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Muscle

Tönnis Grade 2 Osteoarthritis Is Associated With Widespread Muscle Volume Reduction in Symptomatic Hip Dysplasia

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ABSTRACT

Hip dysplasia can alter periarticular muscle biomechanics, but the extent and distribution of muscle changes across the hip and thigh remain incompletely characterized. This retrospective cross-sectional study evaluated 72 patients with unilateral symptomatic hip dysplasia and a pain-free contralateral hip who underwent eccentric rotational acetabular osteotomy. Preoperative computed tomography images were analyzed using an artificial intelligence-based three-dimensional segmentation system to quantify bilateral muscle volume and mean attenuation in 19 muscles or muscle regions, summarized into six functional groups. Total assessed muscle volume and overall muscle attenuation were lower on the symptomatic side. After false discovery rate correction, symptomatic-side reductions remained significant for quadriceps muscle volume and gluteus maximus mean CT attenuation among the six functional muscle groups. After adjustment for clinical and radiographic factors, Tönnis grade 2 osteoarthritis was associated with a 6.99-percentage-point greater symptomatic-side reduction in total assessed muscle volume compared with grades 0 and 1 and with greater volume reductions across all six functional groups. Tönnis grade 2 was not independently associated with overall muscle attenuation asymmetry, and acetabular morphology was not associated with either primary outcome. These findings suggest that, among patients with symptomatic hip dysplasia undergoing eccentric rotational acetabular osteotomy, more advanced osteoarthritis is associated with widespread muscle volume reduction.

Statement of Clinical Significance: Recognition of widespread periarticular hip and thigh muscle involvement in patients with more advanced osteoarthritis may support more comprehensive preoperative muscle assessment and inform future studies of perioperative rehabilitation.

1 | Introduction

Hip dysplasia (HD) is characterized by insufficient acetabular coverage, which increases joint contact pressure and instability and can lead to labral injury, cartilage damage, and osteoarthritis (OA) progression [1–4]. Abnormal osseous morphology in HD can alter hip muscle biomechanics during gait and place periarticular muscles at a mechanical disadvantage [5]. Because these muscles contribute to pelvic stabilization and dynamic hip

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stability [6, 7], altered muscle mechanics may contribute to weakness, pain, and functional impairment [8, 9]. However, muscle changes in symptomatic HD may not be fully explained by acetabular morphology alone. Factors accompanying joint degeneration, such as pain and reduced physical activity, may also contribute to these changes. Studies in related populations have reported gluteal muscle atrophy and fatty infiltration in hip OA, as well as increased intermuscular adipose tissue with reduced physical activity [10–12]. However, these findings were derived primarily from general hip OA populations and may not be directly applicable to patients with symptomatic HD. Imaging studies in patients with HD have reported changes in muscle size or composition in selected muscles [13, 14], but the extent and distribution of these changes across the periarticular hip and thigh musculature remain incompletely characterized.

Addressing this gap requires assessment of multiple muscles over their full three-dimensional extent. Single-slice measurements may not adequately represent the quantitative and qualitative characteristics of an entire muscle, whereas manual three-dimensional assessment is time-consuming [15, 16]. Recent artificial intelligence (AI)-based automated segmentation methods allow three-dimensional assessment of the volume and mean Hounsfield unit (HU) values of multiple muscles [17, 18]. Beyond identifying which muscles are involved, it is also important to determine which disease features are associated with muscle changes. Although acetabular morphology and OA severity are related, they represent different aspects of disease status. We therefore examined both to determine whether muscle changes were more closely associated with underlying acetabular morphology or with the severity of established joint degeneration.

Accordingly, we asked: (1) In patients with unilateral symptomatic HD, which periarticular hip and thigh muscle groups show reductions in muscle volume and quality? (2) Which factors are associated with reductions in muscle volume and quality?

2 | Methods

2.1 | Study Design and Patients

This was a Level III, single-center retrospective cross-sectional observational study of patients who underwent eccentric rotational acetabular osteotomy (ERAO) at our institution. The study was approved by our institutional review board (approval no. 2020-0272) and was conducted in accordance with the Declaration of Helsinki. The requirement for written informed consent was waived because of the retrospective nature of the study.

Between January 2017 and February 2026, 159 patients underwent ERAO at our institution. ERAO is a type of periacetabular osteotomy in which a spherically osteotomized acetabular fragment is rotated laterally to improve femoral head coverage [19]. We excluded patients with a symptomatic-side lateral center-edge angle (LCEA) of $\geq 25°$ ($n = 5$), those who underwent an additional osteotomy concurrently with ERAO ($n = 3$), those with contralateral hip pain, defined as a Japanese Orthopaedic Association hip pain score of < 40 points or a pain visual analog scale (VAS) score > 0 mm ($n = 28$), those with a history of surgery involving either lower extremity ($n = 50$), and those with Tönnis grade 2 osteoarthritis (OA) in the contralateral hip ($n = 1$). Ultimately, 72 patients with unilateral symptomatic HD and a pain-free contralateral hip were included in the analysis (Figure 1).

