

Proteomic reference map for sarcopenia research: mass spectrometric identification of key muscle proteins of organelles, cellular signaling, bioenergetic metabolism and molecular chaperoning

Paul Dowling,^{1,2} Stephen Gargan,^{1,2} Margit Zweyer,^{3,4} Michael Henry,⁵ Paula Meleady,⁵ Dieter Swandulla,⁶ Kay Ohlendieck^{1,2}

¹Department of Biology, Maynooth University, National University of Ireland, Maynooth, Co. Kildare, Ireland; ²Kathleen Lonsdale Institute for Human Health Research, Maynooth University, Maynooth, Co. Kildare, Ireland; ³Department of Neonatology and Paediatric Intensive Care, Children's Hospital, University of Bonn, Bonn, Germany; ⁴German Center for Neurodegenerative Diseases, Bonn, Germany; ⁵National Institute for Cellular Biotechnology, Dublin City University, Dublin, Ireland; ⁶Institute of Physiology, Medical Faculty, University of Bonn, Bonn, Germany.

This article is distributed under the terms of the Creative Commons Attribution Noncommercial License (CC BY-NC 4.0) which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

Abstract

During the natural aging process, frailty is often associated with abnormal muscular performance. Although inter-individual differences exist, in most elderly the tissue mass and physiological functionality of voluntary muscles drastically decreases. In order to study age-related contractile decline, animal model research is of central importance in the field of biogerontology. Here we have analyzed wild type mouse muscle to establish a proteomic map of crude tissue extracts. Proteomics is an advanced and large-scale biochemical method that attempts to identify all accessible proteins in a given biological sample. It is a technology-driven approach that uses mass spectrometry for the characterization of individual protein species. Total protein extracts were used in this study in order to minimize the potential introduction of artefacts due to excess subcellular fractionation procedures. In this report, the proteomic survey of aged muscles has focused on organellar marker proteins, as well as proteins that are involved in cellular signaling, the regulation of ion homeostasis, bioenergetic metabolism and molecular chaperoning. Hence, this study has established a proteomic reference map of a highly suitable model system for future aging research.

Key Words: aging, mass spectrometry, muscle proteomics, skeletal muscle.

Eur J Transl Myol 12565, 2024 doi: 10.4081/ejtm.2024.12565

Mass spectrometry (MS) based proteomics is a key method of modern protein chemistry,¹ including skeletal muscle biochemistry,² that can be employed for both the targeted or untargeted detection and characterization of specific proteins.^{3,4} The various molecular forms of a muscle protein product that is encoded by a particular gene and influenced by alternative RNA splicing of its transcript,⁵ plus dynamic post-translational modifications,⁶ are referred to as proteoforms,⁷ which form the basic units of the proteome.⁸ Mass spectrometry can be used for comparative studies,⁹ or the systematic cataloguing of tissue-specific protein constellations,¹⁰ such as the human skeletal muscle proteome.¹¹⁻¹³ In principle, the main proteomic approaches can be divided into bottom-up *versus* top-down analyses,¹⁴ which differ in their starting material prior to mass spectrometric analysis.¹⁵ Bottom-up proteomics is a

gel-free and peptide-focused methodology for protein identification,^{16,17} while top-down proteomics specializes on proteoform-centric and often the gel-based detection and characterization of intact protein species.^{18,19}

To date, a variety of proteomic studies have focused on the characterization of skeletal muscle tissues using MS-based proteomics.¹² This has included skeletal muscle specimens and its secretome from various species using both top-down and bottom-up proteomics.^{9,11,20-23} Systematic protein cataloguing studies,²⁴⁻²⁷ have resulted in the identification of a large number of dynamic proteoforms that are characteristic for voluntary striated muscles.¹¹ The proteomic screening of contractile tissues has revealed crucial information on myofiber types in slow *versus* fast muscles,²⁸⁻³¹ the transformation of muscles due to changed activity patterns,³²⁻³⁴ the impact of physical activity,³⁵⁻³⁸ the pathophysiological

effects of primary muscular disorders,³⁹⁻⁴¹ dysfunctions of the musculature in the context of co-morbidities,⁴²⁻⁴⁴ and the natural aging process.⁴⁵⁻⁵⁰

The underlying objective of this study was to establish a proteomic reference map of a highly suitable model system for aging research of the neuromuscular system. Crude protein extracts from normal tissue specimens of 100 mg wet tissue weight were used to establish a methodological approach for the optimum utilization of small muscle biopsy specimens. In addition, a minimum of preparative steps was employed to simplify the overall experimental bottom-up protocol, accelerate and streamline the proteomic pipeline procedure and avoid the introduction of potential bioanalytical artefacts for the routine detection of key protein species in aged skeletal muscles. This report has focused on the detailed proteomic analysis of aged skeletal muscles with specific emphasis on proteins that are intrinsically involved in cellular signaling mechanisms, the regulation of ion homeostasis, excitation-contraction coupling, bioenergetic metabolism and molecular chaperoning. In addition, proteomic markers of organelles, such as the sarcolemma, caveolae, transverse tubules, sarcoplasmic reticulum, triad junctions, ribosomes, Golgi apparatus, peroxisomes, proteasomes, lysosomes, nucleus, cytosol, the neuromuscular junction, motor neurons and glial cells, were investigated.

Materials and Methods

Materials

Analytical grade chemicals from GE Healthcare (Little Chalfont, Buckinghamshire, UK), Sigma Chemical Company (Dorset, UK) and Bio-Rad Laboratories (Hemel-Hempstead, Hertfordshire, UK) were used for the proteomic analysis of aged mouse hindlimb muscles. MS-grade trypsin, protease inhibitors (cOmplete™, mini protease inhibitor cocktail) and spin filters (Vivacon 500, VN0H22; 30,000 MWCO) were from ThermoFisher Scientific (Dublin, Ireland), Roche (Mannheim, Germany) and Sartorius (Göttingen, Germany), respectively. The determination of protein concentration was carried out with the Pierce 660 nm Protein Assay Reagent from ThermoFisher Scientific (Dublin, Ireland).

Senescent murine hindlimb muscle

Hindlimb muscles were dissected from freshly prepared *post mortem* specimens from 24 months old wild type C57BL6 mice according to institutional regulations. Mouse populations were handled in strict adherence to local governmental and institutional animal care regulations and were approved by the Institutional Animal Care and Use Committee (Amt für Umwelt, Verbraucherschutz und Lokale Agenda der Stadt Bonn, North Rhine-Westphalia, Germany).²⁷ Mice were kept under specific pathogen-free conditions in isolated, ventilated cages with free access to water and food. A maximum of 4 mice were kept per cage at a temperature of 21-22°C with a 12-hour light/12-hour dark cycle. Tissue samples were quick-frozen in liquid nitrogen and transported on dry ice to Maynooth University in accordance with the regulations of the Department of Agriculture (animal by-product register number 2016/16 to the

Department of Biology, National University of Ireland, Maynooth).⁵¹ The mass spectrometric analysis of total skeletal muscle preparations was performed with protein extracts from 6 wild type mice.

Protein extraction from muscle specimens

Total protein extracts were used for the bottom-up proteomic analysis of aged hindlimb muscles from wild type C57BL6 mice.⁴¹ Standardized procedures were employed for optimum muscle tissue preparation, homogenization with help of pulverization of specimens by grinding in liquid nitrogen and subsequent protein extraction.⁵² Tissue homogenization was carried out in lysis buffer, consisting of 0.1 M dithiothreitol, 4% (w/v) sodium dodecyl sulfate, 100 mM Tris-Cl, pH 7.6. The solution was supplemented with a protease inhibitor cocktail.⁴¹ The suspensions were briefly treated in a sonicating water bath and then heated for 3 min at 95°C.⁵³ Samples were then centrifuged at 16,000×g for 5 minutes and the protein-containing supernatant extracted for mass spectrometric analysis. Protein determination was carried out with the Pierce 660 nm Protein Assay system.⁵³ Protein samples were mixed with 8 M urea, 0.1 M Tris, pH 8.9 in Vivacon 500 spin filter units.⁵⁴ Following a centrifugation step at 14,000×g for 15 min, the further processing of samples, the switching of buffers and peptide generation by trypsin digestion was carried out by the filter-aided sample preparation (FASP) technique.⁵⁵

