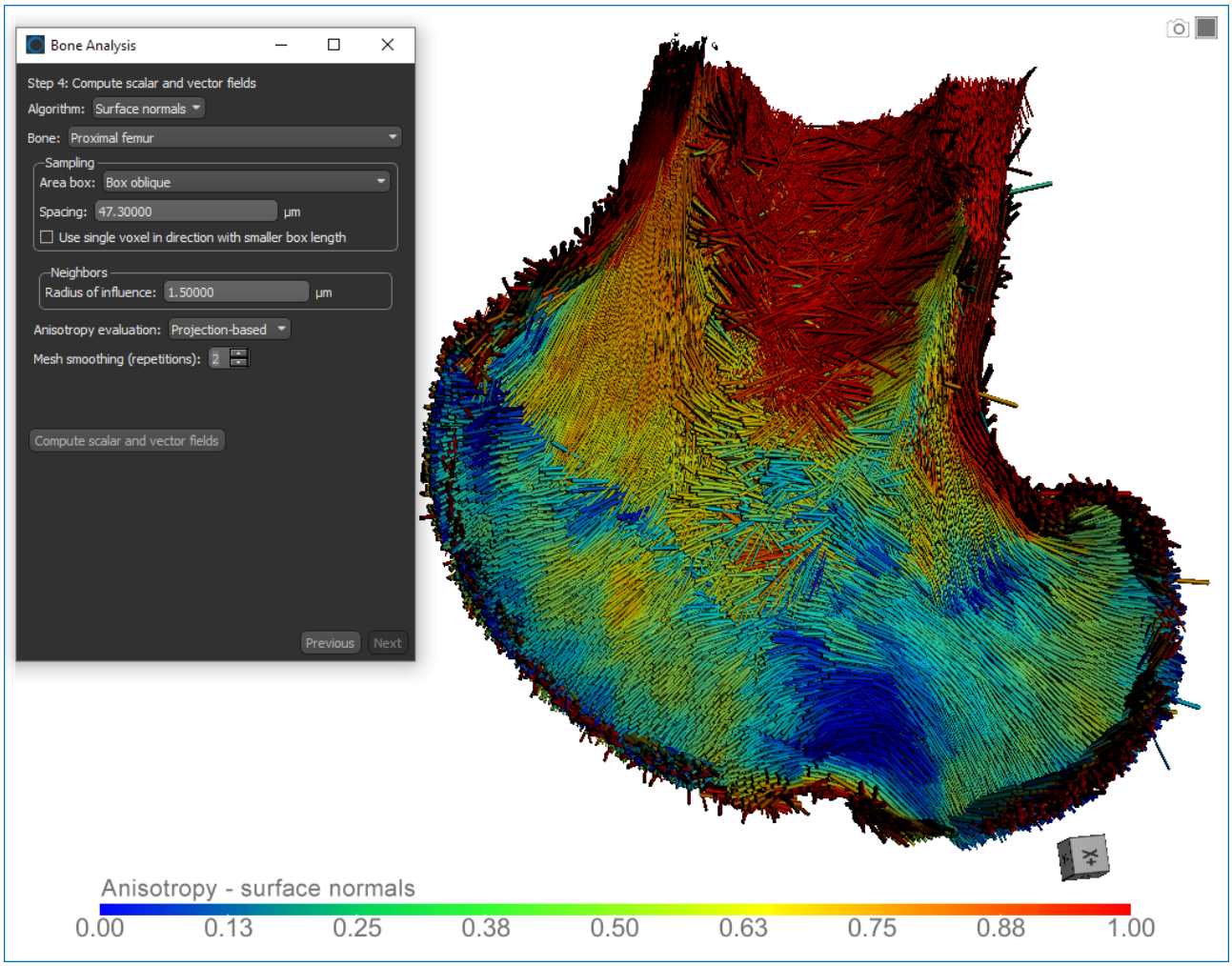
DRAGONFLY BONE ANALYSIS

Three-dimensional mapping of trabecular anisotropy and volume fraction



Local surface anisotropy vector field, in which assigned colors represent magnitude, and the Dragonfly Bone Analysis dialog.

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This application note describes and illustrates 3D mapping of anisotropy, which is a special feature of Dragonfly's Bone Analysis module that can facilitate investigations of the associations between observed structural features and the mechanical function of a bone.

Anisotropy (Greek: "an" - non; "iso" - equal; "tropos" - way) – the opposite of isotropy – is a property of having a certain texture, or preferred orientation, of the components within a whole structure. It is presented as a 3D vector field in Dragonfly, the density of which is configurable.

This publication also discusses 3D mapping of bone volume fraction, which is presented as averaged, scalar values that reflect trabecular density and can be used as a proxy for bone strength.

