ACCSCIENCE PUBLISHING

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REVIEW ARTICLE

Bioprinting strategies for skeletal muscle regeneration: Advances in bioinks, technologies, and functional reconstruction

Supplementary file

Table S1. Summary of studies on bioinks for skeletal muscle regeneration

Reference	Design_type	Bioink/scaffold	Species_model	Outcome_metrics	Ref_No
Maimaiti D 2024	Rat VML repair	Methacrylated fucoidan cryogel	Rat	↑ vascularization, muscle thickness	5
Lee H 2021	In vitro aligned 3D muscle	ECM-based hydrogel	C2C12	↑ alignment & twitch force	21
Kim W 2023	In vitro NMJ model	Collagen + endothelial spheroids	C2C12 + HUVEC	NMJ formation, Ca^{2+} transients	39
Shiwarski DJ 2025	High-res perfusable scaffold	Collagen (LIFT-printed)	Human SkM	>90 % viability, sustained perfusion	57
Yoshida A 2025	Drug-testing platform	Aligned GelMA	Human SkM	Dose-response contractile force	189
Christensen KW 2022	Rat VML implant	Collagen AC-DC fibers	Rat	≈70 % torque recovery	60
Rodriguez Ayala A 2025	Mouse VML porous scaffold	Cell-scale porous PEGDA	Mouse	↑ innervation density, ↓ FBR	206
Fischer EO 2024	Perfusable vascular flap	Fibrin-dECM	Rat	↑ capillary density, tetanic force	210
Costantini M 2021	Myo-substitutes (murine/human)	Alginate-fibrin coaxial fibers	Athymic mouse	12 wk survival, gait score ↑	229
Kim JH 2020	Neural integration in VML	Collagen + neural progenitors	mdx mouse	Grip strength ↑, fibrosis ↓	59
De Paolis F 2023	Large-animal (swine) VML	Fibrin-dECM patch	Pig	MRI volume & torque restoration	228
Gao L 2024	Pennate fiber architecture	Micro-grooved GelMA	Human SkM	Controlled pennation, max force ↑	190
Han S 2023	Nano-enabled scaffold	MXene-GelMA composite	C2C12	↑ conductivity, fusion index	125
Li S 2024	Fibrin variant screening	Custom fibrin blends	Human SkM	Rheology ↔ myogenesis correlation	82
Boularaoui S 2021	Conductive composite hydrogel	GelMA + MXene + AuNP	C2C12	Voltage-stimulated twitch force	121
Zhang H 2023	Vascularization assay	dECM + VEGF microspheres	HUVEC + SkM	↑ lumen density & O_2 diffusion	23
Filippi M 2023	Perfusable biohybrid	GelMA organohydrogel	Human SkM	Real-time mechanosensing, perfusion	204
Cakal SD 2022	Aligned 3D muscle	Hydrogel (wet-spun)	Human & Murine	Longitudinal alignment, viability	62