Proteomic analysis

For the label-free liquid chromatography mass spectrometric analysis of senescent hindlimb muscles from normal mice (n=6 biological repeats; n=2 technical repeats), a Thermo Orbitrap Fusion Tribrid mass spectrometer from Thermo Fisher Scientific (Waltham, MA, USA) was used.⁴¹ The detailed description of all analytical steps, including the listing of buffer composition, FASP protocol, timing of preparative stages, data-dependent acquisition, and bioinformatic data handling, used during the proteomic analysis of muscle proteins, has been described in a recently published methods paper.⁵⁶ A Thermo UltiMate 3000 nano system was used for reversed-phase capillary high-pressure liquid chromatography and directly coupled in-line with the Thermo Orbitrap Fusion Tribrid mass spectrometer. The qualitative data analysis of mass spectrometric files was carried out with the UniProtKB-SwissProt database (species: *Mus musculus*) with Proteome Discoverer 2.2 using Sequest HT (Thermo Fisher Scientific) and Percolator. Parameters for the mass spectrometric detection of hindlimb muscle proteins were as follows: i) a value of 0.02 Da for MS/MS mass tolerance, ii) a value of 10 ppm for peptide mass tolerance, iii) variable modification settings for methionine oxidation, iv) fixed modification settings in relation to carbamido-methylation and v) tolerance for the occurrence of up to two missed cleavages. Peptide probability was set to high confidence. A minimum XCorr score of 1.5 for 1, 2.0 for 2, 2.25 for 3 and 2.5 for 4 charge state was employed for the filtering of peptides. The software analysis programme Progenesis Q1 for Proteomics (version 2.0; Nonlinear Dynamics, a Waters company, Newcastle

upon Tyne, UK) was used to carry out quantitative label-free data analysis. Proteome Discoverer 2.2 using Sequest HT (Thermo Fisher Scientific) and a percolator were employed for the identification of peptides and proteins. Datasets were imported into Progenesis QI software for further analysis. The multi-consensus MS file and listings of proteins in aged murine skeletal muscle that were generated by this proteomic study have been deposited under the title 'Proteomic analysis of senescent mouse hindlimb muscles' with the unique identifier '37txb' to the Open Science Foundation (<https://osf.io/37txb/>). The standard bioinformatic analysis tools STRING (<https://string-db.org>) was used for the identification of potential protein-protein interaction patterns.⁵⁷

Results

The mass spectrometric analysis of crude tissue extracts from the aged mouse hindlimb musculature resulted in the identification of a large number of proteins involved in cellular signaling, bioenergetic metabolism and molecular chaperoning. The underlying objective of this investigation was to establish a proteomic reference map of aged skeletal muscles for future sarcopenia research.

Proteomic profiling of proteins involved in the regulation of excitation-contraction coupling and calcium homeostasis in aged skeletal muscle

The temporal and spatial fluxing of calcium ions through subcellular structures in myofibers is tightly regulated and plays a central role in the physiological facilitation of excitation-contraction coupling in skeletal muscles. Members of key protein complexes that are involved in the regulation of calcium homeostasis and second messenger signaling cascades were identified by mass spectrometric screening of aged mouse hindlimb muscles, including i) the voltage-sensing L-type calcium channel complex of the transverse tubules (alpha-1S (voltage sensor), alpha-2/delta-1 and beta-1 subunits of the dihydropyridine receptor), ii) the calcium release channel complex of the triad junctions that is positioned between the transverse tubules and terminal cisternae region of the sarcoplasmic reticulum (ryanodine receptor calcium release channel isoforms RYR1 and RYR2, and the auxiliary proteins triadin, junctophilin JPH1 and JPH2, and the junctional sarcoplasmic reticulum protein JSRP1), iii) luminal high-capacity calcium buffering proteins of the sarcoplasmic reticulum (calsequestrin isoforms fast CSQ1 and slow CSQ2, sarcalumenin), iv) calcium-pumping ATPase complexes involved in the fast re-uptake or removal of calcium from the sarcosol (sarcoplasmic reticulum calcium ATPases of the fast SERCA1 and slow SERCA2 type, as well as the plasma membrane calcium-transporting ATPase PMCA1), and v) additional calcium homeostasis regulators (parvalbumin, protein S100-A1, SH3 and cysteine-rich domain-containing protein STAC3, and stromal interaction molecule STIM1), and are listed in below Table 1. Excitation-contraction uncoupling is one of the mechanisms that is widely discussed to play a central role in the pathophysiological process that may lead to sar-

copenia of old age. Findings from previous studies on muscle aging,^{45-50,58-65} imply reduced expression patterns and/or shifting to slower isoforms of calcium-handling proteins, such as the voltage sensor complex of transverse tubules, the calcium release channels of triad junctions, luminal and cytosolic calcium-binding proteins and calcium pumps of the sarcoplasmic reticulum.

Proteomic profiling of proteins involved in major bioenergetic pathways in aged skeletal muscle

Since sustained levels of contractile activity require a constant supply of energy in the form of ATP, the regulation and maintenance of bioenergetic pathways is of crucial importance for the proper functioning of the neuromuscular system. The mass spectrometric analysis of aged mouse hindlimb muscles has identified a large number of enzymes involved in skeletal muscle energy metabolism. Table 2 lists major components that are involved in anaerobic glycolysis versus oxidative mitochondrial pathways. This includes proteins of the glycolytic pathway, gluconeogenesis and glycogen metabolism, as well as markers of the mitochondrial outer membrane, inner membrane and matrix that are essential components of respiratory complexes I to V. Listed are also key metabolite transporters, such as fatty acid-binding proteins (FABP3, FABP4, FABP5), albumin and the oxygen transporter myoglobin (Table 2). The higher susceptibility of type II fibers to age-related muscular atrophy results in a fast-to-slow transition process, which is clearly reflected by isoform switching of major sarcomeric proteins, as recently reviewed.⁶⁶ In analogy, age-associated fiber type shifting was shown to also affect the abundance of bioenergetic enzymes. Previously published reports on skeletal muscle aging,^{45-50,58-65} suggest indirect glycolytic-to-oxidative changes in energy metabolism in senescent myofiber populations. Decreased muscle proteins include key enzymes of glycolysis, such as pyruvate kinase and phosphofructokinase. In contrast, increased proteins of oxidative metabolism were identified as mitochondrial succinate dehydrogenase, ATP synthase and NADH dehydrogenase.

Proteomic profiling of molecular chaperones involved in the cellular stress response in aged skeletal muscle

The cellular stress response plays an essential role in the prevention of proteotoxic side effects in skeletal muscles. Both, the various classes of heat shock proteins and associated modulating enzymes are crucial factors that prevent abnormal protein folding and/or facilitate the swift removal of misfolded protein aggregates. Table 3 lists the mass spectrometric identification of key members of heat shock protein (HSP) classes HSPB/HSPE (small HSPs of 10-40 kDa) HSP40 (HSP70 co-chaperones, DNAJ), HSP60 (HSP70 co-chaperone, chaperonin), HSPA (HSP70s of approximately 70 kDa), and HSPC/HSPH (large HSP90/HSP110 of approximately 90 kDa), as well as calcium-binding chaperones of the luminal endoplasmic reticulum (calnexin and calreticulin/calregulin) and protein disulfide isomerase (PDI) in aged mouse hindlimb muscles. The proteomic profiling of the superfamily of peptidyl-prolyl cis-trans isomerases (PPIase) is shown in below Table 4.

Proteomic reference map for sarcopenia research Part 2

Eur J Transl Myol 12565, 2024 doi: 10.4081/ejtm.2024.12565

Table 1. Mass spectrometry-based proteomic profiling of proteins involved in the regulation of excitation-contraction coupling and calcium homeostasis in aged mouse hindlimb muscle.

Accession	Protein name	Gene	Peptides	Coverage (%)	Molecular mass (kDa)
(i) Transverse tubular voltage-sensing complex					
Q02789	Voltage-dependent L-type calcium channel, alpha-1S	Cacna1s	18	12.3	210.3
O08532	Voltage-dependent calcium channel, alpha-2/delta-1	Cacna2d1	30	39.6	124.6
Q8R3Z5	Voltage-dependent L-type calcium channel subunit beta-1	Cacnb1	12	25.1	65.5
(ii) Triad junction calcium release complex					
E9PZQ0	Ryanodine receptor RYR1	Ryr1	157	46.0	565.0
E9Q401	Ryanodine receptor RYR2	Ryr2	9	2.4	564.8
E9Q9K5	Triadin	Trdn	14	19.6	77.8
Q9ET80	Junctophilin JPH1	Jph1	10	19.7	71.9
Q9ET78	Junctophilin JPH2	Jph2	12	27.2	74.7
Q3MI48	Junctional sarcoplasmic reticulum protein JSRP1	Jsrp1	6	34.3	36.1
(iii) Luminal calcium buffering in sarcoplasmic reticulum					
O09165	Calsequestrin CSQ1, fast	Casq1	16	60.7	46.4
O09161	Calsequestrin CSQ2, slow	Casq2	10	42.4	48.2
Q7TQ48	Sarcalumenin	Srl	24	62.5	54.3
(iv) Calcium removal via sarcoplasmic reticulum and sarcolemma					
Q8R429	Calcium ATPase SERCA1, fast	Atp2a1	58	55.1	109.4
O55143	Calcium ATPase SERCA2, slow	Atp2a2	47	48.7	114.9
G5E829	Plasma membrane calcium-transporting ATPase PMCA1	Atp2b1	16	18.4	134.8
(v) Calcium homeostasis regulation					
P32848	Parvalbumin	Pvalb	17	84.5	11.9
P56565	Protein S100-A1	S100a1	2	29.8	10.5
Q8BZ71	SH3 and cysteine-rich domain-containing protein STAC3	Stac3	4	16.9	41.0
P70302	Stromal interaction molecule 1	Stim1	15	30.4	77.6

Proteomic reference map for sarcopenia research Part 2

Eur J Transl Myol 12565, 2024 doi: 10.4081/ejtm.2024.12565

Table 2. Mass spectrometry-based proteomic profiling of key proteins involved in major bioenergetic pathways in aged mouse hindlimb muscle.

