

Index

- articular cartilage structure
 - balloon and string model of, 79–83
 - Benninghoff's arcade model, 12–13
 - cohesive strength of matrix
 - destructuring, influence of, 76
 - discontinuous fibril models,
 - difficulties with, 21
 - fibril interconnectivity and lateral force
 - transmission, 75–76
 - fibril-proteoglycan interactions insufficient to explain cohesion, 24
 - problems with composite theory, 21–24
 - early structural studies, 10–13
 - entwinement versus non-entwinement fibril models, 24–25
 - non-entwinement mode predominates, 31–35, 37–39
 - evidence from directional strength and extensivity studies, 18–20
 - evidence from rupture propagation studies, 18–20
 - fibril interconnectivity models and 2-D analogue, 25–31
 - fibril orientation and continuity, 15, 16–17, 21
 - fibrillar network transformation, 20–21
 - destructuring, concept of, 24, 147–48
 - enzymically induced, 20–21
 - OA matrix and destructuring, 39
 - traumatically induced, 21
 - fibril-to-fibril interconnectivity, potential linking agents, 39–41
 - fibrosity in matrix, its structural significance, 31, 36, 37
 - imaging limitations with SEM and TEM, 15
 - malacic matrix, structure of, 31–37
 - matrix swelling behaviour and fibril interconnectivity, 35–39
 - network connectivity, importance of, 21–24
 - pin-prick patterns, significance of, 11–12
 - pseudo-random structural model, 17–18, 25
 - structural implications of abnormal swelling, 35–37
 - transverse swelling as indicator of matrix abnormality, 35–36
- articular cartilage, general considerations
 - cartilage loss, consequences of, 3–4
 - compliance, importance of, 3–5
 - composition, 10
 - contact stress reduction, 3–5
 - experimental demonstration of, 5
 - macro- and micro-level considerations, 3–5
 - physical examples of, 5
 - ink staining to reveal surface disruption, 49–50
 - quantified using Outerbridge grading system, 51
 - its variable response to loading, significance of, 3
 - primary function of, 4–5
 - swelling potential, physicochemical origin of, 10
 - tissue studies based on bovine patella model
 - its utility, 49
 - lesion development in, 51–52
 - relevance to human OA, 50–51
- calcified cartilage
 - advancing tidemark and increasing mineralisation, 79
 - relation to pre-OA state, 79
- bony spicules
 - formation in calcified cartilage, 52–55
 - influence of mechanical environment, 60–61
 - involvement in healing of bone fractures, 58–60
 - relation to angiogenesis, 59–60
- intervertebral disc-endplate, component of, 192–93, 194–95, 197–98, 199–201
- involvement in osteochondral junction failure, 85–86, 121–24, 128–30
- microcrack formation in osteochondral tissues, 131–32, 136–39
- mineralised fibrocartilage and entheses development, 304
- new bone formation in, role of repetitive micro-injury, 77
- remodelling of, 43–45
- role as mechanical transition layer challenged, 78–79
- vascular penetration of, 43–45

- elastic stiffness, concept of
- elastic limit in conventional materials, 8
 - its structural basis, 8
 - relation to ductile and brittle behaviour, 8
 - strain-energy considerations, 8
 - large-strain elasticity, 187–91
 - elastin behaviour described as, 188–89
 - general entropic theory of, 188
 - Gough-Joule effect, 188
 - strain-energy, its relation to, 187–88
 - low- versus large-strain elasticity in tissues, 8–10
 - relation to collagen crimp, 9
 - relation to hierarchical structure of collagen fibril, 8–9
- elastin properties and function
- a biological elastomer, 188–89
 - elastomeric behaviour, theories of
 - evidence suggests mix of mechanisms, 190–91
 - hydrophobic interactions, importance of, 189–91
 - librational entropy model, 189–90
 - liquid droplet model, 189
 - oiled coil model, 189
 - importance of hydration, 188–89
 - role in intervertebral disc, 178–87
 - role in tendons and ligaments, 294
- intervertebral disc-endplate system
- anatomical overview, 157–60
 - annulus, 162
 - combined imaging and micromechanical studies, 166–68
 - crimp in fibres, functional role of, 165–66
 - J-type stress-strain response, 203–4
 - cross-ply structure of, 160–61
 - inter- and intra-lamellar connectivity, models of, 168–75
 - inter- and intra-lamellar relationships, 166–68
 - inter-lamellar bridges, 170
 - debate concerning origin, 176–77
 - in human discs, 176