The ERAO-treated hip was defined as the symptomatic side, and the contralateral hip was used as the within-patient reference. Radiographic HD was defined as an LCEA of $< 25°$ on an anteroposterior pelvic radiograph [20]. A contralateral hip with an LCEA of $< 25°$ was considered to have contralateral radiographic HD. Preoperative pain intensity in the symptomatic hip was assessed using a 100-mm VAS, with higher scores indicating greater pain intensity. Patient demographic and clinical characteristics are summarized in Table 1. There were no missing data for the primary outcomes or variables included in the multivariable analyses.

2.2 | Assessment of Muscle Volume and Quality

To determine which periarticular hip and thigh muscles showed reductions in muscle volume and quality, we analyzed preoperative computed tomography (CT) scans covering the pelvis to the distal femur. CT images were acquired with patients in the supine position and both lower extremities in a neutral resting position using a CT scanner (Toshiba Medical Systems Corporation, Otawara, Japan) operated at 120 kV and 320 mA, with a reconstructed slice

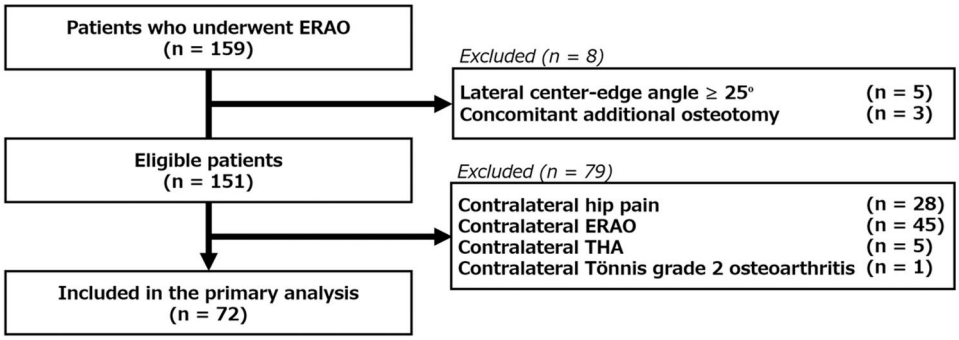


FIGURE 1 | Patient selection flowchart. Of 159 patients who underwent eccentric rotational acetabular osteotomy (ERAO), 72 patients with unilateral symptomatic hip dysplasia were included in the primary analysis. THA, total hip arthroplasty.

thickness of 1 mm. The CT images were analyzed using an AI-based automated muscle segmentation system incorporating a previously described Bayesian U-Net [17]. This system has been validated for automated segmentation of bones and muscles and for quantitative assessment of muscle volume and mean CT attenuation on clinical CT images encompassing the hip and knee joints [18]. The pelvic and thigh muscles were automatically segmented in three dimensions, and all segmentation results were visually inspected by the first author (Figure 2).

TABLE 1 | Demographic and clinical characteristics of the study cohort.

Parameter	Value
Patients, *n*	72
Age, years [IQR]	30 [20–42]
Sex, *n* (%)	
Male	10 (14)
Female	62 (86)
Height, cm ± SD	160 ± 7
Body weight, kg ± SD	58 ± 12
Body mass index, kg/m^2 ± SD	23 ± 4
Symptomatic side, *n* (%)	
Right hip	43 (60)
Left hip	29 (40)
Symptomatic-side Tönnis grade, *n* (%)	
Grade 0	32 (44)
Grade 1	22 (31)
Grade 2	18 (25)
Symptomatic-side pain VAS, mm [IQR]	40 [24–58]

Abbreviations: IQR, interquartile range; SD, standard deviation; VAS, visual analog scale.

Muscle volume (cm^3) and mean CT attenuation (Hounsfield units [HU]) were calculated bilaterally for 19 muscles or muscle regions. Muscle volume was used as a measure of muscle quantity, whereas mean CT attenuation was used as an indicator of muscle quality. The muscles were classified into six functional groups, as shown in Table 2 [21]. Five muscles or muscle regions that could not be clearly assigned to one of the six predefined functional groups were excluded from the functional-group analyses but were included in the total muscle analysis to provide a comprehensive assessment of the periarticular hip and thigh musculature. Functional-group volume was calculated as the sum of the constituent muscle volumes, and functional-group attenuation was calculated as the volume-weighted mean HU. Total assessed muscle volume was calculated as the sum of the volumes of all 19 muscles or muscle regions, and overall muscle attenuation was calculated as the volume-weighted mean HU across all 19 muscles or muscle regions. The primary outcomes were side-to-side differences in total assessed muscle volume and overall muscle attenuation. Analyses of the six functional muscle groups were considered secondary outcomes, whereas analyses of individual muscles or muscle regions were considered exploratory.

2.3 | Clinical and Radiographic Factors Associated With Muscle Volume and Quality

To identify factors associated with reductions in muscle volume and quality, we evaluated OA severity, acetabular morphology, contralateral radiographic HD, age, sex, body mass index (BMI), and symptomatic-side pain VAS. OA severity was assessed on preoperative anteroposterior pelvic radiographs using the Tönnis grading system [22]. Acetabular morphology was assessed using the LCEA and acetabular roof obliquity (ARO). Radiographic measurements were independently performed twice by two authors (HF and HI), with an interval of at least 1 month between measurements. The measurements demonstrated high reliability,

