Degenerative Changes of the Sacroiliac Auricular Joint Surface - Validation of Influential Factors

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Abstract

The purpose of this study was to clarify the relevance of degenerative changes in the sacroiliac joint (SIJ) and the joints in the lower limb and lumbar spine using age estimation methods. We also examined the shape of the auricular surface to determine the effect of degenerative changes on each joint. A total of 200 iliac auricular surfaces from 100 Japanese male skeletons were examined macroscopically in accordance with conventional methods of age estimation. From the obtained estimated age, we calculated the deflection values, which represented the degree of degenerative changes of the joints. For comparison, we used osteophyte score data of the hip, knee, and zygapophyseal joints in lumbar spines from previous studies which had used the same bone specimens. As a quantitative indicator of auricular surface morphology, we defined the constriction ratio (CR) of the auricular surface and compared the CR values obtained with various measured values. Degenerative changes in the SIJ were positively correlated with those in both the hip joint and zygapophyseal joint, but a correlation with knee joints was found only on the left side. In skeletons from individuals aged C60 years as time of death, the CR was significantly different between the group with high scores and those with low scores in both the hip and sacroiliac joints. It has been suggested that degenerative changes in SIJs interact with those in the hip joint and zygapophyseal joint. In addition, the shape of the auricular surface may also be a relevant factor for degenerative changes in these joints.

Keywords

Auricular surface, Degenerative changes, Hip joint Sacroiliac joint, Zygapophyseal joint

Introduction

The sacroiliac joint (SIJ) is important because it transmits mechanical loads between the body trunk and the lower extremities in bipedal humans (Lovejoy 1988; Aiello and Dean 1990). Although this joint is considered to be one of the causative factors for lower back pain, only a limited number of studies have addressed the structure and functions of the SIJ (Hungerford and Gilleard 2007; Beales et al. 2009, 2010; Hu et al. 2010). Therefore, evaluation and treatment of the SIJ are considered to be important components of therapy for patients with pelvic girdle dysfunction, such as lower back pain (Mens et al. 1999, 2001, 2002; Hungerford et al. 2003; Vleeming et al. 2012).

Many studies have investigated degenerative changes in the SIJ (Lovejoy et al. 1985; Vleeming et al. 1990a, b; Buckberry and Chamberlain 2002; Shibata et al. 2002; Igarashi et al. 2005). However, very few of these have correlated such degenerative changes in the SIJ with those in other joints at the level of individual differences.

The aim of this study was to clarify the relevance of degenerative changes in the SIJ, lumbar spine, and lower limb joints by applying age estimation methods to quantitatively evaluate the degree of degenerative changes in the auricular surfaces of individual skeletons. We also studied the shape of the auricular surface to determine the effects of degenerative changes in each joint.

Materials and Methods

Materials

A total of 200 iliac auricular surfaces from 100 Japanese male skeletons were examined macroscopically. The skeletons had been obtained from cadavers that had been voluntarily donated to Nagasaki University School of Medicine for anatomical dissection by medical students between the 1950s and 1970s. Nowadays most cadavers remain anonymous. After they had been dissected by medical students, their soft tissues were almost entirely removed to produce dry skeletal preparations. Skeletons from cadavers with various pathological conditions, such as rheumatoid arthritis, infectious diseases, and fractured bones, were excluded from this study, as were those with systemic diseases, metabolic diseases, and injuries possibly due to accidents in order to limit the changes to the effects of increasing age on degenerative changes in the SIJ. The precise age at time of death had been precisely registered for each individual whose skeleton was included in the study, with a mean age-at-death of 56.5 (range 19–83) years (Table 1).

The study was approved by the local ethics committee of Nagasaki University Graduate School of Biomedical Sciences. All experimental procedures were conducted in accordance with the Declaration of Helsinki.

Evaluation of degenerative changes of the auricular surfaces of the ilium

For the purpose of evaluating the degree of degenerative changes in each auricular surface of the ilium, we choose an index value using two age estimation systems, namely, those of Buckberry and

Chamberlain (2002) (Method B) and of Igarashi et al. (2005) (Method I). We first estimated the age of each joint surface using these two methods and then averaged the ages thus calculated to obtain a single value which we referred to as the average estimated age (AEA). Using a regression formula, we then constructed a regression line between the AEA value and true age at death for all 200 joints from the 100 skeletons and subsequently calculated the calibrated age value of the auricular surface (aCA) for each AEA. Disparity between the AEA value and the aCA for each joint was defined as the auricular surface deflection (aDEF). In about half of the joints, the values of aDEF were positive, namely, the degenerative changes in these auricular surfaces were larger than the aCA. In the joints where aDEF values were negative, the degenerative changes in these auricular surfaces were smaller than the aCA (Fig. 1).

Indexes for degenerative changes in hip, knee, and lumbar apophyseal joints

Indexes of degenerative changes of the hip, knee, and lumbar apophyseal joints were obtained from previously reported studies. The index used for the hip and knee joints was the ‘‘osteophyte score’’ (OS) reported by Tsurumoto et al. (2013), and that used for the lumbar apophyseal joint was the ‘‘degenerative joint score’’ (DJS) of Imamura et al. (2014). These studies were carried out using the same bone specimens as those in the present study (hip joint: 200 sides; knee joint: 102 sides; lumbar spine: 42 bodies). These data were obtained by scoring marginal osteophytes according to the original grading system in hip joints (acetabulum and femoral head), knee joints (distal surface of femur, proximal surface of tibia, and patellar surface), and lumbar spine (zygapophyseal joints in L1-5). Then, with respect to the hip joint, we calculated the regression line between the true age at death and the OS of the hip joint. By means of this formula, we calculated the calibrated age value of the OS of hip joint (hCA) for each age. We then defined the hip joint deflection (hDEF) as the difference between the measured value of the hip joint OS and the hCA. Knee joint OS and zygapophyseal joint DJS were also used to calculate kDEF and zDEF, respectively, in the same manner.

Morphometric assessment of the auricular surfaces of the ilium

There is substantial polymorphism in the shape of the auricular surfaces of the ilium in humans, with some individuals having L-shaped surfaces and others having triangular shaped ones. In order to distinguish quantitatively between these morphological variations in the surfaces, we defined the constriction ratio (CR). To obtain this ratio, we first drew a straight line (reference line) that connected the upper and lower rearmost points on the posterior border of the auricular surface. We then determined along this reference line the position from which we could draw a line perpendicular to the reference line which spanned the longest distance to the anterior border (Line a, Fig. 2). Subsequently, we determined along the same reference line the position from which we could draw a line perpendicular to the reference line which spanned the longest distance to the posterior border (Line b, Fig. 2). The CR of the auricular surface of the iliac bone was defined by dividing the length of Line b by that of Line a (Fig. 2). All such measurements were made from photographs taken with a digital camera (PEN Lite E-PL5; Olympus Corp., Tokyo, Japan) positioned 60 cm above the auricular surface.

Statistical analysis

The strength of the association between each numerical value was examined using Pearson's product-moment correlation coefficient. Intergroup values were compared using one-way analysis of variance, and post hoc analysis was performed using the Scheffe test. Significance was set at $p < 5\ \%$.

