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ORIGINAL ARTICLE

Possible application of CT morphometry of the calcaneus and talus in forensic anthropological identification

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Abstract Computed tomography (CT) data provide information for volumetric and radiographic density analysis. The present study investigated the application of virtual CT volumetry of the tarsal bones to estimation of the sex, stature, and body weight using postmortem CT (PMCT) data of forensic autopsy cases. Three-dimensional (3D) images of the bilateral foot bones of intact Japanese subjects after adolescence (age ≥15 years, n=179, 100 males and 79 females) were reconstructed on an automated CT image analyzer system. Measured parameters were mass volume, mean CT value (HU), and total CT value of the talus and calcaneus. Mean CT values of these bones showed age-dependent decreases in elderly subjects over 60 years of age for both sexes, with significant sex-related differences especially in the elderly. The mass volumes and total CT values of the talus and calcaneus showed significant sex-related differences, and also moderate correlations with body height and weight for bilateral bones in all cases (r=0.58–0.78, p<0.0001); however, the correlations of these parameters of the female talus with body weight were insufficient (r=0.41–0.61, p<0.0001). These observations indicate the applicability of virtual CT morphometry of the talus and calcaneus using an automated analyzer to estimate the sex and stature in forensic identification; however, greater variations should be considered in body weight estimations of females.

Keywords Forensic anthropology · Sex estimation · Stature estimation · Talus · Calcaneus

Introduction

In identification of human remains and single bones, forensic anthropology is essential for estimation of the sex, age, and stature, combined with DNA analyses of sex and genetic polymorphisms [1–6]. In this process, radiology detects anatomical characteristics, specific pathologies of bones and foreign bodies including surgical materials, as well as sex-related differences and age-dependent changes, and provides measurements for stature estimation [7, 8]. Besides conventional radiology, computed tomography (CT) is useful for the documentation and reconstruction of skeletal data in autopsy routines. Several studies have demonstrated the successful application of virtual bone measurement using CT for stature and sex estimation [9–23]. Postmortem CT (PMCT) data provide information for volumetric and radiographic density analysis in addition to two-dimensional measurement [13, 23].

In forensic routine, identification of tarsal bones is needed when recovering dismembered remains or single bones. Previous studies have provided osteometric data of the tarsal bones for sex and stature estimation in several modern different ethnic populations using manual and radiographic procedures [24–35]; however, no Japanese data have been published. Furthermore, there are no published CT volumetric data, which may especially be useful for the identification of short bones, such as tarsal bones. It may also be possible to estimate body weight in addition to sex and body height [36, 37].

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From the abovementioned observations, the aim of the present study was to investigate the efficacy of virtual CT volumetry of the tarsal bones in estimating sex, stature, and body weight using an automated three-dimensional (3D) CT data system in forensic autopsy cases of Japanese subjects after adolescence.

Materials and methods

Postmortem CT data

Postmortem CT scans were routinely performed immediately before autopsy within the frame of routine case work using a scanner (ECLOS; Hitachi Medical Co., Tokyo; 120 kVp, 200 mAs, 1.25 pitch factor, 2.5×4 mm collimation, and 16×1.25 mm section thickness). Serial forensic autopsy cases of Japanese subjects of known sex, age, and stature after adolescence (age ≥15 years) without advanced decomposition, evident fracture, destruction, or advanced osteoarthrosis, in which complete foot bone CT data were available, during a 3.5-year period from January 2012 to June 2015, were used: a total of 192 subjects, including 108 males and 84 females, who were aged 15–95 years (mean 54.5, median 52.5). In addition, three cases of advanced decomposition or mummification (about 30–85 days postmortem) were used to examine postmortem interference. Demographic and anatomical data were collected from autopsy documents, including the sex, age, and stature. The cadaveric stature was measured in centimeters from the top of the head to the soles in a supine position on an autopsy table using a measuring tape [11, 12, 38].

CT data analysis

The 3D images of bilateral talus and calcaneus bones were virtually reconstructed on the automated CT image analyzing system Volume Analyzer SYNAPSE VINCENT version 3 (FUJIFILM Medical Co., Ltd., Tokyo, Japan), using the original analysis algorithm without operator intervention (Fig. 1) [13, 23]. The measured parameters were the mass volume, mean CT value (HU), and total CT value (mean HU×mass volume) of the bilateral talus and calcaneus. The mean CT value (HU) was automatically provided for the whole extracted bone. Manual procedures were not used in the present study.