 - probable functional role of, 175–76
 - internal strains and structural disruption of, 184–86
 - intrinsic compressive stiffness of, 158
 - sectioning plane, importance of, 163–65, 171–75
 - serial thick sections, advantages of, 170
 - annulus-endplate junction
 - annular bundles and sub-bundles, involvement of, 195–97
 - discordant structural continuity, concept explained, 206
 - fibre-reinforced composite theory, its relevance, 208–12
 - requires fibril stiffening via intra-fibril mineralisation, 210–12
 - steel-reinforced concrete, features in common with, 208–10
 - fibril-level view of, 205–6, 212–14
 - flexion and compression, response to, 202–4
 - influence of maturity level, 212–14
 - inner annular fibre anchorage, 193
 - microstructural view of, 195–97
 - choice of section plane critical, 195–97
 - outer annular fibre anchorage, 193–95
 - ovine versus human, 214–16
 - sub-bundles also in human endplate, 216
 - step-change in stiffness, implications of, 201
 - structural model of anchorage system, 197–201
 - sub-bundles, an important structural feature, 212
 - torsion and compression, response to, 201–2
 - annulus-endplate junction failure, 239–50
 - directional loading, significance of, 239–40
 - torsion, flexion, axial tension, responses to, 248–50
 - fibril-level view of, 245
 - in human tissue, 250
 - influence of demineralisation, 243–45
 - cement line failure, promoted by, 245
 - macro-level view of, 240–43
 - potential stress-reducing mechanisms, 204–5
 - stress-induced failure achieved with difficulty, 204
 - tidemark and cement line, involvement of, 242
 - toughness and junction failure, 204–5
 - composition of primary regions, 162–63
 - annulus, 162
 - endplates, 163
 - nucleus, 163
 - elastic fibres in disc, 178
 - 3-D network of, 181–82
 - co-localisation with collagen, 182–83
 - comprising elastin and microfibrils, 182–83
 - early studies of disc elastin, 178–80
 - extensive network revealed using advanced imaging, 180–82
 - functional role of, 179, 183
 - relation to inter-lamellar connectivity, 183–84
 - role in managing high internal strains, 185–86
 - special role within lamellae, 186–87
 - endplate, detailed description of, 192–93
 - cartilaginous endplate, its calcification, 192–93
 - cement line, 279–80
 - epiphyseal ring, 192, 215–16
 - main components of, 192–93
 - perforating channels, function of, 192
 - tidemark, 193
 - nucleus, detailed description of, 217–18
 - amorphous or pseudo-amorphous?, 217–18, 226–27
 - biochemical composition of, 217
 - collagen types in, 162–63

- connectivity with annulus, demonstrated
 - experimentally, 220
 - early descriptions of, 217–18
 - elastic fibres in, 178–80, 180, 217, 219
 - endplate-to-endplate continuity of its fibres, 226–27
 - integration with endplate
 - fibres convoluted and anchored, 228
 - fibril-level analysis of, 231–35
 - fibrous insertion nodes, morphology and density of, 224–26
 - influence of maturity level, 229–30
 - investigated using ‘ring-severing’ experiment, 221–24
 - mechanical evidence for, 220–24
 - microstructural evidence for, 224–27
 - ovine and human integration compared, 236–38
 - structural model of, 227–28
 - models illustrating integration with annulus and endplate, 235–36
 - nucleus-to-annulus transition, a metabolically-active zone, 218
 - proteoglycan component, role of, 217
 - structure not readily demonstrated with histology, 227–28
 - swelling potential of, 161, 217
 - tethered mobility of its fibres, 228, 229
 - nucleus-annulus-endplate integration, macro-level description of, 161–62
 - ovine and human discs compared, 281–82
 - intervertebral disc-endplate, integrated failure of,
 - combined compression and flexion, 271
 - annulus disruption and differential fibre-set recruitment, 280–81
 - apical ridge and strain profile in annular fibres, 277
 - cement line, not a natural plane of weakness, 279–80
 - failure modes and loading rate, 271–77
 - higher rates favour mixed-mode herniations, 277
 - loading rate and modulus mismatch, 279
 - low rate favours endplate fracture, 271–72
 - nucleus hydrostatic pressure and loading rate, 277–79
 - physiological relevance of loading rate, 271
 - regional disruption of annulus, 280–81
 - endplate fracture in simple compression, 256–57