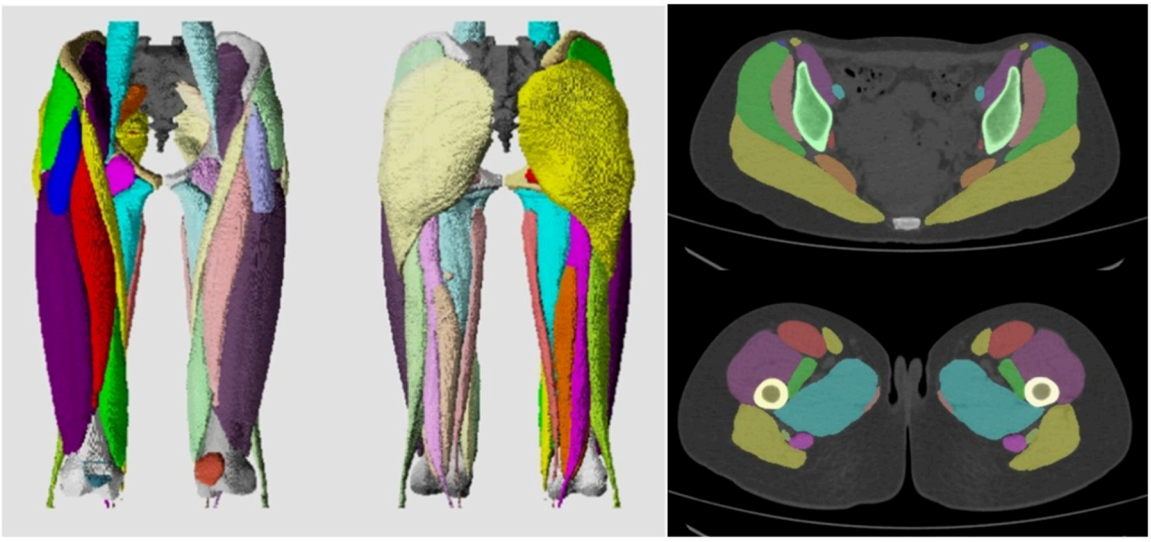


FIGURE 2 | Artificial intelligence–based three-dimensional muscle segmentation. Representative three-dimensional reconstructions and axial computed tomography images showing automated segmentation of the periarticular hip muscles. Different colors indicate individual muscles or muscle regions.

TABLE 2 | Classification of the 19 segmented muscle regions for functional group and total muscle analyses.

Segmented muscle	Functional muscle group
Gluteus maximus	Gluteus maximus
Gluteus medius	Hip abductors
Gluteus minimus	Hip abductors
Vastus lateralis/intermedius	Quadriceps
Vastus medialis	Quadriceps
Rectus femoris	Quadriceps
Biceps femoris	Hamstrings
Semimembranosus	Hamstrings
Semitendinosus	Hamstrings
Adductor	Hip adductors
Gracilis	Hip adductors
Pectineus	Hip adductors
Iliacus	Iliopsoas
Psoas major	Iliopsoas
Obturator externus	Not assigned
Obturator internus	Not assigned
Piriformis	Not assigned
Sartorius	Not assigned
Tensor fasciae latae	Not assigned

Note: Muscles classified as "Not assigned" were included in the total muscle analysis but not in the functional muscle group analyses.

with intraclass correlation coefficients ranging from 0.88 to 0.92 for intraobserver reliability and from 0.82 to 0.91 for interobserver reliability. For analyses of factors associated with muscle changes, muscle volume asymmetry was calculated as (symptomatic side − contralateral side)/contralateral side × 100 and expressed as a percentage. Muscle attenuation asymmetry was calculated as the symptomatic-side mean HU minus the contralateral-side mean HU. Thus, more-negative values indicated greater reductions in muscle volume or quality on the symptomatic side.

2.4 | Statistical Analysis

Continuous variables are presented as mean ± standard deviation or median [interquartile range (IQR)], as appropriate. Paired comparisons between the symptomatic and contralateral sides were performed using the Wilcoxon signed-rank test for continuous and ordinal variables and the McNemar test for paired binary variables. Paired differences in muscle volume and attenuation were summarized as medians with interquartile ranges. For graphical presentation, muscle volume asymmetry and attenuation asymmetry were summarized using Hodges–Lehmann estimates with 95% confidence intervals (CIs). To account for multiple testing, the Benjamini–Hochberg false discovery rate (FDR) procedure was applied across the 50 secondary and exploratory paired comparisons (six functional muscle groups and 19 individual muscles or muscle regions × two outcomes). The two primary outcomes were not included in this FDR family. Associations of symptomatic-side Tönnis grade, LCEA, and ARO with muscle volume and attenuation asymmetry were initially evaluated using Spearman rank correlation coefficients, with Tönnis grade treated as an ordinal variable. For the functional muscle-group correlation analyses, FDR correction was applied across the six functional muscle groups for each predictor and outcome separately.

