We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Composition and Function of Extracellular Matrix in Development of Skeletal Muscle

Zishuai Wang and Zhonglin Tang

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/62645>

Abstract

Skeletal muscle extracellular matrix (ECM), surround of muscle fibers, the amount of which is just <5%, appeals less attention in the field of skeletal muscle physiology. Thus, at one time, the function of skeletal muscle ECM was arbitrarily considered as general structural support that is typical in other tissues. However, an increasing number of recent evidences have indicated that the ECM plays a critical role in muscle fiber force transmission, proliferation, differentiation, migration, and polarization of cells. Alterations of molecules within the ECM are involved in fibrosis, muscle aging, regeneration, and myopathies. In this chapter, we review the composition and functions of ECM in skeletal muscle development.

Keywords: extracellular matrix, skeletal muscle, myogenesis, regeneration, fibrosis, myopathies

1. Introduction

The process of skeletal muscle formation in vertebrates begins from myogenic progenitors originating in the somites. However, somitic cells are the source of several cell lineages and only a subset are committed to a muscle fate [1]. Those cells destined for a muscle fate then undergo the process of myogenesis, during which the progenitors become specified and determined as myoblasts, which will proliferate, migrate, and fuse to one another to form multinucleated myofibers [2]. Thus, myogenesis seem to be critical in myoblast alignment and fusion into multinucleated myotubes. And the formation of myotubes is central to skeletal muscle development.

Extracellular matrix (ECM) has been considered as a structural scaffold between cells. It has been clear for many years that the ECM is a dynamic structure that influences cell behavior through the interaction of ECM molecules with each other, interaction with growth factors, and through cell–ECM signal transduction pathways [3]. Although the compositions of the ECM differ between tissues, all ECMs share the common function of structural support, cell adhesion, cell-to-cell communication, and differentiation [4]. Since the discovery that skeletal muscle ECM participate in the conversion of myoblasts to myotubes [5], the field of skeletal muscle physiology begins to focus on the relationship between muscle cells and ECM. In this review, we will give more details about the compositions of skeletal muscle ECM and how they affects muscle's normal functions.

2. Composition of skeletal muscle ECM

Anatomic studies indicate that vertebrate skeletal muscle can be typically classified into three layers: skeletal muscle fibers, enclosed by endomysium; muscle fasciculus, enclosed by perimysium; and entire muscle enclosed by epimysium. Thus, skeletal muscle ECM can also be organized into hierarchical structure: endomysial, perimysial, and epimysial connective tissues. According to the structure topology studies, the ECM can be classified into two layers: the interstitial matrix and the basement membrane. Interstitial matrix appears in the intercellular spaces, while basement membrane is a static structure on which cells rest. The interstitial matrix is filled by fibrous proteins and fibroblasts which is responsible for producing collagen, fibronectin, proteoglycans (PGs) and glycosidase, and matrix metalloproteinase (MMPs) [6–8]; while basement membrane is composed of basal lamina and fibrillar reticular lamina [9]. Muscle ECM is made up of numerous macromolecules including collagens, glycoprotein and matricellular proteins, PGs, and matrix remodeling enzymes [10].

In common with other tissues, the major protein of skeletal muscle ECM is collagen [11], synthesized and excreted by fibroblasts, including types I, III, IV, VI, XI, XII, XIII, XIV, XV, and XVIII [12–15]. According to their structure and functions, these types can be divided into several groups. Fibrillar collagens: collagens that have the ability to self assemble into fibrils including types I, III, XI. Network-forming collagens: collagens that have the ability to form a network including types IV and VI. Association collagens: collagens that have the ability to associate with fibrils including types XII and XIV. Transmembrane collagens including type XIII. Multiplexin: multiple triple helix domains with interruptions including types XV and XVIII [16]. Among these isoforms, the predominant distributors in ECM are types I and III as type I appears in perimysium, whereas type III prefers to distribute between endomysium and epimysium [17]. Types IV, VI, XV/XVIII, and XIII collagen are ingredients of the basement membrane [12, 18, 19]. Types XII and XIV collagen are perimysial fibril-associated collagens with interrupted triple helices [14].

Basement membrane, the specific region of ECM, is a reticular lamina knitted by collagen IV and glycoproteins including laminins, fibronectins, and entactin/nidogen [20]. Specifically, laminins bind to integrins and α -dystroglycan, while fibronectins bind to integrins and

laminins. Laminins and collagen type IV are linked to each other by entactin/nidogen [21–25]. Besides, there are other functional matricellular proteins appear in skeletal muscle ECM including tenascin-C, tenascin-Y, osteopontin, thrombospondin. Particularly, only during muscle regeneration can osteopontin be detected. And Tenascin-C appear to be located to the neuromuscular junction [26–31].

PG is heavily glycosylated proteins that is composed of a central core protein with one or more covalently attached glycosaminoglycan (GAG) chain(s) [32, 33]. Typically, the GAG is a polymer of disaccharide repeats including hyaluronan (HA), chondroitin sulfate (CS), dermatan sulfate (DS), heparan sulfate (HS), and keratan sulfate (KS). Most of the PGs appeared in skeletal muscle ECM belongs to the small leucine-rich proteoglycan (SLRP) family. And the majority of SLRP family present in muscle ECM is decorin that is covalently attached by CS/DS and biglycan [34]. Decorin can associate with fibrillar collagen, types I and III collagens [3]. Moreover, heparan sulfate proteoglycans (HSPGs) including types XV, VIII collagen, perlecan, and agrin are intrinsic constituents of basement membranes that are famous for its interaction with growth factors [35, 36]. Matrilins are a novel family of oligomeric ECM proteins. The matrilin family has four members, which are named matrilin 1, 2, 3, and 4 that all share a structure made up of von willebrand factor A (VWA) domains [37, 38]. In skeletal muscle ECM, matrilin-2 is widely distributed while other members are rarely present. Matrilin-2 has two VWA domains that are connected by ten epidermal growth factor (EGF)-like modules and is believed to be involved in the development and homeostasis of the ECM network by participating in filamentous network forming [38–41].

Dynamic equilibrium of skeletal muscle ECM is maintained by degradation enzyme and cells that can secrete ECM productions. It is well known that the majority of ECM components are secreted the fibroblast. Besides, myogenic cells can also secrete collagens, MMP-2 and decorin [42–44], and embryonic myoblasts secrete collagens [45]. There are at least six categories of enzymes that can digest ECM compositions: prolinase, serine protease, cysteine protease, asparagine proteinase, glycosidase, and matrix metalloproteinase (MMP). Since MMP can widely degrade collages and PGs, it is regarded as the most important regulator in keeping the integrity and homeostasis of ECM [43, 46–48].

Briefly, ECM is a complicated supermolecular network composed by collagen, glycoprotein, and PGs. Each component contains different isoforms and form complicated complexes by connecting with each other. Thus, it is hard to characterize skeletal muscle ECM constructors fully, and for much more details about these components, new techniques are needed.