Results

Verification of the accuracy of age-estimation methods

There were strong positive correlations between the age estimated by Methods I and B and the true age (Method B: right $r = 0.78$, left $r = 0.78$; Method I: right $r = 0.77$, left $r = 0.72$). There was also a strong positive correlation between the AEA and actual age (right $r = 0.81$; left $r = 0.81$).

Relationship of deflections in each joint

The left and right aDEF values were confirmed to be positively correlated ($r = 0.68$, $p < 0.01$) (Fig. 3). A positive correlation between hDEF and aDEF was also con- firmed on both sides (right: $r = 0.41$, $p < 0.01$; left: $r = 0.40$, $p < 0.01$) (Fig. 4a). A positive correlation between the kDEF and aDEF was only observed on the right side (left: $r = 0.31$, $p < 0.05$) (Fig. 4b), and a positive correlation between zDEF and average aDEF was confirmed on both sides (right: $r = 0.35$, $p < 0.05$, left: $r = 0.48$, $p < 0.01$) (Fig. 4c).

Relationship between degenerative changes in each joint and the CR

The relationship between the left and right CR was con- firmed first as this relationship provides a quantitative evaluation of the shape of the iliac auricular surface; our analysis confirmed that these values were positively correlated ($r = 0.54$, $p < 0.01$) (Fig. 5). There was no significant correlation between the true age and CR value ($r = -0.113$, $p = 0.108$). A significant correlation between CR and aDEF, hDEF, kDEF, or zDEF, respectively, of the ipsilateral sides was not proven (Table 2). We then performed a similar analysis by dividing all of the skeletons into two groups, namely, those from individuals aged ¥60 years at time of death (the ‘‘younger’’ group, n = 106) and those from individuals aged ≥ 60 years at time of death (the ‘‘older’’ group, n = 94). A significant correlation was not found between the CR and aDEF of the ipsilateral sides or between the CR and hDEF of the ipsilateral sides in skeletons of the younger group. A significant correlation between the CR and zDEF of the ipsilateral sides was also not proven (Table 3). To the contrary, we did observe a significant correlation between the CR and zDEF in skeletons from individuals aged ≥ 60 years at time of death (Table 4). In a subsequent analysis, we divided these two groups further into four groups according to aDEF and hDEF values: Group A, aDEF ≥ 0 and hDEF ≥ 0; Group B, aDEF ≥ 0 and hDEF < 0; Group C, aDEF < 0 and hDEF ≥ 0; Group D, aDEF < 0 and hDEF < 0. All analyses were performed on the ipsilateral sides. The results of these analyses revealed that there was no significant difference in CR values between each group when all skeletons were considered and when only the skeletons of the younger group was considered (Figs. 6, 7).

Considering only the skeletons of the older group, there was a significant difference in CR values between Groups A and D, with the average CR value in Group A being higher than that in Group D ($p < 0.01$) (Fig. 8)

Discussion

Structure and function of the sacroiliac joint

The SIJ is classified as an amphiarthrosis—i.e., a slightly movable joint. The auricular surface of the sacrum has a thicker hyaline cartilage and the surface of the ilium has a thinner fibrocartilage (Sashin 1930; Bowen and Cassidy 1981). Fine irregularities are seen on both auricular surfaces, and the capsules are closely coupled at the articular margins with many strong ligaments. Therefore, the mobility of SIJ is strongly limited by this structure. In general, the rotation movement of the sacrum around the ilium is termed nutation (forward nodding) and counter-nutation (backward nodding) (Kapandji 1974). The functions of the SIJ are important for bipedal humans to transmit the load from the upper body to the lower limbs; therefore, stability is required more than mobility in the SIJ (Abitbol 1987a, b, 1988; Aiello and Dean 1990; Lovejoy 2007). This joint is a plane joint, and its surfaces are continuously exposed to shear forces in the upright position; it is located in a perpendicular position to the horizontal plane. The stability of the SIJ is compensated by form closure between both bones and force closure with the tension of the muscles and fascia (Vleeming 1990; Vleeming et al. 1990a, b).

Evaluation of degenerative changes in the SIJ

In this study, we estimated the age of the skeleton at death of the individual using the methods of Buckberry and Chamberlain (2002) and Igarashi et al. (2005). We then calculated the aDEF, which represents the degree of deviation of degenerative changes seen in the skeleton from the real age. Positive aDEF values indicated that the degenerative changes present in the iliac auricular surface were more advanced relative to the real age; conversely, negative aDEF values indicated that the degenerative changes were not more advanced relative to the real age. We found a positive correlation between the aDEF for the left and right sides (Fig. 3). The osteophytes around joint surfaces emerge and grow gradually during an individual's lifetime, and with the ageing process physiological reactions progress to pathological conditions. Therefore, an increase in the mechanical load of a local joint according to personal lifestyle and labor may promote the formation of osteophytes. Moreover, the formation of osteophytes is believed to cause degenerative joint diseases, such as osteoarthritis (Molnar and Wim 2007). The purpose of this study was to investigate the degree of growth of osteophytes caused by the effect of mechanical load on a local joint. To this end, it was necessary to eliminate the influence of osteophyte proliferation with aging. To standardize of the effect of aging, we calculated the CA at each joint and then determined the DEF by subtracting the CA from the evaluation score of each joint.

Relationship between degenerative changes in the hip joint, zygapophyseal joint and SIJ

An association between degeneration of the lumbar intervertebral joints and the hip joints has been suggested by a number of authors (Sato et al. 1989; Itoi 1991; Stupar et al. 2010). The concept of "hip–spine syndrome", as proposed by Offierski and Macnab (1983), is commonly cited in such studies as a factor in joint disease of the spine and hip joint. In addition to Offierski and Macnab (1983), Yoshimoto et al. (2005) reported that alignment abnormalities, such as an increase in sacral slope and enhancement of lumbar lordosis, occur in patients with osteoarthritis of the hip joint. This association is considered to be based on the coordinated movement of the hip joint and lumbar spine and that limitations in one area will affect other areas (Redmond et al. 2015). The kinematic function of the SIJ in the lumbopelvic region is not clear. In the joints investigated in our study, we found a positive correlation between degenerative changes in the SIJ and those in the hip joint (Fig. 4a). We also found a positive correlation in degenerative changes between the SIJ and lumbar spine (Fig. 4c). Therefore, we considered the possibility that the SIJ is also related to the kinematic function of the lumbopelvic area.

To the contrary, we could only confirm a correlation on the left side for degenerative changes between the knee joint and the SIJ (Fig. 4b). It should be noted that knee joints are located much further away from the SIJ than are the lumbar spine and hip joints and that the kinematic relationship between the SIJ and knee joints is small. Therefore, we consider that degenerative changes of the knee joint have only a small effect on the SIJ.

One of the limitations of this study is the absence of personally identifiable information other than sex and age at the time of death. Such information was not available because most of the skeletons examined in this study had been donated anonymously. Therefore, it is unclear whether the individuals to whom the skeletons belonged had symptoms in the areas of the lumbar spine–pelvis–hip joints. Moreover, pathophysiological causality between degenerative changes in the SIJ and those in the hip joint could not be assessed. However, we did consider that the relevance of degenerative changes around the lumbopelvic region was influenced by failure of the stability mechanism of the spine–pelvis–hip joint and these degenerative changes could have progressed due to muscle weakness and/or abnormal alignments of these regions.