Multivariable linear regression analyses were then performed for the two primary outcomes and for muscle volume and attenuation outcomes in each of the six functional muscle groups. Tönnis grade 2, symptomatic-side LCEA, symptomatic-side ARO, contralateral radiographic HD, age, sex, BMI, and symptomatic-side pain VAS were entered simultaneously as independent variables. These variables were selected to account for OA severity, acetabular morphology, characteristics of the contralateral reference hip, and patient-related factors potentially associated with muscle volume or quality. Multicollinearity among the independent variables in the multivariable models was assessed using variance inflation factors (VIFs). Tönnis grade 2 was modeled as a binary variable, with Tönnis grades 0 and 1 combined as the reference category to compare more advanced OA with absent-to-mild OA. For the functional muscle-group multivariable analyses, FDR correction was applied across the six functional muscle groups for each predictor and outcome separately. Results are reported as unstandardized regression coefficients (B) with 95% CIs. As a sensitivity analysis, paired comparisons of the primary muscle outcomes were repeated in patients with a nondysplastic contralateral hip, defined as a contralateral LCEA of ≥ 25°. Distributions of the primary outcomes across Tönnis grades were illustrated using box-and-whisker plots with individual data points. Statistical analyses were performed using EZR version 1.41 [23]. All tests were two-sided, and $p < 0.05$ or FDR-adjusted $p < 0.05$, as applicable, was considered statistically significant.

3 | Results

3.1 | Muscle Volume and Attenuation Differences Between Sides

Total assessed muscle volume was lower on the symptomatic side than on the contralateral side (3610 cm^3 [IQR 3207 to 3936] *vs.* 3665 cm^3 [IQR 3247 to 4092]; median paired difference, −53 cm^3 [IQR −151 to 49]; $p = 0.005$). After FDR correction, lower muscle volume on the symptomatic side was observed in the quadriceps among the six functional muscle groups.

Overall muscle attenuation was also lower on the symptomatic side (47 HU [IQR 45 to 52] *vs.* 48 HU [IQR 46 to 53]; median paired difference, −0.3 HU [IQR −1.1 to 0.2]; $p = 0.002$). After FDR correction, lower mean CT attenuation on the symptomatic side was observed in the gluteus maximus (Table 3). Side-to-side differences across the functional muscle groups are shown in Figure 3. In exploratory analyses, after FDR correction, lower symptomatic-side muscle volume remained significant for the vastus medialis and lower attenuation for the gluteus maximus (Table S-1).

3.2 | Factors Associated With Muscle Volume and Attenuation Asymmetry

The symptomatic side had a smaller LCEA and greater ARO than the contralateral side. All symptomatic hips met the radiographic definition of HD, whereas radiographic HD was present in 54 of 72

TABLE 3 | Comparison of muscle volume and attenuation between the symptomatic and contralateral sides.

Muscle outcome	Symptomatic side	Contralateral side	Median difference	*p* value	FDR-adjusted *p* value
Muscle volume, cm^3 [IQR]					
Total assessed muscle	3610 [3207 to 3936]	3665 [3247 to 4092]	−53 [−151 to 49]	0.005	—
Gluteus maximus	654 [551 to 749]	652 [578 to 769]	−9 [−41 to 16]	0.053	0.127
Hip abductors	309 [286 to 356]	313 [286 to 350]	−5 [−17 to 6]	0.071	0.148
Iliopsoas	159 [145 to 178]	163 [146 to 183]	−2 [−8 to 4]	0.075	0.149
Hip adductors	602 [524 to 697]	621 [536 to 716]	−11 [−57 to 16]	0.011	0.080
Quadriceps	1169 [988 to 1334]	1216 [1046 to 1325]	−27 [−70 to 19]	0.002	0.020
Hamstrings	448 [397 to 504]	454 [398 to 504]	−3 [−17 to 8]	0.114	0.175
Muscle attenuation, HU [IQR]					
Overall muscle attenuation	47 [45 to 52]	48 [46 to 53]	−0.3 [−1.1 to 0.2]	0.002	—
Gluteus maximus	38 [33 to 45]	39 [35 to 46]	−0.7 [−2.7 to 0.6]	0.001	0.020
Hip abductors	48 [45 to 52]	49 [46 to 53]	−0.6 [−1.9 to 0.7]	0.021	0.080
Iliopsoas	57 [54 to 60]	58 [55 to 60]	−0.2 [−1.1 to 0.6]	0.081	0.151
Hip adductors	49 [46 to 52]	49 [46 to 52]	−0.3 [−1.0 to 0.3]	0.022	0.080
Quadriceps	54 [51 to 57]	55 [52 to 57]	−0.3 [−0.8 to 0.3]	0.035	0.110
Hamstrings	46 [42 to 51]	46 [43 to 50]	−0.1 [−1.0 to 0.5]	0.201	0.265

Note: Benjamini–Hochberg false discovery rate (FDR) correction was applied across the 50 secondary/exploratory paired comparisons (six functional groups and 19 individual muscles × two outcomes). The two primary outcomes were not included in the FDR family.
Abbreviations: HU, Hounsfield units; IQR, interquartile range.