Accession	Protein name	Gene	Peptides	Coverage (%)	Molecular mass (kDa)
(i) Glycolysis, gluconeogenesis and glycogen metabolism					
P17710	Hexokinase-1	Hk1	19	21.5	108.3
O08528	Hexokinase-2	Hk2	32	43.6	102.5
P47857	Phosphofructokinase, muscle	Pfkm	32	54.6	85.3
P05064	Fructose-bisphosphate aldolase ALDOA	Aldoa	37	89.3	39.4
P17751	Triosephosphate isomerase	Tpi1	13	67.9	26.7
P16858	Glyceraldehyde-3-phosphate dehydrogenase	Gapdh	24	80.8	35.8
P09411	Phosphoglycerate kinase 1	Pgk1	37	84.2	44.6
Q9D0F9	Phosphoglucomutase-1	Pgm1	36	77.4	61.4
P17182	Alpha-enolase	Eno1	28	79.5	47.1
P52480	Pyruvate kinase PKM	Pkm	45	80.2	57.8
Q9R062	Glycogenin-1	Gygl	11	49.2	37.4
Q9WUB3	Glycogen phosphorylase, muscle	Pygm	53	62.6	97.3
Q9Z1E4	Glycogen synthase, muscle	Gys1	21	40.9	83.9
(ii) Mitochondria					
Q60932	Voltage-dependent anion-selective channel protein 1 (mt-VDAC1; outer mitochondrial membrane)	Vdac1	21	76.0	32.4
Q9DCS9	NADH dehydrogenase (inner mitochondrial membrane complex I)	Ndufb10	6	47.7	21.0
Q9CQA3	Succinate dehydrogenase (inner mitochondrial membrane complex II)	Sdhb	16	55.3	31.8
Q9DB77	Cytochrome b-c1 (inner mitochondrial membrane complex III)	Uqcrc2	17	49.4	48.2
P56391	Cytochrome c oxidase (inner mitochondrial membrane complex IV)	Cox6b1	5	61.6	10.1
P56480	ATP synthase subunit beta (inner mitochondrial membrane complex V)	Atp5b	37	79.2	56.3
P54071	Isocitrate dehydrogenase (mitochondrial matrix)	Idh2	26	49.8	50.9
(iii) Metabolite transportation					
P11404	Fatty acid-binding protein, heart	Fabp3	8	64.7	14.8
P04117	Fatty acid-binding protein, adipocyte	Fabp4	9	67.4	14.7
Q05816	Fatty acid-binding protein, epidermal	Fabp5	4	30.4	15.1
P07724	Serum albumin	Alb	48	73.7	68.7
P04247	Myoglobin	Mb	10	77.3	17.1

Proteomic reference map for sarcopenia research Part 2

Eur J Transl Myol 12565, 2024 doi: 10.4081/ejtm.2024.12565

Table 3. Mass spectrometry-based proteomic profiling of molecular chaperones involved in the cellular stress response in aged mouse hindlimb muscle.

Accession	Protein name	Gene	Peptides	Coverage (%)	Molecular mass (kDa)
(i) Small heat shock proteins (10-40 kDa, HSPB, HSPE)					
P14602	HSPB1 (Hsp27, beta-1)	Hspb1	11	68.9	23.0
Q99PR8	HSPB2 (MKBP, beta-2)	Hspb2	6	56.6	20.4
Q9QZ57	HSPB3 (b-3)	Hspb3	2	26.0	17.2
P23927	HSPB5 (alphaB-Crystallin, alphaBC)	Cryab	8	55.4	20.1
Q5EBG6	HSPB6 (Hsp20, beta-6)	Hspb6	6	61.7	17.5
P35385	HSPB7 (cvHsp, beta-7)	Hspb7	6	48.5	18.6
Q9JK92	HSPB8 (Hsp22; beta-8)	Hspb8	5	25.5	21.5
Q64433	HSPE (10 kDa Hsp, mt)	Hspe1	8	79.4	11.0
(ii) HSP40 heat shock proteins (HSP70 co-chaperones, DNAJ)					
P63037	DnaJ A1 HSP	Dnaja1	5	22.9	44.9
Q9QYJ0	DnaJ A2 HSP	Dnaja2	11	40.0	45.8
Q99M87	DnaJ A3 HSP	Dnaja3	9	30.6	52.4
Q9JMC3	DnaJ A4 HSP	Dnaja4	3	12.1	44.9
(iii) HSP60 heat shock proteins (HSP70 co-chaperone, chaperonin)					
P63038	HSPD1 (60 kDa Hsp, mt)	Hspd1	55	75.0	61.0
(iv) HSP70 heat shock proteins (HSPA)					
Q61696	HSPA1A (70 kDa protein 1A, Hsp72, inducible Hsp70)	Hspa1a	14	27.0	70.1
P17156	HSPA2 (heat shock-related 70 kDa protein 2, Hsp70-2)	Hspa2	28	45.0	69.6
Q61316	HSPA4 (heat shock 70 kDa protein 4, Hsp-110)	Hspa4	28	43.9	94.1
P20029	HspA5 (GRP78, BiP), ER	Hspa5	64	73.4	72.4
P63017	HSPA8 (Hsc70, Hsp73, constitutive Hsp70)	Hspa8	55	83.0	70.9
Q99M31	HSPA14 (heat shock 70 kDa protein 14, Hsp60)	Hspa14	2	5.9	54.7
(v) HSP90/HSP110 large heat shock proteins (90 kDa, HSPC, HSPH)					
P07901	HSPC1 (Hsp90AA1, HSP90a)	Hsp90aa1	47	64.7	84.9
P11499	HSPC3 (Hsp90AB1, HSP 90b)	Hsp90ab1	67	80.7	83.3
P08113	HSPC4 (Hsp90B1, GRP94, endoplasmic reticulum chaperone), ER	Hsp90b1	70	67.0	92.5
Q9CQN1	HSPC5 (75 kDa Hsp, mt)	Trap1	27	36.7	80.2
Q61081	Hsp90 co-chaperone Cdc37	Cdc37	7	19.5	44.6
Q61699	HSPH1 (Hsp110)	Hsph1	19	29.4	96.4

To be continued on next page

Proteomic reference map for sarcopenia research Part 2

Eur J Transl Myol 12565, 2024 doi: 10.4081/ejtm.2024.12565

Table 3. Continued from previous page.

Accession	Protein name	Gene	Peptides	Coverage (%)	Molecular mass (kDa)
(vi) Ca²⁺-binding chaperones of the luminal endoplasmic reticulum					
P35564	Calnexin (CNX)	Canx	27	45.9	67.3
P14211	Calreticulin (CRT), calregulin	Calr	24	72.4	48.0
(vii) Protein disulfide isomerase					
P27773	PDI A3	Pdia3	38	64.0	56.7
P08003	PDI A4	Pdia4	24	36.4	72.0
Q921X9	PDI A5	Pdia5	13	25.5	59.3
Q922R8	PDI A6	Pdia6	10	28.6	48.1

Table 4. Mass spectrometry-based proteomic profiling of the superfamily of peptidyl-prolyl cis-trans isomerases in aged mouse hindlimb muscle.

Accession	Protein name	Gene	Peptides	Coverage (%)	Molecular mass (kDa)
P17742	PPIase PPIA	Ppia	13	77.4	18.0
P24369	PPIase PPIB	Ppib	14	55.1	23.7
P30412	PPIase PPIC	Ppic	2	11.8	22.8
Q9CR16	PPIase PPID	Ppid	16	42.2	40.7
Q9QZH3	PPIase PPIE	Ppie	3	14.6	33.4
Q99KR7	PPIase PPIF, mt	Ppif	7	39.3	21.7
A2AR02	PPIase PPIG	Ppig	5	9.0	88.3
Q9D868	PPIase PPIH	Ppih	3	14.9	20.5
P26883	PPIase FKBP1A	Fkbp1a	9	79.6	11.9
P45878	PPIase FKBP2	Fkbp2	5	31.4	15.3
Q62446	PPIase FKBP3	Fkbp3	11	48.2	25.2
P30416	PPIase FKBP4	Fkbp4	17	38.0	51.6
O54998	PPIase FKBP7	Fkbp7	6	25.7	24.9
O35465	PPIase FKBP8	Fkbp8	6	20.4	43.5
Q9Z247	PPIase FKBP9	Fkbp9	14	27.5	63.0
Q61576	PPIase FKBP10	Fkbp10	11	30.3	64.7
Q9D1M7	PPIase FKBP11	Fkbp11	2	14.4	22.1
P59024	PPIase FKBP14	Fkbp14	3	16.1	24.3
Q9QUR7	PPIase NIMA-interacting PIN1	Pin1	3	29.7	18.4

Since skeletal muscle aging is associated with impaired microcirculation, imbalanced proteostasis, mitochondrial dysfunction, abnormal ion handling and stem cell exhaustion, a high degree of cellular and oxidative stress occurs in senescent fibers. Although the hierarchy within these different degenerating pathways has not yet been determined, it is clear from the characterization of aged muscles that a variety of molecular chaperones are upregulated during sarcopenia.^{45-50,58-65} This includes a considerable number of large heat shock proteins, but especially drastically elevated levels of small heat shock proteins, such as alphaB-crystallin/HspB5 and the muscle-specific cardiovascular cvHsp/HspB7.⁶⁵

Importantly, PPIases are intrinsically involved in the cellular stress response in skeletal muscles. The PPIases mediate a rate-limiting step during protein folding by catalyzing the cis/trans-isomerization of the peptidyl-prolyl peptide bond. This is a crucial step of peptide synthesis that generates a properly folded and functional protein species. The members of this superfamily of immunophilins, that was identified by the mass spectrometric screening of aged mouse hindlimb muscles, are listed in Table 4. This detailed table of identified PPIases is included in this report to demonstrate the biochemical sensitivity of the streamlined bottom-up proteomic approach used to generate a reference map of proteins from crude extracts of senescent mouse muscles.