Anisotropy of trabecular bone

Biomechanical significance of anisotropy

Anisotropy of trabecular bone is a result of life-long functional adaptation. Anisotropy physiologically increases from infancy to maturity[1,2], and it is more pronounced at skeletal sites where mechanical loading is predictable, consistent, and strenuous[3]. In joints, a broad range of movement results in a lower anisotropy of the articulating bones, and a narrower range of movement results in higher trabecular anisotropy[4]. This reflects the parsimonious nature of bone structural adaptation: only the most relevant directions are reinforced as so called "stress lines", and form overall more oriented trabecular texture. Besides these general biomechanical factors, certain local features, such as muscle attachments, vascular canals, or vestiges of the growth plate (metaphyseal scar), can alter the texture of the tissue fabric and contribute to its inhomogeneity. For this reason, 3D mapping of some descriptors of trabecular bone tissue within an entire anatomical entity can be useful for investigating the associations between observed structural features and the mechanical function of a bone in life.

Measurement of anisotropy

The classic method of anisotropy measurement using Mean Intercept Length (MIL)[5,6] is a local statistical method and it requires the sampling volume to be about 4-5 intertrabecular spaces. The pure surface anisotropy measurement developed for Dragonfly is based on the construction of a surface mesh populated by a set of vectors perpendicular to the mesh faces with their magnitude being proportional to the local mesh face area (S). The Coefficient of Anisotropy (CA, ≥ 1) is converted into the Degree of Anisotropy (DA) for the purpose of normalization. The local surface anisotropy, is calculated with the radius of the sampling volume of approximately 0.5 mm or more (i.e., 1 mm spatial resolution). The algorithm uses a vector operation and projection of the face normals (n) on the principal axes (I) associated with the eigenvectors of the inertia tensor (*see* equation below). A perfectly isotropic surface (as of a sphere) gives a value of 0, while a perfectly anisotropic surface (as of an infinite line) gives a value of 1. Fractions of unity can be also expressed as percentage.

$$\mathrm{CA} = \frac{\sum_{i \in \text{faces}} S_i \cdot \|\vec{n}_i \times \vec{I}_0\|}{\sum_{i \in \text{faces}} S_i \cdot |\vec{n}_i \cdot \vec{I}_0|} - 1; \quad \mathrm{DA} = 1 - 1/\mathrm{CA}$$

3D mapping of anisotropy using vector-field visualization

Both magnitude and directionality of the local surface anisotropy can be displayed as vector fields using color scales to represent vector magnitude. For example, as a temperature map in which blue is assigned a DA of 0 and red is assigned a DA of 1, or as an orientation map in which vectors aligned to the principle axes are colored as follows: red - X axis, green -Y axis, and blue - Z axis.

NOTE ABOUT THE SAMPLE AND SPECIMEN

Information about scanned sample and bone specimen presented in the following illustrations is available in TN015-A Morphological and quantitative analysis of a large microCT scan of a sheep femur. This application note also describes the morphometric indices available in Dragonfly's Bone Analysis module and how to evaluate volume thickness maps of trabecular bone.

[1] Acquaah, F., Robson Brown, K. A., Ahmed, F., Jeffery, N. & Abel, R. L. Early trabecular development in human vertebrae: overproduction, constructive regression, and refinement. *Frontiers in Endocrinology* **6**, doi:doi: 10.3389/fendo.2015.00067 (2015)

[2] Ryan, T. M. & Krovitz, G. E. Trabecular bone ontogeny in the human proximal femur. *J Hum Evol* **51**, 591-602 (2006)

[3] Reznikov, N. *et al.* Functional adaptation of the calcaneus in historical foot binding. *J Bone Miner Res* **32**, 1915-1925 (2017)

[4] Gibson, L. J., Ashby, M.F. *Cellular solids. Structure and properties.* (Cambridge University Press, 2001)

[5] Odgaard, A. Three-dimensional methods for quantification of cancellous bone architecture. *Bone* **20**, 315-328 (1997)

[6] Odgaard, A. in *Bone Mechanics*, (ed CRC press LCC), (2001)

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An example of the anisotropy vector field plotted by magnitude over the entire distal femur is presented in the figure below. Note that the vectors comprising the 3D map are abstract, mathematical entities and that their scale can be changed to alter visualizations. For example, using longer vector arrows makes the 3D map visually more saturated, but can create surface roughness where the arrows extend beyond the physical boundaries of the sample. The radius of the sampling volume defines the spatial resolution and the sampling spacing defines the extent of the running averaging of the map. A sampling volume radius of 0.5 mm and sampling spacing of 1.5 mm can generate a well-resolved and densely populated, rich vector field. Using larger values may speed up computation times, but could decrease the quality of the 3D map. A compromise solution to obtain a rich vector field at minimal computation cost is to confine the mapping to a smaller bounding box.

