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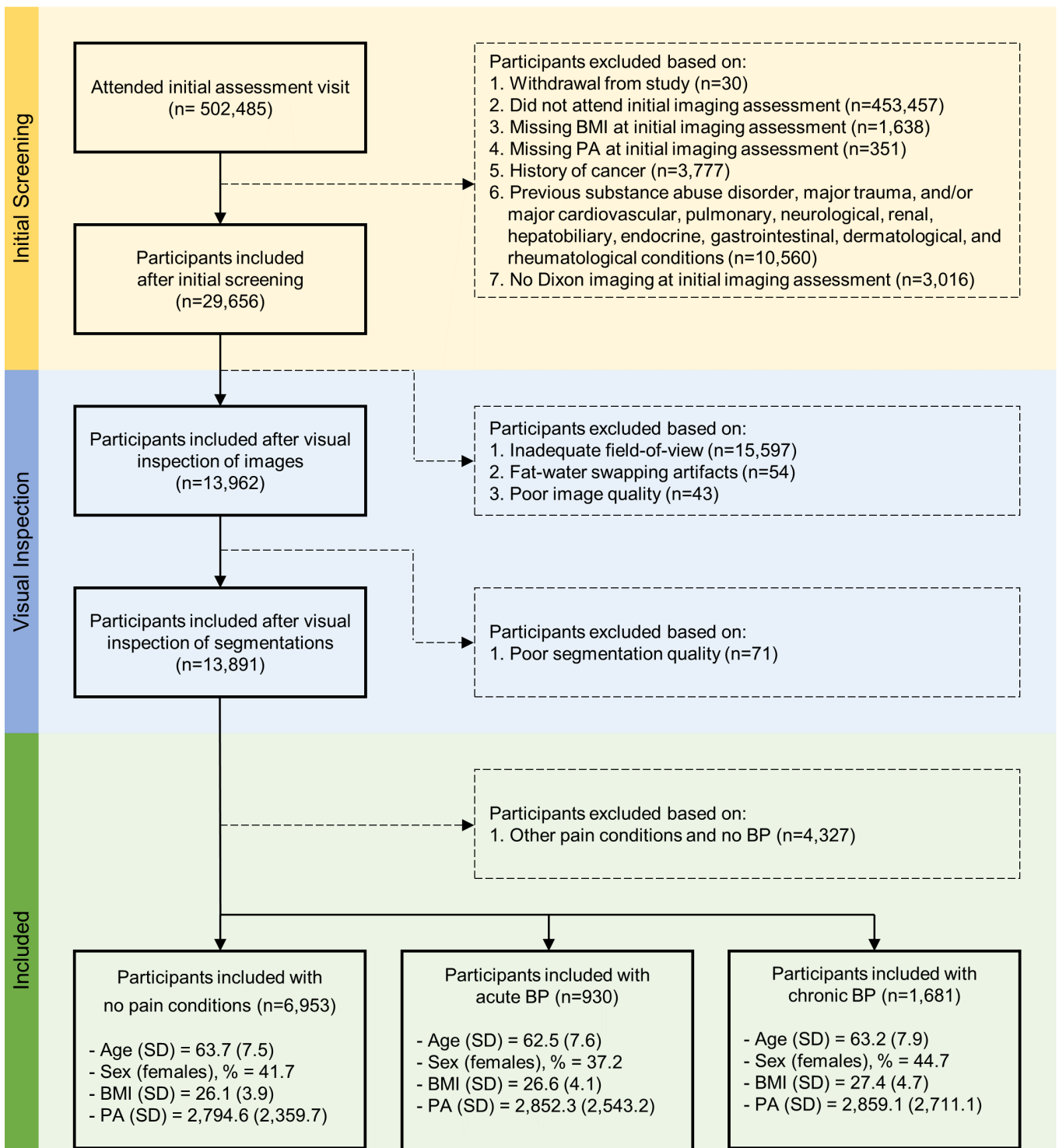
SUPPLEMENTARY FIGURE 1. Flowchart for inclusion and exclusion of participants from the UK Biobank. Demographic variables per group (no pain, acute BP and chronic BP) are presented as mean + SD for age, BMI and self-reported physical activity (PA).
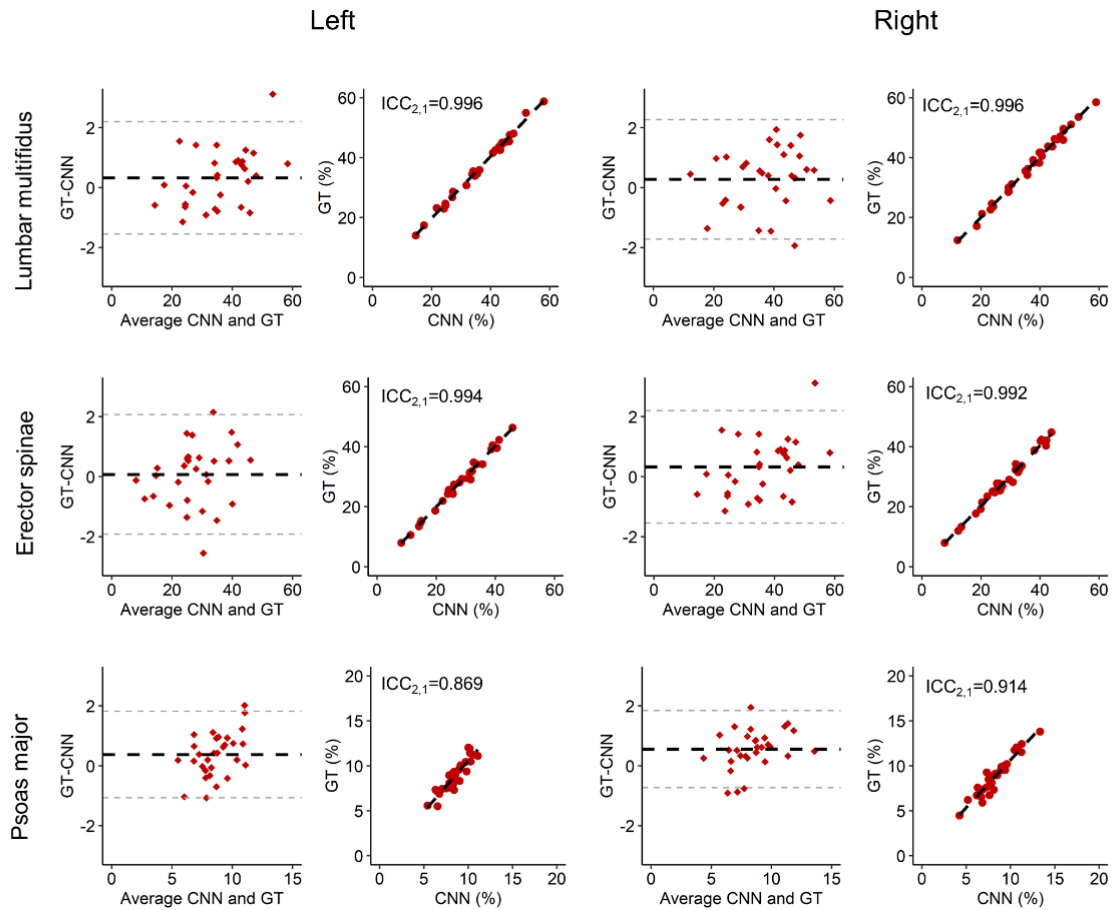
SUPPLEMENTARY FIGURE 2. Reliability and accuracy of the Convolutional Neural Network. Bland