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Ronzoni FL 2022	Myoblast 3D print	Alginate-gelatin	C2C12	↑ differentiation efficiency	67
Yang GH 2021	Electric-field 4D printing	GelMA	C2C12	Alignment & contractility ↑	80
Lee S 2023	Blade-casting assisted	Collagen	C2C12	↑ myogenic markers	110
Smoak MM 2021	Electrospun dECM fibers	Decellularized ECM	C2C12	↑ myotube fusion	78
Hwangbo H 2022	Aligned GelMA grid	GelMA	C2C12	Uniform myotube alignment	79
Kim D 2021	Submerged bioprinting	Collagen filaments	C2C12	Efficient myogenesis	81
Lee J 2023	Photo-crosslinked muscle graft	Gelatin derivative	Mouse	Muscle restoration in vivo	110
Heo G 2025	Comb-assisted bioprinting	Collagen-based	C2C12	↑ mechanotransduction	112
Luo W 2024	Ischemic limb repair	PCL-fibrin-alginate	Rat	Angiogenesis & immune modulation	114
de Barros NR 2023	Microparticle maturation	GelMA + growth-factor MPs	C2C12	↑ maturation markers	138
Volpi M 2024	Myotendinous junction	Wet-spun hydrogel fibers	Human SkM	Robust interface formation	167
Fornetti E 2023	Novel extrusion system	Alginate-based	C2C12	↑ print fidelity & viability	140
Müller SJ 2023	Computational + in vitro	Generic shear-thinning hydrogel	C2C12	Predicted stress ↔ viability	148
Lombardi L 2025	Optimized nozzle	Hydrogel (generic)	C2C12	↑ post-print viability	149
Silva C 2020	Triple-layer coaxial extruder	Multilayer hydrogel	C2C12	Cell viability optimization	174
Sun J 2025	Coaxial extrusion optimization	Gelatin-based	C2C12	↑ precision, viability	164
Hwangbo H 2025	In situ magnetic bioprinting	Magnetorheological GelMA	Mouse	Alignment & stress ↑	180
Niknezhad SV 2024	Durable bacterial hydrogels	Super-durable hydrogel	Rat VML	Muscle volume & function ↑	207
Zhao N 2024	Mouse masseter VML model	— (surgical)	Mouse	Impaired mastication ↔ nutrition	208
Whitaker R 2025	Injury-size immunology	—	Rat	Immune-cell dynamics profiled	209
Hoffman DB 2025	Vibration therapy	—	Mouse VML	Functional recovery ↑	213
Johnson D 2024	Regenerative rehabilitation	Collagen scaffold + rehab	Rat	Contractile strength ↑	214
Mehrotra P 2024	Muscle reprogramming	—	Rat nerve injury	Reinnervation ↑	215
Rousseau E 2023	Actuated muscle graft	Tissue-engineered graft	Rat	Restored mobility	227
Loi G 2024	Bioreactor-integrated printing	Hydrogel	C2C12	Benchmarking maturation ↑	205
Gao H 2021	Microgrooved topography	Patterned surface	C2C12	↑ differentiation	181
Kamal KY 2024	Cyclic-strain bioreactor	—	Engineered SM	Hypertrophy markers ↑	182
Borisov V 2023	Upscaled vascularized tissue	Hydrogel constructs	Mouse	In vivo vascularization	183
Fuentes J 2024	Ferrofluid bioink	Ferrofluid-GelMA	C2C12	↑ force, magnetic response	132
Kim MH 2024	High-throughput spheroid print	Hydrogel micro-array	Various	Scalable fabrication	178