Effect of the form of the auricular surface on degenerative changes in the SIJs, zygapophyseal joints, and hip joints

In our study, there was no significant correlation between the shape of the iliac auricular surface and age ($r = -0.113$, $p = 0.108$), indicating that the shape of the SIJ did not appear to vary with aging and suggesting that the shape could be determined by other factors, such as genetic factors. In the older group, there was a statistically significant correlation between the CR and zDEF of the ipsilateral sides (Table 4). As a consequence, degenerative changes in the lumber spine in the older group were more severe in individuals with an L-shaped auricular surface than in those with a triangle-shaped auricular surface. Moreover, in the older group, there was a statistically significant correlation between the CR in Group A and the CR in Group D (Fig. 8). Accordingly, in the older group, individuals with severe degenerative changes in their auricular surface and hip joints had L-shaped auricular surfaces.

For further consideration of the relationship between the form and function of the iliac auricular surface, it will be necessary to examine a sufficient amount of material because there are currently few published studies with data for comparison. In addition, because the CR values used by this study were obtained by simplifying the form of the complicated auricular surface, it is necessary to further investigate the three-dimensional structure.

Conclusion

The results of our study show that there is a mutual relationship between degenerative changes in the SIJ and hip joint and the zygapophyseal joint. We also found differences in the form of the iliac auricular surface that may affect degenerative changes in the SIJ and hip joint. These findings provide useful basic data to elucidate pathological conditions of patients with joint disease of the spine–pelvic–hip region.

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Conflict of interest

The authors declare no conflict of interest.

References

Abitbol MM (1987a) Evolution of the lumbosacral angle. Am J Phys Anthropol 72: 361-372

Abitbol MM (1987b) Evolution of the sacrum in hominoids. Am J Phys Anthropol 74: 65-81

Abitbol MM (1988) Evolution of the ischial spine and of the pelvic floor in the Hominoidea. Am J Phys Anthropol 75:53-67

Aiello L, Dean C (1990) Bipedal locomotion and the postcranial skeleton. An Introduction to Human Evolutionary Anatomy. Academic Press, London

Beales DJ, O'Sullivan PB, Briffa NK (2009) Motor control patterns during an active straight leg raise in chronic pelvic girdle pain subjects. Spine 34:861-870

Beales DJ, O'Sullivan PB, Briffa NK (2010) The effects of manual pelvic compression on trunk motor control during an active straight leg raise in chronic pelvic girdle pain subjects. Man Ther 15:190-199.

Bowen V, Cassidy JD (1981) Macroscopic and microscopic anatomy of the sacroiliac joint from embryonic life to the eighth decade. Spine (Phila Pa 1976) 6:620-628

Buckberry JL, Chamberlain AT (2002) Age estimation from the auricular surface of the ilium: a revised method. Am J Phys Anthropol 119:231-239

Hu H, Meijer OG, van Dieen JH, Hodges PW, Bruijn SM, Strijers RL, Nanayakkara PW, van Royen BJ, Wu W, Xia C (2010) Muscle activity during the active straight leg raise (ASLR), and the effects of a pelvic belt on the ASLR and on treadmill walking. J Biomech 43:532-539

Hungerford B, Gilleard W (2007) The pattern of intrapelvic motion and lumbopelvic muscle recruitment alters in the presence of pelvic girdle pain. In: Movement, Stability, and Lumbopelvic Pain: Integration and Research. (eds Vleeming A, Mooney V, Stoeckart R) Churchill Livingstone, Edinburgh

Hungerford B, Gilleard W, Hodges P (2003) Evidence of altered lumbopelvic muscle recruitment in the presence of sacroiliac joint pain. Spine (Phila Pa 1976) 28:1593-1600

Igarashi Y, Uesu K, Wakebe T, Kanazawa E (2005) New method for estimation of adult skeletal age at death from the morphology of the auricular surface of the ilium. Am J Phys Anthropol 128 (2):324-339

Imamura T, Saiki K, Okamoto K, Maeda M, Matsuo M, Wakebe T, Ogami K, Manabe Y, Koseki H, Tomita M, Tagami A, Osaki M, Shindo H, Tsurumoto T (2014) Characterization of individuals with sacroiliac joint bridging in a skeletal population: analysis of degenerative changes in spinal vertebrae. BioMed Research International 2014:1-9

Itoi E (1991) Roentgenographic analysis of posture in spinal osteoporosis. Spine 16:750-756

Kapandji IA (1974) The physiology of the joints. Churchill Livingstone, Edinburgh

Lovejoy CO, Richard SM, Thomas RP, Robert PM (1985) Chronological metamorphosis of the auricular surface of the ilium: a new method for the determination of adult skeletal age at death. Am J Phys Anthropol 68:15-28

Lovejoy CO (1988) Evolution of human walking. Sci Am 259:118-125

Lovejoy CO (2007) Evolution of the human lumbopelvic region and its relationship to some clinical deficits of the spine and pelvis. In Movement, Stability and Lumbopelvic Pain: Integration and Research. (eds Vleeming A, Mooney V, Stoeckart R) Churchill Livingstone, Edinburgh

Mens JM, Vleeming A, Snijders CJ, Stam HJ, Ginai AZ (1999) The active straight leg raising test and mobility of the pelvic joints. Eur Spine J 8:468-473

Mens JM, Vleeming A, Snijders CJ, Koes BW, Stam HJ (2001) Reliability and validity of the active straight leg raise test in posterior pelvic pain since pregnancy. Spine 26:1167-1171

Mens JM, Vleeming A, Snijders CJ, Koes BW, Stam HJ (2002) Validity of the active straight leg raise test for measuring disease severity in patients with posterior pelvic pain after pregnancy. Spine 27:196-200

Molnar P, Wim B (2007) Osteophytes: relevance and biology. Osteoarthritis Cartilage 15: 237–244.

Offierski CM, Macnab I (1983) Hip-spine syndrome. Spine 8:316-321

Redmond MJ, Gupta A, Nasser R, Domb GB (2015) The Hip-Spine Connection: Understanding Its Importance in the Treatment of Hip Pathology. Orthopedics (Online) 38.1 Jan: 49-55

Sashin D (1930) A critical analysis of the anatomy and the pathological changes of the sacro-iliac joints. J Bone Joint Surg 28:891-910

Sato K, Itoi E, Kasama F (1989) Abnormal posture associated with osteoporosis. J Musculoskeletal System; 2:1451-1462

Shibata Y, Shirai Y, Miyamoto M (2002) The aging process in the sacroiliac joint: helical computed tomography analysis. J Orthop Sci 7 (1):12-18

Stupar M, Côté P, Hawker GA (2010) The association between low back pain and osteoarthritis of the hip and knee: a population-based cohort study. Journal of Manipulative & Physiological Therapeutics 33 (5):349-354

Tsurumoto T, Saiki K, Okamoto K, Imamura T, Maeda J, Manabe Y, Wakebe T (2013) Periarticular osteophytes as an appendicular joint stress marker (JSM): Analysis in a contemporary Japanese skeletal collection. PLoS One 8 (2):e57049

Vleeming A (1990) The Sacroiliac Joint: A Clinical Anatomical Biomechanical and Radiological Study, Thesis Erasmus University Rotterdam. Rotterdam

Vleeming A, Stoeckart R, Volkers AC, Snijders CJ(1990a) Relation between form and function in the sacroiliac joint. Part I: clinical anatomical aspects. Spine (Phila Pa 1976) 15:130-132

Vleeming A, Volkers AC, Snijders CJ, Stoeckart R(1990b) Relation between form and function in the sacroiliac joint. Part II: biomechanical aspects. Spine (Phila Pa 1976) 15:133-136

Vleeming A, Schuenke MD, Masi AT, Danneels L, Willard FH (2012) The sacroiliac joint: An overview of its anatomy, function and potential clinical implications. J Anat 221 (6):537-567

Yoshimoto H, Sato S, Masuda T, Kanno T, Shundo M, Hyakumachi T, Yanagibashi Y (2005) Spinopelvic alignment in patients with osteoarthrosis of the hip: a radiographic comparison to patients with low back pain. Spine 30:1650-1657.

