Towards defining muscular regions of interest from axial magnetic resonance imaging with anatomical cross-reference: a scoping review of lateral hip musculature

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Abstract

Background: Measures of hip muscle morphology and composition (e.g., muscle size and fatty infiltration) are possible with magnetic resonance imaging (MRI). Standardised protocols or guidelines do not exist for evaluation of hip muscle characteristics, hindering reliable and valid inter-study analysis. This scoping review aimed to collate and synthesise MRI methods for measuring lateral hip muscle size and fatty infiltration to inform the future development of standardised protocols.

Methods: Five electronic databases (Medline, CINAHL, Embase, SportsDISCUS and AMED) were searched. Healthy or musculoskeletal pain populations that used MRI to assess lateral hip muscle size and fatty infiltration were included. Lateral hip muscles of interest included tensor fascia latae (TFL), gluteus maximus, gluteus medius, and gluteus minimus. Data on MRI parameters, axial slice location, muscle size and fatty infiltrate measures were collected and analysed. Cross referencing for anatomical locations were made between MRI axial slice and E-12 anatomical plastinate sections.

Results: From 2684 identified publications, 78 studies contributed data on volume ($n=31$), cross sectional area (CSA) ($n=24$), and fatty infiltration ($n=40$). Heterogeneity was observed for MRI parameters and anatomical boundaries scrutinizing hip muscle size and fatty infiltration. Seven single level axial slices were identified that provided consistent CSA measurement, including three for both gluteus maximus and TFL, and four for both gluteus medius and minimus. For assessment of fatty infiltration, six axial slice locations were identified including two for TFL, and four for each of the gluteal muscles.

Conclusions: Several consistent anatomical levels were identified for single axial MR slice to facilitate muscle size and fatty infiltration muscle measures at the hip, providing the basis for reliable and accurate data synthesis and improvements in the validity of future between studies analyses. This work establishes the platform for standardised methods for the MRI assessment of lateral hip musculature and will aid in the examination of musculoskeletal conditions around the hip joint. Further studies into whole muscle measures are required to further optimise methodological parameters for hip muscle assessment.

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Keywords: Hip muscles, Magnetic resonance imaging, Muscle morphology, Muscle fat infiltration, Manual segmentation

Background
Magnetic resonance imaging (MRI) has been used to assess skeletal muscle morphology and composition for over four decades [1–3]. Assessment of skeletal muscle with MRI can contribute to improved understanding of normal responses to physical activity and changes associated with healthy ageing, muscle injury, and pathology [1, 4]. Advancing MRI technologies, including a range of faster, higher resolution techniques continue to emerge with the aim of improving visualisation and quantification of muscle characteristics [5–7].

The use of MRI to evaluate hip muscle morphology and composition in healthy and musculoskeletal pain populations is becoming more common. Interest in hip muscle size and quality is driven by the knowledge that the muscles spanning the hip joint contribute to hip joint forces [8–10]. The capacity of a muscle to generate force has been linked to its size, including cross sectional area (CSA) and volume [11, 12]. Hip joint forces have, in turn, been associated with joint health, pain and/or other symptoms [13, 14]. How the size and quality of muscles spanning the hip joint contribute to hip joint forces is an area of particular interest [8–10].

The lateral hip muscles including the gluteus maximus, gluteus medius, gluteus minimus and the tensor fascia latae (TFL) generate forces around the hip joint for both movement and stability, particularly in single leg stance and during gait [15–18]. In people with musculoskeletal hip pain, several studies have demonstrated muscle atrophy and increased intramuscular fatty infiltration of the lateral hip muscles when compared to age-matched controls and asymptomatic contralateral limb [19–25]. As such, muscle size and fatty infiltration present as possible targets for interventions. Preliminary evidence indicates that these muscles can respond to exercises targeting the hip and other regions [26–28]. Further work assessing size and adiposity of these muscles will help to establish the most responsive type and dose of exercise to use, as well as the relationship to symptom recovery.

Recent systematic reviews have highlighted heterogeneity and inconsistencies in published MRI methods designed to assess muscle size and composition of the lateral hip muscles [7, 17, 29]. Common to all studies remains the challenges of accurately differentiating and consistently measuring the borders of individual muscles on conventional MRI which may lead to difficulties in comparing results. For the lateral hip muscles, the individual gluteal muscle borders are difficult to identify at the region between the upper border of the acetabulum and the superior tip of the greater trochanter [26, 30]. The use of high-resolution E-12 anatomical plastinates alongside MRI, may improve the ability to visualise anatomical regions by comparing and identifying key features at specific locations [5, 31, 32]. Currently, there is an urgent need for robust and reproducible MRI methods for identifying, measuring, and interpreting hip muscle images, particularly to enable comparison of results across studies and data pooling.

