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Age- and sex-adjusted CT-based reference values for temporal muscle thickness, cross-sectional area and radiodensity

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Muscle mass has been traditionally assessed by measuring paraspinal muscle areas at the level of the third lumbar vertebra on computed tomography (CT). Neurological or neurosurgical patients seldom undergo CT scans of the lumbar region. Instead, temporal muscle thickness (TMT), cross-sectional area (TMA) and radiodensity measured from head CT scans are readily available measures of muscle mass and quality in these patient cohorts. The purpose of this retrospective study was to establish CT-based reference values for TMT, TMA and radiodensity for each decade of age from 0 to 100 years normalized by age and sex, and to define cut-off values for subjects at risk for sarcopenia as defined by the European Working Group on Sarcopenia in Older People (EWGSOP). Subjects diagnosed with a concussion at the Oulu University Hospital between January 2014 and December 2022 (*n* = 9254) were identified to obtain a reference population. Subjects with significant pre-existing co-morbidities were excluded. TMT, TMA and radiodensity were measured, measurement reliability was quantified, and sex-adjusted reference values were calculated for each age decade. Quantile regression was used to model age-related changes in muscle morphomics. A total of 500 subjects [250 (50.0%) males] with a mean age of 49.2 ± 27.9 years were evaluated. Inter- and intra-observer reliability was almost perfect for TMT and TMA, and substantial-to-almost perfect for radiodensity. The mean TMT, TMA and radiodensity were 5.2 ± 1.9 mm, 284 ± 159 mm^2 and 44.6 ± 17.7HU, respectively. The cut-off values for reduced TMT, TMA and radiodensity for males/females using the European Working Group on Sarcopenia in Older People compliant criteria were ≤ 4.09 mm/≤3.44 mm, ≤ 166 mm^2/≤156 mm^2, and ≤ 35.5HU/≤35.2HU, respectively. We described a standardized CT-based TMT and TMA measurement protocol practical for clinical use with almost perfect reliability. Using the protocol, we produced quantile regression models for the detection of reduced TMT, TMA and radiodensity at the lowest 5th, 10th, 20th, 30th, 40th and 50th percentiles as well as the EWGSOP compliant criteria cut-off values for reduced muscle mass to facilitate generalizable radiological sarcopenia research.

Keywords Temporal muscle thickness, Temporal muscle area, Computed tomography, Nutrition, Sarcopenia, Aging, Reference values

Abbreviations

BMI	Body mass index
EWGSOP	European Working Group on Sarcopenia in Older People
CI	Confidence interval
CT	Computed tomography
MRI	Magnetic resonance imaging
OR	Odds ratio
HU	Hounsfield unit

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SD	Standard deviation
TMT	Temporal muscle thickness
TMA	Temporal muscle cross-sectional area

Ageing and geriatric syndromes such as malnutrition, sarcopenia and frailty are associated with loss of muscle mass[1,2], which can be readily measured using cross-sectional imaging[3]. Muscle mass has been traditionally assessed by measuring the paraspinal muscle areas at the level of the third lumbar vertebra from computed tomography (CT) scans, which correlate with whole body muscle mass[4]. However, neurological or neurosurgical patients seldom undergo CT scans of the lumbar region. CT imaging of the head is often the only imaging modality used in the assessment of neurological and neurosurgical conditions. Temporal muscle thickness (TMT) correlates with muscle measurements at the level of the third lumbar vertebra among patients with glioblastoma, primary central nervous system lymphoma and brain metastases[5–7], and both TMT and temporal muscle cross-sectional area (TMA) have been associated with outcomes in several neurological diseases, such as stroke, central nervous system malignancies and traumatic brain injury[8,9]. A strong positive correlation between TMT and muscle strength has been observed in healthy individuals and in patients with various neurological disorders[10].

The use of clinical head CT scans allows straightforward evaluation of TMT and TMA with no additional radiation exposure or cost[11]. However, the lack of standardized cut-off values for TMT and TMA has hindered their clinical translation. Previously applied cut-off values are based on samples affected by the studied conditions, which contribute to the decrease of muscle mass[12–17] complicating the translation of these cut-off values to other conditions.

Normative ranges of TMT and TMA measured from magnetic resonance imaging (MRI) have been reported previously[5,10,12,14–24], but CT-based reference values for TMT, TMA and radiodensity have not been published. CT data inherently contains information on radiodensity of the tissues of interest, which cannot be objectively quantified with MRI[25], but may indicate changes in muscle quality due to vulnerability-related changes such as myosteatosis. Therefore, we aimed to establish normative age- and sex-adjusted reference values for TMT, TMA and radiodensity measured from CT scans. We defined (1) sex-adjusted reference values for each decade of age from 0 to 100 years, (2) cut-off values for subjects at risk of sarcopenia as defined by the European Working Group on Sarcopenia in Older People (EWGSOP)[26], and (3) quantile regression models for reduced TMT, TMA and radiodensity at the level of the lowest 5th, 10th, 20th, 30th, 40th and 50th percentiles for TMT, TMA and radiodensity.

Methods

This retrospective observational study was approved by the Institutional Review Board of the Oulu University Hospital (157/2023) and complied with the Declaration of Helsinki. Informed consent and ethical board review was waived due to the retrospective setting of the study.

Patient characteristics

As it is ethically unjustifiable to predispose healthy subjects to ionizing radiation without a clinical indication for its use, we selected patients who had undergone a clinical CT head scan due to a concussion as our reference cohort. Concussion is the most common and sporadic type of brain injury that occurs to patients representative of a healthy population[27]. We retrospectively identified subjects diagnosed with the International Classification of Diseases, 10th Revision code S06.0 ('concussion') treated at Oulu University Hospital between January 2014 and December 2022. The sample size for the TMT measurements was determined to be 25 subjects for each sex-specific age group based on a 95% CI with a 1 mm margin of error in the TMT reference values compared to the actual population mean, and the estimated population standard deviation (SD) of 2.5 mm[28]. The same sample size was estimated to be sufficient for the TMA and Hounsfield unit (HU) measurements. Therefore, ten 10-year age groups each comprising 25 male and female subjects were randomly selected (50 subjects in each 10-year age group) and screened for prior comorbidity.