Legends

Fig. 1 Determination of the degree of degenerative changes in the sacroiliac joint (SIJ). A regression formula was used to construct a regression line between the true age at death and average estimated age (AEA), from which we calculated the calibrated age value of the auricular surface (aCA). The difference between the aCA and the AEA was defined as the auricular surface deflection (aDEF)

Fig. 2 Method for determining the constriction ratio (CR) of the iliac auricular surface. A reference line (thick line) was drawn on a photograph of the iliac auricular surface. Line a represents the longest distance between the reference line and the anterior border along a perpendicular line to the reference line, Line b represents the longest distance between the reference line and the posterior border along a line perpendicular to the reference line. The CR was defined by dividing the length of Line a by the length of Line b

Fig. 3 Relationship between the auricular surface deflection (aDEF) on the left and right sides. A strong positive correlation was proven between the left and right sides ($r = 0.68$, $p < 0.01$)

Fig. 4 Relationships between the auricular surface deflection (aDEF), hip joint deflection (hDEF), knee joint deflection (kDEF), and zygapophyseal joint deflection (zDEF). a–c Relationship between aDEF and hDEF (a), between aDEF and kDEF (b), and between aDEF and zDEF (c). A positive correlation was confirmed between aDEF and hDEF on both sides (right sider = 0.41; left sider = 0.40) (a), a positive correlation on only the left side was proven between aDEF and kDEF (left sider = 0.31) (b), and a positive correlation was confirmed between aDEF and zDEF on both sides (right sider = 0.35, left sider = 0.48) (c)

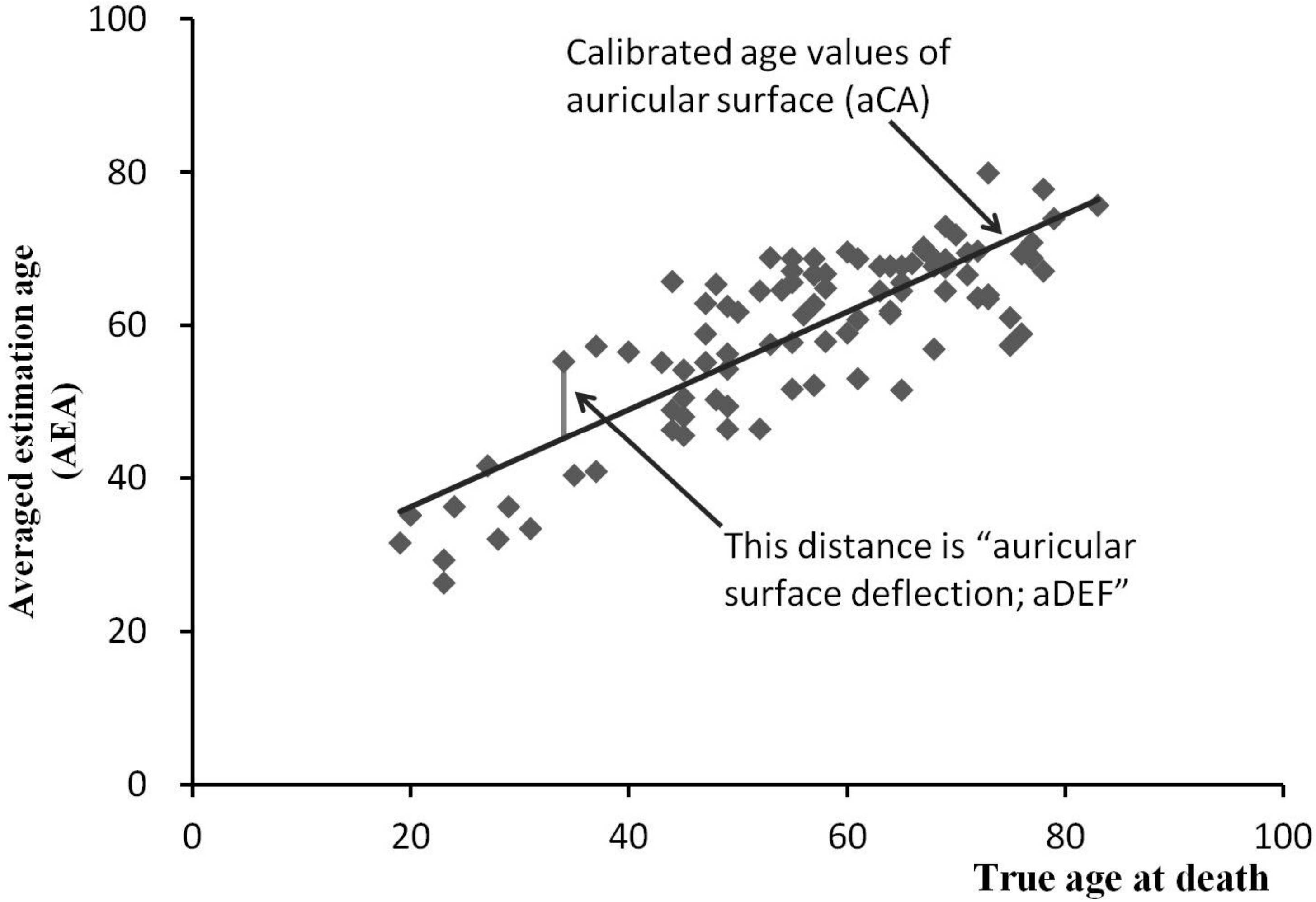
Fig. 5 Relationship between the left and right constriction ratios (CRs). The CRs of the right and left sides showed a positive correlation ($r = 0.54$, $p < 0.01$)

Fig. 6 Constriction ratio (CR) in all skeletons. A total of 200 pairs of hip joints and auricular surfaces of the ipsilateral sides were analyzed. The values are presented as the mean (bar) ± standard deviation (whiskers). The skeletons were divided into four groups: Group A aDEF ≥ 0, hDEF ≥ 0; Group B aDEF ≥ 0, hDEF < 0; Group C aDEF < 0, hDEF ≥ 0, Group D aDEF < 0, hDEF < 0. There was no significant difference in CR values between each of the groups

Fig. 7 Constriction ratio (CR) in skeletons of individuals aged <60 years at time of death. A total of 106 pairs of hip joints and auricular surfaces of the ipsilateral sides were analyzed. The values are presented as the mean (bar) ± standard deviation (whiskers). The skeletons were divided into four groups as described in the caption to Fig. 6. There was no significant difference in CR values between each of the groups

