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The stiffness of living tissues and its implications for tissue engineering

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Table S1 The stiffness of living tissues

Tissue	**Technique**	**Moduli (type)**	**Moduli (value)**	**Refs.**
Nervous tissue				
Brain (mouse)	Atomic force microscopy indentation	Elastic (*E*)	0.4–3.0 kPa	[1,2]
Brain (cow)	Nanoindentation	Elastic (*E*)	0.59–2.36 kPa	[3]
Brain (pig)	Tensile deformation	Elastic (*E*)	3.1 kPa (up to 6.5 kPa)	[4]
Brain (human)	Magnetic resonance elastography	Shear (*G*)	1–3 kPa	[5–7]
Spinal cord (rat)	Microindentation	Elastic (*E*)	0.50–6.63 kPa	[8,9]
Spinal cord (rabbit)	Pipette aspiration	Elastic (*E*)	3–4 kPa	[10]
Spinal cord (human)	Tensile deformation	Elastic (*E*)	1.23 MPa	[11]
Sciatic nerve (mouse)	Tensile deformation	Elastic (*E*)	7 MPa	[12]
Sciatic nerve (rat)	Tensile deformation	Elastic (*E*)	0.5–4.0 MPa	[13]
Sciatic nerve (rabbit)	Tensile deformation	Elastic (*E*)	2 MPa[a]	[14]
Ulnar nerve (human)	Tensile deformation	Elastic (*E*)	5 MPa[a]	[15]
Connective tissue				
Tibial trabecular bone (human)	Ultrasound elastography	Elastic (*E*)	14.8 GPa	[16]
Tibial trabecular bone (human)	Tensile deformation	Elastic (*E*)	10.4 GPa	[16]
Tibial cortical bone (human)	Ultrasound elastography	Elastic (*E*)	20.7 GPa	[16]
Tibial cortical bone (human)	Tensile deformation	Elastic (*E*)	18.6 GPa	[16]
Metacarpal bone (horse)	Nanoindentation	Elastic (*E*)	12.4–12.8 GPa wet; 17.6–20.8 GPa dry	[17]
Femoral neck bone (human)	Atomic force microscopy indentation	Elastic (*E*)	1.28–1.97 GPa	[18]
Articular cartilage (human)	Compression	Elastic (*E*)	431.7–447.1 MPa	[19]
Articular cartilage (human)	Compression	Shear (*G*)	5.7–6.2 MPa	[19]
Articular cartilage (pig)	Compression	Elastic (*E*)	1 MPa	[20]
Articular cartilage (cow)	Rheology	Shear (*G*)	1.51 MPa	[21]
Articular cartilage (cow)	Tensile deformation	Elastic (*E*)	1.06 MPa	[22]
Articular cartilage (sheep)	Tensile deformation	Elastic (*E*)	5.0–12.9 MPa	[23]
Articular cartilage (goat)	Rheology	Shear storage (*G*′)	0.9 MPa	[24]
Articular cartilage (rat)	Microindentation	Elastic (*E*)	2.6–4.2 MPa	[25]
Articular cartilage (cow)	Atomic force microscopy, rheology	Elastic (*E**)	0.15–2.5 MPa	[26]
Adipose tissue (human)	Compression	Elastic (*E*)	3.1 kPa pericardial; 5.5 kPa thymic; 3.5 kPa abdominal	[27]
Adipose tissue (human)	Tensile deformation	Elastic (*E*)	1.6–2.9 kPa	[28]
Adipose tissue (human)	Compression	Elastic storage (*E*′)	2 kPa	[29]
Patellar tendon (human)	Shear wave elastography	Elastic (*E*)	200 kPa	[30]
Supraspinatus tendon (mouse)	Macroindentation	Elastic (*E*)	20–40 kPa	[31]
Supraspinatus tendon (mouse)	Atomic force microscopy rheology	Elastic (*E*)	4–20 kPa	[31]