3. Role of ECM in skeletal muscle development

As a fundamental component of the microenvironment of muscle fibers, the functions of ECM are traditionally considered as force transmission and structure integrity maintenance. However, an increasing number of evidence demonstrating ECM also plays an important role in myogenesis, cell proliferation, differentiation, migration, and muscle regeneration [49].

As mentioned above, providing structural and biochemical support to the surrounding cells is a common function of ECM in all cells. However, the transmission of force from contractile

elements in the muscle fiber to the resultant movement of a joint seems to be the primary function of skeletal muscle ECM [50]. In order to achieve this function, ECM was linked to cytoskeleton by integrins, dystroglycan, and PGs at the cell surface [51–53]. Specifically, integrins can convert mechanical signals to adaptive responses in the cell [54–56] and dystrophin–glycoprotein complex is critical in mechanotransduction of muscle and tendon tissue [56]. In this way, adhesion complexes composed by ECM and transmembrane proteins establish a mechanical continuum along which forces can be transmitted from inside of the cell to outside, and vice versa.

One generally held idea is that many growth factors bind to their signaling receptors using GAG chains attached to ECM and membrane proteins as cofactors. For example, the binding of fibroblast growth factor (FGF) to FGF receptor depends on a HS chain binding at the same time [57]. Fibronectin and vitronectin bind to hepatocyte growth factor (HGF) and form the HGF receptor complexes to enhance cell migration [58]. And vascular endothelial growth factor (VEGF) binds to fibronectin type III (FN3) domains to promote cell proliferation [59]. Together, these evidences suggested that ECM proteins bind and present growth factors as organized solid-phase ligands. And considering growth factors including HGF, IGF, FGF, and the TGF- β superfamily are involved in controlling the proliferation and differentiation of myoblasts. Thus, it seems to be clear that ECM proteins can participate in skeletal muscle development by connecting with growth factors.

In vitro studies have shown that collagen fibrils are necessary during orientation and alignment of muscle fibers [60], and the inhibition of collagen synthesis suppresses the differentiation of myoblasts [49]. The functional importance of collagen network can be further proved through studies of mutant knockout models. Defection of types IV, IX, XIII, XV collagen [61–64] and mutations of collagen type VI will cause myopathy symptomatology [65]. Furthermore, lacking collagen types IX or XI will lead to abnormal collagen fibrils [66, 67], while lacking collagen type X chondrodysplasia will present [68].

PGs can also affect skeletal muscle development by modulating the activation of growth factors. For instance, perlecan can activate basic FGF (bFGF) tyrosine kinase receptors, which is a strong inhibitor of myogenic differentiation [69]. Syndecan-4 and glypican-1 participate in muscle cell proliferation and differentiation by regulating FGF2 [70]. Furthermore, syndecan-1 and -3 can also modulate the biological activity of FGF-2 [71, 72].

Decorin obstructs muscle cell proliferation [73, 74], by inhibiting the activity of transforming growth factor- β 1 (TGF- β 1). Myostatin, belonging to TGF- β superfamily, is a negative factor in muscle development. And decorin can also enhance myoblasts differentiation by restraining myostatin [75]. Moreover, fibromodulin, lumican, and biglycan can stimulate myostatin, insulin-like growth factor (IGF), or HGF [76–78].

Laminin is another critical matrix component that affects myogenesis. Specifically, evidences indicate that laminin can promote myoblast adhesion, proliferation, and myotube formation by regulating myostatin activity [79–81]. And lacking laminin mice characterize growth retardation and muscle dystrophy. On the other hand, laminin and collagen IV provide binding sites for PGs that can regulate growth factors activity. However, fibronectin, another

glycoprotein, prevents myoblast differentiation by selectively promoting adhesion of fibroblasts [81, 82].

TGF- β 1 signal pathway is reported to prevent myogenic differentiation partly by inhibiting matrilin-2 expression. In return, the matrilin-2 promotes cell differentiation and regeneration processes in myogenic by binding to other ECM proteins and integrins to regulate the TGF- β /BMP-7/Smad and other signaling pathways [83].

Skeletal muscle is a regenerative tissues and such regeneration requires the activity of a population of tissue-specific adult stem cells referred to as satellite cells. The satellite cell reside in mature skeletal muscle and is normally quiescent; however, when injury occurs, these muscle progenitor populations will proliferate, migrate, and fuse into new muscle fibers [84]. These special cells are wedged in basal lamina, of which the most abundant proteins are collagen type IV and laminin-2. In vitro studies showed that when satellite cells will rapidly enter cell cycle and proliferate after leaving basal lamina [85]. What is more, satellite cells cultured on matrigel with collagen VI are more inclined to be quiescence compare to these without collagen VI [86]. Thus, it seems that the basal lamina can prevent satellite cell proliferation and differentiation in the absence of damage [20]. When it comes to muscle regeneration, ECM components will positively participate in cell mitosis and differentiation as we mentioned before. Syndecan-3, one member of HSPGs, can regulate homeostasis of the satellite cell population and myofiber size by cooperating with Notch [87]. Together, these evidences show that ECM compositions play an important role in keeping satellite cells quiescent under normal circumstances and proliferation, differentiation during regeneration process.

4. ECM and myopathies

Abnormal accumulation of ECM is clinically termed “fibrosis”, which is characterized by increased endomysium and perimysium in skeletal muscle. Skeletal muscle fibrosis can be detected in nearly all muscular dystrophies, aging, and muscle injury [88–92]. However, it is hard to precisely quantify skeletal muscle fibrosis as the components are complicated and dynamically changed. Furthermore, in normal muscle, the amount of ECM area fraction is 5%, but this value can dramatically increase in muscle fibrosis cases. This is because the muscle fibers will become atrophic in diseased, such as severe atrophy, chronic inflammation, and dystrophies or injured states even ECM structure remains the same [93]. Whether muscle fibrosis is characterized by excessive production of ECM components remains unclear, but the participation of these components in muscle fibrosis has been proved.

TGF- β has long been believed to be a central mediator of the fibrotic response as it can induces fibroblasts to synthesize type-I collagen and fibronectin [94]. Moreover, TGF- β can induces the expression of connective tissue growth factor (CTGF), a downstream mediator of the effects of TGF- β on fibroblasts [95, 96], and the matrix protein fibronectin, a critical factor in enhancing the expression of collagen type I [97].

In skeletal muscular dystrophies, the expressions of decorin and biglycan are increased [98, 99], which will cause alteration of TGF- β signaling and eventual fibrosis [100]. Besides,

treatments using decorin and TGF- β inhibitors in injured muscle enhance regeneration and prevent fibrosis [101–103].

Fibrin, a structural component of the ECM, accumulates in areas of degeneration and inflammation in dystrophic muscle, whereas knockout fibrinogen was shown to reduce fibrosis development in mdx mice. Fibrin can induce the expression of TGF- β to promote fibrosis [104]. Fibrin can activate fibroblasts to synthesize and secrete collagens by binding to α V β 3 integrin receptor [105]. Considering the synthesis and degradation of collagens is controlled by MMPs, the importance of proteases in muscle fibrosis is absolutely obvious [106].