Altman (black dashed line = mean error, grey dashed lines = 95% limits of agreement) and correlation plots (black dashed line = best fit line) are shown for IMF (in %) of the left and right lumbar paraspinal muscles. *GT* Ground truth.
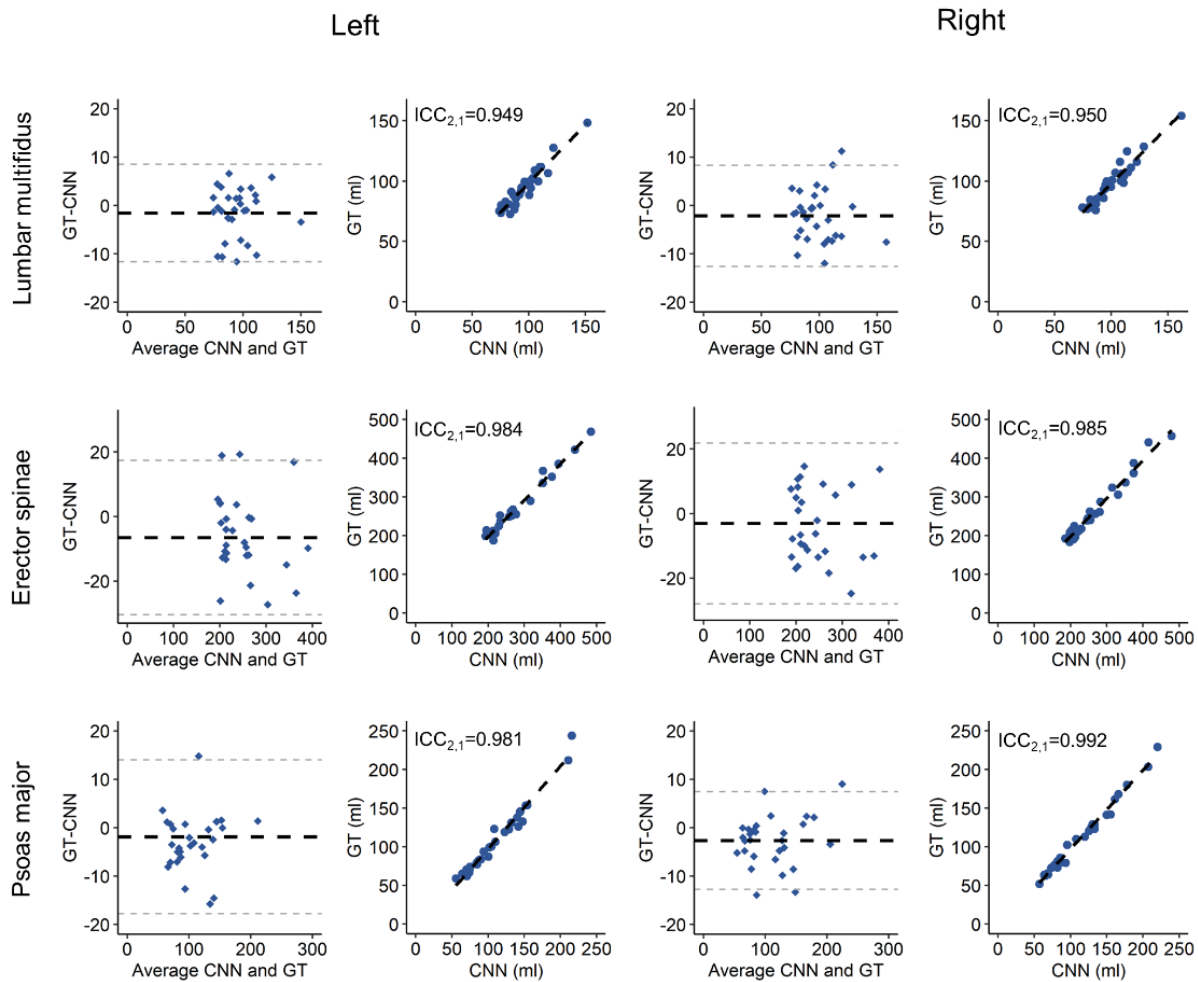
SUPPLEMENTARY FIGURE 3. Reliability and accuracy of the CNN. Bland Altman (black dashed line = mean error, grey dashed lines = 95% limits of agreement) and correlation plots (black