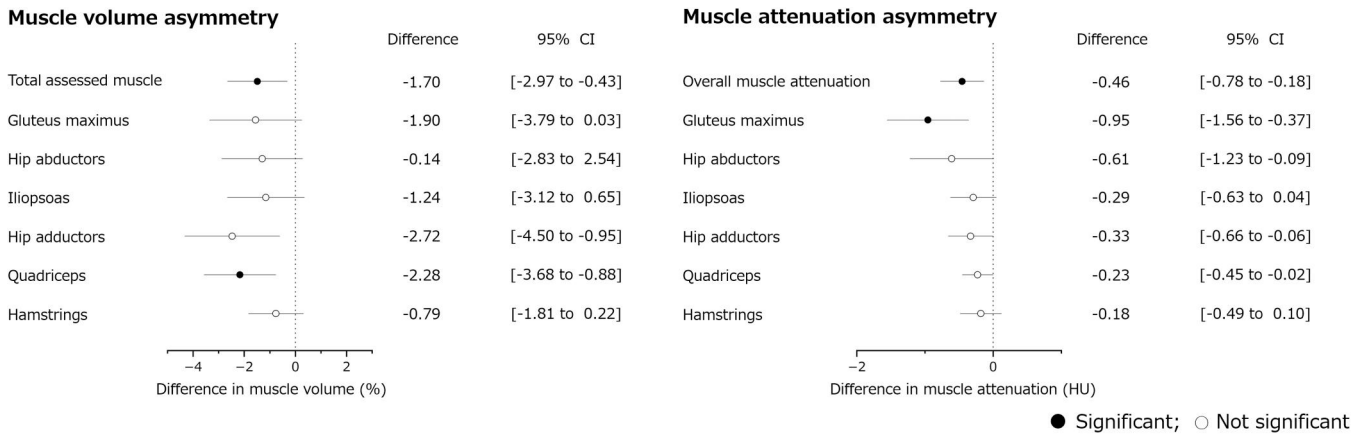


FIGURE 3 | Side-to-side differences in muscle volume and attenuation. Points represent Hodges–Lehmann estimates of paired differences, and horizontal lines indicate unadjusted 95% confidence intervals (CIs). Muscle volume asymmetry was calculated as (symptomatic side − contralateral side)/contralateral side × 100, and attenuation asymmetry as symptomatic side − contralateral side. Negative values indicate lower volume or attenuation on the symptomatic side. For the primary outcomes, significance was based on raw *p* values. For the functional muscle-group outcomes, significance was based on FDR-adjusted *p* values. Filled and open circles indicate statistically significant and nonsignificant results, respectively.

contralateral hips (75%) (Table 4). Symptomatic-side Tönnis grade was negatively correlated with total assessed muscle volume asymmetry ($\rho = -0.337$; 95% CI, −0.545 to −0.094; $p = 0.004$) and overall muscle attenuation asymmetry ($\rho = -0.327$; 95% CI, −0.547 to −0.072; $p = 0.005$), whereas neither LCEA nor ARO was associated with either primary outcome (Table 5). Among the six functional muscle groups, the hip abductors showed the strongest correlations with Tönnis grade for both muscle volume asymmetry ($\rho = -0.469$; FDR-adjusted $p = 0.002$) and attenuation asymmetry ($\rho = -0.411$; FDR-adjusted $p = 0.003$) (Table S-2).

In multivariable analysis, Tönnis grade 2 was independently associated with a 6.99-percentage-point greater reduction in total assessed muscle volume on the symptomatic side compared with Tönnis grades 0 and 1 (adjusted B = −6.99; 95% CI, −9.94 to −4.04; $p < 0.001$), but not with overall muscle

TABLE 4 | Paired comparison of radiographic hip characteristics between symptomatic and contralateral hips.

Radiographic characteristic	Symptomatic side	Contralateral side	*p* value
Lateral center-edge angle, ° [IQR]	15 (9–21)	19 (14–25)	< 0.001
Acetabular roof obliquity, ° [IQR]	19 (15–24)	15 (10–20)	< 0.001
Radiographic hip dysplasia, *n* (%)	72 (100)	54 (75)	< 0.001
Tönnis grade, *n* (%)			< 0.001
Grade 0 or 1	54 (75)	72 (100)	
Grade 2	18 (25)	0 (0)	

Abbreviation: IQR, interquartile range.

TABLE 5 | Correlations of symptomatic-side osteoarthritis severity and acetabular morphology with the primary muscle asymmetry outcomes.

Symptomatic side characteristic	ρ (95% CI)	*p* value
Muscle volume asymmetry, %		
Tönnis grade	−0.337 (−0.545 to −0.094)	0.004
Lateral center-edge angle	0.032 (−0.211 to 0.274)	0.793
Acetabular roof obliquity	0.036 (−0.225 to 0.283)	0.765
Muscle attenuation asymmetry, HU		
Tönnis grade	−0.327 (−0.547 to −0.072)	0.005
Lateral center-edge angle	0.076 (−0.171 to 0.318)	0.523
Acetabular roof obliquity	−0.039 (−0.293 to 0.214)	0.742

Note: Symptomatic side values were used for Tönnis grade, lateral center-edge angle, and acetabular roof obliquity.
Abbreviations: CI, confidence interval; HU, Hounsfield units.

TABLE 6 | Multivariable associations of factors with the primary muscle asymmetry outcomes.