On the other hand, defects in or deficiencies of ECM molecules will cause myopathies and inherited connective tissue disorders. As we mentioned before, ECM and cytoskeleton are connected by transmembrane proteins named dystroglycan, sarcoglycan, integrin. Dystroglycan has two subunits α and β , β -dystroglycan intracellularly binds to dystrophin and extracellularly to α -dystroglycan, which is associated with the ECM proteins laminin α 2, biglycan, and perlecan [16, 107]. Defects in α -dystroglycan can lead to congenital muscular dystrophy (MDC) and limb-girdle muscular dystrophy (LGMD) that can also be caused by deficiency of laminin α 2 [108]. Sarcoglycans can extracellularly binds to biglycan and is closely associated with the dystroglycan complex [109–111]. Mutations in sarcoglycans result in autosomal-recessive limb-girdle muscular dystrophies. In integrin knocked mice, mild form of muscular dystrophy appears [112]. Furthermore, clinical studies show that collagen VI deficiency lead to Bethlem myopathy and Ullrich congenital muscular dystrophy [61, 113, 114].

Extracellular fat is another pathological response of skeletal muscle to disease or injury that is accompanied by pathological diseases include Duchenne muscular dystrophy, obesity, type-2 diabetes, and aged muscle [115–117]. Recent studies have identified a PDGFR α + progenitor cell population that is responsible for intracellular fat deposition as the cell can differentiate into adipose tissue under nonregenerating conditions [118]. Moreover, these cells were found to distribute more in perimysium than endomysium [119].

5. MMPs and skeletal muscle

MMPs are famous for its irreplaceable role in degrading ECM compositions. In skeletal muscle, MMP-2 and MMP-9 [43] can degrade type-IV collagen, fibronectin, PGs, and laminin, while MMP-1 [48] and MMP-13 [120] degrade types I and III collagen. The activities of MMPs are controlled by tissue inhibitors of matrix metalloproteinases (TIMPs). TIMP-1 binds to active forms of MMPs forming noncovalent complexes, whereas TIMP-2 stabilizes the inactive form of the enzyme, and thus inhibits the formation of active proteolytic enzyme [47, 48]. In normal muscle tissues, the expression of MMPs are very low but increased in injured muscles mainly because they are secreted by inflammatory cells [121]. Although studies rarely show the functions of MMPs in skeletal muscle, they have been implicated in many pathological processes including myogenesis, muscle growth, development, aging, and regeneration [122, 123]. MMP-2 knockout mice developed significantly less hypertrophy and ECM remodeling in response to overload compared to a significant increase in MMP-2 activity and upregulation of ECM components and remodeling enzymes in wild-type mice [124]. In vivo study shows

that MMP-2 is essential for myoblast migration [125], while in vitro study indicates MMP-2 is secreted at all stages from cell to myotubes [126]. Acute muscle ischemia results in remodeling of the basal lamina which is accompanied by increased MMP gelatinases [127]. And increased MMPs (MMP-2 and MMP-9) are also responsible to the degradation of ECM in skeletal muscle atrophy [128]. Furthermore, satellite cells are reported to synthesize and secrete MMP-2 and induce MMP-9 activity in human skeletal muscles [129]. During regeneration, MMP-2 activation appears go along with the formation of new myofibers, whereas MMP-9 expression is related to the inflammatory response [43]. Expression changes of MMPs have been involved in different myopathies. Distinctly increased MMP-9 appears in inflammatory myopathies [130], MMP-7 upregulation is prominent in case of polymyositis, whereas MMP-2 is only slightly elevated in inflamed muscle [131].

6. Conclusion

Skeletal muscle fibers are surrounded by ECM, and the ECM is an important part of the cellular microenvironment consists of a complex mixture of structural and functional proteins including glycoproteins, collagen, and PGs. These molecules interact with each other and form a super molecular network in order to maintain skeletal muscle integrity and participate in the development of skeletal muscle. Additionally, skeletal muscle fibrosis, characterized by abnormal accumulation of ECM, is an obvious clinical characteristic of myopathies such as age-related sarcopenia, muscular dystrophy, and Duchenne muscular dystrophy. Genetic diseases, dysregulation of TGF- β signaling and physical activity can cause defects in or deficiencies of molecules within the skeletal muscle ECM.

Author details

Zishuai Wang and Zhonglin Tang*

*Address all correspondence to: zhonglinqy_99@sina.com

Institute of Animal Science, Chinese Academy of Agricultural Sciences, Beijing, PR China

References

- [1] Christ B, Jacob M, Jacob HJ. On the origin and development of the ventrolateral abdominal muscles in the avian embryo. An experimental and ultrastructural study. *Anatomy and Embryology (Berl)*. 1983; 166: 87–101.

- [2] Buckingham M, Vincent SD. Distinct and dynamic myogenic populations in the vertebrate embryo. *Current Opinion in Genetics & Development*. 2009; 19: 444–453. doi:10.1016/j.gde.2009.08.001.
- [3] Nishimura T. Role of extracellular matrix in development of skeletal muscle and postmortem aging of meat. *Meat Science*. 2015; 109: 48–55. doi:10.1016/j.meatsci.2015.05.015.
- [4] Watt FM, Fujiwara H. Cell-extracellular matrix interactions in normal and diseased skin. *Cold Spring Harbor Perspectives in Biology*. 2011; 3: a005124. doi:10.1101/cshperspect.a005124.
- [5] Hauschka SD, Konigsberg IR. The influence of collagen on the development of muscle clones. *Proceedings of the National Academy of Sciences USA*. 1966; 55: 119–126.
- [6] Gatchalian CL, Schachner M, Sanes JR. Fibroblasts that proliferate near denervated synaptic sites in skeletal muscle synthesize the adhesive molecules tenascin(J1), N-CAM, fibronectin, and a heparan sulfate proteoglycan. *Journal of Cell Biology*. 1989; 108: 1873–1890.
- [7] Kuhl U, Ocalan M, Timpl R, Mayne R, Hay E, von der Mark K. Role of muscle fibroblasts in the deposition of type-IV collagen in the basal lamina of myotubes. *Differentiation*. 1984; 28: 164–172.
- [8] Archile-Contreras AC, Mandell IB, Purslow PP. Phenotypic differences in matrix metalloproteinase 2 activity between fibroblasts from 3 bovine muscles. *Journal of Animal Science*. 2010; 88: 4006–4015. doi:10.2527/jas.2010-3060.
- [9] Bosman FT, Stamenkovic I. Functional structure and composition of the extracellular matrix. *The Journal of Pathology*. 2003; 200: 423–428. doi:10.1002/path.1437.
- [10] Gillies AR, Lieber RL. Structure and function of the skeletal muscle extracellular matrix. *Muscle & Nerve*. 2011; 44: 318–331. doi:10.1002/mus.22094.
- [11] Dransfield E. Intramuscular composition and texture of beef muscles. *Journal of the Science of Food and Agriculture*. 1977; 28: 833–842.
- [12] Myers JC, Dion AS, Abraham V, Amenta PS. Type XV collagen exhibits a widespread distribution in human tissues but a distinct localization in basement membrane zones. *Cell and Tissue Research*. 1996; 286: 493–505.
- [13] Marvulli D, Volpin D, Bressan GM. Spatial and temporal changes of type VI collagen expression during mouse development. *Developmental Dynamics*. 1996; 206: 447–454. doi:10.1002/(SICI)1097-0177(199608)206:4<447::AID-AJA10>3.0.CO;2-U.
- [14] Listrat A, Lethias C, Hocquette JF, Renand G, Menissier F, Geay Y, Picard B. Age-related changes and location of types I, III, XII and XIV collagen during development of skeletal muscles from genetically different animals. *Journal of Histochemistry & Cytochemistry*. 2000; 32: 349–356.