dashed line = best fit line) are shown for volume (in ml) of the left and right paraspinal muscles. *GT* Ground truth.
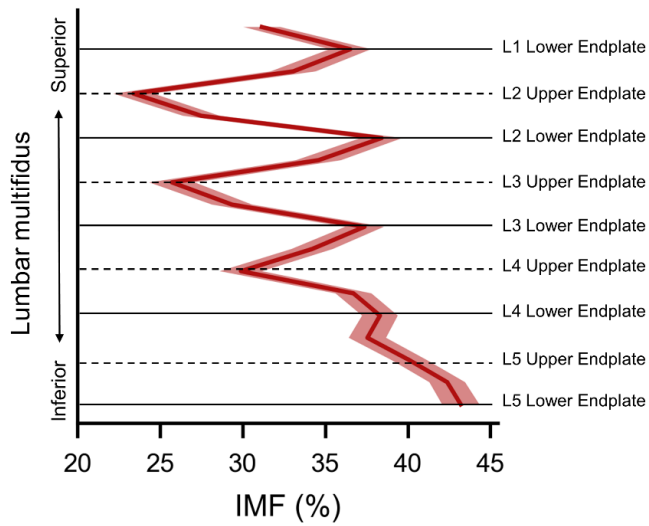
SUPPLEMENTARY FIGURE 4. Slice identification after calculating intramuscular fat levels for the lumbar multifidus per level in 130 participants used for CNN training and testing. The total length is normalized from inferior (lower endplate of L5) to superior (mid vertebral level L1). IMF = Intramuscular Fat.