Variable	Adjusted B (95% CI)	*p* value
Muscle volume asymmetry, %		
Symptomatic-side Tönnis grade 2 (vs 0–1)	−6.99 (−9.94 to −4.04)	< 0.001
Symptomatic-side lateral center-edge angle	0.06 (−0.13 to 0.26)	0.504
Symptomatic-side acetabular roof obliquity	0.07 (−0.20 to 0.34)	0.597
Contralateral HD (yes vs no)	1.47 (−1.44 to 4.38)	0.317
Age, years	0.07 (−0.04 to 0.17)	0.204
Female sex	0.07 (−3.26 to 3.40)	0.967
Body mass index, kg/m^2	0.16 (−0.17 to 0.48)	0.330
Symptomatic-side pain VAS, mm	−0.01 (−0.06 to 0.05)	0.834
Muscle attenuation asymmetry, HU		
Symptomatic-side Tönnis grade 2 (vs 0–1)	−0.72 (−1.74 to 0.30)	0.162
Symptomatic-side lateral center-edge angle	0.04 (−0.03 to 0.10)	0.290
Symptomatic-side acetabular roof obliquity	0.04 (−0.05 to 0.14)	0.342
Contralateral HD (yes vs no)	0.04 (−0.96 to 1.05)	0.929
Age, years	−0.03 (−0.06 to 0.01)	0.144
Female sex	1.08 (−0.07 to 2.23)	0.064
Body mass index, kg/m^2	0.08 (−0.03 to 0.19)	0.144
Symptomatic-side pain VAS, mm	0.01 (−0.01 to 0.03)	0.263

Abbreviations: CI, confidence interval; HD, hip dysplasia; HU, Hounsfield units; VAS, visual analog scale.

attenuation asymmetry (adjusted B = −0.72; 95% CI, −1.74 to 0.30; $p = 0.162$). None of the other clinical or radiographic factors were independently associated with either primary outcome (Table 6). Variance inflation factors were 1.32 for Tönnis grade 2, 2.55 for LCEA, 2.74 for ARO, 1.28 for contralateral radiographic HD, 1.42 for age, 1.07 for sex, 1.29 for BMI, and 1.10 for symptomatic-side pain VAS, indicating no substantial multicollinearity among the independent variables.

At the functional muscle group level, Tönnis grade 2 was associated with greater symptomatic-side reductions in muscle volume across all six functional groups, and all associations remained after FDR correction. The hip abductors showed one of the largest adjusted reductions (adjusted B = −10.43; 95% CI, −17.14 to −3.71; FDR-adjusted $p = 0.003$). For muscle attenuation, no associations with Tönnis grade 2 remained statistically significant after FDR correction (Table S-3). Adjusted associations are illustrated in Figure 4.

The unadjusted median total assessed muscle volume asymmetry was −1.0% in patients with Tönnis grade 0 and −0.8% in those with grade 1, compared with −6.5% in those with grade 2. Overall muscle attenuation asymmetry also tended to be lower in patients with Tönnis grade 2, although the distributions overlapped among the three grades (Figure 5). Functional muscle group distributions according to Tönnis grade are shown in Figure S-1. In a sensitivity analysis restricted to the 18 patients with a nondysplastic contralateral hip, total assessed muscle volume and overall muscle attenuation remained lower on the symptomatic side ($p = 0.016$ and $p = 0.008$, respectively) (Table S-4).

4 | Discussion

Muscle dysfunction is common in patients with symptomatic hip dysplasia (HD) and may be associated with pain and functional impairment. However, the extent and distribution of muscle volume and quality changes across the periarticular hip and thigh musculature remain incompletely understood. Identifying factors associated with these muscle changes may help recognize patients with more extensive muscle involvement and improve our understanding of the muscular changes accompanying symptomatic HD. In this study, total assessed muscle volume and overall muscle attenuation were lower on the symptomatic side. At the functional muscle-group level,

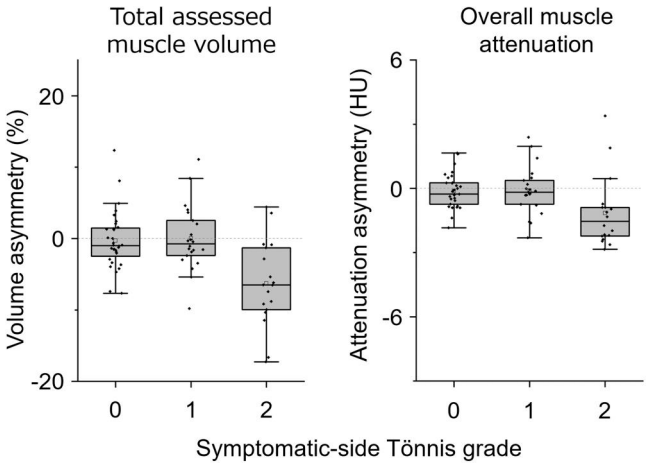


FIGURE 5 | Primary muscle outcomes according to symptomatic-side Tönnis grade. Boxplots show the unadjusted distributions of total assessed muscle volume asymmetry and overall muscle attenuation asymmetry. Central lines indicate medians, boxes indicate interquartile ranges, and points represent individual patients. Negative values indicate lower volume or attenuation on the symptomatic side.