Subjects with substantial prior comorbidities, substance abuse or CT head scan with a slice thickness > 1.25 mm were excluded and replaced by suitable subjects. The following comorbidities were considered insignificant and thus allowed: mild asthma and/or migraines; well-controlled hypertension and/or benign prostatic hyperplasia for subjects aged ≥ 80 years; medically treated hypothyroidism, well-controlled type 2 diabetes, mild coronary artery disease and/or mild osteoarthritis for subjects aged ≥ 90 years. Patients with other medical conditions were excluded. Sex, date of birth, weight, height, previous diagnoses, and the date of the CT scan were extracted from the patient records. Body mass index (BMI) was calculated for subjects aged ≥ 20 years who had been weighed within one year before or after the CT scan. BMI data was available for 156/400 subjects (39.0%).

Imaging and measurement protocol

The non-contrast-enhanced CT head soft tissue image stacks windowed to linear width/level 80/40 HU using Neaview Radiology (v.2.31, Neagen Oy, Helsinki, Finland) were used for the analyses. The muscle measurements were made using the inbuilt measurement functionality of the same software. Slice thickness was 0.5–1.25 mm, and slice interval was 0.4–0.8 mm. A researcher (E.K.P., 2 years of experience in imaging research) and a neurosurgeon (T.K.K., 10 years of experience in imaging research) independently conducted the measurements blinded to clinical information. Head CT scans of patients with their temporomandibular joints in a non-neutral position were excluded from the study to rule out the effect of jaw position on the muscle measurements. Patients with any traumatic lesions or other radiological abnormalities affecting their temporal muscles were also excluded. The use of dentures was recorded. To maintain imaging consistency and measurement comparability, the CT scanners (Ingenuity CT, Philips Healthcare, the Netherlands; Acquilion One Vision Edition, Canon

Medical Systems, Japan; SOMATOM Drive, Siemens Healthcare, Germany; SOMATOM Force, Siemens Healthcare, Germany) used during the study period underwent weekly calibration and quality assurance testing to verify that the HU value of water remained within 0 ± 4 HU range, in compliance with European guidelines. As the attenuation of muscle tissue is close to that of water, this weekly calibration ensures that the observed HU value of the temporal muscle remains relatively stable[29].

Using the three multiplanar reconstruction dimensions, the scans were oriented parallel to the anterior skull base (semi-axial plane), parallel to the falx cerebri (sagittal plane), and tangential to the floor of the middle cranial fossae (coronal plane). The semi-axial plane was used for TMT, TMA and radiodensity measurements[30]. The measurements were made on the first semi-axial slice above the soft tissues of the orbit. Suitable measurement planes were identified individually for the left and right hemispheres as required. A line connecting the external tables of the most medial part of the temporal fossa and the most lateral part of the temporoparietal bone was drawn. The thickest part of the temporal muscle perpendicular to this line was recorded as TMT. TMA and radiodensity were measured using a free-hand polygon measurement tool in the same slice positioning. Fat, fascia and vasculature were not included in the measurement. The slice orientation and measurement protocol are shown in Fig. 1. E.K.P. measured TMT, TMA and radiodensity of all 500 patients twice, and T.K.K. measured a randomly selected subset of 50 patients twice. Both readers had an interval of 3 months between their measurement sessions to eliminate recall bias.

Statistical analysis

The Kruskal-Wallis H test was used to evaluate differences in TMT, TMA and radiodensity between age groups. Binary logistic regression was used to evaluate differences in TMT, TMA and radiodensity between sexes. The binary logistic odds ratios (ORs) were reported with the associated 95% confidence interval (CI). Scatter plots of TMT, TMA and radiodensity vs. age and BMI were illustrated with locally weighted scatterplot smoothing (Epanechnikov kernel, 50% of points fitted). P-values < 0.05 were considered statistically significant.

Measurement reliability

The means of left and right TMT, TMA and radiodensity from E.K.P.'s two measurement rounds were used in the analyses. Normally distributed continuous variables were summarized as means and presented with SD. Inter-