Proteomic profiling of organellar and subcellular markers in aged skeletal muscle

Robust marker proteins that are enriched in subcellular structures are extremely important for the swift cell biological characterization of changes in senescent skeletal muscles. Table 5 lists identified marker proteins of the sarcolemma, caveolae, ribosomes, the Golgi apparatus, peroxisomes, proteasomes, lysosomes, the nucleus and cytosol in aged muscles. In addition, proteomic markers of the neuromuscular junction, motor neurons and Schwann cells are listed in Table 5. Above tables have already covered proteomic markers of the transverse tubular membrane system, triad junctions and the sarcoplasmic reticulum.

Bioinformatic analysis of potential protein-protein interactions within protein clusters in aged skeletal muscle

Following mass spectrometric identification, muscle proteins were analyzed for potential protein interaction patterns. As shown in Figure 1, bioinformatic STRING analyses,⁵⁷ indicates interaction patterns within protein clusters that are involved the regulation of excitation-contraction coupling, calcium homeostasis and major bioenergetic pathways of aerobic and anaerobic metabolism, as well as the cellular stress response. Due to the complexity of functional and physical protein clustering and the large number of interacting protein species, the illustrations depicted in Figure 1 are not presented to give detailed information on individual protein interactions, but instead are shown to provide a general overview of complex formation of identified protein groupings in aged skeletal muscles.

Discussion

Skeletal muscles contribute to approximately half of the biomass in the average human body.⁶⁷ Voluntary muscles are involved in locomotion, posture, balance, bodily protection, respiration, heat homeostasis and communication.⁶⁸⁻⁷⁰ The range of muscular disorders ranges from genetic diseases of early childhood,⁷¹ to progressive muscle wasting syndromes in the elderly.⁷²⁻⁷⁶ It is therefore crucial to establish proteomic reference maps of skeletal muscles at different age.⁷⁷⁻⁸² This report focused on the establishment of the proteomic profile of the senescent mouse hindlimb musculature. The proteomic databank can now be used as the scientific basis for detailed future studies into age-associated alterations in distinct muscle protein families.

The proteomic analysis has covered important markers of organelles, such as the nucleus, Golgi apparatus, sarcolemma, caveolae, transverse tubules, triad junctions, sarcosol, sarcoplasmic reticulum, mitochondria, lysosomes, proteasomes and peroxisomes. Metabolic adaptations of aged muscles can be studied at the level of both aerobic and anaerobic bioenergetic pathways. The proteomic strategy presented here has identified key markers for such studies, including enzymes that are present in major mitochondrial substructures.⁸³ This is important, since mitochondrial abnormalities and oxidative stress have been implicated in sarcopenia of old age.^{84,85} The identified mitochondrial markers encompass the voltage-dependent anion-selective channel VDAC1, NADH dehydrogenase, succinate dehydrogenase, cytochrome b-c1, cytochrome c oxidase, ATP synthase subunit beta and isocitrate dehydrogenase of the outer membrane, inner membrane complexes I to V and the mitochondrial matrix, respectively.⁸⁶ The presence of glycolytic enzymes and other components involved in glucose metabolism were clearly revealed by proteomics.⁸⁷ Especially interesting was the identification of both hexokinase isoforms, HKI and HKII, the enzymes that mediate the initial priming step of muscle glycolysis and are differentially affected by hormonal regulation.⁸⁸

Excitation-contraction coupling and calcium handling were previously shown to be impaired in aged skeletal muscles.⁸⁹⁻⁹¹ The proteomic catalogue presented here lists all major players of this crucial signaling mechanism, including the voltage-sensing L-type calcium channel of the transverse tubules, the ryanodine receptor calcium release channel of the sarcoplasmic reticulum and its auxiliary complex at the triad junctions, as well as crucial regulatory proteins and luminal calcium binding proteins. This will enable future systems biological investigations to better determine the mechanisms that underlie excitation-contraction uncoupling and associated muscular weakness in aged organisms.⁹¹

The expression levels of the protein constituents of the cellular stress response are highly abundant and diverse in skeletal muscles,⁹² and considerably affected during muscle adaptations and neuromuscular disease.⁹³ The proteomic cataloguing of aged skeletal muscles reported in this article has listed a large number of molecular chaperones and heat shock proteins. This included small heat shock proteins (HSPB/HSPE), which are present at high

Proteomic reference map for sarcopenia research Part 2

Eur J Transl Myol 12565, 2024 doi: 10.4081/ejtm.2024.12565

Table 5. Mass spectrometry-based proteomic profiling of organellar and subcellular markers in aged mouse hind-limb muscle.

Accession	Protein name	Gene	Peptides	Coverage (%)	Molecular mass (kDa)
(i) Sarcolemma					
Q8VDN2	Na ⁺ /K ⁺ -ATPase, alpha-1	Atp1a1	34	38.7	113.0
Q6PIE5	Na ⁺ /K ⁺ -ATPase, alpha-2	Atp1a2	30	36.8	112.2
Q9WV27	Na ⁺ /K ⁺ -ATPase, alpha-4	Atp1a4	7	7.8	114.9
P14094	Na ⁺ /K ⁺ -ATPase, beta-1	Atp1b1	6	27.6	35.2
P14231	Na ⁺ /K ⁺ -ATPase, beta-2	Atp1b2	8	32.8	33.3
P97370	Na ⁺ /K ⁺ -ATPase, beta-3	Atp1b3	2	9.7	31.8
Q9ESD7	Dysferlin	Dysf	27	18	237.9
Q69ZN7	Myoferlin	Myof	34	21	233.3
P82348	Sarcoglycan, gamma	Sgcg	2	11.3	32.1
(ii) Caveolae					
P49817	Caveolin-1	Cav1	12	68	20.5
Q9WVC3	Caveolin-2	Cav2	4	40.7	18.2
P51637	Caveolin-3	Cav3	3	25.8	17.4
(iii) Organellar markers (ribosome, Golgi apparatus, peroxisome, proteasome, lysosome)					
P14206	40S ribosomal protein SA (ribosome)	Rpsa	18	63.1	32.8
P55937	Golgin-160 (Golgi apparatus)	Golga3	6	6.0	167.2
P24270	Catalase (peroxisome)	Cat	30	63.9	59.8
P61089	Ubiquitin-conjugating enzyme E2 (proteasome)	Ube2n	8	55.3	17.1
P11438	Lysosome-associated membrane glycoprotein 1 (lysosome)	Lamp1	3	7.6	43.9
(iv) Nucleus					
O08579	Emerin (inner nuclear membrane)	Emd	5	28.2	29.435
P48678	Lamin-A/C (nuclear lamina)	Lmna	60	73.7	74.2
P21619	Lamin-B2 (nuclear lamina)	Lmnb2	15	24.8	67.3
P10922	Histone H1.0	H1f0	5	27.3	20.9
Q64522	Histone H2A	Hist2h2ab	8	66.2	14.0
P02301	Histone H3.3	H3f3c	7	47.1	15.3
P62806	Histone H4	Hist1h4a	12	60.2	11.4

To be continued on next page

Table 5. Continued from previous page.

Accession	Protein name	Gene	Peptides	Coverage (%)	Molecular mass (kDa)
(v) Cytosol					
P13634	Carbonic anhydrase CA1	Ca1	2	10	28.3
P00920	Carbonic anhydrase CA2	Ca2	3	22.7	29.0
P16015	Carbonic anhydrase CA3	Ca3	17	85	29.4
P06151	Lactate dehydrogenase	Ldha	23	74.4	36.5
P09528	Ferritin heavy chain	Fth1	10	62.1	21.1
P29391	Ferritin light chain 1	Ftl1	6	48.6	20.8
(vi) Neuromuscular junction, motor neuron and Schwann cells					
P13595	Neural cell adhesion molecule NCAM1	Ncam1	10	12.4	119.4
P27573	Myelin protein P0	Mpz	5	20.2	27.6
P04370	Myelin basic protein	Mbp	4	17.6	27.2
Q9CQW1	Synaptobrevin	Ykt6	3	15.2	22.3
O09117	Synaptophysin	Sypl1	2	13	28.9

density in myofibers,^{65,94,95} the group of co-chaperoning Hsp40 and Hsp60 proteins, the highly diverse Hsp70 (HSPA) family of constitutive and inducible chaperoning proteins,⁹⁶ the Hsp90 (HSPC/HSPH) class of large heat shock proteins,⁹⁷ protein disulfide isomerases, calcium-binding chaperones and the superfamily of PPIases that catalyze the cis/trans-isomerization of the peptidyl-prolyl peptide bond during protein folding.^{98,99}