 - nucleus extrusion through endplate, 256–57
 - Schmorl’s nodes, origin of, 256–57
 - general concepts relevant to failure, 251–52
 - crack propagation through inhomogeneous structure, 251
 - fracture mechanics, principles of, 251–52
 - strain energy release and crack propagation, 251–52
- herniation
 - classification of types, 252–54
 - definition of, 252
 - differential loading of oblique-counter oblique fibres, 202–4
 - possible cause of lateral annulus disruption, 202–3
 - endplate junction failure common in humans, 270–71
 - induced using internal pressurisation
 - experimental method described, 257
 - micro-CT imaging of disc disruption, 258
 - pressurisation in neutral posture, 259–60
 - pressurisation rate, influence of, 265–67
 - pressurisation with combined torsion and flexion, 260–64
 - pressurisation with flexion, 260
 - utility and limitations of, 258, 268–69, 270
 - tissue types extruded, 254–55, 255, 270–71
 - herniation and pain, 255–56
 - inflammatory effects, 255
 - modic changes, 255
 - resorption of extruded material, 255
- lubrication of joints
 - boundary lubrication, 6
 - coefficient of friction, 5
 - consolidation principle, relevance of, 7
 - hydrodynamic theory, 5–6
 - interstitial fluid, role of, 7
 - multiple mechanisms involved, 7
 - protection of cartilage, 5
 - weeping lubrication, 6–7
 - osteocondral junction failure under shear loading
 - a semi-quantitative dynamic approach, 118–19
 - adolescent tissue failure, 121–22
 - experimental technique described, 118–19
 - immature tissue failure, 119–21
 - mature tissue failure, 122–24
 - calcified cartilage, its influence on mechanics of junction failure, 85–86
 - fracture mechanics analysis, 124–27
 - critical energy release rate for cartilage delamination, 125–27
 - energy of fracture for total cartilage delamination, 125
 - fracture strength versus fracture toughness, 124–25
 - influence of maturity, clinical implications of, 127–28, 129–30
 - why junction structure influences toughness, 128–30
 - shear forces, clinical relevance of, 84–85
 - shear strength of junction under quasi-static loading, 116–18

- osteocondral junction failure under shear loading
 (*cont.*)
 whole condyle failure, 115–16
 osteochondritis dissecans, updated definitions
 of, 116
 zones of failure and influence of loading rate,
 115
- osteocondral junction, general considerations
 a stress conversion system, 86
 articular cartilage, force-transmitting role of, 345
 articular cartilage, its involvement in junction
 mechanics, 76–77
- cement line, 47
 advance of, 60
 fibril-level structure of, 47–49
- early studies of, 42–43
- growth and remodelling of, 43–44
 and etiology of cartilage degeneration, 44–45
 bony spicules, significance of, 52–55, *See also*
under ‘calcified cartilage’
 relation to maintenance of joint incongruity, 44
- imaging of, 46–47
- integrating role of, 42
- tidemark. *See also under* ‘osteocondral tissues
 described’
- osteocondral tissue damage induced in vivo
 equine Thoroughbred model
 advantages of, 132–33
 bone bruising, 139–40
 fracture mechanism in hard tissue, 140–43
 bone comminution, morphology described,
 140
 concrete failure in compression, similarity
 with, 141–43
 hard and soft tissue damage, relation between,
 143–44
 hard tissue damage beneath near-intact
 articular surface, 134–36
 joint site and loading intensity, relation to,
 133–34
 loading history, relation to, 135–36
- osteocondral lesions
 composition of lesion contents, 144–46
 destructuring of adjacent articular cartilage,
 147–48
 evidence for tissue destruction and repair,
 136
 mechanical properties of lesion contents, 146
 mechanism of formation, 148–50
 structural detail of, 144–50
 subchondral bone cysts, 150–51
 conflicting theories concerning origin of,
 151–54
 present in the OA joint, 151–52
 relation to stress, 154
 stress-related pathologies, general description
 of, 133–34
- microcrack formation in human calcified
 cartilage, biological significance of,
 131–32
- osteocondral fracture uncommon in immature
 human joint, 85–86
- rabbit failure model and repetitive impact, 79
 relevant *in vivo* forces in human joint, 84
 horizontal splitting along uncalcified-calcified
 junction, 84–85
 repetitive physiological loading, relevance of,
 131
- osteocondral tissue failure under direct