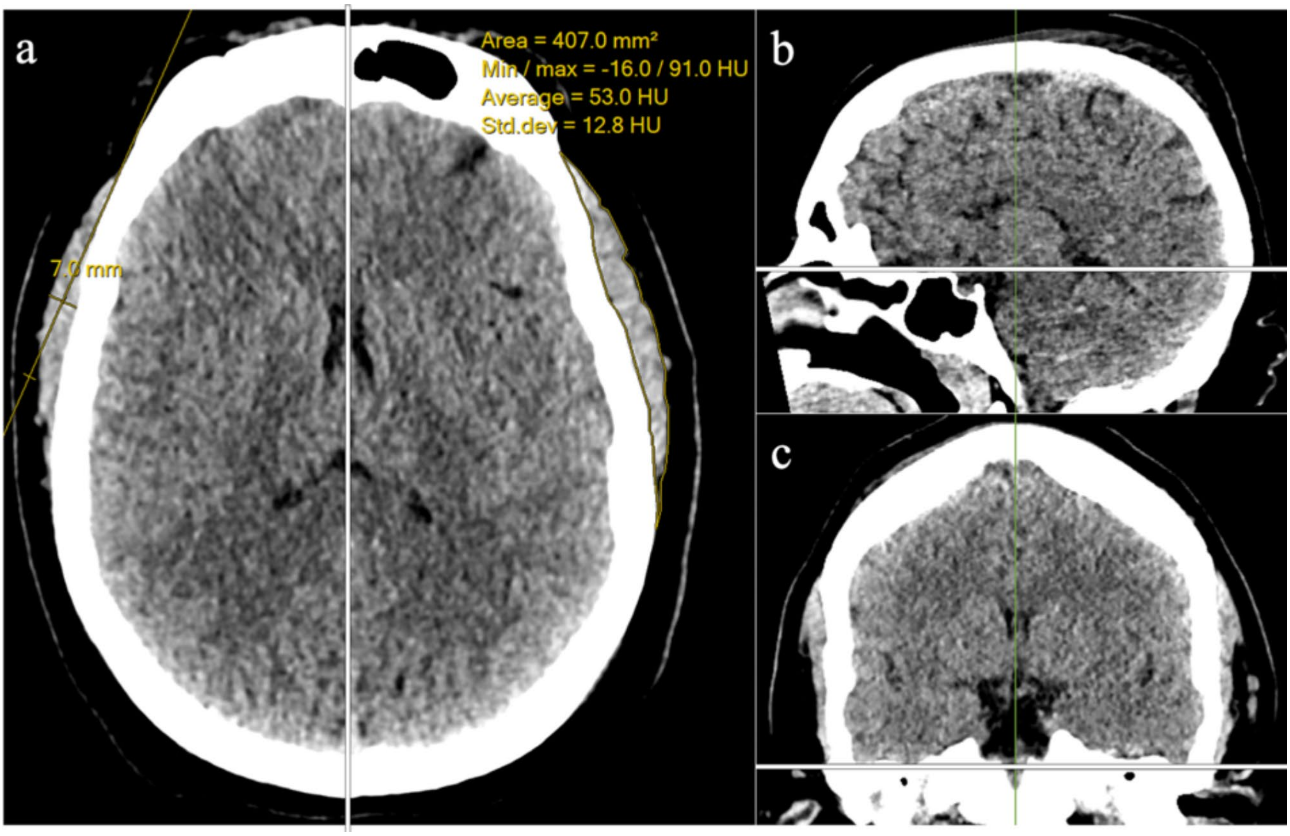

Fig. 1. A head CT scan demonstrating temporal muscle thickness (TMT) measured on the patient's right (shorter yellow line; 7.0 mm), and temporal muscle area (TMA) and radiodensity on the patient's left (yellow line; 407.0 mm^2, 53.0 HU) (**a**). The measurement slice was aligned parallel to the anterior skull base semi-axially (**b**; white line), parallel to the falx cerebri sagittally (a; white line), and tangential to the floor of the middle cranial fossae coronally (**c**; white line). The measurements were performed on the first semi-axial slice superior to the soft tissues of the orbit (**a**).

observer reliability was calculated by comparing the measurements of E.K.P. to those of T.K.K. Intra-observer reliability was calculated for both using intra-class correlation coefficient (ICC, single measures two-way mixed model). Relibilities were reported with the associated 95% CI. Reliability was defined poor if ICC was < 0.00, slight if 0.00–0.20, fair if 0.41–0.60, substantial if 0.61–0.80 and almost perfect if > 0.80[31].

Cut-off values

Cut-off values for TMT, TMA and radiodensity suggesting the risk of sarcopenia, as defined in the EWGSOP recommendations, were calculated for the elderly (> 65 years) as 2SDs below the sex-specific means of healthy 18–40-year-olds[26,32]. Additionally, cut-off values of -2.5SDs were calculated to allow for a more conservative diagnosis as suggested by the EWGSOP[26,32]. Quantile regression was used to model the lowest 5th, 10th, 20th, 30th, 40th and 50th percentile cut-off ranges for TMT, TMA and radiodensity across the age distribution. A cubic term of age was fitted to the quantile regression models and used as the independent variable for TMT, TMA and radiodensity. Statistical analyses were conducted with IBM SPSS (v. 23, IBM Corporation, Armonk, NY). The data that support the findings of this study are available on reasonable request from the corresponding author E.K.P. The CT images are not publicly available due to the European Union data protection requirements.

Results

Patient characteristics

We included 500 patients (mean age 49.2 ± 27.9 years, 250 males) (Table 1; Fig. 2): ten 10-year age groups each comprising 25 male and female subjects were randomly selected. One-hundred-and-twenty-two (24.4%) subjects had pre-existing comorbidities. 49/500 (1.0%) of patients had dentures. The use of dentures did not affect temporal muscle radiodensity, but patients with dentures had slightly lower TMT and TMA (Table S1).

Measurement reliability

Intra- and inter-rater agreements were almost perfect for TMT and TMA, although slightly higher for TMA. For radiodensity, the intra-rater reliability was almost perfect, and inter-rater reliability was substantial (Table S2).

Temporal muscle measurements

The mean TMT of all subjects was 5.2 mm (± 1.9, range 0.7–11.6 mm) and mean TMA was 284 mm^2 (± 159, range 8-1106mm^2). The mean temporal muscle radiodensity was 44.6HU (± 17.7, range 9.3-70.0HU) for all subjects.

The mean TMT, TMA and radiodensity for each 10-year age group are reported in Table 2. Female sex was associated with lower TMT, TMA and radiodensity (Fig. 3). BMI correlated very weakly–weakly with TMT and TMA, whereas a single-knot spline shape was observed for the correlation between age, and TMT, TMA and radiodensity (Figs. 4 and 5). No correlation existed between BMI and radiodensity.