Fig. 8 Constriction ratio (CR) in skeletons of individuals aged ≥60 years at time of death. A total of 94 pairs of hip joints and auricular surfaces of the ipsilateral sides were analyzed. The values are presented as the mean (bar) ± standard deviation (whiskers). The skeletons were divided into four groups as described in caption to Fig. 6. There was a significant difference in CR values between Groups A and D; the average CR value in Group A was significantly higher than that in Group D ($p < 0.01$)

Fig. 1



100
80
60
40
20
0
0
20
40
60
80
100
Averaged estimation age (AEA)
True age at death
Calibrated age values of auricular surface (aCA)
This distance is "auricular surface deflection; aDEF"

Fig. 2

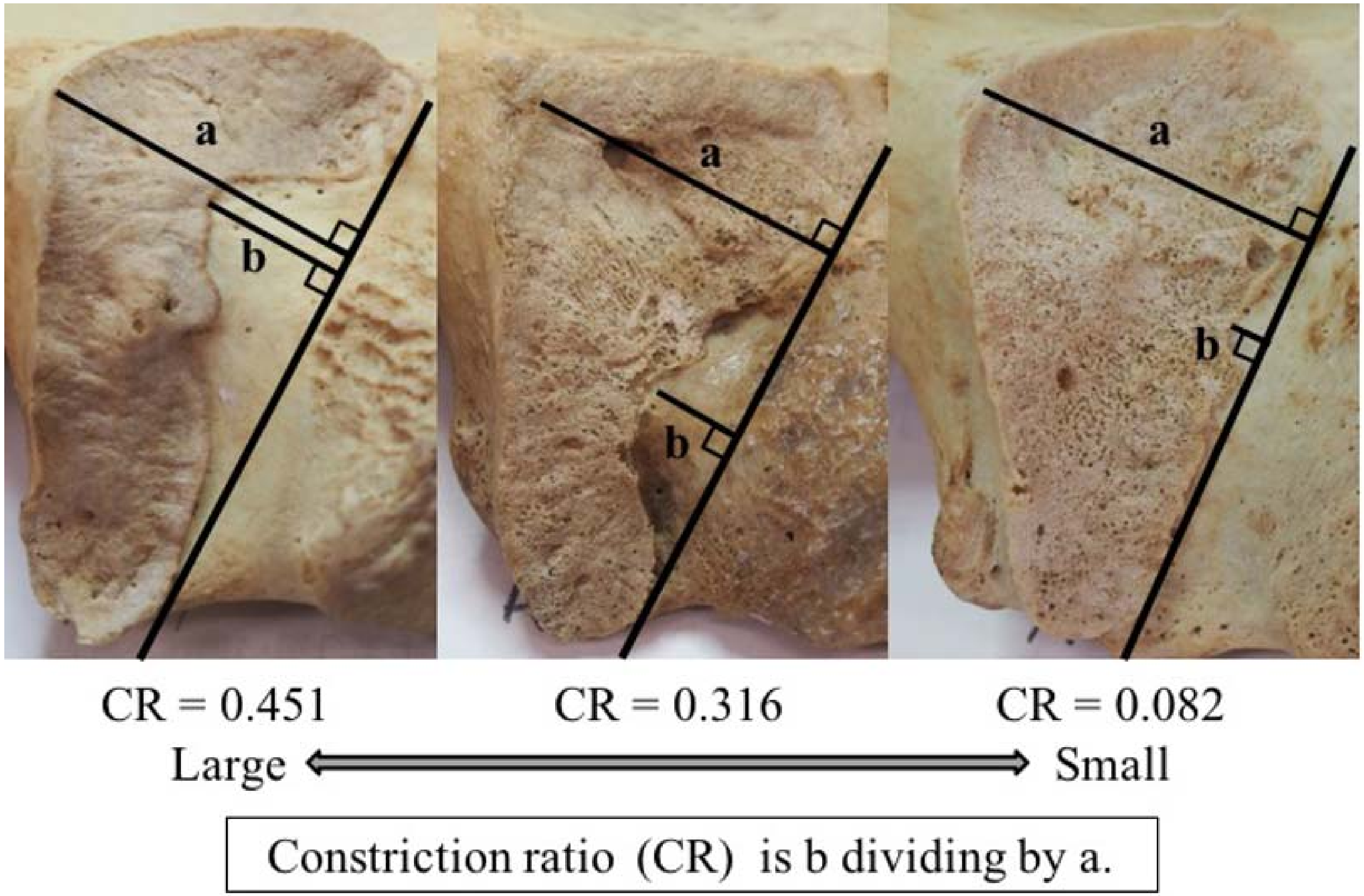
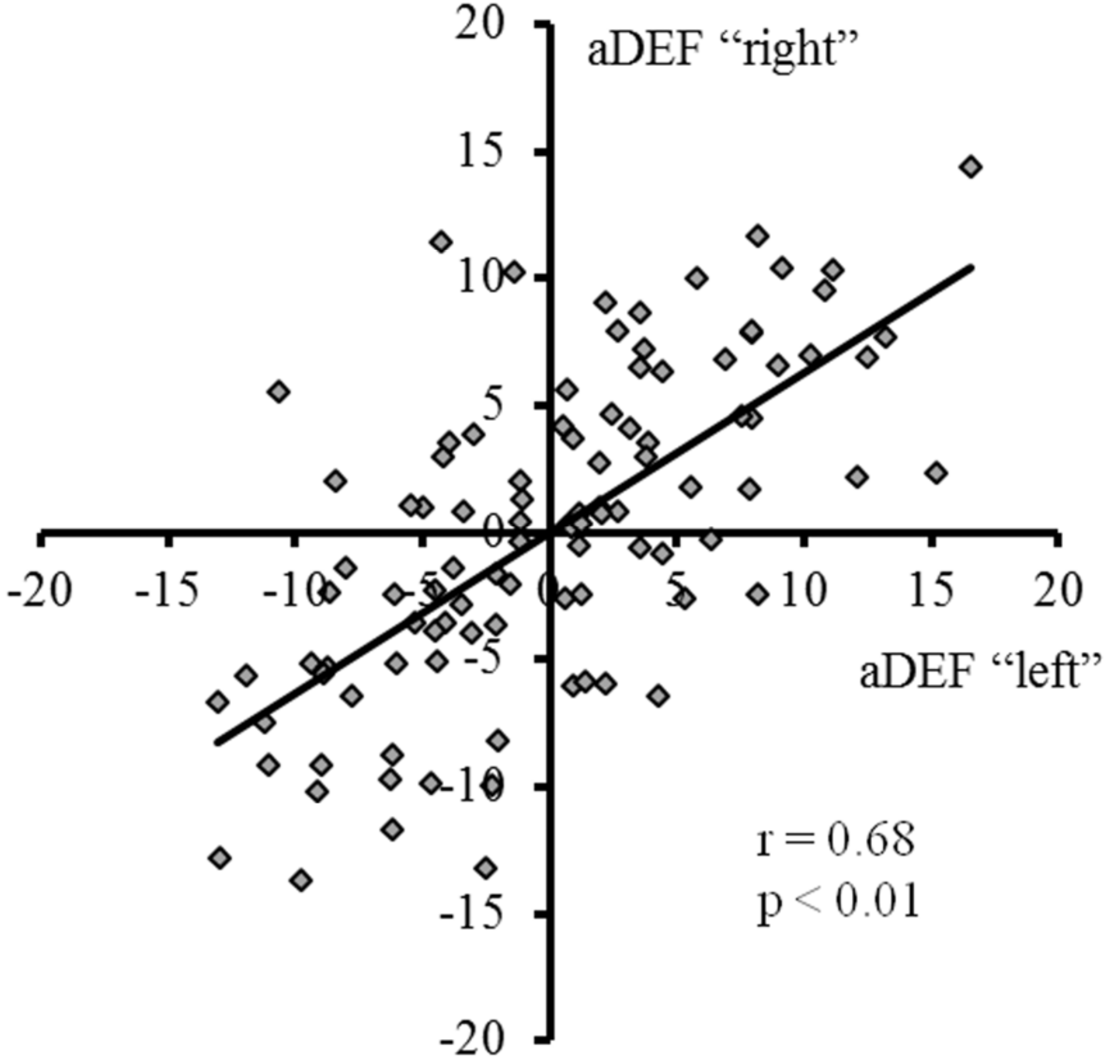