- [15] Brandan E, Gutierrez J. Role of skeletal muscle proteoglycans during myogenesis. *Matrix Biology*. 2013; 32: 289–297. doi:10.1016/j.matbio.2013.03.007.
- [16] Voermans NC, Bonnemann CG, Huijting PA, Hamel BC, van Kuppevelt TH, de Haan A, Schalkwijk J, van Engelen BG, Jenniskens GJ. Clinical and molecular overlap between myopathies and inherited connective tissue diseases. *Neuromuscular Disorders*. 2008; 18: 843–856. doi:10.1016/j.nmd.2008.05.017.
- [17] Light N, Champion AE. Characterization of muscle epimysium, perimysium and endomysium collagens. *Biochemical Journal*. 1984; 219: 1017–1026.
- [18] Whittaker CA, Bergeron KF, Whittle J, Brandhorst BP, Burke RD, Hynes RO. The echinoderm adhesome. *Developmental Biology*. 2006; 300: 252–266. doi:10.1016/j.ydbio.2006.07.044.
- [19] Sanes JR. Laminin, fibronectin, and collagen in synaptic and extrasynaptic portions of muscle fiber basement membrane. *Journal of Cell Biology*. 1982; 93: 442–451.
- [20] Sanes JR. The basement membrane/basal lamina of skeletal muscle. *Journal of Biological Chemistry*. 2003; 278: 12601–12604. doi:10.1074/jbc.R200027200.
- [21] Ervasti JM, Campbell KP. A role for the dystrophin-glycoprotein complex as a transmembrane linker between laminin and actin. *Journal of Cell Biology*. 1993; 122: 809–823.
- [22] Wu C, Keivens VM, O'Toole TE, McDonald JA, Ginsberg MH. Integrin activation and cytoskeletal interaction are essential for the assembly of a fibronectin matrix. *Cell*. 1995; 83: 715–724.
- [23] Fox JW, Mayer U, Nischt R, Aumailley M, Reinhardt D, Wiedemann H, Mann K, Timpl R, Krieg T, Engel J, et al. Recombinant nitrogen consists of three globular domains and mediates binding of laminin to collagen type IV. *EMBO Journal*. 1991; 10: 3137–3146.
- [24] Mayer U, Nischt R, Poschl E, Mann K, Fukuda K, Gerl M, Yamada Y, Timpl R. A single EGF-like motif of laminin is responsible for high affinity nidogen binding. *EMBO Journal*. 1993; 12: 1879–1885.
- [25] Rao CN, Margulies IM, Liotta LA. Binding domain for laminin on type IV collagen. *Biochemical and Biophysical Research Communicate*. 1985; 128: 45–52.
- [26] Cotman SL, Halfter W, Cole GJ. Identification of extracellular matrix ligands for the heparan sulfate proteoglycan agrin. *Experimental Cell Research*. 1999; 249: 54–64. doi:10.1006/excr.1999.4463.
- [27] Chung CY, Erickson HP. Glycosaminoglycans modulate fibronectin matrix assembly and are essential for matrix incorporation of tenascin-C. *Journal of Cell Science*. 1997; 110(Pt 12): 1413–1419.
- [28] Uaesoontrachoon K, Yoo HJ, Tudor EM, Pike RN, Mackie EJ, Pagel CN. Osteopontin and skeletal muscle myoblasts: association with muscle regeneration and regulation of

- myoblast function in vitro. *International Journal Biochemistry & Cell Biology*. 2008; 40: 2303–2314. doi:10.1016/j.biocel.2008.03.020.
- [29] Malek MH, Olfert IM. Global deletion of thrombospondin-1 increases cardiac and skeletal muscle capillarity and exercise capacity in mice. *Experimental Physiology*. 2009; 94: 749–760. doi:10.1113/expphysiol.2008.045989.
- [30] Chiquet M, Fambrough DM. Chick myotendinous antigen. I. A monoclonal antibody as a marker for tendon and muscle morphogenesis. *Journal of Cell Biology*. 1984; 98: 1926–1936.
- [31] Chiquet M, Fambrough DM. Chick myotendinous antigen. II. A novel extracellular glycoprotein complex consisting of large disulfide-linked subunits. *Journal of Cell Biology*. 1984; 98: 1937–1946.
- [32] Fransson LA, Havsmark B, Chiarugi VP. Co-polymeric glycosaminoglycans in transformed cells. Transformation-dependent changes in the co-polymeric structure of heparan sulphate. *Biochemical Journal*. 1982; 201: 233–240.
- [33] Kjellen L, Lindahl U. Proteoglycans: structures and interactions. *Annual Review of Biochemistry*, Vol 81. 1991; 60: 443–475. doi:10.1146/annurev.bi.60.070191.002303.
- [34] Brandan E, Inestrosa NC. Isolation of the heparan sulfate proteoglycans from the extracellular matrix of rat skeletal muscle. *Journal of Neurobiology*. 1987; 18: 271–282. doi:10.1002/neu.480180303.
- [35] Mundhenke C, Meyer K, Drew S, Friedl A. Heparan sulfate proteoglycans as regulators of fibroblast growth factor-2 receptor binding in breast carcinomas. *American Journal of Pathology*. 2002; 160: 185–194. doi:10.1016/S0002-9440(10)64362-3.
- [36] Iozzo RV, San Antonio JD. Heparan sulfate proteoglycans: heavy hitters in the angiogenesis arena. *Journal of Clinical Investigation*. 2001; 108: 349–355. doi:10.1172/JCI13738.
- [37] Deak F, Wagener R, Kiss I, Paulsson M. The matrilins: a novel family of oligomeric extracellular matrix proteins. *Matrix Biology*. 1999; 18: 55–64.
- [38] Deak F, Piecha D, Bachrati C, Paulsson M, Kiss I. Primary structure and expression of matrilin-2, the closest relative of cartilage matrix protein within the von Willebrand factor type A-like module superfamily. *Journal of Biological Chemistry*. 1997; 272: 9268–9274.
- [39] Piecha D, Muratoglu S, Morgelin M, Hauser N, Studer D, Kiss I, Paulsson M, Deak F. Matrilin-2, a large, oligomeric matrix protein, is expressed by a great variety of cells and forms fibrillar networks. *Journal of Biological Chemistry*. 1999; 274: 13353–13361.
- [40] Klatt AR, Becker AK, Neacsu CD, Paulsson M, Wagener R. The matrilins: modulators of extracellular matrix assembly. *International Journal of Biochemistry & Cell Biology*. 2011; 43: 320–330. doi:10.1016/j.biocel.2010.12.010.