Sex	Age group	Mean age, years (SD)	Subjects with previous medical history, *n* (%)[a]
Female	0–9	5.1 (2.8)	1 (4%)
	10–19	16.1 (2.2)	0 (0%)
	20–29	24.7 (3.0)	0 (0%)
	30–39	34.7 (2.8)	5 (20%)
	40–49	43.6 (2.6)	2 (8%)
	50–59	54.5 (2.8)	4 (16%)
	60–69	63.8 (2.8)	5 (20%)
	70–79	73.0 (2.3)	7 (28%)
	80–89	83.5 (3.0)	17 (68%)
	90–99	91.9 (1.8)	23 (92%)
Male	0–9	5.4 (2.1)	1 (4%)
	10–19	16.0 (2.2)	0 (0%)
	20–29	24.6 (3.1)	2 (8%)
	30–39	34.2 (3.4)	3 (12%)
	40–49	45.1 (2.3)	2 (8%)
	50–59	53.6 (2.8)	2 (8%)
	60–69	64.8 (2.4)	4 (16%)
	70–79	73.0 (2.9)	7 (28%)
	80–89	83.4 (2.5)	14 (56%)
	90–99	92.3 (1.8)	23 (92%)

Table 1. Baseline characteristics of subjects in each age group. Each age group comprises 25 subjects from both sexes. *SD* standard deviation, *n* number of subjects [a]Mild asthma and/or well-controlled migraine were allowed. A history of hypertension and/or benign prostatic hyperplasia was allowed for subjects ≥ 80 years. Additionally, well-controlled hypothyroidism, type 2 diabetes, osteoarthritis and/or coronary artery disease were allowed for subjects aged ≥ 90 years.

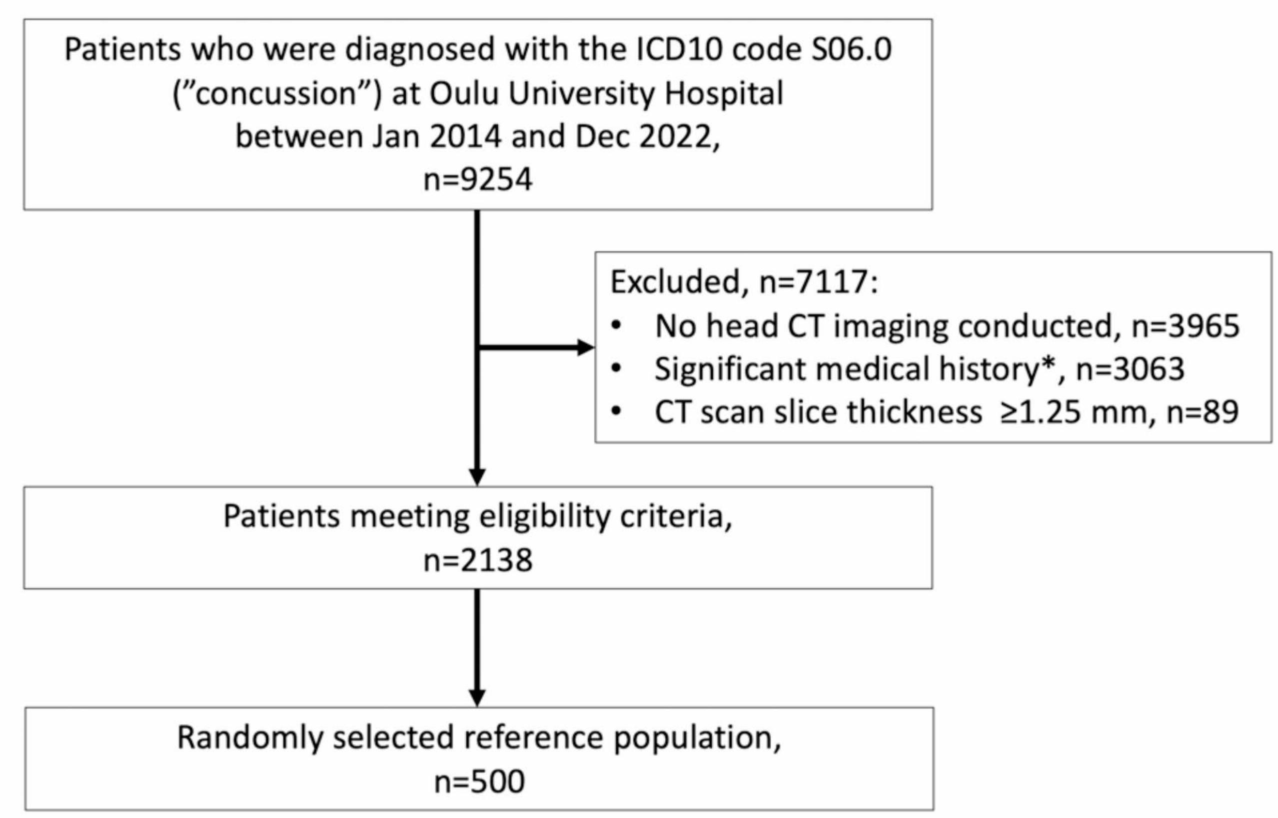

Fig. 2. Flowchart of patient selection. *The following comorbidities were considered insignificant and allowed: mild asthma and/or migraines; well-controlled hypertension and/or benign prostatic hyperplasia for patients aged ≥ 80 years; hypothyroidism, type 2 diabetes, mild coronary artery disease and/or mild osteoarthritis for patients aged ≥ 90 years.