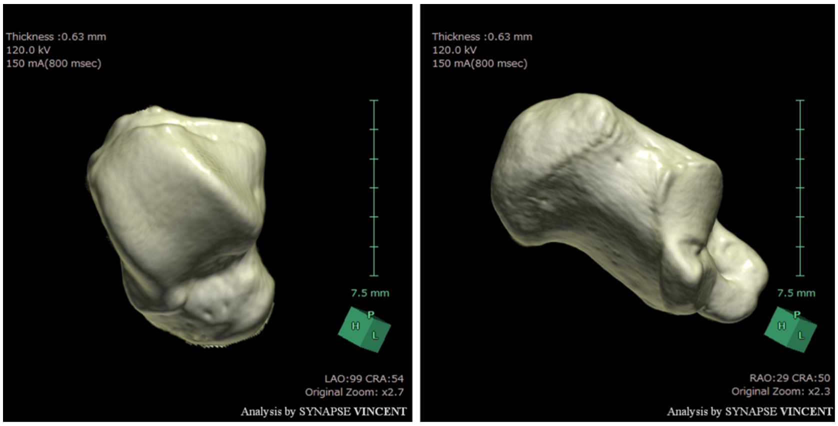
Statistical analysis

Analyses were performed using Microsoft Excel, Statview (version 5.0; SAS Institute Inc.) and SPSS 17.0 (Statistical Software Package, Inc., Chicago, IL). The Kruskal-Wallis and Mann-Whitney *U* tests were used for non-parametric multiple and two-group comparisons among the age of subjects, respectively. The comparisons of measured values between sexes were evaluated with unpaired *t* test analysis. The relationships between bone measurements and stature were determined by Pearson correlation analysis. The regression formulae were calculated by linear regression analysis for stature estimation using each parameter of individual bones. In these analyses, a *p* value <0.05 was considered significant. The Bland-Altman method was used to assess agreement between the measured stature and estimated values using the abovementioned bone parameters. For sex estimation, a receiver operating characteristic (ROC) analysis was performed to estimate the cut-off points for each parameter of individual bones to compare the efficacy. With the cut-off value, the accuracy of sex estimation was examined, dividing the number of cases identified by the total number of cases; cases above and below the cut-off values were estimated as males and females, respectively.

Results

Efficacy of automated bone reconstruction and mean CT values with regard to the age of subjects

The bilateral talus and calcaneus were successfully reconstructed using the automated 3D image reconstruction



(a) (b)

Fig. 1 Representative three-dimensional figures of reconstructed talus (**a**) and calcaneus (**b**) using the automated CT image analyzing system

Table 1 Descriptive statistics of subjects examined (n=179) and bone parameters

Parameter		Male (n=100)			Female (n=79)		
		Range	Average	Median	Range	Average	Median
Age (years)		15–95	54	52	18–93	54	54
Body height (cm)		150–183	166	166	133–169	155	154
Body weight (kg)		33.4–122	63	63	26.4–99.8	50	47
Talus	Mass volume (ml)	27.9–57.1	40.2	39.1	21.6–49.8	30.0	29.7
	Mean CT value (HU)	242.8–574.1	431.5	433.2	147.7–565.1	384.6	401.8
	Total CT value (/10^3)	9.4–26.2	17.3	17.4	4.6–23.4	11.6	11.8
Calcaneus	Mass volume (ml)	50.4–107.5	72.9	71.9	34.6–77.2	54.7	54.9
	Mean CT value (HU)	157.8–452.2	311.7	314.3	94.3–444.5	271.0	280.1
	Total CT value (/10^3)	11.4–33.8	22.7	22.0	4.9–29.6	14.9	15.6

Mean CT value (HU) indicates the mean of whole-bone CT attenuation automatically calculated and total CT value indicates mean CT value×mass volume

system except for several elderly subjects with advanced degenerative osteoarthrosis that obstructed the separation of individual bones (n=8, 4.1 %), for which manual trimming was needed. In addition, minor fractures of the talus and/or calcaneus were detected in extracted foot bones of several young subjects (n=5, 2.6 %). These cases were excluded from further investigation. Once foot bone extraction was successfully performed using the automated 3D image reconstruction, reproducibility of bone data was 100.0 %, independent of the operator. These data are shown in Table 1 (age ≥15 years, n=179, 100 males and 79 females).