 compression
 impact loading
 articular cartilage, minimal role in shock
 absorption, 94, 345
 damage artefacts, risk of, 103–5
 curvilinear surface and indenter contact, 105
 indenter edge effects, 104–5
 damage grading system, micro-level, 97–98
 degeneration, influence of, 102–3
 failure morphologies, 93, 94–96, 98–99
 consistent with quasi-brittle behaviour, 93
 depth of rupture propagation, 94
 hard tissue failure and maximum shear
 stress, 95
 impact energy, influence of, 92–94, 99–100
 indenter characteristics, influence of, 94–97
 matrix fluid, its influence on dynamic
 mechanical properties, 89–91
 maturity level, influence of, 100–102
 practical considerations relating to impact
 experiments, 92
 repetitive micro-injury and repair, 77
 stress level and chondrocyte death, 99–100
 tangential layer, its role in rupture initiation,
 93–94
 whole condyle response versus abstracted
 sample, 103–4
- impact loading with prior creep
 damage correlated with impact energy and
 stress, 113–14
 damage modes defined, 109–13
 experimental procedure, description of, 106–8
 macro-level damage, 109
 mechanical effects of, 109
 micro-level damage, 109–13
 physiological relevance of, 105, 106
- quasi-static loading
 absence of tidemark failure at low rates, 87–89
 influence of loading rate, 86–91
 matrix fluid and importance of outflow path,
 91–92
 relevant forces *in vivo*, 84–86
- osteocondral tissues described
 balloon and string model of, 79–80
 construction described, 80–82

- features modelled, 80
 - load-bearing function demonstrated, 82–83
- bovine patella model. *See also under* ‘articular cartilage, general considerations’
- and human OA, histological comparison of, 50–51
- channel indentation experiment
 - bulge morphology, significance of, 74–76
 - shear band development
 - influenced by degeneration, 68–69
 - oblique-counter oblique nature of, 66–68
- imaging of osteochondral tissues
 - at fibril level, 47–49
 - DIC microscopy, advantages of, 46–47
- mechanobiological adaptation of, 346–48
- microstrain environment
 - experimental determination of, 61–63
 - explored using channel indentation experiment, 65–69
 - influence of
 - articular surface, 69–71
 - degeneration, 63–65
 - focal disruption, 71–74
 - matrix swelling pressure, 69–71
 - transverse interconnectivity, 71
 - lines of chondrocyte continuity
 - chevron discontinuity, altered by degeneration, 63–65
 - chevron discontinuity, significance of, 61–63
 - mapping matrix deformation, 61
 - mineralised components, respective roles of, 77–79
 - calcified cartilage as mechanical transition layer challenged, 78–79
 - material properties, relation to morphology, 77–78
- subchondral bone stiffening, influence of repeated loading, 79
- tidemark
 - absent in young tissue, 45
 - duplication of, 45, 346–48
 - influenced by proximity to lesion site, 51–52
 - may involve graded mineralisation, 342
 - mechanobiological adaptation, possible evidence for, 346–48
 - morphology of, 45
 - relation to loading history, 45
 - undulations in, possible mechanical significance of, 76–77
- tendon and ligament biomechanics
 - biochemical constituents
 - elastin variability, mechanical implications of, 294
 - influence on mechanical properties, 294–95
- collagen crimp
 - functional significance of, 296–98
 - its variability over ligament cross-section, 295
 - quantification of, 295–96
 - variability and readiness for ‘action’, 296–98, 300–301
- collagen fibre recruitment, 298–300
 - differential loading inferred, 300
 - experimental determination of, 298–300
 - its dependence on joint stance, 298–301
- failure mechanisms
 - bone evulsion, 287
 - loading rate, influence of, 302
 - maturity level, influence of, 302
 - sites involved, 302
 - soft tissue strains and micro-rupture of fibres, 302–3
- hierarchical structure of tendons and ligaments, 289–94
 - additional levels identified with SEM, 291
 - collagen fibril, its multilevel molecular structure, 291
 - fibril diameter, its influence on strain energy distribution, 293
 - provides for biomechanical optimisation, 291–94
 - relevant to distribution of strain energy, 291
 - resilience arising from interaction with proteoglycans, 293–94
- ligaments, 287–89
 - anterior cruciate ligament
 - design reflects complex function, 287–89