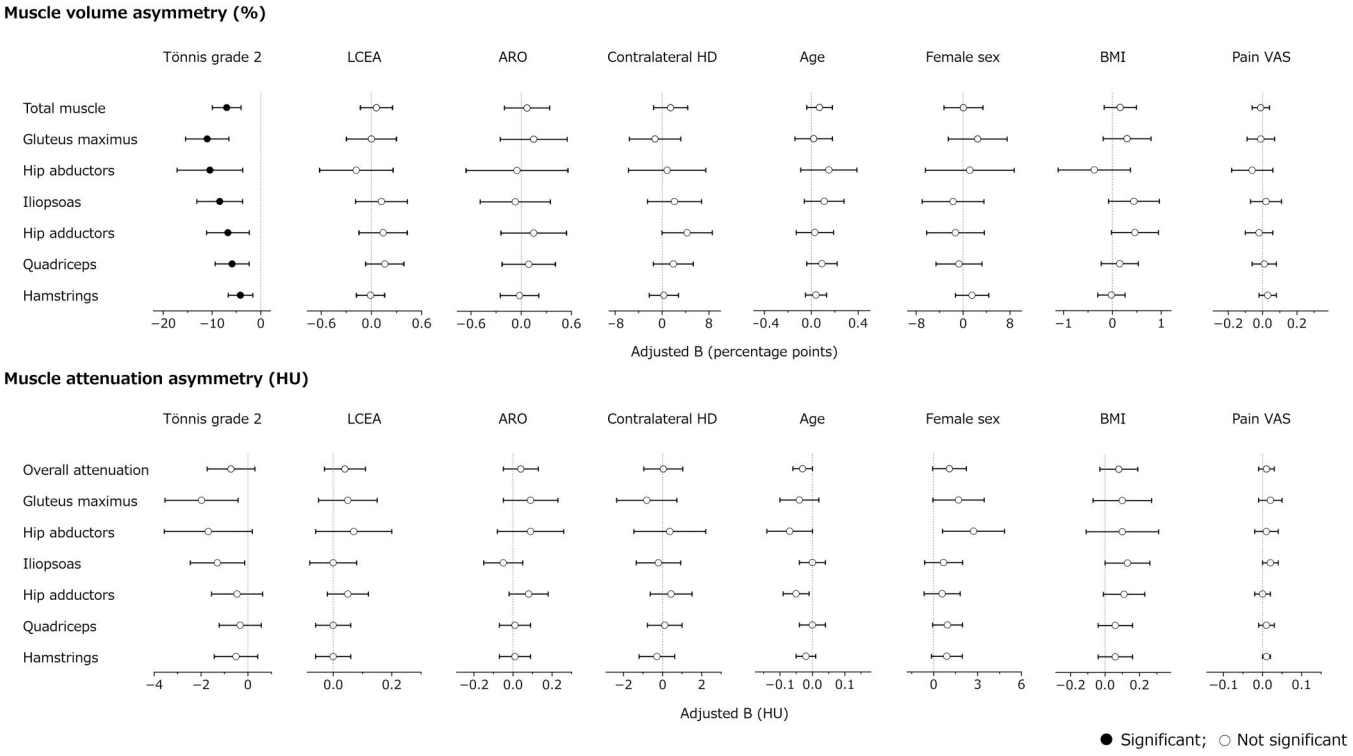


FIGURE 4 | Multivariable associations with muscle volume and attenuation asymmetry. Points represent adjusted unstandardized regression coefficients (B), and horizontal lines indicate 95% confidence intervals. All variables shown were entered simultaneously into each model. Negative coefficients indicate greater symptomatic-side reductions. For the primary outcomes, filled and open circles indicate $p < 0.05$ and $p \geq 0.05$, respectively. For the functional muscle-group outcomes, filled and open circles indicate FDR-adjusted $p < 0.05$ and FDR-adjusted $p \geq 0.05$, respectively. LCEA, lateral center-edge angle; ARO, acetabular roof obliquity; BMI, body mass index; HD, hip dysplasia; VAS, visual analog scale.

side-to-side differences were observed in the quadriceps for muscle volume and in the gluteus maximus for CT attenuation. In addition, Tönnis grade 2 was associated with muscle volume reductions across all six functional muscle groups. These findings suggest that patients with Tönnis grade 2 OA may have widespread muscle volume reduction extending beyond the hip abductors.

4.1 | Muscle Volume and Attenuation Differences Between Sides

Muscle volume was lower on the symptomatic side overall, with a side-to-side difference observed in the quadriceps among the six functional muscle groups. Previous imaging studies in patients with HD have evaluated selected muscles, particularly the gluteal muscles, using cross-sectional measurements [13, 14]. In contrast, our three-dimensional assessment of multiple periarticular hip and thigh muscles demonstrated a reduction in quadriceps volume rather than a change confined to muscles immediately surrounding the dysplastic hip. The quadriceps are important for weight-bearing activities such as rising from a chair, climbing stairs, and walking [24]. Pain-related unloading and reduced use of the symptomatic lower extremity may therefore contribute to quadriceps volume loss, although this mechanism was not directly assessed in the present study. These findings suggest that muscle volume changes in symptomatic HD may involve muscles of the thigh rather than being limited to the periarticular hip musculature.

Mean CT attenuation was lower on the symptomatic side in the gluteus maximus among the six functional muscle groups. Notably, the gluteus maximus showed lower attenuation despite no detectable side-to-side difference in muscle volume. Previous studies in patients with hip OA have also reported reduced muscle radiological density and fatty infiltration of the gluteal muscles [10, 25]. Because skeletal muscle CT attenuation is associated with intramuscular lipid content [26], our findings suggest that compositional muscle changes may be present even when no detectable side-to-side difference in muscle volume is observed. Thus, muscle volume and CT attenuation may reflect different aspects of muscle involvement in symptomatic HD, supporting the assessment of both muscle quantity and quality.