SUPPLEMENTARY METHODS

Automated Assessment of Lumbar Paraspinal Muscle Composition and Size

Model Training and Testing

We used a modified 2D U-Net CNN architecture for image segmentation because of good performance in highly anisotropic image data as previously reported[2]. We increased the amount of filter maps (64, 128, 256, 512, and 1,026) to deal with high morphometric muscle variability for low- to mid-level features like edges, contrasts, and shapes. A NVIDIA RTX 3090 24GB graphical processing unit (GPU, NVIDIA, Santa Clara, CA, USA) (spatial window batch size=1, batch size=1, optimizer=AdamW, loss function=DiceCEloss, weight decay=0.0001, and learning rate=0.001) was used for model training. The images were randomly cropped to a spatial window size with the centre being a foreground or background voxel based on a positive/negative ratio of one. The 2D model was trained on axial slices using a spatial window size of 160×160×1. The model was initialized with random weights using equivalent randomizations, and the deterministic seed was set to zero.

One blinded rater (EW) with extensive training in lumbar spine anatomy and imaging manually segmented the muscles of interest (i.e., left and right lumbar multifidus, erector spinae, and psoas major) from a dataset of 65 participants with no pain and 65 participants with chronic BP using anatomical cross-references as previously described[3]. In addition, the images were resampled to 2.23mm × 2.23mm x 4.50mm, and the range of pixel values were normalized per participant to generate an equivalent standard intensity scale between the images. All voxels in the image were normalized by subtracting to the mean intensity of all voxels per subject divided by the standard deviation of all voxels per subject. Data augmentation was used to increase the variability in the training images[4]. Affine transformations were applied to the training scheme with a probability of 0.4, including scaling (-2.5–2.5%), rotation (x=-2.5 – 2.5°, y=-2.5 – 2.5°, z=-2.5 – 2.5°) and translation (in voxels relative to the centre of the input image, x=-25 – 25 voxels, y=-25 – 25 voxels, z=-2 – 2 voxels). These specific augmentation hyperparameters were chosen to mimic variations in positioning on the scanner bed and to prevent the network from fixating on specific regions of its perceptive field[5, 6].The images were smart-cached to the RAM to improve training speed. Data augmentation, model training, and model testing were performed using MONAI, an

open-source community supported, Pytorch-based framework for deep learning in healthcare imaging[7].

CNN performance was evaluated on the testing dataset using the Sørensen-Dice index, the Jaccard index, conformity index, true positive rate, true negative rate, positive predictive value, and volume ratio. CNN performance was also calculated for IMF and aCSA using the mean absolute error (MAE), root squared mean error (RSME), coefficient of determination (R^2) and the intra-class coefficient (two-way random effect, absolute agreement for single rater; $ICC_{2,1}$). Results were visually presented as correlation and Bland-Altman plots.