Sex	Age	Mean TMT (SD) in mm	TMT range in mm	Mean TMA (SD) in mm^2	TMA range in mm^2	Mean radiodensity in HU (SD)	Radiodensity range in HU
FEMALE	0–9	3.44 (1.80)	0.75, 8.60	111 (79)	13, 321	42.4 (14.2)	33.3, 58.3
	10–19	6.15 (1.02)	4.50, 8.23	299 (63)	162, 423	46.9 (14.9)	37.5, 56.3
	20–29	6.14 (1.09)	4.65, 9.70	322 (67)	203, 454	49.5 (15.3)	38.0, 63.5
	30–39	5.98 (1.56)	3.61, 9.08	312 (99)	93, 522	48.2 (15.7)	37.5, 62.5
	40–49	5.87 (1.35)	2.85, 8.25	330 (99)	116, 506	46.1 (17.8)	33.0, 62.0
	50–59	5.04 (1.29)	2.05, 7.43	255 (98)	40, 470	44.9 (20.6)	9.3, 56.5
	60–69	4.60 (1.08)	3.00, 7.15	214 (82)	111, 508	45.7 (21.3)	33.3, 60.8
	70–79	4.01 (1.38)	0.65, 6.10	172 (82)	8, 289	36.9 (17.6)	19.5, 52.8
	80–89	3.55 (1.29)	1.65, 6.03	142 (86)	34, 339	36.7 (19.2)	14.5, 61.5
	90–99	3.10 (1.23)	1.25, 6.00	116 (63)	35, 229	36.2 (15.9)	21.5, 50.0
MALE	0–9	3.48 (1.59)	0.98, 6.95	106 (67)	11, 263	41.3 (13.8)	29.5, 55.0
	10–19	6.74 (1.16)	4.63, 9.23	417 (131)	163, 652	48.2 (14.2)	39.3, 61.8
	20–29	7.54 (1.67)	5.05, 11.63	515 (191)	242, 1106	50.0 (18.8)	31.5, 61.5
	30–39	6.81 (1.38)	4.86, 10.15	437 (117)	240, 677	50.8 (17.7)	33.0, 66.0
	40–49	7.36 (1.33)	5.03, 9.90	493 (119)	321, 762	50.6 (18.7)	42.5, 61.3
	50–59	5.97 (1.34)	2.95, 9.73	382 (108)	138, 631	47.4 (20.5)	36.3, 64.0
	60–69	5.98 (1.35)	3.28, 8.75	393 (132)	178, 721	44.8 (20.8)	27.0, 58.3
	70–79	4.59 (1.31)	2.45, 6.66	246 (79)	100, 370	39.2 (19.1)	26.8, 51.0
	80–89	4.61 (1.52)	2.05, 7.58	243 (114)	70, 510	44.8 (18.2)	34.5, 57.8
	90–99	3.67 (1.80)	1.95, 6.85	183 (89)	41, 362	41.4 (19.1)	21.0, 70.0

Table 2. Baseline characteristics of subjects in each age group. Each age group comprises 25 subjects from both sexes. *TMT* temporal muscle thickness, *TMA* temporal muscle cross-sectional area, *mm* millimeter, *SD* standard deviation, *HU* Hounsfield unit

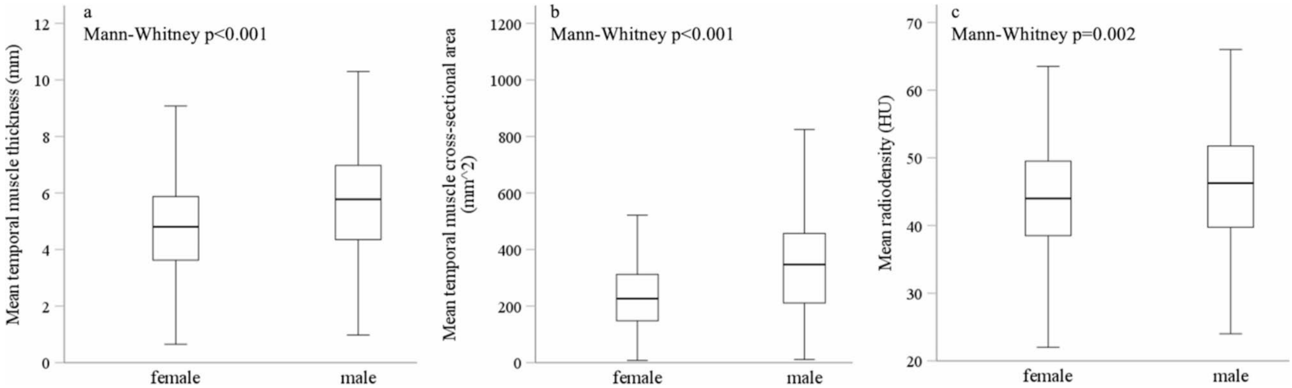

Fig. 3. Boxplots of temporal muscle thicknesses (**a**), temporal muscle cross-sectional areas (**b**) and radiodensities (**c**) in female and male patients.

EWGSOP-compliant cut-off values

We defined cut-offs for reduced TMT, TMA and temporal muscle radiodensity following the EWGSOP criteria. The −2SD cut-off values for reduced TMT were 4.09 mm for males and 3.44 mm for females, and the stricter −2.5SD cut-off values were 3.34 mm for males and 2.79 mm for females. The −2SD cut-off value for abnormal TMA was 166mm^2 for males and 156 mm^2 for females, and the −2.5SD cut-off value 89 mm^2 for males and 116 mm^2 for females. The −2SD cut-off value for abnormal temporal muscle radiodensity was 35.5HU for males and 35.2HU for females, and the −2.5SD cut-off value was 31.9HU for both sexes. Based on the −2SD EWGSOP criteria, 110 (22.0%) of had reduced TMT, 115 (23.0%) TMA and 78 (15.6%) low radiodensity.

Quantile regression models

The quantile regression curves for reduced TMT, TMA and radiodensity at the levels of the lowest 5th, 10th, 20th, 30th, 40th and 50th percentiles are shown in Fig. 6. The functions of these curves are given in Table S3.

Discussion

We presented the first CT-based age- and sex-adjusted reference values for TMT, TMA and radiodensity determined from 500 subjects. The reference values could be applied in future research – the current practice of defining loss of muscle mass using thresholds generated from a single dataset comprising only subjects with the condition in question[12–17] is suboptimal, as it leads to separate reference values for each neurological and neurosurgical diseases. Furthermore, comparing temporal muscle measurements between studies has been complicated due to varying measurement protocols[23]. CT-based reference values are needed as CT is the most common imaging modality in acute neurological conditions.