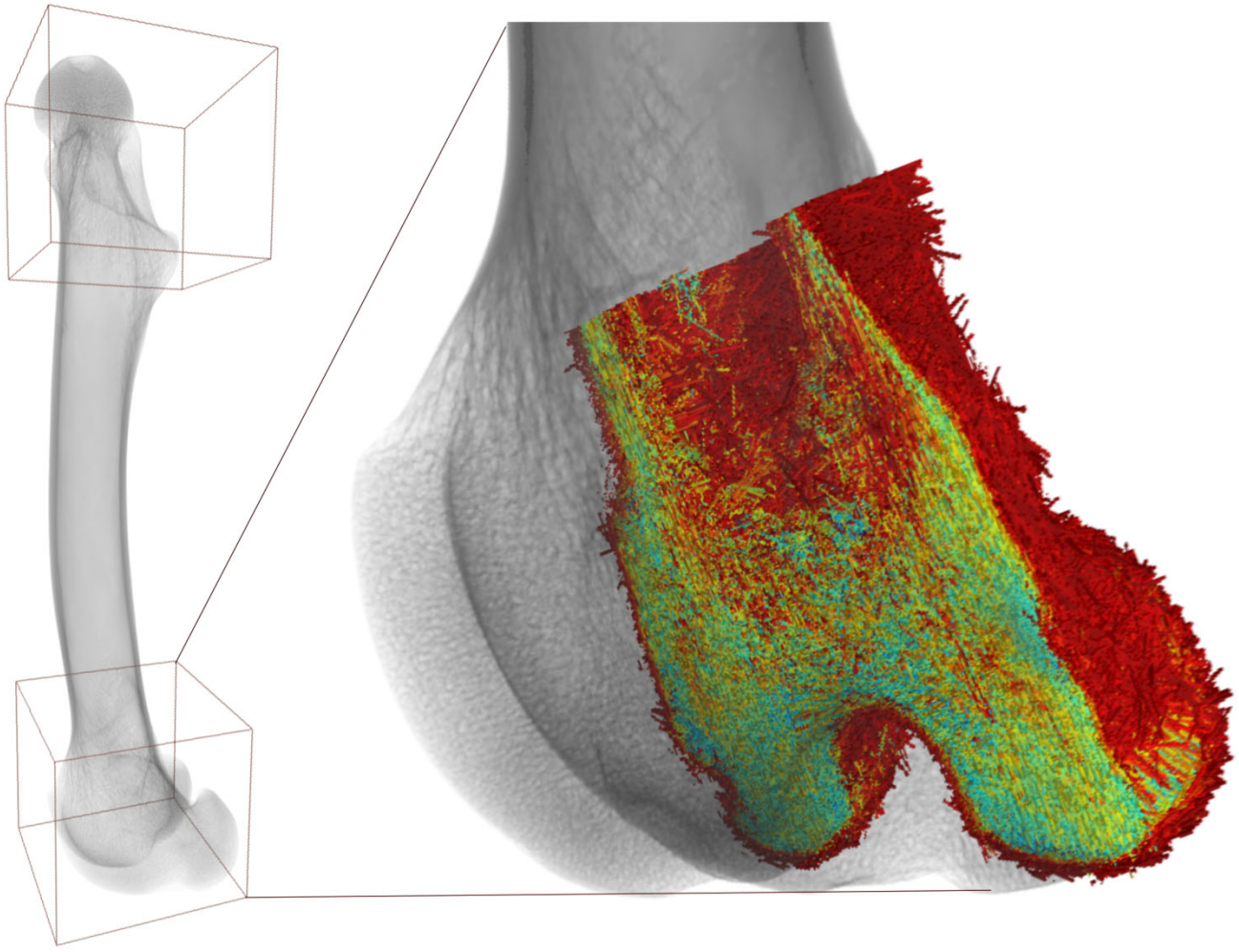

Figure 1. Local surface anisotropy vector field is plotted as a 3D temperature map in which the color of the vector stands for its magnitude. The complete bone on the left shows the distal and proximal ends outlined in boxes. These bounding boxes are required for the vector field computation. The vector field constructed over the distal box is shown on the right. The anterior half of the vector field has been clipped in order to expose the variations of the local anisotropy values within the interior of the bone. Note that the cortical shell that has a smooth surface produces high values of local anisotropy, even in the locations where it is very thin, such as in the subchondral area of the epiphysis. The interior of the vector field shows a top-to-bottom gradient from high to low values.