The newly presented proteomic map of muscle-associated proteins in senescent mice can now be employed for the systematic evaluation of complex changes and adaptations during age-related muscle degeneration. This could have significant implications for the establishment of new proteomic biomarker signatures of aging.^{78,79,100,101} Hence, the new MS-based reference map could be useful for detailed future evaluations of (i) muscle fiber type shifting,^{33,66,102} (ii) metabolic disturbances and alterations of the gut-muscle axis,¹⁰³ (iii) mitochondrial dysfunction, inflammation and impaired cellular signaling,⁸⁴ and (iv) protein modifications,⁶ as well as the potential influence of (v) pharmacological therapies and related treatments,^{74,75,104} (vi) physical activity levels,^{105,106} (vii) nutritional interventions,^{104,107-109} and (viii) gender specific differences,¹¹⁰ on the development of different forms of sarcopenia.⁷¹⁻⁷³ Hence, novel proteomic biomarkers could be beneficial for better defining and differentiating the pre-sarcopenic loss of skeletal muscle mass and decline in

contractile function,^{111,112} from acute *versus* chronic forms of sarcopenia of old age.^{113,114}

The quality of life can be severely impacted by the progressive loss of muscle mass and accompanying dysfunction of the skeletal musculature in the elderly. In order to better understand the multi-factorial etiology of age-related muscle wasting, it is imperative to determine in more detail the molecular mechanisms that trigger myofiber degeneration in the senescent organism. Animal models of aging play a critical role in sarcopenia research.^{100,115,116} This report has outlined the mass spectrometric analysis of total protein extracts from crude muscle tissue extracts, which has resulted in the establishment of a proteomic reference map of the aged mouse hindlimb musculature. Figure 2 gives an overview of identified protein groupings in senescent skeletal muscles using bottom-up proteomics.

The established protein clusters that are associated with the contractile apparatus in sarcomeres, various organelles, the excitation-contraction coupling apparatus, the extra-sarcomeric cytoskeleton, the extracellular matrix, bioenergetic pathways, the molecular chaperoning system and the nerve-muscle connection, are crucial entities for normal physiological functioning and efficient adaptability of the neuromuscular system. Many of these protein families are affected in sarcopenia of old age and are therefore crucial targets for studying the cellular mechanisms that cause the age-related loss in skeletal muscle

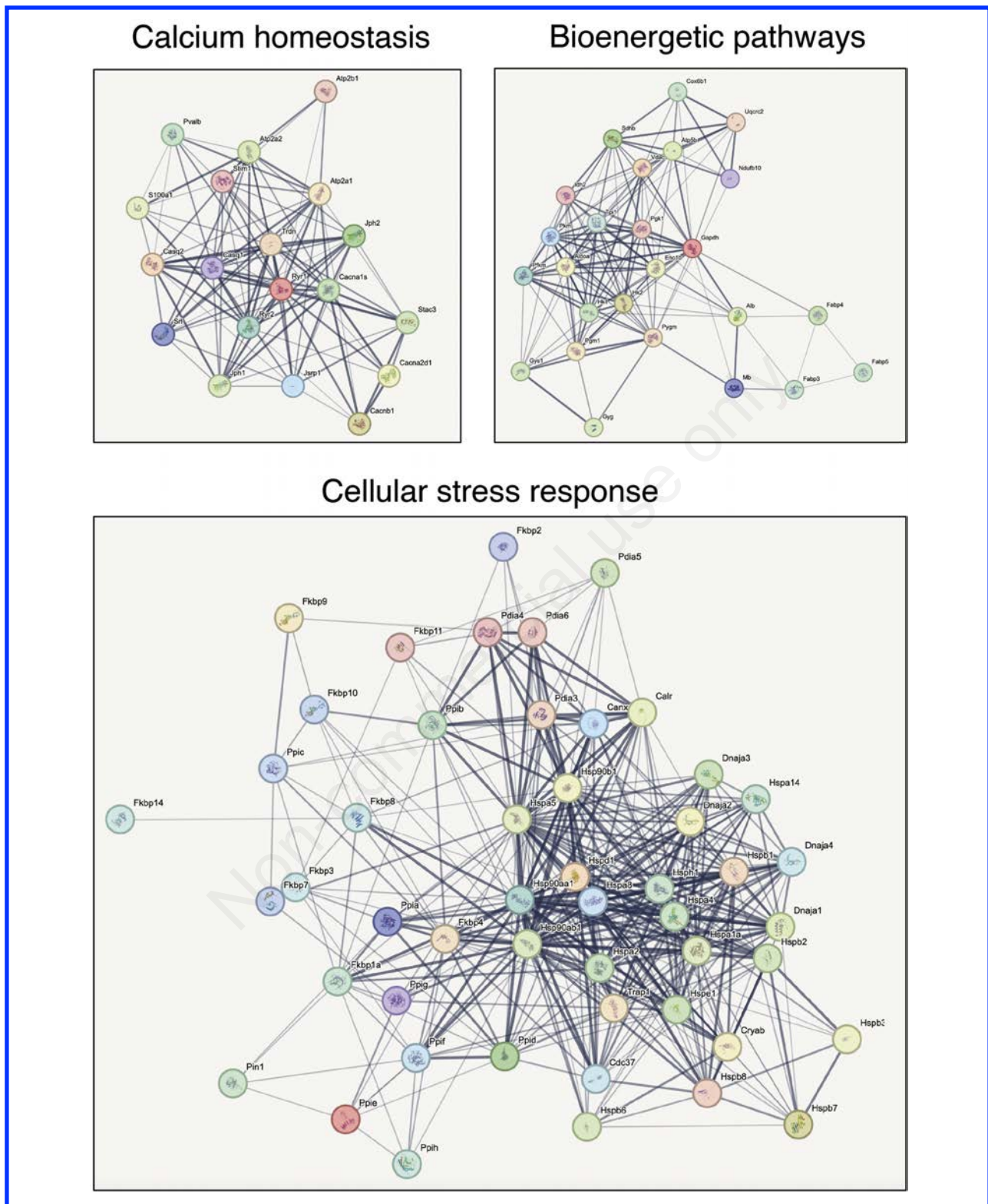


Figure 1. Overview of potential protein-protein interactions within major protein complexes that were detected by bottom-up proteomics of total extracts from aged mouse skeletal muscle. The data used to generate the individual images are the listings of identified protein families that are linked to calcium homeostasis and the regulation of excitation-contraction coupling (Table 1), bioenergetic pathways and metabolite transportation (Table 2), and molecular chaperones involved in the cellular stress response (Tables 3 and 4). The publicly available bioinformatic analysis tool STRING (<https://string-db.org>) was used for the analysis of protein interaction patterns.⁵⁷

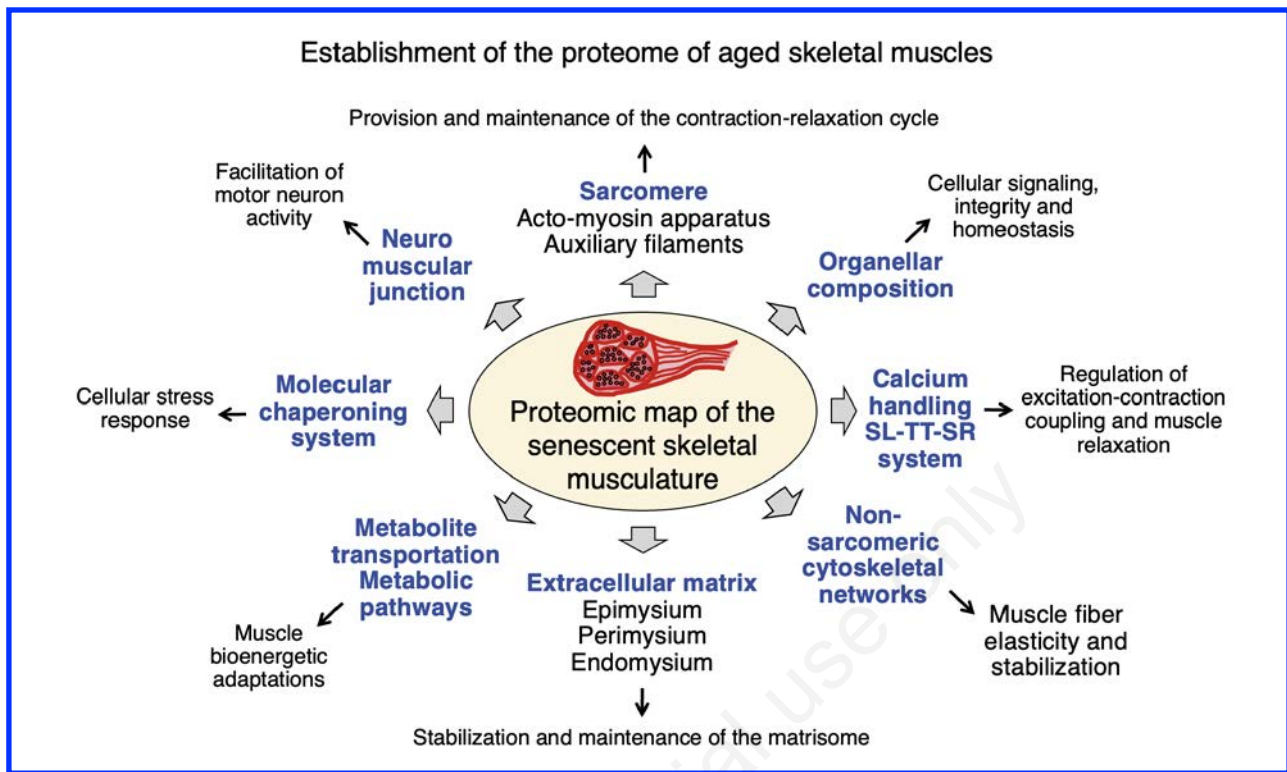


Figure 2. Overview of mass spectrometrically identified protein groupings in aged mouse hindlimb muscles.

mass and contractile strength.^{45-50,58-65} The proteomic reference map presented in this article covers the main constituents involved in the regulation and maintenance of the excitation-contraction-relaxation cycle and its structural embedding in the intracellular cytoskeleton and provision of lateral force transmission through costameres and the extracellular matrix.