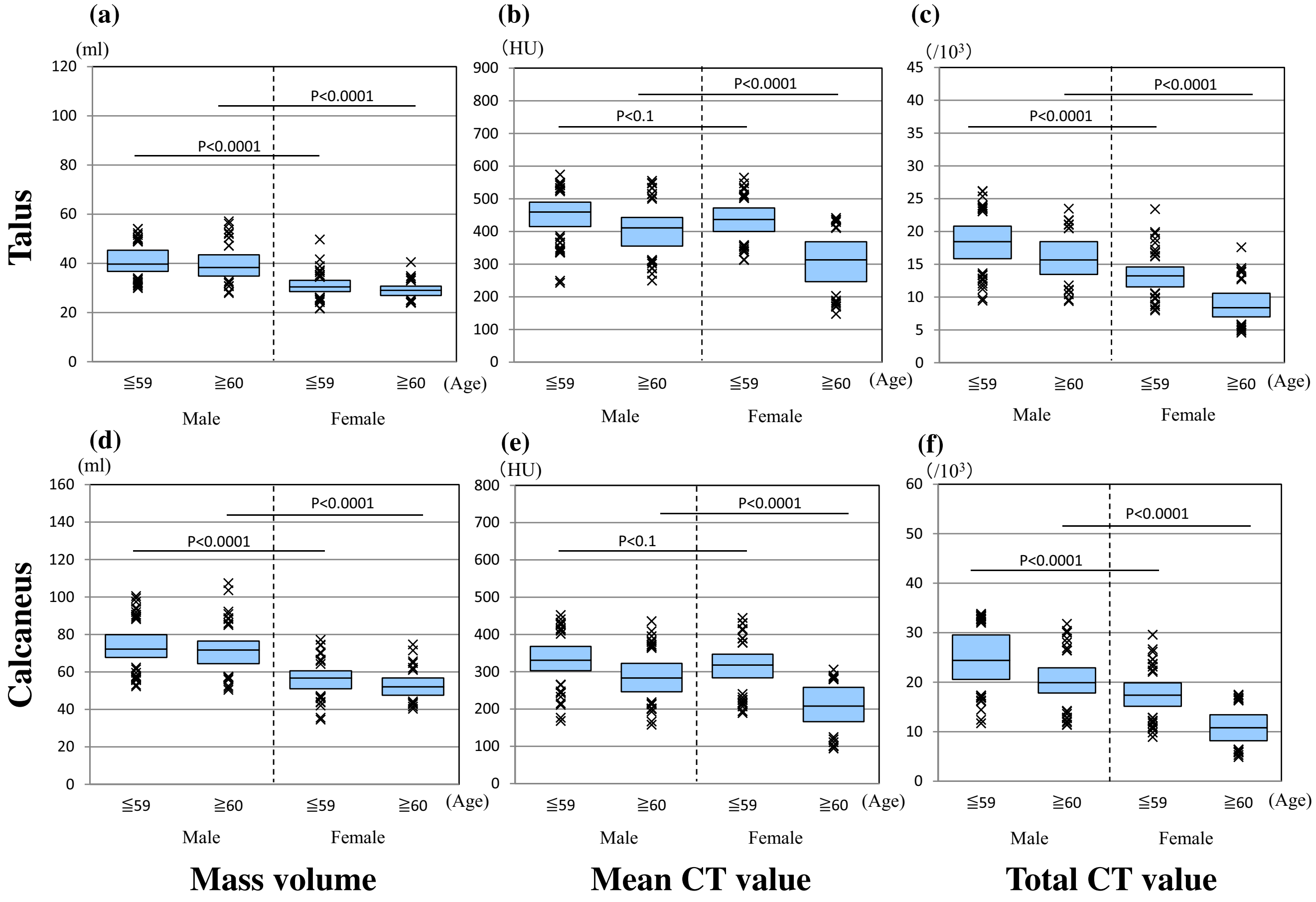


Fig. 2 Age dependency of bone mass volumes, and mean and total CT values of the talus (**a**–**c**) and calcaneus (**d**–**f**)

Table 2 Cut-off values with sensitivities and specificities, accuracies, and correctly identified rates using individual bone parameters for sex estimation

Case	Specimen	Parameter	Cut-off value	Sensitivity (%)	Specificity (%)	Accuracy (%)	Correctly identified rate (%)	
							Male	Female
All cases	Talus	Mass volume (ml)	34.00	87.5	91.1	88.8	87.0	91.1
		Mean CT value (HU)	415.24	64.0	58.9	61.5	63.5	58.9
		Total CT value (/10^3)	14.93	76.0	88.6	81.3	75.5	88.6
	Calcaneus	Mass volume (ml)	63.83	84.5	91.8	87.4	84.0	91.8
		Mean CT value (HU)	301.72	60.0	63.9	61.5	59.5	93.9
		Total CT value (/10^3)	19.06	74.5	82.3	77.7	74.0	82.3
	Talus+calcaneus	Mass volume (ml)	96.50	86.0	89.2	87.1	85.5	89.2
		Mean CT value (HU)	705.38	65.0	58.2	61.7	64.5	58.2
		Total CT value (/10^3)	33.46	77.0	81.0	78.5	76.5	81.0
≥60 years of age	Talus	Mass volume (ml)	33.13	89.3	92.2	89.9	88.1	92.2
		Mean CT value (HU)	352.17	78.6	68.8	73.6	77.4	68.8
		Total CT value (/10^3)	12.78	85.7	90.6	87.2	84.5	90.6
	Calcaneus	Mass volume (ml)	59.17	85.7	85.9	85.1	84.5	85.9
		Mean CT value (HU)	259.14	69.0	75.0	70.9	67.9	75.0
		Total CT value (/10^3)	14.73	89.3	84.4	86.5	88.1	84.4
	Talus+calcaneus	Mass volume (ml)	91.76	90.5	87.5	88.5	89.3	87.5
		Mean CT value (HU)	646.79	67.9	81.3	73.0	66.7	66.7 81.3
		Total CT value (/10^3)	26.00	90.5	84.4	87.2	89.3	84.4

Bone volumetry and total CT value

Age dependence

There was no age dependence of the virtual bone mass volumes of the talus and calcaneus. Mean CT values of the talus and calcaneus showed significant age-dependent decreases in both sexes (for the talus, $y=-0.1218x+103.8$, $r=0.49$, $p<0.0001$; for the calcaneus, $y=-0.1459x+97.027$, $r=0.52$, $p<0.0001$) and were significantly lower in elderly male and female subjects over 60 years of age ($p<0.05$) than in younger subjects under 60 years of age when stratified according to decades of age; such tendencies were greater in females, showing a distinct age-dependent difference, and also that in the total CT value (Fig. 2). The elderly female subjects had lower mean and total CT values than the other groups (males and younger females); the respective cut-off values were estimated to be 361.90 HU (sensitivity 0.59 and specificity 0.94) and 10.2×10^3 (sensitivity 0.47 and specificity 0.94).