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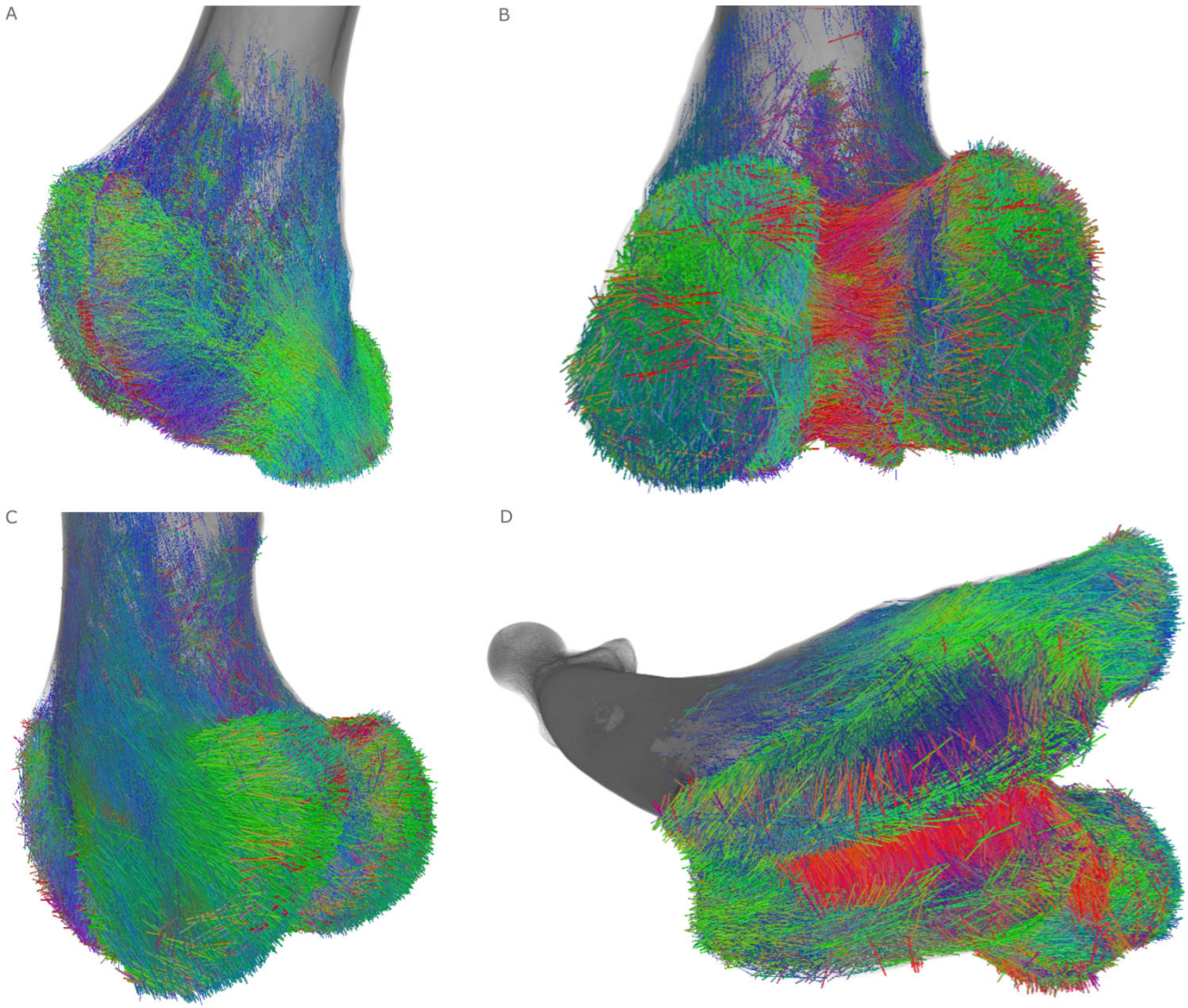

Figure 2. Local surface anisotropy vector field plotted as a 3D map in which the color of the vector stands for its direction (red – X-axis, green – Y-axis, blue – Z-axis). Panel A shows that in the areas of the condyles and the patellar surface the vectors are oriented predominantly normal to the surface. In Panel B, a distinct red band illustrates that the preferred orientation of the trabecular elements in the intercondyllar fossa is transverse, which makes that band appear like a ligament that would be pulling the two loaded condyles together. Panel C shows the maximal condyle curvature in the posterior-medial aspect and the radial course of the anisotropy vectors, normal to the curved surface of the condyles. Panel D contains the same sample shown in the bottom-to-top perspective.