In agreement with existing literature, TMT, TMA and radiodensity increased from birth until 30–40 years of age and started to decrease thereafter, and males had higher TMT, TMA and radiodensity than females (Figs. 3 and 4)[13,14,17,21,23,33]. The shape of the age-dependent distribution of our reference values for TMT, TMA and temporal muscle radiodensity resemble those published for TMT by Katsuki et al. and Steindl et al. using MRI scans of healthy volunteers[10,23]. The absolute TMT values were lower in our study likely due to the lower soft-tissue resolution of CT compared to MRI, and that the windowing in our study reduces the visibility of adipose tissue. No previous study has reported normative radiodensity values for the temporal muscle, which may be useful in the assessment of muscle quality due to vulnerability-related changes such as myosteatosis[34]. Intrestingly, high BMI correlated only very-weakly-to-weakly positively with higher TMT and TMA in our study, but there was no correlation between BMI and radiodensity. Previous studies suggest slightly positive[23,35,36] to low or no correlation[19] between BMI and TMT. In the current study, the dispersion of TMT and TMA was highest between the BMIs of 20–30 kg/m^2 (Fig. 5) suggesting even weaker correlation within this subgroup that includes most of the general population. Furthermore, BMI data was available for 156/400 (39.0%) subjects aged ≥ 20 years in the current study. As such, conclusions regarding BMI and temporal muscle mass require further research to assess the modifying effect of BMI and other anthropometric variables on muscle mass and outcomes. Indeed, sarcopenic obesity, i.e., low muscle mass in obese patients may be a particularly strong predictor of poor outcomes[37].

Defining normalcy is critical in the clinical translation of temporal muscle measurements – determining appropriate cut-offs for each clinical outcome of interest requires careful consideration. Clinically relevant reduction in TMA, TMT and radiodensity likely depends on the outcome of interest, i.e. identifying subjects who could benefit from therapies directed at increasing muscle mass vs. determining predictors of clinical outcomes such as mortality and ability to recover from insults or interventions, or quality of life. To this end, we were the first to report the predicted lower boundaries of the 5th percentile and the five lowest deciles of TMT, TMA and temporal muscle radiodensity using quantile regression modelling (Fig. 6). The functions defining these limits (Table S3) can be used to test the significance of different magnitudes of temporal muscle mass changes on different outcomes in various conditions. Furthermore, the EWGSOP criteria suggest using 2.0SDs below the mean of healthy young adults to diagnose sarcopenia, and −2.5SD for a more conservative diagnosis[26,32].