Plantaris tendon (mouse)	Tensile deformation	Elastic (*E*)	100–200 MPa	[32]
Ocular tendon (cow)	Atomic force microscopy nanoindentation	Elastic (*E*)	60 MPa	[33]
Ligaments (human)	Tensile deformation	Elastic (*E*)	25–93 MPa	[34–36]
Annular ligament (human)	Atomic force microscopy indentation	Elastic (*E*)	1.1–1.2 MPa	[37]
Muscle				
Smooth muscle — blood vessels (human)	Tensile deformation	Elastic (*E*)	30–100 kPa	[38]
Smooth muscle — aortic rings (rat)	Tensile deformation	Elastic (*E*)	10–23 kPa	[39]
Cardiac muscle (rat, cow)	Tensile deformation	Elastic (*E*)	30–145 kPa	[40]
Cardiac muscle (human)	Tensile deformation	Elastic (*E*)	5–50 kPa	[41,42]
Cardiac muscle (cow, sheep)	Shear wave elastography	Elastic (*E*)	10–90 kPa	[43]
Cardiac muscle (human)	Magnetic resonance elastography	Shear (*G*)	8 kPa	[44]
Cardiac muscle (rat)	Magnetic resonance elastography	Shear (*G*)	2–4 kPa	[45]
Cardiac muscle (pig)	Tensile deformation	Elastic (*E*)	110 kPa	[46]
Cardiac muscle (pig)	Magnetic resonance elastography	Shear (*G*)	3 kPa	[46]
Cardiac muscle (mouse)	Atomic force microscopy nanoindentation	Elastic (*E*)	21–39 kPa	[47]
Skeletal muscle (rat)	Tensile deformation	Elastic (*E*)	20 kPa single fibres; 200 kPa bundles	[48]
Skeletal muscle (mouse)	Tensile deformation	Elastic (*E*)	15–150 kPa	[49,50]
Skeletal muscle (human)	Shear wave elastography	Shear (*G*)	5–170 kPa	[51–54]
Skeletal muscle (pig)	Shear wave elastography	Shear (*G*)	Up to 150 kPa	[55]
Skeletal muscle (pig)	Tensile deformation	Elastic (*E*)	Up to 800 kPa	[55]
Skeletal muscle (mouse)	Atomic force microscopy nanoindentation	Elastic (*E*)	3–8 kPa	[56]
Endothelial and epithelial tissues				
Skin (human)	Torsional deformation	Elastic (*E*)	420–850 kPa	[57]
Skin (human)	Shear wave elastography	Elastic (*E*)	60–130 kPa	[58,59]
Skin (bat wing)	Tensile deformation (biaxial)	Elastic (*E*)	131 kPa	[60]
Skin dermis (pig)	Tensile deformation	Elastic (*E*)	50–150 kPa	[61]
Skin (human)	Indentation	Elastic (*E*)	35 kPa dermis; 2kPa hypodermis	[62]
Skin (mouse)	Atomic force microscopy nanoindentation	Elastic (*E*)	7.3–13.5 MPa dermis; 0.49–1.51 MPa epidermis	[63]
Skin (human)	Atomic force microscopy nanoindentation	Elastic (*E*)	4.5 MPa epidermis; 0.1 MPa dermis	[64]
Lung (human)	Magnetic resonance elastography	Shear (*G*)	0.84–1.50 kPa	[65,66]
Decellularized lung (rat)	Atomic force microscopy nanoindentation	Elastic (*E*)	15–60 kPa	[67]
Decellularized lung (mouse)	Atomic force microscopy indentation	Elastic (*E*)	20–100 kPa	[68]
Decellularized lung (mouse)	Rheology	Shear storage (*G′*)	10 kPa	[68]
Lung (rat)	Atomic force microscopy nanoindentation	Elastic (*E*)	1.5 kPa	[69]