Table 3 Cut-off values with sensitivities and specificities, accuracies, and correctly identified rates using individual bone parameters for sex estimation in random resampling and reanalysis ($n=100$)

Specimen	Parameter	Cut-off value	Sensitivity (%)	Specificity (%)	Accuracy (%)	Correctly identified rate (%)	
						Male	Female
Talus	Mass volume (ml)	33.13	90.0	100.0	88.8	86.5	78.6
	Mean CT value (HU)	391.09	78.0	100.0	71.6	74.3	58.6
	Total CT value (/10^3)	14.93	72.0	100.0	85.8	82.4	77.1
Calcaneus	Mass volume (ml)	62.72	82.0	100.0	83.6	77.0	78.6
	Mean CT value (HU)	285.71	69.0	100.0	70.9	73.0	58.6
	Total CT value (/10^3)	19.09	70.0	100.0	86.6	78.4	82.9
Talus+calcaneus	Mass volume (ml)	95.92	85.0	100.0	87.3	87.8	74.3
	Mean CT value (HU)	361.90	59.0	100.0	72.4	77.0	57.1
	Total CT value (/10^3)	32.12	78.0	100.0	85.8	87.8	71.4

Table 4 Correlations of body height with bone mass volumes, mean CT values, and total CT values of the talus and calcaneus

Height		Talus				Calcaneus			
		Correlation equation	r	p	Measurement error (range)	Correlation equation	r	p	Measurement error (range)
All cases: bilateral	Mass volume (ml)	$y=0.9167x+128.41$	0.71	<0.0001	−0.8–0.8 (1.6)	$y=0.5569x+124.93$	0.78	<0.0001	−0.7–0.7 (1.4)
	Mean CT value (HU)	$y=0.0586x+137.03$	0.51	<0.0001	−0.8–1.0 (1.8)	$y=0.0640x+142.30$	0.49	<0.0001	−0.8–1.0 (1.8)
	Total CT value $(/10^3)$	$y=1.6038x+137.38$	0.78	<0.0001	−0.7–0.7 (1.4)	$y=1.1049x+139.77$	0.78	<0.0001	−0.7–0.7 (1.4)
Left	Mass volume (ml)	$y=0.9311x+128.11$	0.71	<0.0001	−0.8–0.7 (1.5)	$y=0.5499x+125.47$	0.78	<0.0001	−0.7–0.6 (1.3)
	Mean CT value (HU)	$y=0.0595x+136.62$	0.52	<0.0001	−0.8–1.0 (1.8)	$y=0.0650x+142.01$	0.50	<0.0001	−0.8–1.0 (1.8)
	Total CT value $(/10^3)$	$y=1.6242x+137.23$	0.78	<0.0001	−0.7–0.8 (1.5)	$y=1.0890x+140.12$	0.78	<0.0001	−0.7–0.7 (1.4)
Right	Mass volume (ml)	$y=0.9052x+128.61$	0.71	<0.0001	−0.8–0.8 (1.6)	$y=0.5643x+124.37$	0.79	<0.0001	−0.7–0.7 (1.4)
	Mean CT value (HU)	$y=0.0576x+137.42$	0.51	<0.0001	−0.8–0.9 (1.7)	$y=0.0629x+142.60$	0.48	<0.0001	−0.8–1.0 (1.8)
	Total CT value $(/10^3)$	$y=1.5856x+137.50$	0.78	<0.0001	−0.7–0.7 (1.4)	$y=1.1218x+139.40$	0.78	<0.0001	−0.7–0.7 (1.4)
Male: bilateral	Mass volume (ml)	$y=0.6049x+141.83$	0.51	<0.0001	−0.9–0.9 (1.8)	$y=0.4142x+135.88$	0.62	<0.0001	−0.9–0.8 (1.7)
	Mean CT value (HU)	$y=0.0354x+150.84$	0.34	<0.0001	−1.0–0.9 (1.9)	$y=0.0377x+154.36$	0.32	<0.0001	−1.0–0.9 (1.9)
	Total CT value $(/10^3)$	$y=1.2509x+144.48$	0.63	<0.0001	−0.8–0.8 (1.6)	$y=0.8193x+147.47$	0.64	<0.0001	−0.8–0.8 (1.6)
Male: left	Mass volume (ml)	$y=0.6128x+141.70$	0.51	<0.0001	−0.9–0.8 (1.7)	$y=0.4018x+136.78$	0.60	<0.0001	−0.9–0.8 (1.7)
	Mean CT value (HU)	$y=0.0362x+150.47$	0.35	<0.0001	−1.0–0.9 (1.9)	$y=0.0377x+154.32$	0.33	<0.0001	−1.0–0.9 (1.9)
	Total CT value $(/10^3)$	$y=1.2470x+144.70$	0.63	<0.0001	−0.8–0.8 (1.6)	$y=0.7862x+148.16$	0.62	<0.0001	−0.8–0.7 (1.5)
Male: right	Mass volume (ml)	$y=0.6003x+141.84$	0.50	<0.0001	−0.9–0.9 (1.8)	$y=0.4266x+134.99$	0.64	<0.0001	−0.9–0.8 (1.7)
	Mean CT value (HU)	$y=0.0345x+151.19$	0.33	<0.0001	−1.0–0.8 (1.8)	$y=0.0377x+154.39$	0.32	<0.0001	−1.0–0.9 (1.9)
	Total CT value $(/10^3)$	$y=1.5856x+137.50$	0.63	<0.0001	−0.8–0.8 (1.6)	$y=0.8541x+146.75$	0.66	<0.0001	−0.8–0.8 (1.6)
Female: bilateral	Mass volume (ml)	$y=1.0456x+123.39$	0.51	<0.0001	−1.5–1.5 (3.0)	$y=0.6883x+117.05$	0.67	<0.0001	−1.2–1.2 (2.4)
	Mean CT value (HU)	$y=0.0466x+136.81$	0.54	<0.0001	−1.4–1.4 (2.8)	$y=0.0504x+141.08$	0.51	<0.0001	−1.6–1.3 (2.9)
	Total CT value $(/10^3)$	$y=1.4577x+137.81$	0.65	<0.0001	−1.3–1.3 (2.6)	$y=1.0529x+139.01$	0.69	<0.0001	−1.2–1.2 (2.4)
Female: left	Mass volume (ml)	$y=1.1089x+121.65$	0.50	<0.0001	−1.5–1.4 (2.9)	$y=0.7053x+116.36$	0.67	<0.0001	−1.2–1.2 (2.4)
	Mean CT value (HU)	$y=0.0478x+136.35$	0.56	<0.0001	−1.4–1.4 (2.8)	$y=0.0513x+140.93$	0.52	<0.0001	−1.6–1.3 (2.9)
	Total CT value $(/10^3)$	$y=1.5195x+137.17$	0.65	<0.0001	−1.3–1.3 (2.6)	$y=1.0870x+138.72$	0.70	<0.0001	−1.2–1.2 (2.4)
Female: right	Mass volume (ml)	$y=1.0004x+124.59$	0.52	<0.0001	−1.5–1.5 (3.0)	$y=0.6750x+117.55$	0.66	<0.0001	−1.2–1.3 (2.5)
	Mean CT value (HU)	$y=0.0454x+137.27$	0.53	<0.0001	−1.4–1.3 (2.7)	$y=0.0495x+141.23$	0.50	<0.0001	−1.6–1.3 (2.9)
	Total CT value $(/10^3)$	$y=1.4030x+138.37$	0.64	<0.0001	−1.3–1.3 (2.6)	$y=1.0236x+139.25$	0.68	<0.0001	−1.2–1.2 (2.4)