- [41] Li L, Zhang L, Shao Y, Wang G, Gong R, Wang Z, Peng J, Wang S, Genochio D, Zhao B, Luo J. Distinct roles of two alternative splice variants of matrilin-2 in protein oligomerization and proteolysis. *Molecular Medicine Reports*. 2012; 6: 1204–1210. doi: 10.3892/mmr.2012.1056.
- [42] Beach RL, Rao JS, Festoff BW. Extracellular-matrix synthesis by skeletal muscle in culture. Major secreted collagenous proteins of clonal myoblasts. *Biochemical Journal*. 1985; 225: 619–627.
- [43] Kherif S, Lafuma C, Dehaupas M, Lachkar S, Fournier JG, Verdiere-Sahuque M, Fardeau M, Alameddine HS. Expression of matrix metalloproteinases 2 and 9 in regenerating skeletal muscle: a study in experimentally injured and mdx muscles. *Developmental Biology*. 1999; 205: 158–170. doi:10.1006/dbio.1998.9107.
- [44] Brandan E, Fuentes ME, Andrade W. The proteoglycan decorin is synthesized and secreted by differentiated myotubes. *European Journal of Cell Biology*. 1991; 55: 209–216.
- [45] Sasse J, von der Mark H, Kuhl U, Dessau W, von der Mark K. Origin of collagen types I, III, and V in cultures of avian skeletal muscle. *Developmental Biology*. 1981; 83: 79–89.
- [46] Ohuchi E, Imai K, Fujii Y, Sato H, Seiki M, Okada Y. Membrane type 1 matrix metalloproteinase digests interstitial collagens and other extracellular matrix macromolecules. *Journal of Biological Chemistry*. 1997; 272: 2446–2451.
- [47] Chin JR, Werb Z. Matrix metalloproteinases regulate morphogenesis, migration and remodeling of epithelium, tongue skeletal muscle and cartilage in the mandibular arch. *Development*. 1997; 124: 1519–1530.
- [48] Singh A, Nelson-Moon ZL, Thomas GJ, Hunt NP, Lewis MP. Identification of matrix metalloproteinases and their tissue inhibitors type 1 and 2 in human masseter muscle. *Archives of Oral Biology*. 2000; 45: 431–440.
- [49] Kjaer M. Role of extracellular matrix in adaptation of tendon and skeletal muscle to mechanical loading. *Physiological Reviews*. 2004; 84: 649–698. doi:10.1152/physrev.00031.2003.
- [50] Patel TJ, Lieber RL. Force transmission in skeletal muscle: from actomyosin to external tendons. *Exercise and Sport Sciences Reviews*. 1997; 25: 321–363.
- [51] Mayer U. Integrins: redundant or important players in skeletal muscle? *Journal of Biological Chemistry*. 2003; 278: 14587–14590. doi:10.1074/jbc.R200022200.
- [52] Michele DE, Campbell KP. Dystrophin-glycoprotein complex: post-translational processing and dystroglycan function. *Journal of Biological Chemistry*. 2003; 278: 15457–15460. doi:10.1074/jbc.R200031200.
- [53] Ingber DE, Dike L, Hansen L, Karp S, Liley H, Maniotis A, McNamee H, Mooney D, Plopper G, Sims J, et al. Cellular tensegrity: exploring how mechanical changes in the

cytoskeleton regulate cell growth, migration, and tissue pattern during morphogenesis. *International Review of Cytology*. 1994; 150: 173–224.

- [54] Carson JA, Wei L. Integrin signaling's potential for mediating gene expression in hypertrophying skeletal muscle. *Journal of Applied Physiology* (1985). 2000; 88: 337–343.
- [55] Shyy JY, Chien S. Role of integrins in cellular responses to mechanical stress and adhesion. *Current Opinion in Cell Biology*. 1997; 9: 707–713.
- [56] Ilsley JL, Sudol M, Winder SJ. The interaction of dystrophin with beta-dystroglycan is regulated by tyrosine phosphorylation. *Cell Signal*. 2001; 13: 625–632.
- [57] Mohammadi M, Olsen SK, Goetz R. A protein canyon in the FGF-FGF receptor dimer selects from an a la carte menu of heparan sulfate motifs. *Current Opinion Structural Biology*. 2005; 15: 506–516. doi:10.1016/j.sbi.2005.09.002.
- [58] Rahman S, Patel Y, Murray J, Patel KV, Sumathipala R, Sobel M, Wijelath ES. Novel hepatocyte growth factor (HGF) binding domains on fibronectin and vitronectin coordinate a distinct and amplified Met-integrin induced signalling pathway in endothelial cells. *BMC Cell Biology*. 2005; 6: 8. doi:10.1186/1471-2121-6-8.
- [59] Wijelath ES, Rahman S, Namekata M, Murray J, Nishimura T, Mostafavi-Pour Z, Patel Y, Suda Y, Humphries MJ, Sobel M. Heparin-II domain of fibronectin is a vascular endothelial growth factor-binding domain: enhancement of VEGF biological activity by a singular growth factor/matrix protein synergism. *Circulation Research*. 2006; 99: 853–860. doi:10.1161/01.RES.0000246849.17887.66.
- [60] Lawson MA, Purslow PP. Differentiation of myoblasts in serum-free media: effects of modified media are cell line-specific. *Cells Tissues Organs*. 2000; 167: 130–137. doi: 10.1159/000016776.
- [61] Bonaldo P, Braghetta P, Zanetti M, Piccolo S, Volpin D, Bressan GM. Collagen VI deficiency induces early onset myopathy in the mouse: an animal model for Bethlem myopathy. *Human Molecular Genetics*. 1998; 7: 2135–2140.
- [62] Bonnemann CG, Cox GF, Shapiro F, Wu JJ, Feener CA, Thompson TG, Anthony DC, Eyre DR, Darras BT, Kunkel LM. A mutation in the alpha 3 chain of type IX collagen causes autosomal dominant multiple epiphyseal dysplasia with mild myopathy. *Proceedings of the National Academy of Sciences USA*. 2000; 97: 1212–1217.
- [63] Kvist AP, Latvanlehto A, Sund M, Eklund L, Vaisanen T, Hagg P, Sormunen R, Komulainen J, Fassler R, Pihlajaniemi T. Lack of cytosolic and transmembrane domains of type XIII collagen results in progressive myopathy. *American Journal of Pathology*. 2001; 159: 1581–1592. doi:10.1016/S0002-9440(10)62542-4.
- [64] Eklund L, Piuhola J, Komulainen J, Sormunen R, Ongvarrasopone C, Fassler R, Muona A, Ilves M, Ruskoaho H, Takala TE, Pihlajaniemi T. Lack of type XV collagen causes a

skeletal myopathy and cardiovascular defects in mice. *Proceedings of the National Academy of Sciences USA*. 2001; 98: 1194–1199. doi:10.1073/pnas.031444798.