SUPPLEMENTARY TABLE 1. Convolutional Neural Network performance. Data is presented as mean + SD

Muscle	Side	Dice	JI	CC	TPR	TNR	PPV	VR
Lumbar multifidus	Left	0.892 (0.02)	0.806 (0.04)	0.756 (0.06)	0.900 (0.03)	1.000 (0.00)	0.885 (0.03)	1.019 (0.06)
	Right	0.898 (0.02)	0.815 (0.02)	0.772 (0.04)	0.908 (0.03)	1.000 (0.00)	0.889 (0.03)	1.024 (0.05)
Erector spinae	Left	0.916 (0.02)	0.846 (0.03)	0.817 (0.05)	0.928 (0.03)	0.999 (0.00)	0.906 (0.03)	1.024 (0.05)
	Right	0.912 (0.01)	0.838 (0.02)	0.806 (0.04)	0.918 (0.03)	0.999 (0.00)	0.907 (0.03)	1.013 (0.05)
Psoas major	Left	0.917 (0.02)	0.848 (0.04)	0.818 (0.05)	0.932 (0.02)	1.000 (0.00)	0.906 (0.04)	1.028 (0.06)
	Right	0.918 (0.02)	0.848 (0.03)	0.820 (0.05)	0.930 (0.04)	1.000 (0.00)	0.905 (0.03)	1.031 (0.05)

Dice = Sørensen-Dice index, JI = Jaccard Index, CC = Conformity Index, TPR = True Positive Rate, TNR = True Negative Rate, PPV = Positive Predictive value, VR = Volume Ratio.

SUPPLEMENTARY TABLE 2. Accuracy and reliability of the Convolutional Neural Network for intramuscular fat (%) and cross-sectional area.

Muscle	Side	Mean	Bias	95% LOA	MAE	RMSE	R^2	$ICC_{2,1}$	95% CI	p
Intramuscular fat (%)										
Lumbar multifidus	Left	36.0 (2.0)	-0.3	-2.20 - 1.54	0.810	0.995	0.991	0.996	0.991-0.998	<0.001
	Right	37.3 (2.0)	-0.3	-2.26 - 1.71	0.897	1.036	0.991	0.996	0.991-0.998	<0.001
Erector spinae	Left	27.4 (1.7)	-0.1	-2.06 -1.91	0.807	1.000	0.988	0.994	0.988-0.997	<0.001
	Right	28.1 (1.7)	-0.3	-2.54 - 1.93	0.919	1.160	0.983	0.992	0.983-0.996	<0.001
Psoas major	Left	8.7 (0.3)	-0.4	-1.82 - 1.07	0.655	0.814	0.645	0.869	0.700-0.940	<0.001
	Right	8.5 (0.4)	-0.6	-1.84 - 0.73	0.736	0.852	0.795	0.914	0.625-0.970	<0.001
CSA (ml)										
Lumbar multifidus	Left	95.0 (3.0)	1.5	-8.52 - 11.63	4.038	5.289	0.892	0.949	0.894-0.975	<0.001
	Right	99.2 (3.2)	2.2	-8.32 - 12.61	4.536	5.672	0.897	0.950	0.890-0.977	<0.001
Erector spinae	Left	263.1 (13.6)	6.5	-17.35 - 30.36	11.32	13.621	0.967	0.984	0.956-0.993	<0.001
	Right	257.6 (13.7)	3.0	-21.83 - 27.93	11.39	12.848	0.970	0.985	0.970-0.993	<0.001
Psoas major	Left	111.3 (7.6)	1.9	-14.02 - 17.78	5.513	8.196	0.957	0.981	0.961-0.991	<0.001
	Right	110.3 (8.2)	2.6	-7.44 - 12.74	4.285	5.711	0.983	0.992	0.979-0.996	<0.001

MAE = Mean Absolute Error, RMSE = Root Mean Square Error, LOA = Limits of Agreement

SUPPLEMENTARY TABLE 3. Intramuscular fat (mean ± SD) by muscle, age, BMI, and sex in 6,953 participants with no pain.