Building on these findings, tissue proteomics can now be used to routinely study small amounts of starting material for the in-depth screening of age-associated processes, such as excitation-contraction uncoupling, myonecrosis, cytoskeletal collapse, an altered cellular stress response, myofiber type shifting, abnormal calcium homeostasis, impaired bioenergetics, contractile weakness and reactive myofibrosis. Hence, the establishment of the proteomic profile of senescent muscles can be utilized as the basis of biomedical knowledge for detailed future investigations into age-related changes and/or adaptations of distinct protein families.

List of abbreviations

BiP, Binding immunoglobulin protein
CA, Carbonic anhydrase
CAM, Neural cell adhesion molecule
cv, cardiovascular
CSQ, Calsequestrin
ER, Endoplasmic reticulum
FABP, Fatty acid binding protein
FASP, Filter assisted sample preparation

FKBP, FK506 binding protein
GRP, Glucose-regulated protein
Hsc, Heat shock cognate
HSP, Heat shock protein
JPH, Junctophilin
JSRP, Junctional sarcoplasmic reticulum protein
MKBP, Myotonic dystrophy protein kinase binding protein
MS, Mass spectrometry
mt, mitochondrial
NIMA, 'never in mitosis gene a' kinase
OSF, Open Science Foundation
PDI, Protein disulfide isomerase
PMCA, Plasma membrane calcium-transporting ATPase
PPIase, Peptidyl-prolyl cis/trans isomerases
RYP, Ryanodine receptor
SERCA, Sarcoplasmic or endoplasmic reticulum calcium ATPase
SL, Sarcolemma
SR, Sarcoplasmic reticulum
STAC3, SH3 and cysteine-rich domain-containing protein
TT, Transverse tubules
VDAC, voltage-dependent anion-selective channel

Contributions

PD, DS and KO were involved in the conceptualization and initiation of this project, as well as the design of the research strategy. SG, MZ and PD were involved in the preparation of muscle tissues and performed the biochemical experiments and analyzed the data. MH and PM per-

formed the mass spectrometric and bioinformatic analysis. All authors were involved in the writing and final editing of the manuscript.

Funding

This work was supported by the Kathleen Lonsdale Institute for Human Health Research at Maynooth University. The Orbitrap Fusion Tribrid mass spectrometer was funded under a Science Foundation Ireland Infrastructure Award to Dublin City University (SFI 16/RI/3701).

Conflict of interest

The authors declare no competing interests.

Ethics approval

Local governmental and institutional animal care regulations were followed and approved by the Institutional Animal Care and Use Committee (Amt für Umwelt, Verbraucherschutz und Lokale Agenda der Stadt Bonn, North Rhine-Westphalia, Germany). Transportation and usage of tissue specimens was in accordance with the regulations of the Department of Agriculture (animal by-product register number 2016/16 to the Department of Biology, National University of Ireland, Maynooth). The study conforms with the Helsinki Declaration of 1964, as revised in 2013, concerning human and animal rights.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Corresponding Author

Kay Ohlndieck, Department of Biology, Maynooth University, National University of Ireland, Maynooth W23F2H6, Co. Kildare, Ireland.
Tel.: 353.1.7083842.
ORCID ID: 0000-0002-6266-4510
E-mail: kay.ohlndieck@mu.ie

Paul Dowling
ORCID ID: 0000-0002-9290-9267
paul.dowling@mu.ie

Stephen Gargan
ORCID ID: 0000-0003-1005-8372
stephen.gargan@mu.ie

Margit Zwyer
ORCID ID: 0000-0001-5615-1869
margit.zwyer@dzne.de

Michael Henry
ORCID ID: 0000-0001-5312-4961
michael.henry@dcu.ie

Paula Meleady
ORCID ID: 0000-0001-5306-310X
paula.meleady@dcu.ie

Dieter Swandulla
ORCID ID: 0000-0003-0923-7090
swandulla@uni-bonn.de

References

1. Aebersold R, Mann M. Mass-spectrometric exploration of proteome structure and function. *Nature* 2016;537:347-55.
2. Dowling P, Swandulla D, Ohlndieck K. Mass spectrometry-based proteomic technology and its application to study skeletal muscle cell biology. *Cells* 2023;12:2560.
3. Uzozie AC, Aebersold R. Advancing translational research and precision medicine with targeted proteomics. *J Proteomics* 2018;189:1-10.
4. Sobsey CA, Ibrahim S, Richard VR, et al. Targeted and untargeted proteomics approaches in biomarker development. *Proteomics* 2020;20:e1900029.
5. Nakka K, Ghigna C, Gabellini D, Dilworth FJ. Diversification of the muscle proteome through alternative splicing. *Skelet Muscle* 2018;8:8.
6. Zhong Q, Zheng K, Li W, et al. Post-translational regulation of muscle growth, muscle aging and sarcopenia. *J Cachexia Sarcopenia Muscle* 2023;14:1212-27.
7. Schaffer LV, Millikin RJ, Miller RM, et al. Identification and quantification of proteoforms by mass spectrometry. *Proteomics* 2019;19:e1800361.
8. Carbonara K, Andonovski M, Coorssen JR. Proteomes are of proteoforms: embracing the complexity. *Proteomes* 2021;9:38.
9. Murphy S, Dowling P, Ohlndieck K. Comparative skeletal muscle proteomics using two-dimensional gel electrophoresis. *Proteomes* 2016;4:27.
10. Adhikari S, Nice EC, Deutsch EW, et al. A high-stringency blueprint of the human proteome. *Nat Commun* 2020;11:5301.
11. Capitanio D, Moriggi M, Gelfi C. Mapping the human skeletal muscle proteome: progress and potential. *Expert Rev Proteomics* 2017;14:825-39.
12. Gonzalez-Freire M, Semba RD, Ubaida-Mohien C, et al. The human skeletal muscle proteome project: a reappraisal of the current literature. *J Cachexia Sarcopenia Muscle* 2017;8:5-18.
13. Dowling P, Zwyer M, Swandulla D, Ohlndieck K. Characterization of contractile proteins from skeletal muscle using gel-based top-down proteomics. *Proteomes* 2019;7:25. Erratum in: *Proteomes* 2019;7.
14. Lermyte F, Tsybin YO, O'Connor PB, Loo JA. Top or Middle? Up or Down? Toward a standard lexicon for protein top-down and allied mass spectrometry approaches. *J Am Soc Mass Spectrom* 2019;30:1149-57.
15. Ercan H, Resch U, Hsu F, et al. A practical and analytical comparative study of gel-based top-down and gel-free bottom-up proteomics including unbiased proteoform detection. *Cells* 2023;12:747.
16. Zhang Y, Fonslow BR, Shan B, et al. Protein analysis by shotgun/bottom-up proteomics. *Chem Rev* 2013;113:2343-94.
17. Manes NP, Nita-Lazar A. Application of targeted mass