The measurement errors (range) for body height estimation were calculated from 95 % confidence interval values

Sex-related difference

Mass volumes of the talus and calcaneus showed significant sex-related differences, independent of age ($p<0.0001$). There were significant sex-related differences in mean CT values of the talus and calcaneus in subjects over 60 years of age ($p<0.0001$), and the total CT values of these bones showed significant sex-related differences, independent of the age ($p<0.0001$). Cut-off values estimated for individual parameters to identify male and female bones are shown, together with their accuracy, in Table 2. The accuracy in sex estimation was higher for mass volumes of the talus (88.8 %) and calcaneus (87.4 %) than other parameters (61.5–81.3 %). When talus and calcaneus data were combined, the accuracy was similar (61.7–87.1 %) (Table 2). In addition, sex estimation in subjects over 60 years of age showed higher accuracies of 89.9 % for the mass volume of the talus and 86.5 % for total CT values of the calcaneus, and 70.9–85.1 % for other parameters. Correctly identified rates using the mass volumes and total CT values of both bones were slightly higher for females (89.2 and 81.0 %, respectively) than for males (85.5 and 76.5 %, respectively) in all cases, showing a high rate for the mass volume of each bone (84.0–91.8 %) and various rates for the other parameters (58.9–93.9 %), but were similar for these parameters in elderly subjects over 60 years of age (84.5–88.1 % for males and 84.4–92.2 % for females), except for the mean CT values of the female talus and male calcaneus (68.8 and 67.9 %, respectively). For these findings, random resampling, and reanalysis, reducing sample numbers (total $n=100$; males $n=70$, females $n=30$) did not show a significant difference in cut-off values and accuracies (accuracy 70.9–88.8 %) (Table 3).

Relationship with body height

Mass volumes and total CT values of the talus and calcaneus showed moderate correlations with body height in all cases ($r=0.71$–0.78, $p<0.0001$; Table 4); however, the correlations of mass volumes of both bones with body height were lower in separated male and female groups ($r=0.51$–0.67). The regression equations for body height estimation using bilateral data were 128.41+(0.9167×talus mass volume); 124.93+(0.5569×calcaneus mass volume); 137.38+(1.6038×total CT values/10^3 of the talus); and 139.77+(1.1049×total CT values/10^3 of the calcaneus). When talus and calcaneus data were combined, the correlation was similar ($r=0.51$–0.79). The measurement error ranges for body height estimation, as calculated from 95 % confidence evaluated by Bland-Altman method, did not show an evident difference between the talus and calcaneus in all cases (mixed-sex groups) but were slightly greater in females (2.6–3.0) than in males (1.6–1.9) (Table 4). For these findings, random resampling, and reanalysis, reducing sample numbers (total $n=100$; males $n=70$, females $n=30$) did not show a significant difference in the correlations between the body height and individual parameters ($r=0.47$–0.79) (Table 5).