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Zhang S 2020	Microfluidic nozzle	High-viscosity bioink	—	Uniform microspheres	134
Askari M 2021	Advanced extrusion 3D print	Hydrogel composites	—	Printability & cell viability	86
Garcia-Lizarribar A 2023	In vitro cachexia model	dECM-based hydrogel	Human SkM	Force decline under TNF-α, drug rescue	26
Alave Reyes-Furrer A 2021	Matrigel 3D muscle	Matrigel	Human SkM	↑ contractility, exercise response	27
Ngan CGY 2021	In vivo vascularized construct	Alginate-GelMA	Mouse	Innervation & perfusion ↑	74
Sunadome K 2023	In vivo mechano-biology	Native tissue (mechanical mod.)	Mouse	Mechanical forces set fiber orientation	37
Mondrinos MJ 2021	Surface-directed anisotropy	Micro-patterned PDMS	Human SkM	Tissue anisotropy ↑	42
Ferrara PJ 2022	Immunomod. aged mice	Macrophage modulation (drug)	Aged Mouse	Functional recovery ↑	43
Wirth G 2023	Hindlimb ischemia	—	Mouse	Capillary dynamics vs damage	44
Zhong T 2025	EV delivery ischemic limb	Engineered EVs	Rat	↑ vascularization & muscle mass	48
Xing J 2022	Anisotropic scaffold	Complex aligned fiber hydrogel	Mouse	Myotube orientation & force ↑	55
Adhikari J 2021	Process param. study	Alginate-GelMA	C2C12	Printing shear vs viability map	73
Marzi J 2022	Raman imaging bioinks	Various hydrogels	C2C12	Non-invasive 3D cell density	89
Khalili M 2023	PEGDA hydrogels	PEGDA variants	—	Printability & mech. props.	92
Lee G 2025	Ischemic limb repair	PCL-fibrin-alginate	Rat	Angiogenesis & immune modulation	106
Poerio A 2022	Neurotrophic delivery	Sustained NGF release	C2C12 + DRG	Enhanced innervation	115
Quint J 2022	Nano-engineered scaffold	CNT-GelMA	C2C12	↑ electrical conductivity & fusion	117
Aparicio-Collado JL 2022	Electroactive hydrogel	Ca-alginate/PCL/rGO	C2C12	Myogenic differentiation ↑	123
Jo SB 2020	Nanofiber matrix	PU + nano-GO	C2C12	↑ myogenic stimulation	124
Tuladhar S 2023	Shear-thinning tuning	GelMA + fibers	—	Rheology vs filament fidelity	136
McCauley PJ 2025	Cell-mechanics vs viability	Generic extrusion hydrogels	C2C12	Process window charted	145
Reina-Romo E 2021	In silico nozzle design	Shear-thinning hydrogels	—	Optimized shear profile	150
Ng WL 2024	Inkjet deposition study	Alginate	C2C12	Cell viability vs droplet size	156
Kryou C 2023	Laser bioprint DNA damage	UV vs vis wavelengths	hMSC	DNA integrity assay	161
Duong VT 2023	DLP gel-norbornene	Gel-NB	HUVEC + SkM	Enhanced vascularization	176
Kim J 2024	Hybrid bioprinting	Self-assembled collagen	C2C12	Fully aligned filaments	178
Fabre P 2025	Lipid mediator switching	— (drug study)	Mouse	Myogenesis modulation	217
Lee MC 2024	hiPSC muscle lattice	Vessel-integrated hydrogel	Human hiPSC	Regeneration in VML model	220
Jo B 2025	In vitro weight training	3D printed load device	C2C12	Hypertrophy markers ↑	225
Vesga-Castro C 2024	Single myotube platform	PDMS micro-grooves	Human	Contractile & Ca^{2+} dynamics	226

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Ebrahimi M 2021	DMD 3D culture	Fibrin hydrogel	Human DMD	Revertant fiber formation	199
Tejedera-Villafranca A 2023	Sarcolemmal damage model	Contractile 3D GelMA	C2C12	Drug testing for DMD	200
Torres MJ 2022	Taxane myotoxicity screen	Human myobundles	Human	Force decline vs dose	201
Madden L 2015	Human myobundle drug resp.	Collagen/Matrigel	Human	Clinically predictive force	202
Raman R 2016	Optogenetic bio-machines	GelMA	C2C12 + HEK	Light-induced motion	203
Yamaoka Y 2024	H&E image ML analysis	—	Mouse VML	Automated regeneration score	211
Hoffman DB 2024	Neuromuscular injury eval.	—	Rat	Re-innervation assessment	216
Fischer EO 2025	Perfusable muscle flap	Fibrin-dECM	Rat	Functional recovery ↑	210

Abbreviations: AC-DC: Assembled cell-decorated collagen; AuNP: Gold nanoparticle; Ca^{2+}: Calcium; dECM: Decellularized extracellular matrix; DLP: Digital light processing; DMD: Duchenne muscular dystrophy; ECM: Extracellular matrix; EV: Extracellular vesicle; eval.: Evaluation; FBR: Foreign body reaction; GelMA: Gelatin methacrylate; GO: Graphene oxide; hiPSC: Human induced pluripotent stem cell; H&E: Hematoxylin and eosin; Immunomod: Immunomodulated; mech.: Mechanical; MPs: Microparticles; MRI: Magnetic resonance imaging; NB: Norbornene; NGF: Nerve growth facto; NMJ: Neuromuscular junction; O_2: Oxygen; param.: Parameter; PCL: Polycaprolactone; PEGDA: Polyethylene glycol diacrylate; PDMS: Poly(dimethylsiloxane); props.: Properties; PU: Polyurethane; res: Resolution; resp: Response; rGO: Reduced graphene oxide; SkM: skeletal muscle satellite cells; TNF-α: Tumor necrosis factor alpha; UV: Ultraviolet; VEGF: Vascular endothelial growth factor; Vis: Visible; VML: Volumetric muscle loss; wk: Week.