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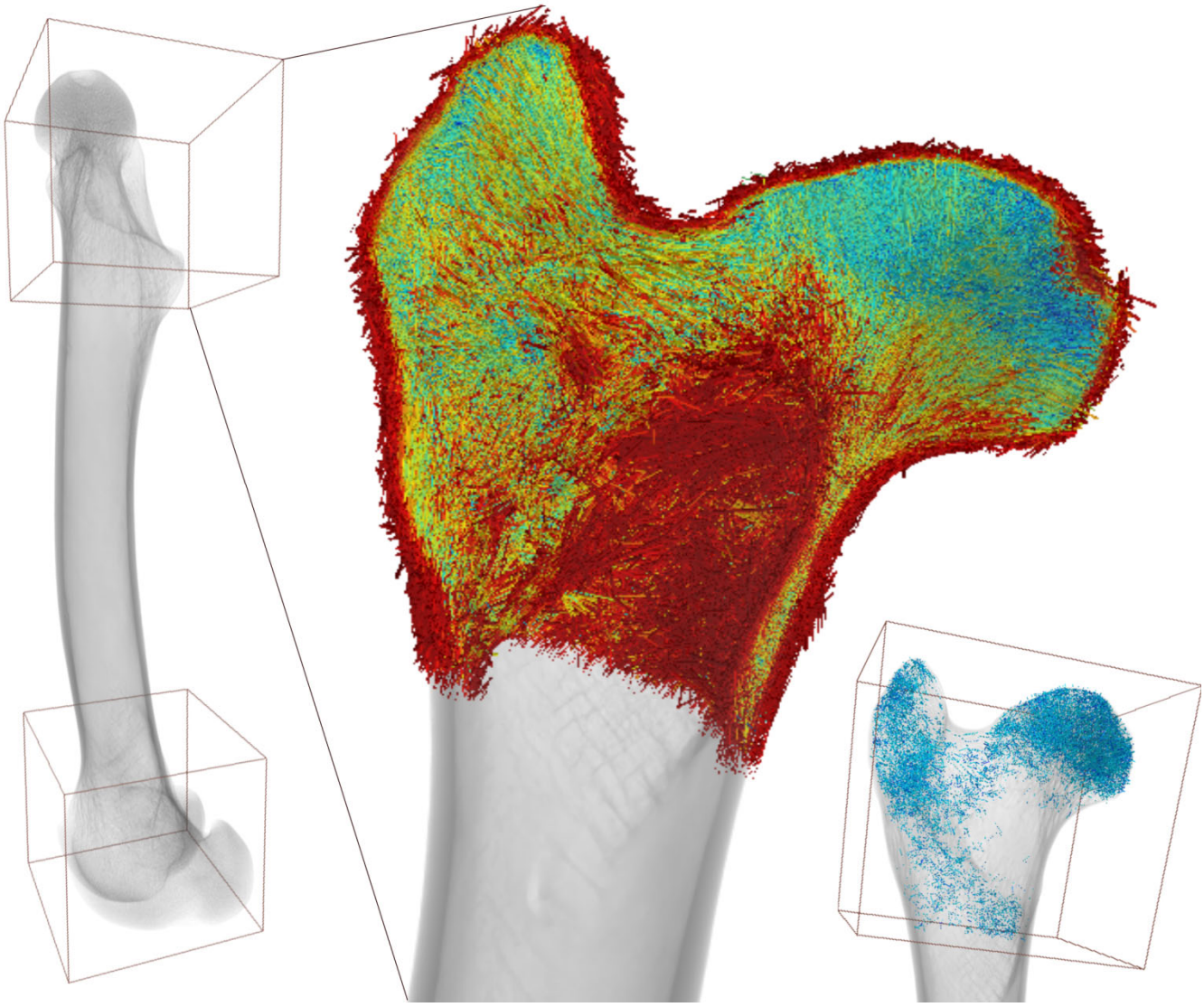

Figure 3. Local surface anisotropy vector field plotted as a 3D temperature map in which the color of the vector represents its magnitude. The complete bone on the left shows the distal and proximal ends outlined in bounding boxes. These boxes are required for the vector field computation. The vector field constructed over the proximal box is enlarged and partly clipped to expose the gradient of the anisotropy values from higher to lower from the shaft towards the articulating femoral head (and the same trend, but less pronounced, from the shaft towards the major trochanter). Note that the coarse trabecular buttresses that sport the highest thickness values (*see* Figure 6 in TN015-A morphological and quantitative analysis of a large microCT scan of a sheep femur), also have the highest anisotropy. The inset in the right bottom corner illustrates that the lowest anisotropy areas are preferentially located in the femoral head, where the joint movement occurs..