a
b
a
b
a
b
CR = 0.451
CR = 0.316
CR = 0.082
Large
Small
Constriction ratio (CR) is b dividing by a.

Fig. 3


aDEF "right"
aDEF "left"
r = 0.68
p < 0.01
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20

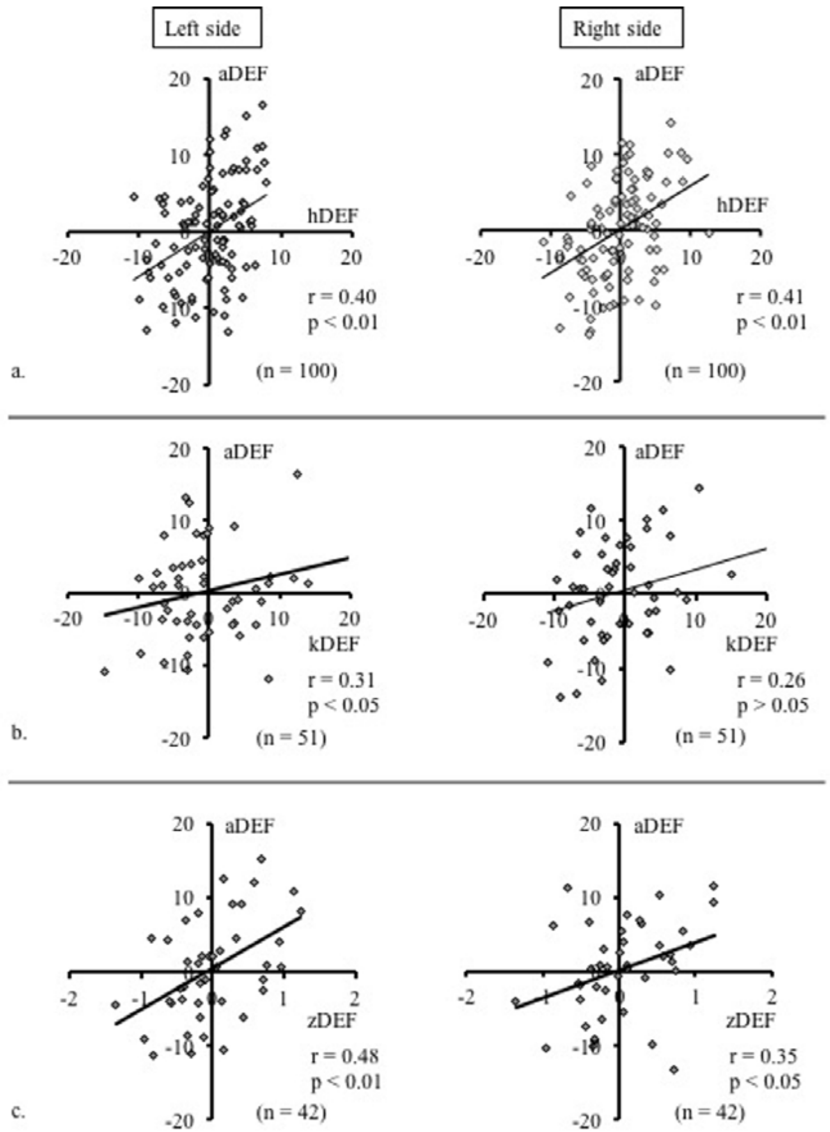

Left side
Right side
aDEF
hDEF
r = 0.40
p < 0.01
(n = 100)
r = 0.41
p < 0.01
(n = 100)
a.
aDEF
kDEF
r = 0.31
p < 0.05
(n = 51)
r = 0.26
p > 0.05
(n = 51)
b.
aDEF
zDEF
r = 0.48
p < 0.01
(n = 42)
r = 0.35
p < 0.05
(n = 42)
c.