Relationship with body weight

Mass volumes and total CT values of the talus and calcaneus showed moderate correlations with body weight in all cases ($r=0.58$–0.67); however, the correlations of mass volumes were lower when males and females were examined separately ($r=0.41$–0.49) (Table 6).

The regression equations for body weight estimation using bilateral data were 11.414+(1.2942×talus mass volume); 10.743+(0.7210×calcaneus mass volume); 22.482+(2.3723×total CT values/10^3 of the talus); and 25.706+(1.6504×total CT values/10^3 of the calcaneus). When talus and calcaneus data were combined, the correlation was similar ($r=0.51$–0.79) (Table 7). The measurement error ranges for body weight estimation, as calculated from 95 % confidence evaluated by the Bland-Altman method, did not show an evident difference between the talus and calcaneus in all cases (mixed-sex groups) but were slightly greater in females (5.3–6.4) than in males (3.7–4.4) (Table 6). For these findings, random resampling, and reanalysis, reducing sample numbers (total $n=100$; males $n=70$, females $n=30$) did not show significant

Table 5 Correlations of body height and weight with bilateral bone mass volumes, mean CT values, and total CT values of the combined talus and calcaneus in random resampling and reanalysis ($n=100$)

		Talus			Calcaneus		
		Correlation equation	r	p	Correlation equation	r	p
Body height	Mass volume (ml)	$y=0.9894x+125.4$	0.71	<0.0001	$y=0.6334x+119.69$	0.79	<0.0001
	Mean CT value (HU)	$y=0.0563x+136.65$	0.55	<0.0001	$y=0.0658x+140.54$	0.56	<0.0001
	Total CT value (/10^3)	$y=1.5897x+137.11$	0.78	<0.0001	$y=1.0957x+139.45$	0.79	<0.0001
Body weight	Mass volume (ml)	$y=1.348x+8.703$	0.60	<0.0001	$y=0.7414x+8.5299$	0.57	<0.0001
	Mean CT value (HU)	$y=0.072x+25.934$	0.43	<0.0001	$y=0.0902x+29.167$	0.47	<0.0001
	Total CT value (/10^3)	$y=2.1244x+25.225$	0.64	<0.0001	$y=1.425x+29.075$	0.64	<0.0001

Table 6 Correlations of body weight with bone mass volumes, mean CT values, and total CT values of the talus and calcaneus