- [65] Jobsis GJ, Keizers H, Vreijling JP, de Visser M, Speer MC, Wolterman RA, Baas F, Bolhuis PA. Type VI collagen mutations in Bethlem myopathy, an autosomal dominant myopathy with contractures. *Nature Genetics*. 1996; 14: 113–115. doi:10.1038/ng0996-113.
- [66] Li SW, Prockop DJ, Helminen H, Fassler R, Lapvetelainen T, Kiraly K, Peltarri A, Arokoski J, Lui H, Arita M, et al. Transgenic mice with targeted inactivation of the Col2 alpha 1 gene for collagen II develop a skeleton with membranous and periosteal bone but no endochondral bone. *Genes & Development*. 1995; 9: 2821–2830.
- [67] Fassler R, Schnegelsberg PN, Dausman J, Shinya T, Muragaki Y, Mc Carthy MT, Olsen BR, Jaenisch R. Mice lacking alpha 1 (IX) collagen develop noninflammatory degenerative joint disease. *Proceedings of the National Academy of Sciences USA*. 1994; 91: 5070–5074.
- [68] Wallis GA, Rash B, Sykes B, Bonaventure J, Maroteaux P, Zabel B, Wynne-Davies R, Grant ME, Boot-Handford RP. Mutations within the gene encoding the alpha 1 (X) chain of type X collagen (COL10A1) cause metaphyseal chondrodysplasia type Schmid but not several other forms of metaphyseal chondrodysplasia. *Journal of Medical Genetics*. 1996; 33: 450–457.
- [69] Larrain J, Alvarez J, Hassell JR, Brandan E. Expression of perlecan, a proteoglycan that binds myogenic inhibitory basic fibroblast growth factor, is down regulated during skeletal muscle differentiation. *Experimental Cell Research*. 1997; 234: 405–412. doi:10.1006/excr.1997.3648.
- [70] Velleman SG. Meat science and muscle biology symposium: extracellular matrix regulation of skeletal muscle formation. *Journal of Animal Science*. 2012; 90: 936–941. doi:10.2527/jas.2011-4497.
- [71] Larrain J, Carey DJ, Brandan E. Syndecan-1 expression inhibits myoblast differentiation through a basic fibroblast growth factor-dependent mechanism. *Journal of Biological Chemistry*. 1998; 273: 32288–32296.
- [72] Fuentealba L, Carey DJ, Brandan E. Antisense inhibition of syndecan-3 expression during skeletal muscle differentiation accelerates myogenesis through a basic fibroblast growth factor-dependent mechanism. *Journal of Biological Chemistry*. 1999; 274: 37876–37884.
- [73] Riquelme C, Larrain J, Schonherr E, Henriquez JP, Kresse H, Brandan E. Antisense inhibition of decorin expression in myoblasts decreases cell responsiveness to transforming growth factor beta and accelerates skeletal muscle differentiation. *Journal of Biological Chemistry*. 2001; 276: 3589–3596. doi:10.1074/jbc.M004602200.

- [74] Yamaguchi Y, Ruoslahti E. Expression of human proteoglycan in Chinese hamster ovary cells inhibits cell proliferation. *Nature*. 1988; 336: 244–246. doi:10.1038/336244a0.
- [75] Kishioka Y, Thomas M, Wakamatsu J, Hattori A, Sharma M, Kambadur R, Nishimura T. Decorin enhances the proliferation and differentiation of myogenic cells through suppressing myostatin activity. *Journal of Cellular Physiology*. 2008; 215: 856–867. doi: 10.1002/jcp.21371.
- [76] Bolton SJ, Barry ST, Mosley H, Patel B, Jockusch BM, Wilkinson JM, Critchley DR. Monoclonal antibodies recognizing the N- and C-terminal regions of talin disrupt actin stress fibers when microinjected into human fibroblasts. *Cell Motility and the Cytoskeleton*. 1997; 36: 363–376. doi:10.1002/(SICI)1097-0169(1997)36:4<363::AID-CM6>3.0.CO;2-6.
- [77] Collinsworth AM, Torgan CE, Nagda SN, Rajalingam RJ, Kraus WE, Truskey GA. Orientation and length of mammalian skeletal myocytes in response to a unidirectional stretch. *Cell Tissue Research*. 2000; 302: 243–251.
- [78] Schmalbruch H, Lewis DM. Dynamics of nuclei of muscle fibers and connective tissue cells in normal and denervated rat muscles. *Muscle & Nerve*. 2000; 23: 617–626.
- [79] Kroll TG, Peters BP, Hustad CM, Jones PA, Killen PD, Ruddon RW. Expression of laminin chains during myogenic differentiation. *Journal of Biological Chemistry*. 1994; 269: 9270–9277.
- [80] Kubo K, Kanehisa H, Miyatani M, Tachi M, Fukunaga T. Effect of low-load resistance training on the tendon properties in middle-aged and elderly women. *Acta Physiologica Scandinavica*. 2003; 178: 25–32. doi:10.1046/j.1365-201X.2003.01097.x.
- [81] Foster RF, Thompson JM, Kaufman SJ. A laminin substrate promotes myogenesis in rat skeletal muscle cultures: analysis of replication and development using antidesmin and anti-BrdUrd monoclonal antibodies. *Developmental Biology*. 1987; 122: 11–20.
- [82] von der Mark K, Ocalan M. Antagonistic effects of laminin and fibronectin on the expression of the myogenic phenotype. *Differentiation*. 1989; 40: 150–157.
- [83] Korpos E, Deak F, Kiss I. Matrilin-2, an extracellular adaptor protein, is needed for the regeneration of muscle, nerve and other tissues. *Neural Regeneration Research*. 2015; 10: 866–869. doi:10.4103/1673-5374.158332.
- [84] Seale P, Rudnicki MA. A new look at the origin, function, and “stem-cell” status of muscle satellite cells. *Developmental Biology*. 2000; 218: 115–124. doi:10.1006/dbio.1999.9565.
- [85] Gilbert PM, Havenstrite KL, Magnusson KE, Sacco A, Leonardi NA, Kraft P, Nguyen NK, Thrun S, Lutolf MP, Blau HM. Substrate elasticity regulates skeletal muscle stem cell self-renewal in culture. *Science*. 2010; 329: 1078–1081. doi:10.1126/science.1191035.
- [86] Urciuolo A, Quarta M, Morbidoni V, Gattazzo F, Molon S, Grumati P, Montemurro F, Tedesco FS, Blaauw B, Cossu G, Vozzi G, Rando TA, Bonaldo P. Collagen VI regulates

satellite cell self-renewal and muscle regeneration. *Nature Communications*. 2013; 4: 1964. doi:10.1038/ncomms2964.