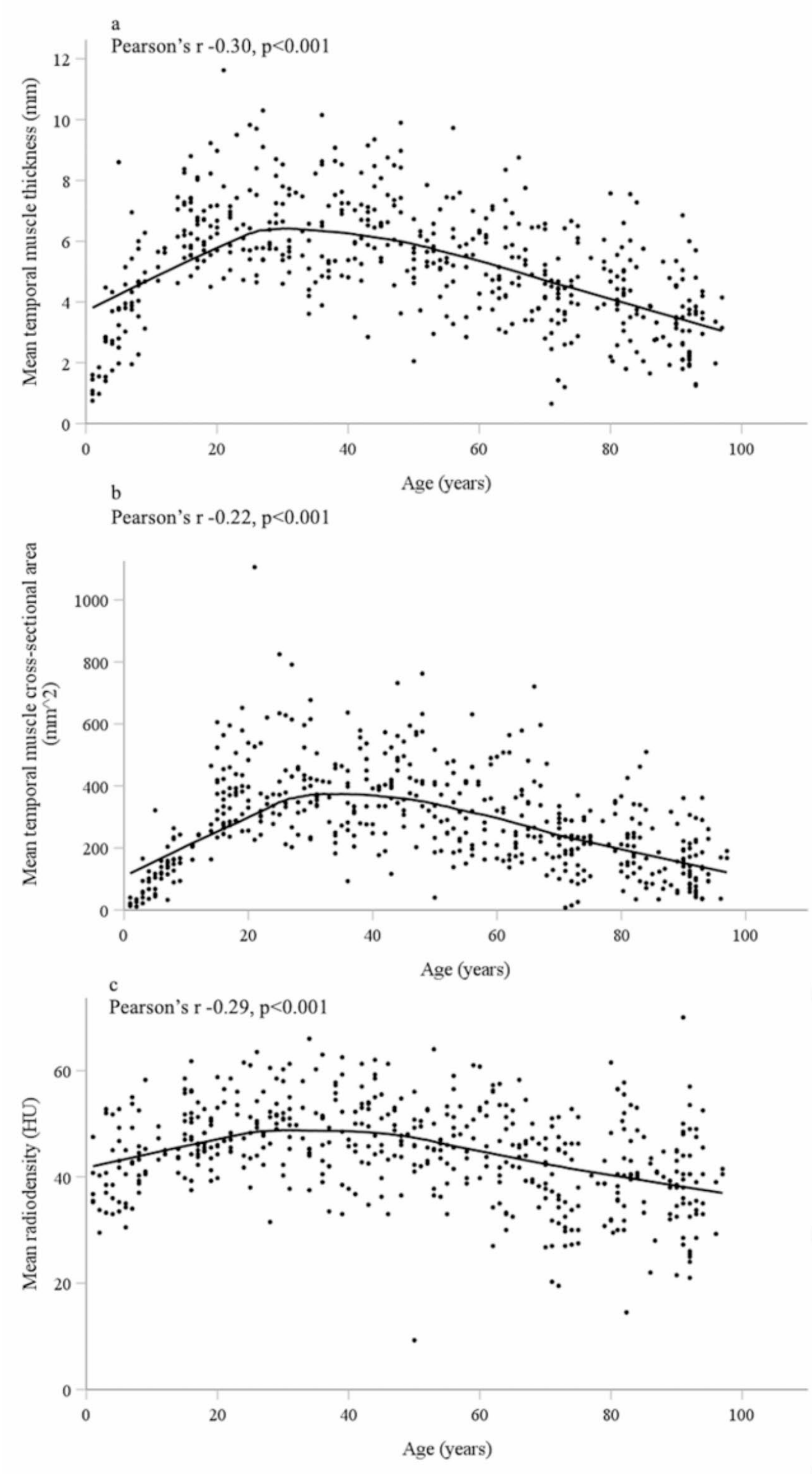

Fig. 4. Age-related distribution of mean temporal muscle thickness (**a**), cross-sectional area (**b**) and radiodensity (**c**) among 500 patients. A locally weighted scatterplot smoothing curve (continuous line) is shown.

The – 2.0SD TMT cut-off values defined according to the EWGSOP guidelines[26,32] were ≤ 4.09 mm for male and ≤ 3.44 mm for female subjects.

Our protocol for TMT and TMA measurements had almost perfect inter- and intra-rater reliability, corroborating previously reported results[11,23,33]. The HU measurements had substantial – almost perfect inter- and intra-rater reliability. Although the reliability of both TMT and TMA measurements was excellent, TMA

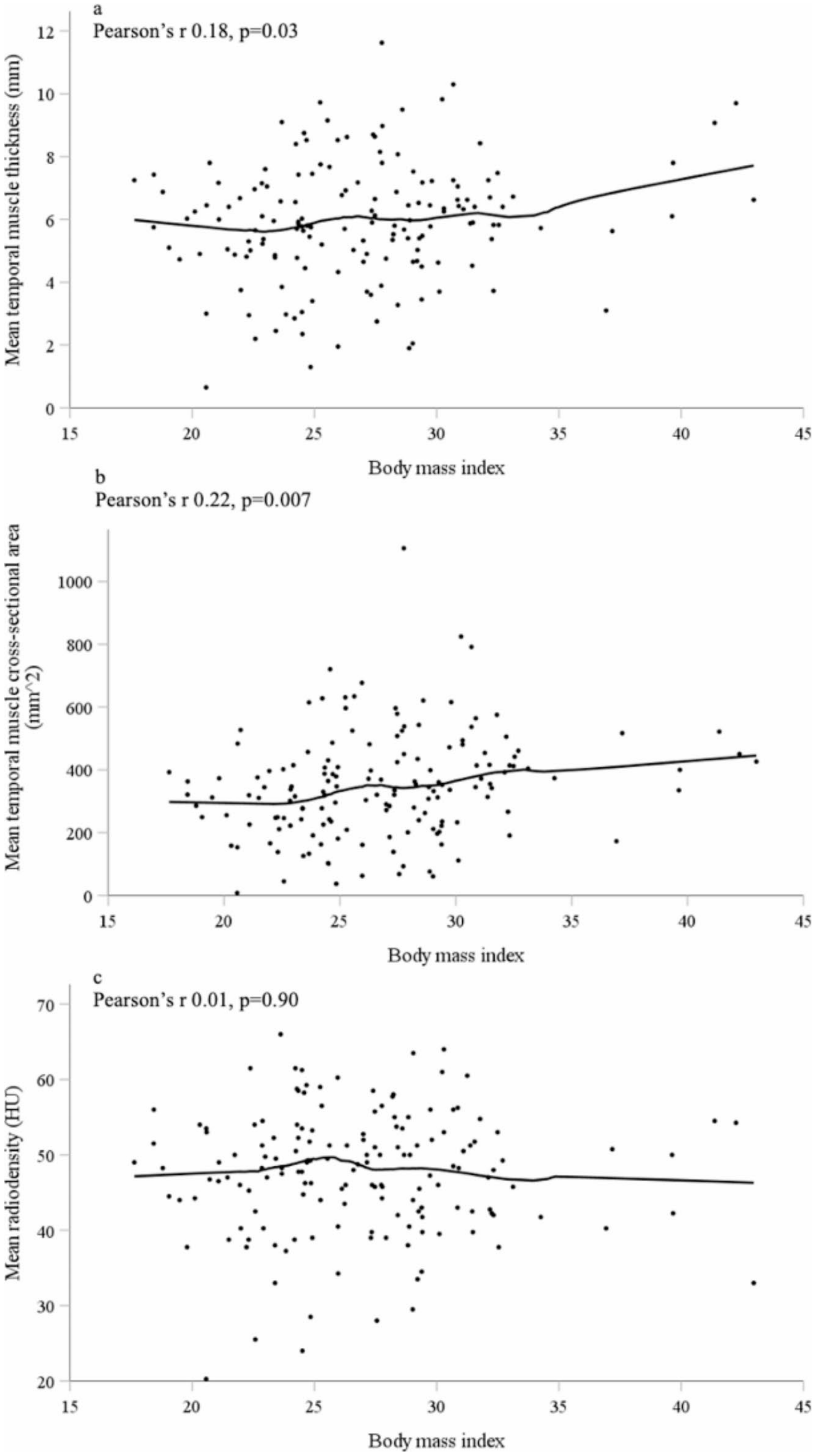

Fig. 5. BMI-related distribution of mean temporal muscle thickness (**a**), cross-sectional area (**b**) and radiodensity (**c**). A locally weighted scatterplot smoothing curve (continuous line) is shown.

was more reliable than TMT. We hypothesize that TMA comprising the whole semi-axial cross-sectional area is less susceptible to measurement inaccuracy than TMT which may be more influenced by minor differences in positioning the start and end points of the measurement (Fig. 1). Although TMT has been used more commonly than TMA in previous research[5,11–21,36], reduced TMA has also been shown to be associated with adverse outcomes in glioblastoma and subarachnoid hemorrhage[24,33], and it may be more compatible with machine learning approaches than TMT[24]. As such, TMA measurements may be preferable to TMT in future research.