The primary aim of this review was to define standardised MRI methods for assessing lateral hip muscle size and fatty infiltration. A secondary aim was to provide illustrative anatomical comparisons between MRI and high-resolution E-12 anatomical plastinates using standardised locations as determined from the literature to improve visibility of muscle borders.

Method
This review followed the PRISMA guideline extension for scoping reviews [33, 34] and was prospectively registered on the open science framework platform (https://osf.io/5nyuq/).

Search strategy
Five electronic databases (Medline, CINAHL, Embase, SportDISCUS and AMED) were searched from inception up to Nov 1st 2021. No language limits were placed. Search terms were mapped to three main concepts; (i) Magnetic resonance imaging, (ii) lateral hip muscles (i.e., TFL, gluteus maximus, gluteus medius and gluteus minimus) and, (iii) muscle morphology and composition (i.e. muscle size and fatty infiltration). Synonyms within each concept were mapped to subject headings, where possible, or searched under title, abstract and/or keywords. Results within each concept were combined with ‘OR’ and between concepts combined with ‘AND’ (Additional file 1).

The search strategy was modified according to the specifications of each database. Manual citation tracking and reference checking of included articles was performed. Ahead of print lists of journals included in the study were screened for additional studies. Grey literature, such as internal reports and conference proceedings, were searched for further eligible studies.

Titles and abstracts of studies retrieved from the databases, as well as those identified from reference-checking and citation-tracking, were screened for eligibility by two
reviewers (ZP and CS). Any disagreements in the eligibility of a study were discussed and a consensus reached with the aid of a third reviewer (AS). The final yield was exported into Covidence online software (www.covidence.org) for eligibility screening against inclusion and exclusion criteria.

**Inclusion/exclusion criteria**
Studies with participants of any age and either healthy or musculoskeletal pain populations were included. People with cancer, neuromuscular and neurological conditions, were excluded as well as those undergoing cosmetic surgery. All MRI investigations which assessed lateral hip muscle size and/or fatty infiltrate were included. Studies were excluded if muscles were assessed as a group rather than reported individually (e.g., gluteals) and if using other imaging modalities (e.g., ultrasound) without comparison to MRI. In line with previous publications establishing regions of interest in axial images [5, 31, 35], studies using axial MRI slices for size and fatty infiltration measures were included. All published peer-reviewed studies were included; opinion pieces/editorials, systematic reviews, narrative reviews, conference abstracts and single case studies were excluded.

For our secondary aim, axial MRI images were compared to E12 anatomical plastinate sections at corresponding anatomical levels to illustrate differences, and thus identify regional morphology. The E12 anatomical plastinate sections used in this study are part of the anatomy collection, in the WD Trotter Anatomy Museum at the University of Otago. Approval to use images of the E12 plastinate sections was granted by the Department of Anatomy, University of Otago. Digital photographs were acquired of selected E12 specimens that were appropriate for the anatomical regions included in this study.

**Risk of bias (quality) assessment**
The primary aim of this review was to report MRI methods rather than individual study results. As such, and in line with the PRISMA extension for scoping reviews (PRISMA-ScR) checklist [34, 36], a risk of bias assessment was not conducted.

**Data extraction**
A standardised data extraction form was used to extract data relating to the individual study characteristics (study purpose, design [37], population, sample size). Countries and institution affiliations of corresponding author were recorded. Details on MRI parameters (e.g. scanner field strength, manufacturer, MRI sequence, slice selection & thickness), specific lateral hip muscles assessed, and details of size (volume and CSA) and fatty infiltration outcomes were collected by two authors (ZP and NF). Any discrepancies were discussed between authors and conflicts resolved by a third author (AS) if required.

Intraclass correlation coefficient (ICC) and the kappa coefficient (\(k\)) statistic are frequently used as a measure of intra- and inter-rater reliability and were collected to assess consistency of the MRI methodology between included studies [38, 39]. ICC values were interpreted as values less than 0.5 as poor reliability, 0.5 -0.75 as moderate reliability, 0.75 -0.9 as good reliability, and values greater than 0.90 as excellent reliability [38]. Kappa coefficient were interpreted as values \(\leq 0.20\) as none to slight, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as substantial, and 0.81–1.00 as almost perfect agreement [40]. Other measures of reliability were not collected.

**Analysis/synthesis**
Descriptive statistics were used to summarize findings across studies for MRI parameter and anatomical locations for regions of interests. Data for muscle size were grouped into volume and CSA. Fatty infiltration measures were grouped into qualitative and quantitative methods. Qualitative measures could include the Goutallier classification system [41], which grades muscle according to the relative amount of fatty tissue that is present, progressing from 0 (regular muscular tissue, no intramuscular fat) to 4 (more fat than muscle), and the Quartile classification [42] which also adopts a 5-step grading system (0%, 25%, 50%, 75% or 100%) to define the percentage of fatty tissue that is present. Quantitative measures could include various calculations incorporating fat-value pixels.