BMI < 18.5											
		Males					Females				
Age		40-49	50-59	60-69	70-79	80-89	40-49	50-59	60-69	70-79	80-89
n		0	3	3	4	0	1	12	19	6	0
Lumbar multifidus	Left	-	19.7(3.5)	34.1(8.0)	36.4(9.2)	-	28.8(0.0)	34.8(5.1)	38.8(7.4)	39.9(5.2)	-
	Right	-	22.0(4.6)	33.2(7.6)	36.0(8.5)	-	28.3(0.0)	34.7(5.2)	37.7(6.2)	38.0(4.5)	-
Erector spinae	Left	-	12.2(2.9)	26.9(11.2)	19.7(3.4)	-	18.9(0.0)	23.7(3.7)	27.9(5.5)	31.7(5.4)	-
	Right	-	11.7(1.7)	25.6(8.4)	19.5(3.0)	-	18.1(0.0)	22.8(4.7)	26.1(4.2)	27.6(5.9)	-
Psoas Major	Left	-	4.8(0.2)	7.9(2.4)	5.7(0.6)	-	5.7(0.0)	5.8(0.8)	6.2(1.0)	6.8(0.9)	-
	Right	-	4.5(0.3)	7.1(2.1)	4.9(0.2)	-	4.8(0.0)	5.1(0.5)	5.4(0.8)	5.6(0.5)	-

BMI 18.5 – 24.9											
		Males					Females				
Age		40-49	50-59	60-69	70-79	80-89	40-49	50-59	60-69	70-79	80-89
n		20	339	637	447	8	34	524	650	258	5
Lumbar multifidus	Left	25.6(7.7)	25.6(6.3)	29.8(7.3)	35.0(8.3)	35.6(6.3)	30.6(7.2)	35.5(7.7)	40.9(7.7)	48.8(7.5)	47.1(7.0)
	Right	25.5(7.0)	25.9(6.5)	30.1(7.2)	35.1(8.3)	34.5(4.9)	30.5(6.7)	35.7(7.7)	41.2(7.8)	45.8(7.6)	45.0(5.8)
Erector spinae	Left	14.9(5.0)	16.7(4.8)	20.6(6.2)	25.1(7.7)	27.0(7.2)	22.6(6.1)	26.5(6.8)	31.0(7.0)	35.3(7.3)	36.9(7.6)
	Right	15.5(5.1)	16.8(5.0)	20.9(6.4)	25.2(7.4)	28.8(7.5)	21.8(5.2)	25.9(6.9)	31.1(7.2)	35.0(7.3)	35.9(6.7)
Psoas major	Left	6.6(1.3)	6.8(1.2)	7.3(1.2)	7.7(1.4)	8.2(1.3)	6.6(0.9)	7.3(1.3)	7.9(1.3)	8.5(1.4)	8.8(1.4)
	Right	6.0(1.4)	6.2(1.2)	6.7(1.3)	7.2(1.6)	7.6(2.2)	5.8(1.0)	6.4(1.2)	6.9(1.4)	7.5(1.5)	7.1(0.7)

BMI 25.0 – 29.9											
		Males					Females				
Age		40-49	50-59	60-69	70-79	80-89	40-49	50-59	60-69	70-79	80-89
n		45	474	846	601	12	27	311	469	202	2
Lumbar multifidus	Left	25.0(7.0)	26.8(6.8)	31.9(8.0)	36.8(8.6)	39.0(5.7)	33.2(4.8)	37.4(7.6)	43.6(8.2)	47.4(8.0)	55.1(12.4)
	Right	25.8(6.6)	27.2(6.9)	32.4(8.0)	37.8(8.5)	40.7(7.5)	33.9(5.2)	38.1(7.6)	44.0(8.5)	48.2(8.3)	54.7(7.2)
Erector spinae	Left	17.1(4.5)	18.3(5.6)	22.8(7.1)	27.4(7.6)	32.2(8.3)	25.8(5.1)	28.8(6.7)	33.9(7.7)	37.5(8.0)	50.1(8.5)
	Right	17.4(4.1)	18.9(5.7)	23.4(6.9)	28.3(7.6)	33.1(9.4)	26.0(5.5)	28.7(6.8)	34.0(7.7)	37.7(7.8)	47.6(4.4)
Psoas major	Left	7.5(1.2)	7.3(1.2)	7.9(1.5)	8.4(1.8)	8.6(1.3)	8.0(0.8)	8.2(1.1)	8.5(1.1)	8.9(1.3)	9.4(2.4)
	Right	7.2(1.3)	7.2(1.3)	7.8(1.7)	8.5(1.9)	8.5(1.5)	7.4(1.0)	7.5(1.2)	7.9(1.2)	8.4(1.4)	7.9(1.5)