 - functional significance of double bundle structure, 296, 300–301, 323
 - its role in knee joint, 287–89
 - elastin content, specialised role in, 294
 - passive stabiliser of joints, primary role of, 287
 - stiffness variations, relation to patterns of injury, 287
- natural design and factors of safety, 301–3
 - challenge for artificial replacements, 301–2
 - relevance to repair and reconstruction, 303
 - relevance to tissue engineering, 303
 - ultimate versus physiological loading, 301–3
- tendons, 296–98, 285–87
 - elastin component, suggested role in energy storage, 294
 - energy storage, importance of, 285
 - functional range of movement, 286–87
 - lubricin, its role in interfascicular sliding, 294
 - mechanical properties and joint function, 286–87
 - stresses in, 285
 - tangent modulus of, 286

- tendon/ligament enthesis
- anterior cruciate ligament enthesis as model system, 323
 - double-bundle insertion sites and morphologies, 324
 - interdigitation-depth differences, implications of, 332–33
 - their demarcation, 325
 - fibre–bone rooting, differences between bundles, 334–36
 - fibre-to-fibril level view of, 334–36
 - imaging with thick, hydrated sections, advantages of, 325–28
 - insertion morphology suggests function, 323–24, 325–32
 - macro-level structure of, 325
 - macro-to-micro structure of, 325–34
 - uncalcified and calcified fibrocartilage, functional significance of, 324
 - composition and tissue components, 304–5
 - influence on mechanical properties, 304–6
 - developmental stages of, 304
 - formation of fibrocartilage, 304
 - hyaline cartilage anlage, initial role of, 304
 - mineralisation of fibrocartilage, 304
 - direct enthesis, 306–14
 - complex stresses in loaded state, 310–11
 - curvilinear force trajectory maintained, 309
 - deep interdigitation of hard tissues, 311–12
 - fibrocartilage, uncalcified and calcified, 309–11
 - its multi-zone morphology, mechanical significance of, 306–9
 - osteon ‘islands’, a possible strengthening role, 313–14
 - soft tissue inserts at large angles, 307
 - step-change in stiffness avoided, 306–7
 - ‘stretching-brake theory’, 309–10
 - tidemark and cement line, present in, 306–7, 312
 - enthesis strength and toughness, 343–45
 - force redistributing mechanisms suggested, 343–44
 - mechanical properties optimised, 344
 - modulus, strength, energy absorption and composition correlation, 344–45
 - most common modes of failure, 343
 - possible mechanisms of energy absorption, 344–45
 - role of enthesis in energy absorption also questioned, 345
 - enthesis, a functionally graded system, 338
 - achieved with its hierarchical structure, 340–41, 341–42
 - collagen types in, 342–43
 - design strategies for effective load transmission, 340
 - enthesis design and stress homeostasis, 341
 - fibre orientation, importance of, 342
 - fibril architecture and graded mineralisation, importance of, 341–43, 345
 - involves small tissue volume, 342, 345
 - management of modulus mis-match, 338, 340, 341
 - mineralisation and percolation threshold, importance of, 342
 - non-biological examples of functional grading, 338–40
 - case-hardening of steels, 339–40
 - piezoelectric ceramic transducers, 339
 - pottery glazes, 340
 - thermal barrier materials, 339
 - stress concentrations reduced by, 338, 340
 - tidemark, a possible redefinition of, 342
 - indirect enthesis, 314–19
 - bone growth and shape change accommodated by, 315–16
 - four distinct tissue zones, 317–18
 - how morphology relates to function, 318–19
 - insertion migration during bone growth, 315–16
 - medial collateral ligament, its indirect insertion in tibia, 314–15
 - mineralised fibrocartilage, involvement of, 321
 - morphological evidence for adaptation, 316–17
 - periosteal layer between soft tissue and bone, 314–15
 - Sharpey’s fibers, role of, 314–15
 - soft tissue inserts at acute angles, 314–15, 316–17
 - mechanobiological adaptation of enthesis
 - mechanical and biological factors, individual and combined effects, 346
 - mechanical factors acting over time, importance of, 346–48
 - micro- to macro-scale events, importance of, 345–46
 - morphology shaped by biological and mechanical influences, 305–6, 324
 - strain field, importance of, 346
 - overall comparison of direct and indirect entheses, 316, 319–22