Weight		Talus				Calcaneus			
		Correlation equation	*r*	*p*	Measurement error (range)	Correlation equation	*r*	*p*	Measurement error (range)
All cases: bilateral	Mass volume (ml)	$y=1.2942x+11.414$	0.58	<0.0001	−1.7–1.7 (3.4)	$y=0.721x+10.743$	0.59	<0.0001	−1.7–1.7 (3.4)
	Mean CT value (HU)	$y=0.0904x+20.411$	0.46	<0.0001	−1.9–1.8 (3.7)	$y=0.109x+25.524$	0.49	<0.0001	−1.9–1.8 (3.7)
	Total CT value (/10^3)	$y=2.3723x+22.482$	0.67	<0.0001	−1.6–1.6 (3.2)	$y=1.6504x+25.706$	0.68	<0.0001	−1.6–1.6 (3.2)
Left	Mass volume (ml)	$y=1.3036x+11.379$	0.58	<0.0001	−1.7–1.6 (3.3)	$y=0.7141x+11.293$	0.59	<0.0001	−1.7–1.7 (3.4)
	Mean CT value (HU)	$y=0.0915x+19.958$	0.47	<0.0001	−1.9–1.8 (3.7)	$y=0.1094x+25.437$	0.49	<0.0001	−1.9–1.8 (3.7)
	Total CT value (/10^3)	$y=2.3947x+22.375$	0.67	<0.0001	−1.6–1.6 (3.2)	$y=1.6263x+26.242$	0.70	<0.0001	−1.6–1.5 (3.1)
Right	Mass volume (ml)	$y=1.2881x+11.336$	0.59	<0.0001	−1.7–1.7 (3.4)	$y=0.7282x+10.166$	0.59	<0.0001	−1.7–1.7 (3.4)
	Mean CT value (HU)	$y=0.0893x+20.858$	0.46	<0.0001	−1.9–1.8 (3.7)	$y=0.1086x+25.615$	0.48	<0.0001	−1.9–1.8 (3.7)
	Total CT value (/10^3)	$y=2.3529x+22.551$	0.67	<0.0001	−1.6–1.6 (3.2)	$y=1.6761x+25.141$	0.68	<0.0001	−1.6–1.6 (3.2)
Male: bilateral	Mass volume (ml)	$y=1.2975x+11.137$	0.49	<0.0001	−2.1–2.1 (4.2)	$y=0.7942x+5.2507$	0.53	<0.0001	−2.0–2.0 (4.0)
	Mean CT value (HU)	$y=0.0723x+31.983$	0.31	<0.0001	−2.2–2.2 (4.4)	$y=0.0901x+35.087$	0.35	<0.0001	−3.2–1.3 (4.5)
	Total CT value (/10^3)	$y=2.5501x+19.117$	0.57	<0.0001	−1.9–1.9 (3.8)	$y=1.701x+24.513$	0.59	<0.0001	−1.9–1.9 (3.8)
Male: left	Mass volume (ml)	$y=1.2802x+12.209$	0.48	<0.0001	−2.1–2.0 (4.1)	$y=0.7867x+5.7962$	0.52	<0.0001	−2.0–2.0 (4.0)
	Mean CT value (HU)	$y=0.0789x+29.13$	0.34	<0.0001	−2.2–2.2 (4.4)	$y=0.0941x+33.76$	0.36	<0.0001	−3.2–1.3 (4.5)
	Total CT value (/10^3)	$y=2.5798x+18.922$	0.58	<0.0001	−1.9–1.9 (3.8)	$y=1.6951x+24.515$	0.59	<0.0001	−1.9–1.9 (3.8)
Male: right	Mass volume (ml)	$y=1.3211x+9.7952$	0.50	<0.0001	−2.1–2.1 (4.2)	$y=0.8017x+4.7093$	0.54	<0.0001	−2.0–2.0 (4.0)
	Mean CT value (HU)	$y=0.0658x+34.775$	0.28	<0.0001	−2.2–2.2 (4.4)	$y=0.086x+36.44$	0.33	<0.0001	−3.2–1.3 (4.5)
	Total CT value (/10^3)	$y=2.526x+19.22$	0.57	<0.0001	−1.9–1.8 (3.7)	$y=1.7079x+24.49$	0.59	<0.0001	−1.9–1.9 (3.8)
Female: bilateral	Mass volume (ml)	$y=1.4222x+7.7648$	0.41	<0.0001	−3.2–3.2 (6.4)	$y=0.5982x+17.652$	0.34	<0.0001	−3.3–3.2 (6.5)
	Mean CT value (HU)	$y=0.075x+21.563$	0.52	<0.0001	−2.7–3.0 (5.7)	$y=0.0912x+25.677$	0.55	<0.0001	−2.8–3.0 (5.8)
	Total CT value (/10^3)	$y=2.3123x+23.551$	0.61	<0.0001	−2.7–2.7 (5.4)	$y=1.5911x+26.647$	0.62	<0.0001	−2.9–2.7 (5.6)
Female: left	Mass volume (ml)	$y=1.4985x+5.6942$	0.40	<0.0001	−3.2–3.2 (6.4)	$y=0.6166x+16.858$	0.35	<0.0001	−3.3–3.2 (6.5)
	Mean CT value (HU)	$y=0.0722x+22.601$	0.50	<0.0001	−2.7–3.0 (5.7)	$y=0.0883x+26.639$	0.53	<0.0001	−2.8–3.0 (5.8)
	Total CT value (/10^3)	$y=2.3034x+23.779$	0.59	<0.0001	−2.7–2.6 (5.3)	$y=1.5838x+27.066$	0.61	<0.0001	−2.9–2.6 (5.5)
Female: right	Mass volume (ml)	$y=1.3682x+9.1835$	0.42	<0.0001	−3.2–3.2 (6.4)	$y=0.5832x+18.274$	0.34	<0.0001	−3.3–3.2 (6.5)
	Mean CT value (HU)	$y=0.0777x+20.529$	0.54	<0.0001	−2.7–3.0 (5.7)	$y=0.0943x+24.666$	0.56	<0.0001	−2.8–3.0 (5.8)
	Total CT value (/10^3)	$y=2.3215x+23.32$	0.63	<0.0001	−2.7–2.7 (5.4)	$y=1.6028x+26.159$	0.63	<0.0001	−2.9–2.7 (5.6)

The measurement errors (range) for body weight estimation were calculated from 95 % confidence interval values

Table 7 Correlations of body height and weight with bone mass volumes, mean CT values, and total CT values in combined analysis of the talus and calcaneus

		Bilateral talus+calcaneus					
		Body height			Body weight		
		Correlation equation	r	p	Correlation equation	r	p
All cases	Mass volume (ml)	$y=0.3623x+124.66$	0.77	<0.0001	$y=0.4831x+8.9641$	0.60	<0.0001
	Mean CT value (HU)	$y=0.0317x+138.78$	0.51	<0.0001	$y=0.0512x+21.489$	0.51	<0.0001
	Total CT value (/10^3)	$y=0.6673x+138.35$	0.79	<0.0001	$y=0.9929x+23.717$	0.79	<0.0001
>60 years of age	Mass volume (ml)	$y=0.3631x+121.35$	0.75	<0.0001	$y=0.4604x+7.3652$	0.62	<0.0001
	Mean CT value (HU)	$y=0.0311x+137.5$	0.53	<0.0001	$y=0.0435x+25.416$	0.53	<0.0001
	Total CT value (/10^3)	$y=0.6511x+137.94$	0.74	<0.0001	$y=0.9035x+26.181$	0.74	<0.0001

difference in the correlations between the body weight and individual parameters (r=0.43–0.64) (Table 5).

Postmortem interference

In a male case of mummification (case 1; estimated postmortem period, about 85 days), and a male and female case of advanced decomposition (cases 2 and 3; estimated postmortem period, about 40 and 30 days, respectively), the individual sex was accurately identified and estimated errors for stature estimation ranged from 0.57 to 3.88 % (Table 8).