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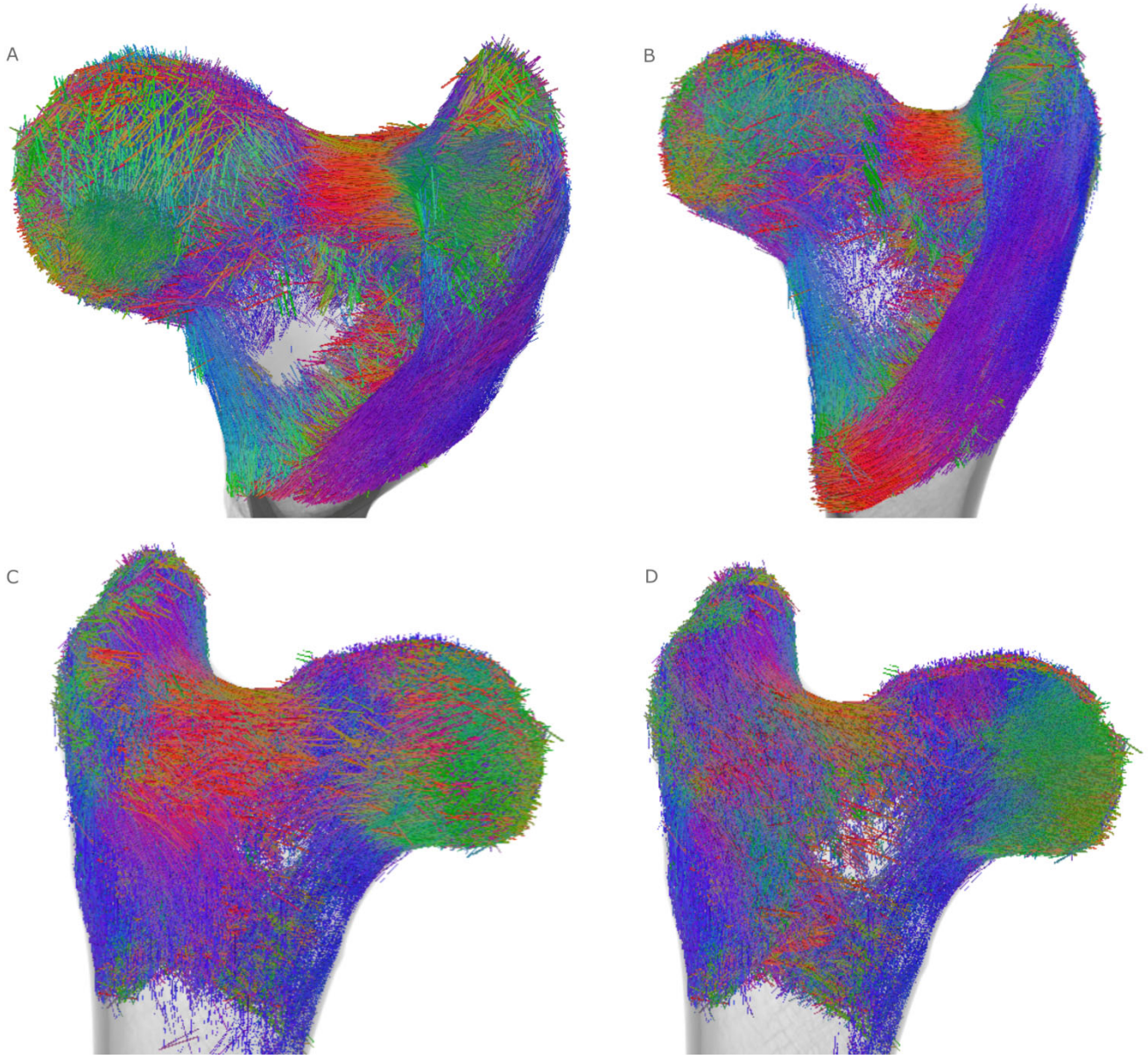

Figure 4. Local surface anisotropy vector field plotted as a 3D map in which the color of the vector stands for its direction (red – x-axis, green – y-axis, blue – z-axis). Panel A – proximal femur viewed from the coronal-posterior direction. Note the outline of a triangle formed by major anisotropy directions between the triangle vertices: femoral head, major trochanter and minor trochanter. Panel B – intertrochanteric crest is visualized as a uniformly textured band of vectors that demonstrate a smooth transition from red to blue via purple. As both major and minor trochanters serve for muscle attachment, this smooth and continuous trajectory of vectors might be the footprint of the forces exerted by the slow-twitch muscles of the lower leg and the morphing effect of that muscular activity on the bone tissue. Panel C – same sample in the anterior aspect. Note nearly even proportions of the three directions. Panel D – same orientation as in C, but clipped in the coronal plane. Note the presence of all directions (seen as a mix of colors) in the interior of the proximal femur.