- spectrometry in bottom-up proteomics for systems biology research. *J Proteomics* 2018;189:75-90.
18. Melby JA, Roberts DS, Larson EJ, et al. Novel strategies to address the challenges in top-down proteomics. *J Am Soc Mass Spectrom* 2021;32:1278-94.
19. Ohlendieck K. Top-down proteomics and comparative 2D-DIGE analysis. *Methods Mol Biol* 2023; 2596:19-38.
20. Burniston JG, Connolly J, Kainulainen H, et al. Label-free profiling of skeletal muscle using high-definition mass spectrometry. *Proteomics* 2014;14:2339-44.
21. Cervone DT, Moreno-Justicia R, Quesada JP, Deshmukh AS. Mass spectrometry-based proteomics approaches to interrogate skeletal muscle adaptations to exercise. *Scand J Med Sci Sports* 2024;34: e14334.
22. Florin A, Lambert C, Sanchez C, et al. The secretome of skeletal muscle cells: A systematic review. *Osteoarthritis Cartil Open* 2020;2:100019.
23. Ohlendieck K. Skeletal muscle proteomics: current approaches, technical challenges and emerging techniques. *Skelet Muscle* 2011;1:6.
24. Deshmukh AS, Murgia M, Nagaraj N, et al. Deep proteomics of mouse skeletal muscle enables quantitation of protein isoforms, metabolic pathways, and transcription factors. *Mol Cell Proteomics* 2015;14: 841-53.
25. Højlund K, Yi Z, Hwang H, et al. Characterization of the human skeletal muscle proteome by one-dimensional gel electrophoresis and HPLC-ESI-MS/MS. *Mol Cell Proteomics* 2008;7:257-67.
26. Parker KC, Walsh RJ, Salajegheh M, et al. Characterization of human skeletal muscle biopsy samples using shotgun proteomics. *J Proteome Res* 2009;8: 3265-77.
27. Murphy S, Zweyer M, Raucamp M, et al. Proteomic profiling of the mouse diaphragm and refined mass spectrometric analysis of the dystrophic phenotype. *J Muscle Res Cell Motil* 2019;40:9-28.
28. Hadrévi J, Hellström F, Kieselbach T, et al. Protein differences between human trapezius and vastus lateralis muscles determined with a proteomic approach. *BMC Musculoskelet Disord* 2011;12:181.
29. Eggers B, Schork K, Turewicz M, et al. Advanced fiber type-specific protein profiles derived from adult murine skeletal muscle. *Proteomes* 2021;9:28.
30. Murgia M, Nagaraj N, Deshmukh AS, et al. Single muscle fiber proteomics reveals unexpected mitochondrial specialization. *EMBO Rep* 2015;16:387-95.
31. Fomchenko KM, Walsh EM, Yang X, et al. Spatial proteomic approach to characterize skeletal muscle myofibers. *J Proteome Res* 2021;20:888-94.
32. Donoghue P, Doran P, Wynne K, et al K. Proteomic profiling of chronic low-frequency stimulated fast muscle. *Proteomics* 2007;7:3417-30.
33. Dowling P, Murphy S, Ohlendieck K. Proteomic profiling of muscle fibre type shifting in neuromuscular diseases. *Expert Rev Proteomics* 2016;13:783-99.
34. Hunt LC, Graca FA, Pagala V, et al. Integrated genomic and proteomic analyses identify stimulus-dependent molecular changes associated with distinct modes of skeletal muscle atrophy. *Cell Rep* 2021;37: 109971.
35. Deshmukh AS, Steenberg DE, Hostrup M, et al. Deep muscle-proteomic analysis of freeze-dried human muscle biopsies reveals fiber type-specific adaptations to exercise training. *Nat Commun* 2021;12:304. Erratum in: *Nat Commun* 2021;12:1600.
36. Li FH, Sun L, Wu DS, Gao HE, Min Z. Proteomics-based identification of different training adaptations of aged skeletal muscle following long-term high-intensity interval and moderate-intensity continuous training in aged rats. *Aging (Albany NY)* 2019;11:4159-4182. Erratum in: *Aging (Albany NY)* 2019;11:10781-2.
37. de Sousa Neto IV, Carvalho MM, Marqueti RC, et al. Proteomic changes in skeletal muscle of aged rats in response to resistance training. *Cell Biochem Funct* 2020;38:500-9.
38. Hesketh SJ, Stansfield BN, Stead CA, Burniston JG. The application of proteomics in muscle exercise physiology. *Expert Rev Proteomics* 2020;17:813-25.
39. Gelfi C, Vasso M, Cerretelli P. Diversity of human skeletal muscle in health and disease: contribution of proteomics. *J Proteomics* 2011;74:774-95.
40. Choi YC, Hong JM, Park KD, et al. Proteomic analysis of the skeletal muscles from dysferlinopathy patients. *J Clin Neurosci* 2020;71:186-90.
41. Gargan S, Dowling P, Zweyer M, et al. Proteomic Identification of Markers of Membrane Repair, Regeneration and Fibrosis in the Aged and Dystrophic Diaphragm. *Life (Basel)* 2022;12:1679.
42. Giebelstein J, Poschmann G, Højlund K, et al. The proteomic signature of insulin-resistant human skeletal muscle reveals increased glycolytic and decreased mitochondrial enzymes. *Diabetologia* 2012;55:1114-27. Erratum in: *Diabetologia* 2012;55:2083.
43. Kruse R, Højlund K. Proteomic study of skeletal muscle in obesity and type 2 diabetes: progress and potential. *Expert Rev Proteomics* 2018;15:817-28.
44. Shum AMY, Poljak A, Bentley NL, et al. Proteomic profiling of skeletal and cardiac muscle in cancer cachexia: alterations in sarcomeric and mitochondrial protein expression. *Oncotarget* 2018;9:22001-22.
45. Gelfi C, Vigano A, Ripamonti M, et al. The human muscle proteome in aging. *J Proteome Res* 2006;5: 1344-53.
46. Staunton L, Zweyer M, Swandulla D, Ohlendieck K. Mass spectrometry-based proteomic analysis of middle-aged vs. aged vastus lateralis reveals increased levels of carbonic anhydrase isoform 3 in senescent human skeletal muscle. *Int J Mol Med* 2012;30: 723-33.
47. Ohlendieck K. Two-CyDye-Based 2D-DIGE Analysis of Aged Human Muscle Biopsy Specimens. *Methods Mol Biol* 2023;2596:265-89.
48. Gueugneau M, Coudy-Gandilhon C, Goubeyre O, et al. Proteomics of muscle chronological ageing in post-menopausal women. *BMC Genomics* 2014;15: 1165.

49. Baraibar MA, Gueugneau M, Duguez S, et al. Expression and modification proteomics during skeletal muscle ageing. *Biogerontology* 2013;14:339-52.
50. Théron L, Gueugneau M, Coudy C, et al. Label-free quantitative protein profiling of vastus lateralis muscle during human ageing. *Mol Cell Proteomics* 2014;13:283-94.
51. Murphy S, Zweyer M, Henry M, et al. Proteomic analysis of the sarcolemma-enriched fraction from dystrophic mdx-4cv skeletal muscle. *J Proteomics* 2019;191:212-27.
52. Dowling P, Gargan S, Zweyer M, et al. Proteomic profiling of the interface between the stomach wall and the pancreas in dystrophinopathy. *Eur J Transl Myol* 2021;31:9627.
53. Gargan S, Ohlndieck K. Sample Preparation and Protein Determination for 2D-DIGE Proteomics. *Methods Mol Biol* 2023;2596:325-37.
54. Wiśniewski JR, Zougman A, Nagaraj N, Mann M. Universal sample preparation method for proteome analysis. *Nat Methods* 2009;6:359-62.
55. Wiśniewski JR. Filter Aided Sample Preparation - A tutorial. *Anal Chim Acta* 2019;1090:23-30.
56. Dowling P, Gargan S, Zweyer M, et al. Protocol for the Bottom-Up Proteomic Analysis of Mouse Spleen. *STAR Protoc* 2020;1:100196.
57. Szklarczyk D, Gable AL, Nastou KC, et al. The STRING database in 2021: customizable protein-protein networks, and functional characterization of user-uploaded gene/measurement sets. *Nucleic Acids Res* 2021;49:D605-12. Erratum in: *Nucleic Acids Res* 2021;49:10800.
58. Doran P, O'Connell K, Gannon J, Kavanagh M, Ohlndieck K. Opposite pathobiochemical fate of pyruvate kinase and adenylate kinase in aged rat skeletal muscle as revealed by proteomic DIGE analysis. *Proteomics* 2008;8:364-77.
59. Capitanio D, Vasso M, Fania C, et al. Comparative proteomic profile of rat sciatic nerve and gastrocnemius muscle tissues in ageing by 2-D DIGE. *Proteomics* 2009;9:2004-20.
60. Lombardi A, Silvestri E, Cioffi F, et al. Defining the transcriptomic and proteomic profiles of rat ageing skeletal muscle by the use of a cDNA array, 2D- and Blue native-PAGE approach. *J Proteomics* 2009;72:708-21.
61. Gannon J, Doran P, Kirwan A, Ohlndieck K. Drastic increase of myosin light chain MLC-2 in senescent skeletal muscle indicates fast-to-slow fibre transition in sarcopenia of old age. *Eur J Cell Biol* 2009;88:685-700.
62. Lourenço Dos Santos S, Baraibar MA, Lundberg S, et al. Oxidative proteome alterations during skeletal muscle ageing. *Redox Biol* 2015;5:267-74.
63. Gregorich ZR, Peng Y, Cai W, et al. Top-down targeted proteomics reveals decrease in myosin regulatory light-chain phosphorylation that contributes to sarcopenic muscle dysfunction. *J Proteome Res* 2016;15:2706-16.
64. Capitanio D, Vasso M, De Palma S, et al. Specific proteomic changes contribute to the differential muscle mass loss during ageing. *Proteomics* 2016;16:645-56.
65. Doran P, Gannon J, O'Connell K, Ohlndieck K. Aging skeletal muscle shows a drastic increase in the small heat shock proteins alphaB-crystallin/HspB5 and cvHsp/HspB7. *Eur J Cell Biol* 2007;86:629-40.
66. Dowling P, Gargan S, Swandulla D, Ohlndieck K. Fiber-type shifting in sarcopenia of old age: proteomic profiling of the contractile apparatus of skeletal muscles. *Int J Mol Sci* 2023;24:2415.
67. Hatton IA, Galbraith ED, Merleau NSC, et al. The human cell count and size distribution. *Proc Natl Acad Sci U S A* 2023;120:e2303077120.
68. Frontera WR, Ochala J. Skeletal muscle: a brief review of structure and function. *Calcif Tissue Int* 2015;96:183-95.
69. Mukund K, Subramaniam S. Skeletal muscle: A review of molecular structure and function, in health and disease. *Wiley Interdiscip Rev Syst Biol Med* 2020;12:e1462.
70. Brooks SV, Guzman SD, Ruiz LP. Skeletal muscle structure, physiology, and function. *Handb Clin Neurol* 2023;195:3-16.
71. Thompson R, Spendiff S, Roos A, et al. Advances in the diagnosis of inherited neuromuscular diseases and implications for therapy development. *Lancet Neurol* 2020;19:522-532.
72. Cruz-Jentoft AJ, Sayer AA. Sarcopenia. *Lancet* 2019;393:2636-46. Erratum in: *Lancet* 2019;393:2590.
73. Larsson L, Degens H, Li M, et al. Sarcopenia: aging-related loss of muscle mass and function. *Physiol Rev* 2019;99:427-511.
74. Nishikawa H, Fukunishi S, Asai A, et al. Pathophysiology and mechanisms of primary sarcopenia (Review). *Int J Mol Med* 2021;48:156.
75. Kim JW, Kim R, Choi H, et al. Understanding of sarcopenia: from definition to therapeutic strategies. *Arch Pharm Res* 2021;44:876-89.
76. Zheng Y, Feng J, Yu Y, et al. Advances in sarcopenia: mechanisms, therapeutic targets, and intervention strategies. *Arch Pharm Res*. 2024;47:301-324.
77. Liu JC, Dong SS, Shen H, et al. Multi-omics research in sarcopenia: Current progress and future prospects. *Ageing Res Rev* 2022;76:101576.
78. Rivero-Segura NA, Bello-Chavolla OY, Barrera-Vázquez OS, et al. Promising biomarkers of human aging: In search of a multi-omics panel to understand the aging process from a multidimensional perspective. *Ageing Res Rev* 2020;64:101164.
79. Pan Y, Ji T, Li Y, Ma L. Omics biomarkers for frailty in older adults. *Clin Chim Acta* 2020;510:363-72.
80. Danese E, Montagnana M, Lippi G. Proteomics and frailty: a clinical overview. *Expert Rev Proteomics* 2018;15:657-64.
81. Fernández-Lázaro D, Garrosa E, Seco-Calvo J, Garrosa M. Potential satellite cell-linked biomarkers in aging skeletal muscle tissue: proteomics and proteogenomics to monitor sarcopenia. *Proteomes* 2022;10:29.
82. Moaddel R, Ubaida-Mohien C, Tanaka T, et al. Pro-