Discussion

Reconstruction of the talus and calcaneus using the automated CT data analysis system was obstructed in elderly subjects with advanced osteoarthrosis but was otherwise successfully performed in the present study, as in previous studies on the lower limb long bones [13, 39]; thus, the accuracy and reproducibility of the measurements were established. All parameters of individual bone, including the volume and CT density, correlated with body stature, showing sexual dimorphism, as previously reported for the lower limb long bones [40]. These findings are consistent with the general concept of bone development depending on hereditary factors and sex with ethnic and regional variations, modified by the influence of acquired factors [41], as well as the sex-related difference of cortical bone development [42], and degenerative changes in the elderly [43]. These bone statuses can be reflected in the mass volume and total CT attenuation value as indicators of the 3D size and robusticity in remains without postmortem decalcification.

For sex estimation, the present study demonstrated the usefulness of volumetry and CT density of the talus and calcaneus; the indicators involving these variables, including the mass volume and total CT attenuation value, were effective for sex identification, especially in elderly subjects. The mean CT attenuation values of each bone also showed sex-related differences. The accuracy in sex estimation using mass volumes of the talus (88.8 %) and the calcaneus (87.4 %) as well as other parameters (61.5–81.3 %) was similar to those described in previous reports using manual and radiographic 2D measurements (about 80–90 %) [19–23, 26–28, 30, 31]. However, the correctly identified rates of these bone parameters in sex estimation were similar for males (59.5–87.0 %) and females (58.2–93.9 %) without bilateral asymmetry, although previous studies of lower limb long bones showed a higher accuracy for females [44–48], which suggested a greater contribution of congenital factors to bone development during adolescence and aging-related degenerative changes in females, involving bone atrophy with a decreasing bone CT density after menopause [43, 49]. The influence of acquired factors including physical activity and age-dependent changes may be greater for tarsal bones, which support the whole body in the erect position. However, statistical bias resulting from the use of limited Japanese population data of forensic autopsy cases should be considered in the present study.

In stature estimation from separate single bones, the most common method is linear regression [50]. Since individual height is influenced by ethnicity and changes over time, it is recommended to use the latest regression formulae derived from the relevant population [51]. In the present study, CT morphometric measurements of the bilateral talus and calcaneus bones showed similar correlations with stature, and the total HU value was highly correlated with stature in both sexes. In stature estimation using individual bone parameters, the accuracies as estimated from 95 % confidence were slightly higher for mixed-sex groups (error range <1.9 cm) than for separated male and female sex groups (error range <3.1 cm), as described in previous studies of foot measurements [1,

Table 8 Sex and stature estimations in cases of mummification (case 1) and advanced decomposition (cases 2 and 3)

Case number	Age (years)	Sex	Measured height	Measured weight	Estimated postmortem time (days)	Talus						Calcaneus					
						Left			Right			Left			Right		
						Volume (ml)	Mean CT	Total CT	Volume (ml)	Mean CT	Total CT	Volume (ml)	Mean CT	Total CT	Volume (ml)	Mean CT	Total CT
1	62	Male	169	9.2	85	48.12	228.55	11.00	48.37	249.32	12.06	66.63	59.44	397.67	55.01	242.65	13.35
2	52	Male	171	47.7	40	46.48	351.86	16.36	49.05	367.01	18.00	84.10	134.55	11.32	82.33	155.47	12.80
3	80	Female	148	28.2	30	28.93	349.73	10.12	28.82	352.60	10.16	50.96	248.01	12.64	51.20	243.95	12.49

Case number	Estimated sex	Estimated height (talus)	Estimated height (calcaneus)	Estimated height (talus+calcaneus)	Estimated error (%)
1	Male	172.7	158.8	165.7	1.97
2	Male	172.3	171.7	172.0	0.57
3	Female	154.8	153.1	154.0	3.88

52], indicating the inclusion of some skeletal variants in both sexes. Although a difference from antemortem stature (about a 2.5-cm increase after death) should be taken into consideration in postmortem measurement [53], the aforementioned accuracy of stature estimation using virtual CT volumetry was higher than that of previous manual or radiographic 2D measurement procedures in other ethnic populations (standard deviation, about 4–6 cm) [25, 27, 29].

In addition, the present study demonstrated possible estimation of body weight using virtual volumetry of the talus and calcaneus, although the correlations were lower than for body height. The accuracies as estimated from 95 % confidence were also slightly higher for mixed-sex groups (error range <3.7 kg) than for separated male and female sex groups (error range <6.5 kg); larger deviations should be considered than in body height estimation, especially for females. Further investigation is needed including combination with two-dimensional parameters for improvement of the procedure.

Further data collection involving various ethnic populations is needed to establish the efficacy of this procedure in routine forensic practice. In addition, improvement of volumetric data analysis is required for practical application, in consideration of postmortem decalcification, although sex and stature estimations were successfully performed in several examples of advanced decomposition and mummification in the present study. However, it was shown that automated CT data analysis is useful to exclude or minimize interobserver deviation.

In conclusion, the observations described above indicate the applicability of CT morphometry of the talus and calcaneus using an automated analyzer for virtual volumetry and radiographic density analysis in evaluating the 3D size, robusticity, and age-related degenerative changes of intact bones for sex and stature estimation in forensic identification, when compared with updated ethnic population data; however, larger deviations should be considered in body weight estimation.

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Conflict of interest The authors declare that they have no competing interests.

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