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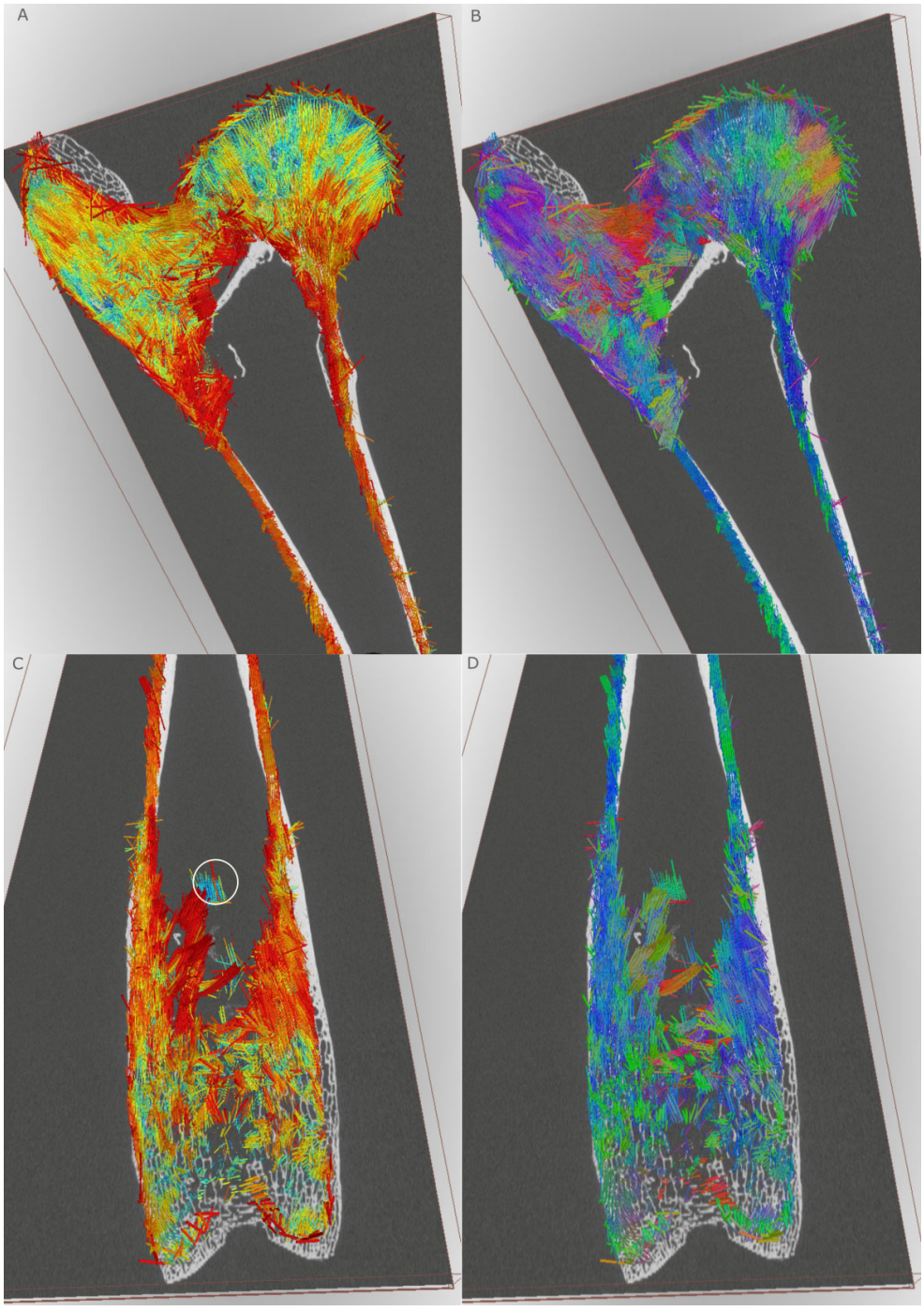

Figure 5. Comparison of the magnitude-based and direction-based vector field anisotropy maps. Panel A – proximal femur, magnitude. Panel B – proximal femur, direction. Panel C – distal femur, magnitude. Panel D – distal femur, direction. The magnitude-based and direction-based maps are independent. For example, in Panel C, the element enclosed in a white circle is a fragment of soft tissue residue. This element has a weak anisotropy signal by the magnitude (in comparison with the bone structures around it), but it yet has a distinct vector orientation.