Fig. 4

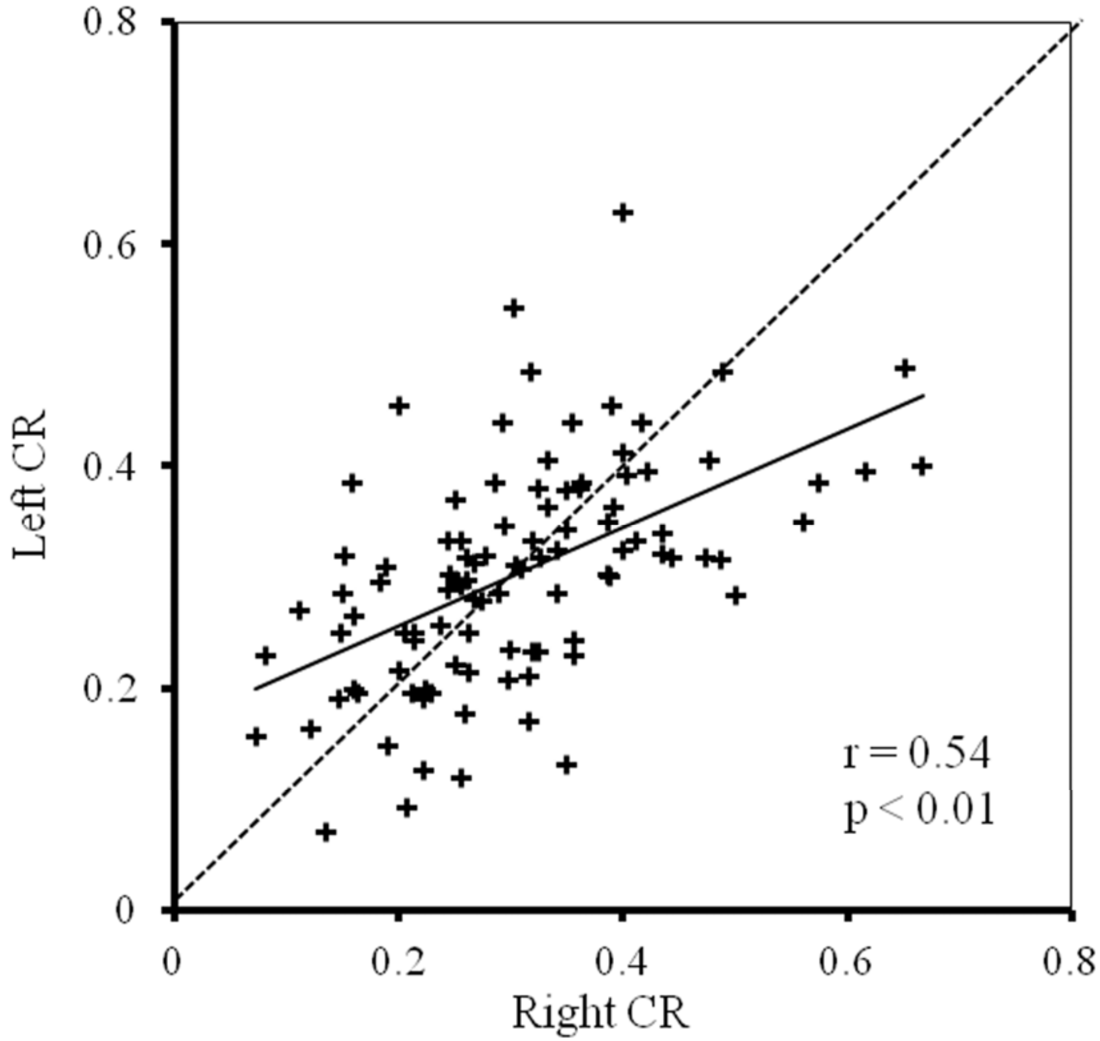


Fig. 5

Fig. 6

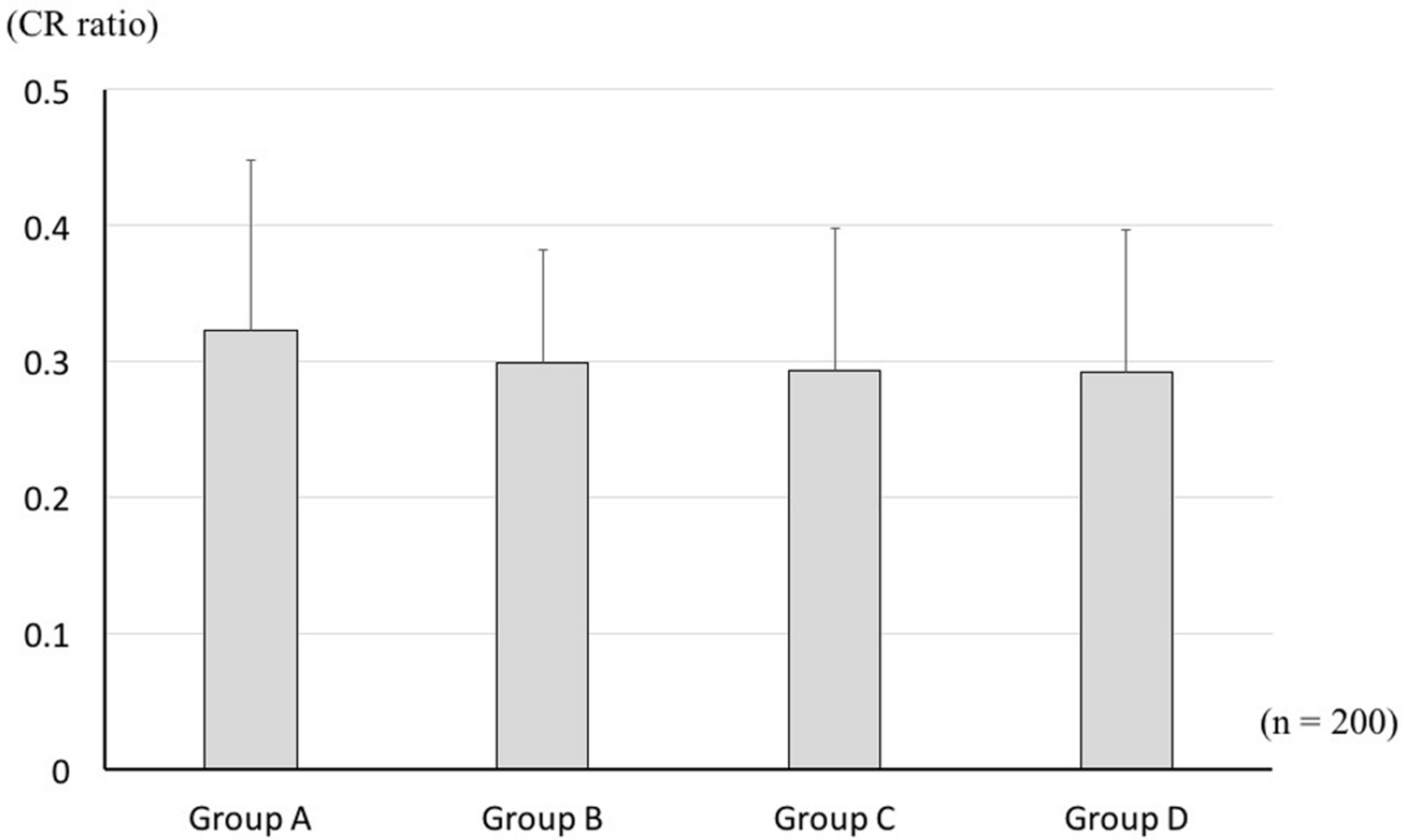


Fig. 7

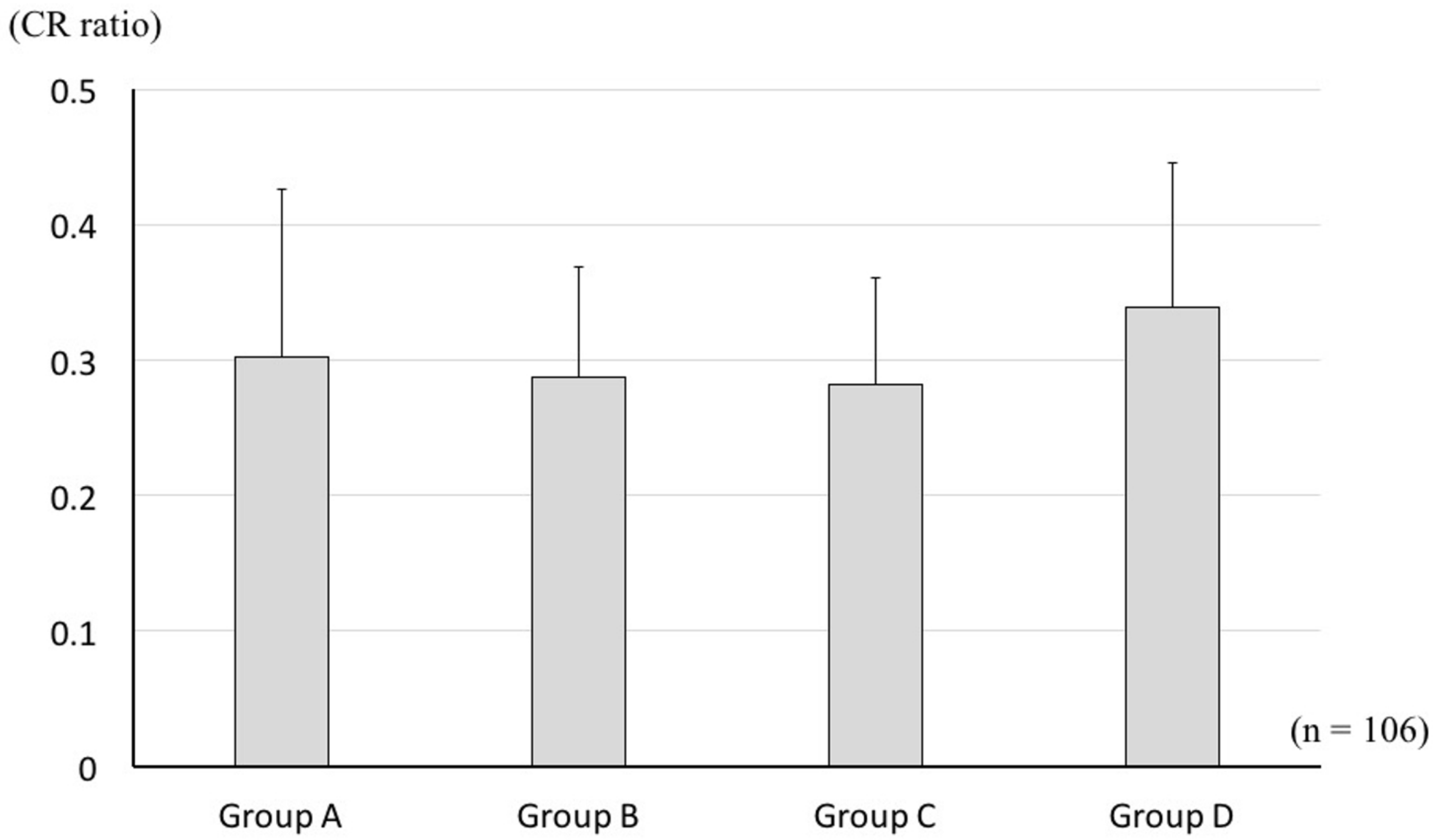


Fig. 8

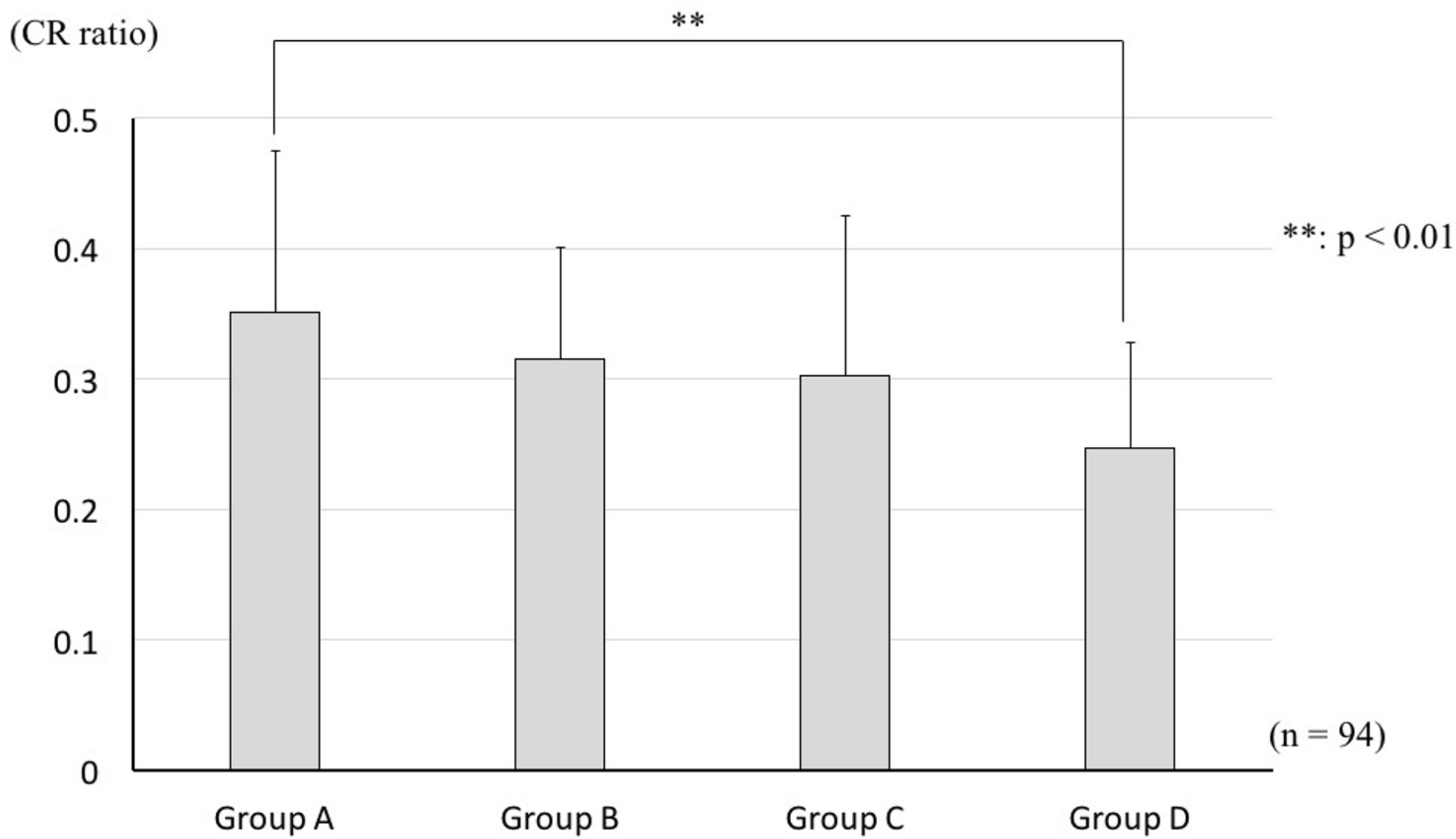


Table 1 Age at time of death of individuals whose skeletons were included in the study

Age (years)	Number of skeletons
10-19	1
20-29	7
30-39	5
40-49	20
50-59	20
60-69	28
70-79	18
80-89	1
Total	100

Table 2 Relationship between auricular surface constriction rate and each term of the ipsilateral sides of all skeletons

Terms	*r*	*p* value
aDEF	0.119	0.091
hDEF	0.110	0.120
kDEF	0.052	0.606
zDEF	0.141	0.200

aDEF auricular surface deflection, hDEF hip joint deflection, kDEF knee joint deflection, zDEF zygapophyseal joint deflection

Table 3 Relationship between auricular surface constriction rate and each term of the ipsilateral sides of skeletons of individuals aged <60 years at time of death

Terms	*r*	*p* value
aDEF	0.041	0.676
hDEF	0.012	0.900
kDEF	0.098	0.482
zDEF	0.089	0.564

Table 4 Relationship of auricular surface constriction rate and each term of the ipsilateral sides of skeletons of individuals aged ≥60 years at time of death

Terms	*r*	*p* value
aDEF	0.230	$p = 0.676$
hDEF	0.156	$p = 0.133$
kDEF	0.071	$p = 0.482$
zDEF	0.340	$p < 0.05$*

*Significant correlation between the zDEF and auricular surface constriction rate at $p < 0.05$