BMI ≥ 30.0											
		Males					Females				
Age		40-49	50-59	60-69	70-79	80-89	40-49	50-59	60-69	70-79	80-89
n		17	168	282	145	2	3	130	172	75	0
Lumbar multifidus	Left	27.4(6.9)	28.3(6.9)	34.2(8.3)	39.8(8.7)	45.5(2.1)	36.9(5.4)	39.5(7.5)	45.9(8.2)	51.5(8.2)	-
	Right	29.5(7.5)	29.2(7.3)	35.2(8.3)	41.4(8.7)	48.6(11.6)	33.6(4.0)	40.1(7.3)	46.7(8.1)	52.1(8.5)	-
Erector spinae	Left	20.8(6.2)	20.0(5.6)	26.1(7.9)	31.1(9.3)	36.5(14.8)	26.9(1.6)	31.3(6.4)	35.9(8.2)	40.6(8.3)	-
	Right	22.3(6.6)	21.4(6.0)	27.4(7.9)	32.8(9.6)	35.1(13.0)	28.7(5.4)	31.7(6.4)	36.7(8.2)	41.2(8.6)	-
Psoas major	Left	8.1(1.5)	7.8(1.4)	8.7(2.0)	9.7(2.6)	11.0(4.8)	8.2(0.3)	8.3(1.2)	8.7(1.2)	9.1(1.3)	-
	Right	8.0(1.7)	8.0(1.4)	9.1(2.0)	10.2(2.7)	9.6(3.7)	8.5(2.1)	8.2(1.4)	8.6(1.4)	9.3(1.9)	-

SUPPLEMENTARY TABLE 4. Average CSA (mean ± SD) by muscle, age, BMI, and sex in 6,953 participants with no pain. Average CSA is calculated by dividing the total CSA by the number of segmented slices.

BMI < 18.5

		Males					Females				
Age		40-49	50-59	60-69	70-79	80-89	40-49	50-59	60-69	70-79	80-89
n		0	3	3	4	0	1	12	19	6	0
Lumbar multifidus	Left	-	535.6(64.0)	525.0(47.7)	515.8(52.7)	-	479.6(0.0)	468.7(66.0)	478.0(62.3)	450.0(58.5)	-
	Right	-	577.0(71.9)	537.9(63.7)	525.2(62.9)	-	500.4(0.0)	472.5(63.2)	474.6(67.1)	448.8(52.6)	-
Erector spinae	Left	-	1618.1(73.4)	1319.0(181.4)	1266.5(197.0)	-	1298.8(0.0)	1202.2(109.6)	1185.1(128.6)	1157.4(156.9)	-
	Right	-	1393.0(79.7)	1281.4(141.4)	1262.8(182.9)	-	1301.6(0.0)	1124.5(112.6)	1102.0(137.1)	1075.5(85.3)	-
Psoas major	Left	-	814.0(200.0)	553.7(54.7)	579.8(183.6)	-	483.5(0.0)	461.4(92.7)	418.4(74.2)	364.0(81.4)	-
	Right	-	771.7(182.6)	533.1(24.9)	522.0(145.1)	-	405.4(0.0)	439.5(78.7)	403.6(68.1)	363.9(87.8)	-

BMI 18.5 – 24.9

		Males					Females				
Age		40-49	50-59	60-69	70-79	80-89	40-49	50-59	60-69	70-79	80-89
n		20	339	637	447	8	34	524	650	258	5
Lumbar multifidus	Left	574.4(94.5)	579.4(74.2)	588.2(73.8)	580.6(75.7)	550.8(52.6)	557.9(80.5)	542.3(71.2)	545.2(73.5)	541.7(70.7)	560.2(113.6)
	Right	587.6(92.4)	591.6(75.5)	599.3(80.6)	592.0(81.3)	568.2(81.0)	573.4(81.8)	552.8(71.4)	558.1(78.7)	555.5(73.1)	589.0(133.1)
Erector spinae	Left	1683.8(226.0)	1700.3(188.8)	1628.7(192.1)	1564.5(191.2)	1447.0(157.8)	1450.9(228.4)	1364.1(147.4)	1332.9(163.3)	1293.9(152.7)	1331.9(95.5)
	Right	1645.6(193.9)	1657.8(184.6)	1588.3(188.9)	1529.6(194.3)	1443.6(180.3)	1401.4(259.3)	1306.8(151.5)	1283.4(167.1)	1245.8(147.2)	1281.2(149.3)
Psoas major	Left	924.7(150.1)	885.0(150.3)	815.7(144.8)	733.3(135.7)	668.1(67.2)	592.1(118.7)	541.3(104.5)	496.1(87.7)	461.2(90.5)	390.2(53.2)
	Right	860.6(125.3)	831.6(139.4)	770.6(135.9)	690.6(124.0)	601.3(51.7)	543.3(112.1)	501.4(89.6)	464.8(81.0)	441.1(85.5)	416.4(30.5)