- [87] Pisconti A, Cornelison DD, Olguin HC, Antwine TL, Olwin BB. Syndecan-3 and Notch cooperate in regulating adult myogenesis. *Journal of Cell Biology*. 2010; 190: 427–441. doi:10.1083/jcb.201003081.
- [88] Duance VC, Stephens HR, Dunn M, Bailey AJ, Dubowitz V. A role for collagen in the pathogenesis of muscular dystrophy? *Nature*. 1980; 284: 470–472.
- [89] Williams PE, Goldspink G. Connective tissue changes in immobilised muscle. *Journal of Anatomy*. 1984; 138(Pt 2): 343–350.
- [90] Alnaqeeb MA, Al Zaid NS, Goldspink G. Connective tissue changes and physical properties of developing and ageing skeletal muscle. *Journal of Anatomy*. 1984; 139(Pt 4): 677–689.
- [91] [91] Berria R, Wang L, Richardson DK, Finlayson J, Belfort R, Pratipanawatr T, De Filippis EA, Kashyap S, Mandarino LJ. Increased collagen content in insulin-resistant skeletal muscle. *American Journal of Physiology-Endocrinology and Metabolism*. 2006; 290: E560–565. doi:10.1152/ajpendo.00202.2005.
- [92] Alexakis C, Partridge T, Bou-Gharios G. Implication of the satellite cell in dystrophic muscle fibrosis: a self-perpetuating mechanism of collagen overproduction. *American Journal of Physiology-Cell Physiology*. 2007; 293: C661–C669. doi:10.1152/ajpcell.00061.2007.
- [93] Lieber RL, Ward SR. Cellular mechanisms of tissue fibrosis. 4. Structural and functional consequences of skeletal muscle fibrosis. *American Journal of Physiology-Cell Physiology*. 2013; 305: C241–C252. doi:10.1152/ajpcell.00173.2013.
- [94] LeRoy EC, Trojanowska MI, Smith EA. Cytokines and human fibrosis. *European Cytokine Network*. 1990; 1: 215–219.
- [95] Grotendorst GR. Connective tissue growth factor: a mediator of TGF-beta action on fibroblasts. *Cytokine Growth Factor Review*. 1997; 8: 171–179.
- [96] Leask A, Denton CP, Abraham DJ. Insights into the molecular mechanism of chronic fibrosis: the role of connective tissue growth factor in scleroderma. *Journal of Investigative Dermatology*. 2004; 122: 1–6. doi:10.1046/j.0022-202X.2003.22133.x.
- [97] Serini G, Bochaton-Piallat ML, Ropraz P, Geinoz A, Borsi L, Zardi L, Gabbiani G. The fibronectin domain ED-A is crucial for myofibroblastic phenotype induction by transforming growth factor-beta1. *Journal of Cell Biology*. 1998; 142: 873–881.
- [98] Fadic R, Mezzano V, Alvarez K, Cabrera D, Holmgren J, Brandan E. Increase in decorin and biglycan in Duchenne muscular dystrophy: role of fibroblasts as cell source of these proteoglycans in the disease. *Journal of Cellular and Molecular Medicine*. 2006; 10: 758–769.

- [99] Zanotti S, Negri T, Cappelletti C, Bernasconi P, Canioni E, Di Blasi C, Pegoraro E, Angelini C, Ciscato P, Prella A, Mantegazza R, Morandi L, Mora M. Decorin and biglycan expression is differentially altered in several muscular dystrophies. *Brain*. 2005; 128: 2546–2555. doi:10.1093/brain/awh635.
- [100] Zanotti S, Saredi S, Ruggieri A, Fabbri M, Blasevich F, Romaggi S, Morandi L, Mora M. Altered extracellular matrix transcript expression and protein modulation in primary Duchenne muscular dystrophy myotubes. *Matrix Biology*. 2007; 26: 615–624. doi: 10.1016/j.matbio.2007.06.004.
- [101] Fukushima K, Badlani N, Usas A, Riano F, Fu F, Huard J. The use of an antifibrosis agent to improve muscle recovery after laceration. *American Journal of Sports Medicine*. 2001; 29: 394–402.
- [102] Chan YS, Li Y, Foster W, Fu FH, Huard J. The use of suramin, an antifibrotic agent, to improve muscle recovery after strain injury. *American Journal of Sports Medicine*. 2005; 33: 43–51.
- [103] Sato K, Li Y, Foster W, Fukushima K, Badlani N, Adachi N, Usas A, Fu FH, Huard J. Improvement of muscle healing through enhancement of muscle regeneration and prevention of fibrosis. *Muscle & Nerve*. 2003; 28: 365–372. doi:10.1002/mus.10436.
- [104] Wynn TA. Cellular and molecular mechanisms of fibrosis. *Journal of Pathology*. 2008; 214: 199–210. doi:10.1002/path.2277.
- [105] Vidal B, Serrano AL, Tjwa M, Suelves M, Ardite E, De Mori R, Baeza-Raja B, Martinez de Lagran M, Lafuste P, Ruiz-Bonilla V, Jordi M, Gherardi R, Christov C, Dierssen M, Carmeliet P, Degen JL, Dewerchin M, Munoz-Canoves P. Fibrinogen drives dystrophic muscle fibrosis via a TGFbeta/alternative macrophage activation pathway. *Genes & Development*. 2008; 22: 1747–1752. doi:10.1101/gad.465908.
- [106] Chen X, Li Y. Role of matrix metalloproteinases in skeletal muscle: migration, differentiation, regeneration and fibrosis. *Cell Adhesion & Migration*. 2009; 3: 337–341.
- [107] Michele DE, Barresi R, Kanagawa M, Saito F, Cohn RD, Satz JS, Dollar J, Nishino I, Kelley RI, Somer H, Straub V, Mathews KD, Moore SA, Campbell KP. Post-translational disruption of dystroglycan-ligand interactions in congenital muscular dystrophies. *Nature*. 2002; 418: 417–422. doi:10.1038/nature00837.
- [108] Brockington M, Blake DJ, Prandini P, Brown SC, Torelli S, Benson MA, Ponting CP, Estournet B, Romero NB, Mercuri E, Voit T, Sewry CA, Guicheney P, Muntoni F. Mutations in the fukutin-related protein gene (FKRP) cause a form of congenital muscular dystrophy with secondary laminin alpha2 deficiency and abnormal glycosylation of alpha-dystroglycan. *American Journal of Human Genetics*. 2001; 69: 1198–1209. doi:10.1086/324412.
- [109] Watkins TC, Zelinka LM, Kesic M, Ansevin CF, Walker GR. Identification of skeletal muscle autoantigens by expression library screening using sera from autoimmune

rippling muscle disease (ARMD) patients. *Journal of Cellular Biochemistry*. 2006; 99: 79–87. doi:10.1002/jcb.20857.