- teomics in aging research: A roadmap to clinical, translational research. *Aging Cell* 2021;20:e13325.
83. O'Connell K, Ohlendieck K. Proteomic DIGE analysis of the mitochondria-enriched fraction from aged rat skeletal muscle. *Proteomics* 2009;9:5509-24.
84. Xu X, Wen Z. The mediating role of inflammaging between mitochondrial dysfunction and sarcopenia in aging: a review. *Am J Clin Exp Immunol* 2023;12:109-26.
85. Miao Y, Xie L, Song J, et al. Unraveling the causes of sarcopenia: Roles of neuromuscular junction impairment and mitochondrial dysfunction. *Physiol Rep* 2024;12:e15917.
86. Staunton L, O'Connell K, Ohlendieck K. Proteomic profiling of mitochondrial enzymes during skeletal muscle aging. *J Aging Res* 2011;2011:908035.
87. Ohlendieck K. Proteomics of skeletal muscle glycolysis. *Biochim Biophys Acta* 2010;1804:2089-101.
88. Vogt C, Ardehali H, Iozzo P, et al. Regulation of hexokinase II expression in human skeletal muscle in vivo. *Metabolism* 2000;49:814-8.
89. Xu H, Ahn B, Van Remmen H. Impact of aging and oxidative stress on specific components of excitation contraction coupling in regulating force generation. *Sci Adv* 2022;8:eadd7377.
90. O'Connell K, Gannon J, Doran P, Ohlendieck K. Reduced expression of sarcalumenin and related Ca²⁺-regulatory proteins in aged rat skeletal muscle. *Exp Gerontol* 2008;43:958-61.
91. Delbono O. Expression and regulation of excitation-contraction coupling proteins in aging skeletal muscle. *Curr Aging Sci* 2011;4:248-59.
92. Fennel ZJ, Amorim FT, Deyhle MR, et al. The heat shock connection: skeletal muscle hypertrophy and atrophy. *Am J Physiol Regul Integr Comp Physiol* 2022;323:R133-48.
93. Brinkmeier H, Ohlendieck K. Chaperoning heat shock proteins: proteomic analysis and relevance for normal and dystrophin-deficient muscle. *Proteomics Clin Appl* 2014;8:875-95.
94. Dimauro I, Antonioni A, Mercatelli N, Caporossi D. The role of α B-crystallin in skeletal and cardiac muscle tissues. *Cell Stress Chaperones* 2018;23:491-505.
95. Tedesco B, Cristofani R, Ferrari V, et al. Insights on human small heat shock proteins and their alterations in diseases. *Front Mol Biosci* 2022;9:842149.
96. Senf SM. Skeletal muscle heat shock protein 70: diverse functions and therapeutic potential for wasting disorders. *Front Physiol* 2013;4:330.
97. Schopf FH, Biebl MM, Buchner J. The HSP90 chaperone machinery. *Nat Rev Mol Cell Biol* 2017;18:345-60.
98. Schiene-Fischer C. Multidomain peptidyl prolyl cis/trans isomerases. *Biochim Biophys Acta* 2015;1850:2005-16.
99. Islam R, Yoon H, Shin HR, et al. Peptidyl-prolyl cis-trans isomerase NIMA interacting 1 regulates skeletal muscle fusion through structural modification of Smad3 in the linker region. *J Cell Physiol* 2018;233:9390-403.
100. Van Long N, Chien PN, Tung TX, et al. Complementary combination of biomarkers for diagnosis of sarcopenia in C57BL/6J mice. *Life Sci* 2023;312:121213.
101. Aging Biomarker Consortium; Bao H, Cao J, et al. Biomarkers of aging. *Sci China Life Sci* 2023;66:893-1066.
102. Ohlendieck K. Proteomic profiling of fast-to-slow muscle transitions during aging. *Front Physiol* 2011;2:105.
103. Liu C, Cheung WH, Li J, et al. Understanding the gut microbiota and sarcopenia: a systematic review. *J Cachexia Sarcopenia Muscle* 2021;12:1393-407.
104. Sakuma K, Hamada K, Yamaguchi A, Aoi W. Current nutritional and pharmacological approaches for attenuating sarcopenia. *Cells* 2023;12:2422.
105. Shen Y, Shi Q, Nong K, et al. Exercise for sarcopenia in older people: A systematic review and network meta-analysis. *J Cachexia Sarcopenia Muscle* 2023;14:1199-211.
106. Mo Y, Zhou Y, Chan H, et al. The association between sedentary behaviour and sarcopenia in older adults: a systematic review and meta-analysis. *BMC Geriatr* 2023;23:877.
107. Ganapathy A, Nieves JW. Nutrition and sarcopenia-what do we know? *Nutrients* 2020;12:1755.
108. Kim J, Lee JY, Kim CY. A comprehensive review of pathological mechanisms and natural dietary ingredients for the management and prevention of sarcopenia. *Nutrients* 2023;15:2625.
109. Cochet C, Belloni G, Buondonno I, et al. The role of nutrition in the treatment of sarcopenia in old patients: from restoration of mitochondrial activity to improvement of muscle performance, a systematic review. *Nutrients* 2023;15:3703.
110. Granic A, Suetterlin K, Shavlakadze T, et al. Hallmarks of ageing in human skeletal muscle and implications for understanding the pathophysiology of sarcopenia in women and men. *Clin Sci (Lond)* 2023;137:1721-51.
111. Coletta G, Phillips SM. An elusive consensus definition of sarcopenia impedes research and clinical treatment: A narrative review. *Ageing Res Rev* 2023;86: 101883.
112. Alhmly HF, Fielding RA. A critical review of current worldwide definitions of sarcopenia. *Calcif Tissue Int* 2024;114:74-81.
113. Yuan S, Larsson SC. Epidemiology of sarcopenia: Prevalence, risk factors, and consequences. *Metabolism* 2023;144:155533.
114. Montero-Erasquin B, Cruz-Jentoft AJ. Acute sarcopenia. *Gerontology* 2023;69:519-25.
115. Christian CJ, Benian GM. Animal models of sarcopenia. *Aging Cell* 2020;19:e13223.
116. Xie WQ, He M, Yu DJ, et al. Mouse models of sarcopenia: classification and evaluation. *J Cachexia Sarcopenia Muscle* 2021;12:538-54.

Disclaimer

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article or claim that may be made by its manufacturer is not guaranteed or endorsed by the publisher.

Submitted: 12 April 2024.
Accepted: 12 April 2024.
Early access: 24 May 2024.

Non-commercial use only