BMI 25.0 – 29.9

		Males					Females				
Age		40-49	50-59	60-69	70-79	80-89	40-49	50-59	60-69	70-79	80-89
n		45	474	846	601	12	27	311	469	202	2
Lumbar multifidus	Left	629.1(66.7)	613.5(76.2)	619.9(77.9)	614.3(75.6)	602.4(84.1)	562.7(92.6)	562.3(66.2)	565.5(73.2)	561.0(70.8)	429.7(6.7)
	Right	645.1(73.6)	628.9(81.0)	628.4(81.3)	623.7(80.5)	603.6(76.7)	580.3(98.3)	569.8(67.7)	576.8(78.6)	573.0(77.2)	473.0(14.1)
Erector spinae	Left	1910.1(246.6)	1882.2(225.9)	1813.9(212.4)	1737.5(203.8)	1659.3(249.3)	1492.9(173.0)	1471.7(160.5)	1425.0(158.0)	1400.7(160.0)	1039.0(68.0)
	Right	1887.8(200.5)	1848.4(211.5)	1782.6(207.7)	1705.3(203.2)	1577.4(189.9)	1467.7(181.0)	1426.7(157.8)	1384.4(150.3)	1371.9(156.0)	1032.7(20.1)
Psoas major	Left	905.3(136.7)	930.3(163.3)	846.4(154.9)	773.9(147.1)	777.3(154.2)	559.3(118.3)	542.5(95.8)	516.5(94.7)	494.4(99.2)	470.2(168.8)
	Right	877.9(143.1)	903.0(151.4)	812.0(147.7)	757.7(131.6)	718.6(142.9)	535.8(97.5)	524.5(89.4)	502.6(89.1)	477.0(91.8)	406.6(120.6)

BMI ≥ 30.0

		Males					Females				
Age		40-49	50-59	60-69	70-79	80-89	40-49	50-59	60-69	70-79	80-89
n		17	168	282	145	2	3	130	172	75	0
Lumbar multifidus	Left	639.8(58.6)	644.5(70.7)	654.9(78.8)	655.7(73.6)	749.8(32.2)	584.0(94.3)	590.5(74.8)	599.1(82.9)	588.9(76.8)	-
	Right	670.3(90.6)	660.0(74.2)	661.6(85.1)	658.8(76.2)	734.6(6.0)	580.0(103.3)	596.4(77.7)	598.0(85.4)	591.8(79.2)	-
Erector spinae	Left	2041.1(236.7)	2029.0(246.2)	1957.7(220.9)	1866.7(222.3)	1855.3(0.5)	1646.6(91.0)	1586.7(191.3)	1566.6(198.3)	1526.8(175.2)	-
	Right	1948.3(178.6)	1987.6(233.1)	1951.0(217.7)	1835.1(216.6)	1763.8(144.4)	1569.0(86.1)	1566.4(190.7)	1536.4(189.4)	1508.3(184.9)	-
Psoas major	Left	1021.6(214.8)	952.2(172.2)	870.8(148.2)	800.4(145.9)	870.9(47.2)	631.0(97.6)	572.5(99.7)	518.3(99.9)	489.8(93.7)	
	Right	975.0(169.4)	930.1(172.7)	852.6(137.5)	799.0(140.5)	861.6(1.4)	664.5(90.1)	572.9(103.1)	518.5(87.3)	486.1(84.7)	-