4.2 | Factors Associated With Muscle Volume and Attenuation Asymmetry

Tönnis grade 2 was the factor most consistently associated with muscle volume reduction. It was independently associated with greater symptomatic-side reductions in total assessed muscle volume and in muscle volume across all six functional groups, whereas LCEA and ARO were not associated with either primary outcome. Among the functional groups, the hip abductors showed one of the largest adjusted reductions in muscle volume. Although no overall side-to-side difference in hip abductor volume was observed, Tönnis grade 2 was associated with reduced hip abductor volume. This may reflect dilution of the grade 2 effect by the predominance of patients with Tönnis grade 0 or 1. Thus, the absence of an overall side-to-side difference should not be interpreted as preservation of hip abductor volume across all stages of symptomatic HD. Previous studies in patients with unilateral hip OA have reported that gluteus medius muscle volume is associated with hip abductor strength [25, 27], suggesting that imaging-detected muscle volume loss may have functional relevance. The widespread reductions observed in patients with Tönnis grade 2 suggest that muscle volume changes in symptomatic HD may accompany more advanced OA rather than simply reflect the degree of acetabular undercoverage. Because this study was cross-sectional, however, we cannot determine whether more advanced OA leads to muscle volume loss through pain, altered loading, or reduced activity, or whether reduced muscle volume contributes to disease severity. Although Tönnis grade was associated with both muscle volume and attenuation asymmetry in the Spearman correlation analyses, Tönnis grade 2 was associated only with total muscle volume in the multivariable linear regression analyses. These analyses differed in both statistical approach and predictor coding: Tönnis grade was treated as an ordinal variable in the Spearman analyses, whereas it was dichotomized as grade 2 versus grades 0–1 in the multivariable regression models, which also included adjustment for clinical and radiographic covariates. Therefore, the difference in the attenuation findings cannot be attributed solely to covariate adjustment. This difference was observed despite the absence of substantial multicollinearity among Tönnis grade, LCEA, and ARO. Previous studies have shown that muscle quality varies according to age and sex [28]. Fatty infiltration of periarticular muscles has also been reported in patients with osteonecrosis of the femoral head [29]. These findings suggest that muscle volume showed a more consistent association with advanced OA than CT attenuation in this cohort.

The widespread muscle volume reductions observed in patients with Tönnis grade 2 may also have implications for postoperative recovery after periacetabular osteotomy. Hip muscle strength has been reported to improve after periacetabular osteotomy; however, deficits compared with healthy individuals may persist for 1 year, and recovery may differ among muscle groups [30, 31]. Preoperative OA severity has also been associated with postoperative muscle strength recovery [32]. Although this cross-sectional study cannot determine whether preoperative muscle volume is associated with postoperative outcomes, our findings highlight the need to recognize that muscle volume reduction in patients with more advanced OA may extend beyond the hip abductors to the broader periarticular hip and thigh musculature. Longitudinal studies are needed to determine whether this widespread muscle involvement is associated with postoperative functional recovery and could inform perioperative rehabilitation.

4.3 | Limitations

This study had several limitations. First, its single-center, retrospective, cross-sectional design precluded determination of causal relationships between OA severity and muscle changes. In addition, because the study included patients with symptomatic HD undergoing eccentric rotational acetabular osteotomy, the findings may not be generalizable to all patients with HD. Second, the contralateral side was used as a within-patient reference. Although all contralateral hips were pain-free, 75% had radiographic HD, and potential muscle changes related to acetabular undercoverage could not be completely

excluded despite adjustment for contralateral radiographic HD. Thus, the magnitude of the observed symptomatic-side reductions may have been affected by muscle changes in the contralateral hip. Nevertheless, within-patient comparisons reduced the influence of interindividual differences in age, sex, body size, genetic background, and overall physical activity. Third, muscle strength, gait, and physical activity were not assessed; therefore, the functional relevance of CT-based differences in muscle volume and attenuation remains unclear. Nevertheless, previous studies have reported associations between gluteus medius muscle volume and hip abductor strength [25, 27], suggesting that at least some imaging-detected muscle changes may have functional relevance. Future longitudinal studies incorporating functional assessments are needed to determine whether these muscle changes are associated with postoperative recovery.

5 | Conclusion

AI-based three-dimensional CT analysis demonstrated lower overall muscle volume and attenuation on the symptomatic side. In patients with symptomatic HD undergoing ERAO, Tönnis grade 2 was associated with widespread muscle volume reduction. These findings suggest that patients with more advanced OA may have widespread muscle involvement extending beyond the hip abductors, which should be considered when evaluating muscle status in symptomatic HD.

Author Contributions

Hiroto Funahashi: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, validation, visualization, writing – original draft, writing – review and editing. **Yusuke Osawa:** conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, validation, writing – review and editing. **Hiroaki Ido:** data curation, investigation, resources, validation. **Yasuhiko Takegami:** data curation, investigation, project administration, resources, writing – review and editing. **Keisuke Uemura:** resources, software, visualization. **Yoshito Otake:** resources, software, visualization. **Masaki Takao:** resources, software, visualization. **Shiro Imagama:** conceptualization, supervision, writing – review and editing. All authors have read and approved the final submitted manuscript.

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Ethics Statement

The study protocol was approved by the Faculty of Medicine, Nagoya University (approval No. 2020-0272), and the study was conducted in accordance with the Declaration of Helsinki.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request but are not publicly available due to privacy or ethical restrictions.

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Supporting Information

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Supporting File: jor70318-sup-0001-Supplementary.docx.