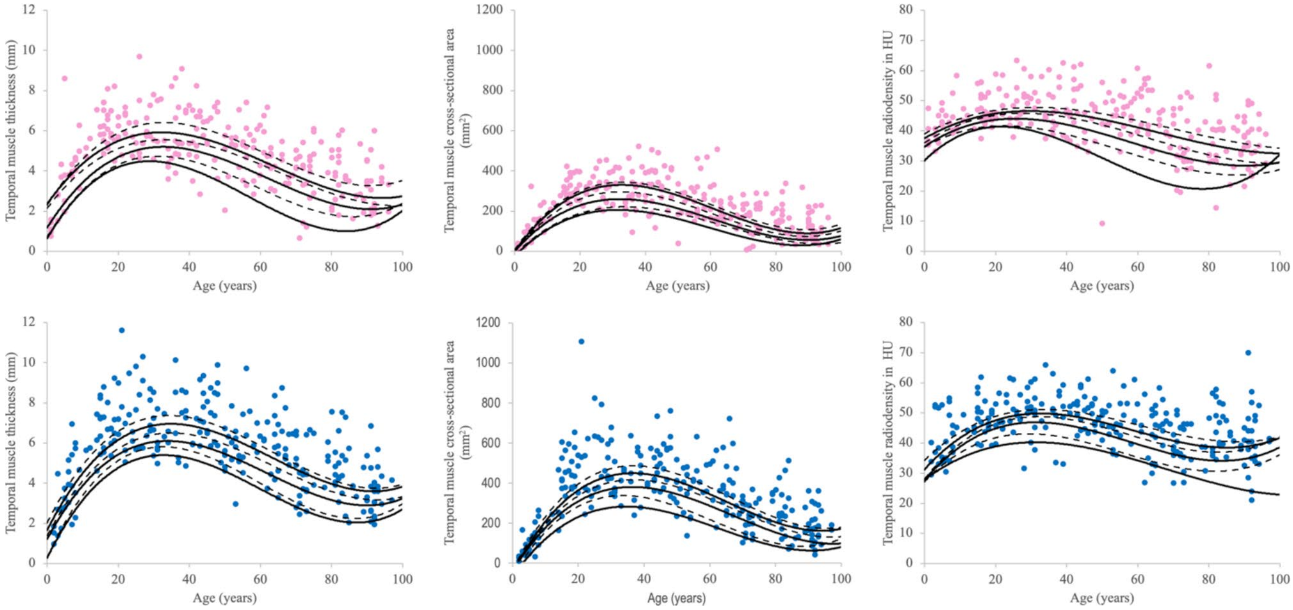

Fig. 6. Quantile regression curves showing the predicted lowest 5th, 20th, and 40th percentile boundaries (continuous lines from the lowest to the highest, respectively) and the lowest 10th, 30th, and 50th percentile boundaries (dotted lines from lowest to highest, respectively) of temporal muscle thickness (left), temporal muscle cross sectional area (middle) and temporal muscle radiodensity (right) among 250 female (upper row) and 250 male patients (bottom row).

Our study has several limitations. The subjects had sustained a concussion. Traumatic brain injuries are more common among patients with previous medical history, such as geriatric syndromes or substance abuse. Although we excluded subjects with significant comorbidities, CT imaging requires a clinical indication, and completely healthy volunteers could not be used in the current study. Patients with concussion were chosen as the reference population, as concussion is the mildest and, therefore, most stochastic type of traumatic brain injury occuring to a sample representative of the general public[27]. As such, we believe our reference values approximate a healthy cohort[25]. Second, the measurements were conducted on a semi-axial plane parallel to the anterior skull base (Fig. 1), in contrast to the anterior commissure – posterior commissure (ACPC) line commonly used in MRI-based measurements. The ACPC line is not recommended for CT imaging due to unreliability in defining the correct line position[38]. Another limitation of the study is that the cohort consisted of subjects with very mild injuries, and as a result, most lacked imaging of the lumbar region, which would have provided additional information of the muscle measurements at the level of the third lumbar vertebra, a more established proxy indicator of whole-body muscle mass. Lastly, as the current study was retrospective, the CT acquisition parameters, i.e., mAs, kVp, and slice thickness were not standardized. Especially kVp may affect the observed temporal muscle attenuation values of various tissues based on previous research[39,40], but this effect appears minimal for soft tissues as shown in the Supplementary Table S1. Such variation is inherent in clinical CT imaging, where the reference values are meant to be used. As the current study cohort only comprised individuals of Finnic descent, the applicability of our results to other ethnic groups, particularly of non-European ancestry, should be evaluated in future studies.

To conclude, we described a standardized CT-based TMT, TMA and temporal muscle radiodensity measurement protocol with almost perfect reliability. Using the protocol, we produced quantile regression models for the detection of reduced TMT, TMA and radiodensity at the lowest 5th, 10th, 20th, 30th, 40th and 50th percentiles as well as the EWGSOP criteria compliant cut-off values for reduced muscle mass to facilitate generalizable radiological sarcopenia research.

Data availability

The data that support the findings of this study are available on reasonable request from the corresponding author E.K.P. The CT images are not publicly available due to the European Union data protection requirements.

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Author contributions
E.K.P., S.T. and T.K.K. did the data collection and analysis. E.K.P. and O.A. wrote the main manuscript text. O.A., N.H., L.P. and J.N. provided suggestions to methods and participated in planning of the study. All authors reviewed the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Ethical approval
The study was conducted in compliance with the 1964 Declaration of Helsinki and its later amendments, and the study protocol was approved by the Institutional Review Board of the Oulu University Hospital.

Additional information
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