Volume fraction of trabecular bone

Volume fraction is a ratio of specifically bone material volume over the entire volume of interest. It is commonly used as a single value that reflects trabecular density and can be used as a proxy for bone strength[7]. However, the classic BV/TV parameter, as any averaged descriptor, does not account for the local variations in 3D that can be of biomechanical significance. As mentioned in the section on Trabecular Analysis in TN015-A Morphological and quantitative analysis of a large microCT scan of a sheep femur, BV/TV in the distal part of the femur is 0.34. In fact, in 3D BV/TV varies between 0 and about 0.8. The variation can be visually presented as a scalar field with a spatial resolution around 1 cubic millimeter or coarser, as shown below.

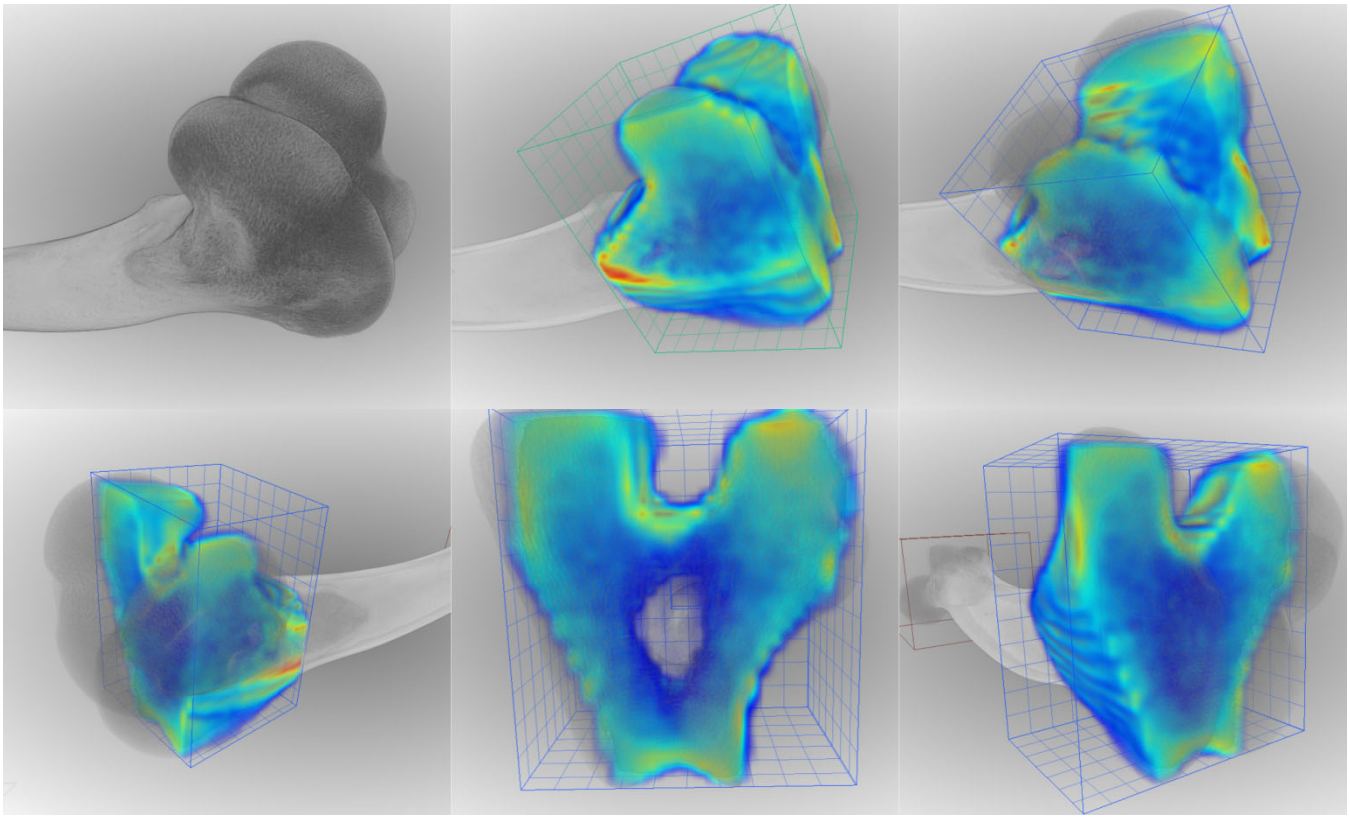

Figure 6. Volume fraction 3D map (scalar field) plotted over the distal femur.

Further reading

Information about computing common global bone morphometric indices and other quantitative measurements for analyzing bone specimens, such as volume thickness, can be found in the related publication:

TN015-A Morphological and quantitative analysis of a large microCT scan of a sheep femur.

[7] Maquer, G., Musy, S. N., Wandel, J., Gross, T. & Zysset, P. K. Bone volume fraction and fabric anisotropy are better determinants of trabecular bone stiffness than other morphological variables. *J Bone Miner Res* **30**, 1000-1008 (2015)