- [110] Matalon R, Surendran S, Campbell GA, Michals-Matalon K, Tyring SK, Grady J, Cheng S, Kaye E. Hyaluronidase increases the biodistribution of acid alpha-1,4 glucosidase in the muscle of Pompe disease mice: an approach to enhance the efficacy of enzyme replacement therapy. *Biochemical and Biophysical Research Communications*. 2006; 350: 783–787. doi:10.1016/j.bbrc.2006.09.133.
- [111] Taniguchi M, Kurahashi H, Noguchi S, Sese J, Okinaga T, Tsukahara T, Guicheney P, Ozono K, Nishino I, Morishita S, Toda T. Expression profiling of muscles from Fukuyama-type congenital muscular dystrophy and laminin-alpha 2 deficient congenital muscular dystrophy; is congenital muscular dystrophy a primary fibrotic disease? *Biochemical and Biophysical Research Communications*. 2006; 342: 489–502. doi: 10.1016/j.bbrc.2005.12.224.
- [112] Mayer U, Saher G, Fassler R, Bornemann A, Echtermeyer F, von der Mark H, Miosge N, Poschl E, von der Mark K. Absence of integrin alpha 7 causes a novel form of muscular dystrophy. *Nature Genetics*. 1997; 17: 318–323. doi:10.1038/ng1197-318.
- [113] Tan Z, Wang TH, Yang D, Fu XD, Pan JY. Mechanisms of 17beta-estradiol on the production of ET-1 in ovariectomized rats. *Life Science*. 2003; 73: 2665–2674.
- [114] Baker NL, Morgelin M, Pace RA, Peat RA, Adams NE, Gardner RJ, Rowland LP, Miller G, De Jonghe P, Ceulemans B, Hannibal MC, Edwards M, Thompson EM, Jacobson R, Quinlivan RC, Aftimos S, Kornberg AJ, North KN, Bateman JF, Lamande SR. Molecular consequences of dominant Bethlem myopathy collagen VI mutations. *Annals of Neurology*. 2007; 62: 390–405. doi:10.1002/ana.21213.
- [115] Leroy-Willig A, Willig TN, Henry-Feugeas MC, Frouin V, Marinier E, Boulier A, Barzic F, Schouman-Claeys E, Syrota A. Body composition determined with MR in patients with Duchenne muscular dystrophy, spinal muscular atrophy, and normal subjects. *Magnetic Resonance Imaging*. 1997; 15: 737–744.
- [116] Goodpaster BH, Stenger VA, Boada F, McKolanis T, Davis D, Ross R, Kelley DE. Skeletal muscle lipid concentration quantified by magnetic resonance imaging. *American Journal of Clinical Nutrition*. 2004; 79: 748–754.
- [117] Visser M, Goodpaster BH, Kritchevsky SB, Newman AB, Nevitt M, Rubin SM, Simonick EM, Harris TB. Muscle mass, muscle strength, and muscle fat infiltration as predictors of incident mobility limitations in well-functioning older persons. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences*. 2005; 60: 324–333.
- [118] Uezumi A, Fukada S, Yamamoto N, Takeda S, Tsuchida K. Mesenchymal progenitors distinct from satellite cells contribute to ectopic fat cell formation in skeletal muscle. *Nature Cell Biology*. 2010; 12: 143–152. doi:10.1038/ncb2014.

- [119] Greco AV, Mingrone G, Giancaterini A, Manco M, Morroni M, Cinti S, Granzotto M, Vettor R, Camastra S, Ferrannini E. Insulin resistance in morbid obesity: reversal with intramyocellular fat depletion. *Diabetes*. 2002; 51: 144–151.
- [120] Wu N, Jansen ED, Davidson JM. Comparison of mouse matrix metalloproteinase 13 expression in free-electron laser and scalpel incisions during wound healing. *Journal of Investigative Dermatology*. 2003; 121: 926–932. doi:10.1046/j.1523-1747.2003.12497.x.
- [121] Choi YC, Dalakas MC. Expression of matrix metalloproteinases in the muscle of patients with inflammatory myopathies. *Neurology*. 2000; 54: 65–71.
- [122] Murphy G, Gavrilovic J. Proteolysis and cell migration: creating a path? *Current Opinion in Cell Biology*. 1999; 11: 614–621.
- [123] Reznick AZ, Menashe O, Bar-Shai M, Coleman R, Carmeli E. Expression of matrix metalloproteinases, inhibitor, and acid phosphatase in muscles of immobilized hindlimbs of rats. *Muscle & Nerve*. 2003; 27: 51–59. doi:10.1002/mus.10277.
- [124] Zhang Q, Joshi SK, Lovett DH, Zhang B, Bodine S, Kim H, Liu X. Matrix metalloproteinase-2 plays a critical role in overload induced skeletal muscle hypertrophy. *Muscles Ligaments and Tendons Journal*. 2014; 4: 362–370.
- [125] El Fahime E, Torrente Y, Caron NJ, Bresolin MD, Tremblay JP. In vivo migration of transplanted myoblasts requires matrix metalloproteinase activity. *Experimental Cell Research*. 2000; 258: 279–287. doi:10.1006/excr.2000.4962.
- [126] Lewis MP, Tippet HL, Sinanan AC, Morgan MJ, Hunt NP. Gelatinase-B (matrix metalloproteinase-9; MMP-9) secretion is involved in the migratory phase of human and murine muscle cell cultures. *Journal of Muscle Research and Cell Motility*. 2000; 21: 223–233.
- [127] Frisdal E, Teiger E, Lefaucheur JP, Adnot S, Planus E, Lafuma C, D'Ortho MP. Increased expression of gelatinases and alteration of basement membrane in rat soleus muscle following femoral artery ligation. *Neuropathology and Applied Neurobiology*. 2000; 26: 11–21.
- [128] Carmeli E, Moas M, Reznick AZ, Coleman R. Matrix metalloproteinases and skeletal muscle: a brief review. *Muscle & Nerve*. 2004; 29: 191–197. doi:10.1002/mus.10529.
- [129] Guerin CW, Holland PC. Synthesis and secretion of matrix-degrading metalloproteases by human skeletal muscle satellite cells. *Developmental Dynamics*. 1995; 202: 91–99. doi:10.1002/aja.1002020109.
- [130] Kieseier BC, Schneider C, Clements JM, Gearing AJ, Gold R, Toyka KV, Hartung HP. Expression of specific matrix metalloproteinases in inflammatory myopathies. *Brain*. 2001; 124: 341–351.

- [131] Schoser BG, Blottner D, Stuerenburg HJ. Matrix metalloproteinases in inflammatory myopathies: enhanced immunoreactivity near atrophic myofibers. *Acta Neurologica Scandinavica*. 2002; 105: 309–313.

IntechOpen

IntechOpen