Lung (human)	Atomic force microscopy nanoindentation	Elastic (*E*)	1.96 kPa	[70]
Intestine (rat)	Tensile deformation	Elastic (*E*)	350 kPa	[71]
Small intestine (guinea pig)	Tensile deformation	Elastic (*E*)	430–441 kPa	[72]
Large intestine (goat)	Compression	Elastic (*E*)	600 kPa[a]	[73]
Intestine (pig)	Tensile deformation	Elastic (*E*)	300–700 kPa	[74]
Viscera				
Kidney (human)	Magnetic resonance elastography	Shear (*G*)	4 kPa cortex; 5 kPa medulla; 8 kPa sinus	[75,76]
Kidney (sheep)	Nanoindentation	Elastic (*E*)	1–13 kPa	[77]
Kidney glomeruli (rat)	Atomic force microscopy indentation	Elastic (*E*)	2.5–4.0 kPa	[78]
Kidney glomeruli (rat)	Capillary aspiration	Shear (*G*)	1 kPa	[78]
Spleen (human)	Shear wave elastography	Shear (*G*)	15–20 kPa	[79–82]
Spleen (pig)	Macroindentation	Elastic (*E*)	110 kPa	[83]
Liver (human)	Shear wave elastography	Elastic (*E*)	4.0–6.5 kPa	[84–86]
Liver (human)	Magnetic resonance elastography	Shear (*G*)	2 kPa	[87,88]
Liver (rat)	Shear wave elastography	Elastic (*E*)	6.5 kPa	[89]
Liver (rat)	Compression	Elastic (*E*)	3.5 kPa	[89]
Liver (mouse)	Atomic force microscopy nanoindentation	Elastic (*E*)	0.15–6.00 kPa	[90]
Decellularized thymus (human)	Macroindentation	Elastic (*E*)	2.11 kPa	[27]
Thyroid nodule (human)	Shear wave elastography	Elastic (*E*)	19–50 kPa	[91,92]
Thyroid (human)	Shear wave elastography	Elastic (*E*)	10.3 kPa	[93]
Thyroid (human)	Magnetic resonance elastography	Shear (*G*)	1.3–1.9 kPa	[94]
Thyroid (human)	Compression	Elastic (*E*)	9–11 kPa	[95]
Pancreas (human)	Magnetic resonance elastography	Shear (*G*)	1.1–2.1 kPa	[96–98]
Pancreas (human)	Shear wave elastography	Elastic (*E*)	2.9 kPa	[99]
Pancreas (mouse)	Compression	Elastic (*E*)	3.1 kPa	[100]
Pancreatic islet (mouse)	Atomic force microscopy nanoindentation	Elastic (*E*)	1 kPa	[101]
Bladder (pig)	Tensile deformation	Elastic (*E*)	200–320 kPa	[74,102]
Bladder body (human)	Ultrasound vibrometry	Shear (*G*)	50 kPa (empty)–100 kPa (full)	[103]
Bladder neck (human)	Shear wave elastography	Elastic (*E*)	22 kPa	[104]
Eye				
Cornea (pig)	Tensile deformation	Elastic (*E*)	0.23–2.89 MPa	[105,106]
Cornea (pig)	Shear wave elastography	Elastic (*E*)	0.19 MPa	[107]
Cornea (human)	Compression	Elastic (*E*)	0.2 MPa	[108]
Cornea basement membrane (human)	Atomic force microscopy nanoindentation	Elastic (*E*)	7.5kPa	[109]
Cornea Bowman's layer (human)	Atomic force microscopy nanoindentation	Elastic (*E*)	109.8kPa	[109]
Cornea anterior stroma (human)	Atomic force microscopy nanoindentation	Elastic (*E*)	33.1 kPa	[109]

Cornea Descemet membrane (human)	Atomic force microscopy nanoindentation	Elastic (*E*)	50 kPa	[109]
Cornea (rat)	Nanoindentation	Elastic (*E*)	2.75–3.33 MPa	[110]
Lens capsule (human)	Tensile deformation	Elastic (*E*)	2.3–3.3 MPa	[111,112]
Lens capsule (human)	AFM nanoindentation	Elastic (*E*)	0.4 MPa	[113]
Lens (cow)	Microindentation	Elastic (*E*)	25.6 kPa	[114]
Lens (human)	Rheology	Shear (*G*)	0.2–10.3 kPa	[115]
Lens (cow)	Cavitation rheology	Elastic (*E*)	0.8 kPa nucleus; 11.8 kPa cortex	[116]
Iris dilator (cow)	Tensile deformation	Elastic (*E*)	27 kPa	[117]
Iris (pig)	Tensile deformation, indentation	Elastic (*E*)	4–6 kPa	[118,119]
Iris (pig)	Microindentation	Elastic (*E*)	4.86 kPa	[120]

[a]Derived from the curves (that is, values were not directly reported by the authors).

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