Anatomical levels for measuring CSA and fatty infiltration were collected. When a single anatomical level contained multiple anatomical features, the most easily identifiable and distinguishable anatomical feature on axial MRI slice was extracted. Axial MRI DIXON sequence images and E12 anatomical plastinate sections were cross referenced. Anatomical levels were compared on a 3D MRI image.

**Results**
The initial search identified 2,684 studies, from which 1,614 duplicates were removed with a further 813 removed after title and abstract screening. An additional 176 were removed following full text screening, which resulted in 78 studies from 81 publications that met the inclusion criteria (Additional file 2 and 3).

**Trends in publication of MRI studies: 1992 to 2020**
Frequency of publication of MRI studies has increased steadily since 1992, growing from one study [43] to 12 in 2020 [44–55] (Fig. 1A). Across the included studies, 17 countries were represented: Australia (n = 16), Japan...
(n = 11), Germany (n = 10), USA (n = 10), United Kingdom (n = 7), Switzerland (n = 5), Finland (n = 4), France (n = 3), Netherlands (n = 3), Spain (n = 3), China (n = 2), Turkey (n = 2), Canada (n = 1), New Zealand (n = 1), Norway (n = 1), Poland (n = 1). Twelve institutions featured across two studies, and four institutions featured in more than two studies (Charité University Medicine, Germany n = 9 [42, 56–62]; La Trobe University, Australia [19, 21, 22, 63] n = 4, Royal National Orthopaedic Hospital, UK n = 3; The University of Queensland, Australia n = 3 [23, 24, 63]) A range of study designs were used including nine randomised controlled trials, 33 prospective cohort, 10 retrospective cohort, 15 case–control and 10 case series study designs (Fig. 1B).

**Patient and non-patient populations**

Twenty-three studies across 25 publications investigated hip related musculoskeletal pain (e.g., hip osteoarthritis, lateral hip pain and intra-articular hip joint pathologies) (Fig. 1C). Three studies examined non-hip related musculoskeletal pain which included low back pain [64, 65] and patellofemoral joint osteoarthritis [66]. Twenty-nine studies, across 33 publications, used healthy comparison groups and 26 studies explored one of three surgical presentations (i.e., total hip arthroplasty, hip arthroscopy and surgical correction for hip dysplasia) (Fig. 1C). Gluteus medius was the most frequently assessed lateral hip muscle (Fig. 1D). Fifty-four studies measured muscle size and 40 studies investigated fatty infiltration (Table 1).

**Measurement of muscle size and quality**

Thirty-six studies reported the profession of the individual(s) interpreting MRIs and calculating size and fatty infiltration measures. The most frequently cited professionals were radiologists (31 studies) with 15 studies reporting radiologists with further training in musculoskeletal presentations. Other health professionals included orthopaedic surgeons and physiotherapists. Ten studies [44, 65, 67–74] reported years of experience for those who interpreted the MRIs, which ranged from 1 to 28 years.

ICC or kappa scores were reported in 33 studies (42%). For size measures, ICC scores reflected moderate to excellent reliability, with data ranging from 0.75 to 1.00 for intra-reliability and 0.70 to 0.99 for inter-reliability. Fatty infiltration ICC values indicated moderate to excellent reliability with scores ranging from 0.75 to 0.99 for intra-rater reliability and 0.70 to 0.99 for inter-rater
Table 1  MRI parameters for individual studies

| Citation               | Field Strength (Tesla) | Axial MRI Sequence                  | Slice thickness (mm) (Gap) | MRI slice selection range                                                                 | Muscle of interest | Size | Fat | Reliability (Kappa Score/ ICC) |
|------------------------|------------------------|-------------------------------------|---------------------------|-------------------------------------------------------------------------------------------|--------------------|------|-----|-------------------------------|
| Ackland et al., 2019 [66] | 3                      | ● T2- FS (water excitation) ● MEDIC | 1 (NR)                    | Sacral promontory to the inferior aspect of the pubic arch (~ 200 slices)                   | TFL Gmed Gmin      | ✓    |     | Intra-rater ICC = 0.997 (Gmin), 0.999 (Gmed), 1.00 (TFL) 5 randomly selected participants, re-evaluated, least 1 month apart |
| Agten et al., 2017 [68] | 1.5                    | ● STIR & optimized inversion pulse ● T1 | 7 & 6 (no gap)            | NR                                                                                       | TFL Gmax Gmed Gmin | ✓    |     | Inter-rater k = 0.548          |
| Amabile et al., 2017 [104] | 1.5          | ● T1 TSE                                           | 5 (no gap)                | Sacrum (S1) to femoral condyles                                                           | TFL Gmax Gmed Gmin | ✓    |     | NA                           |
| Arokoski et al., 2002 [82] | 1.5                    | ● T1 TSE                                           | NR                        | NR                                                                                       | TFL Gmax Gmed Gmin | ✓    |     | NA                           |
| Belzunce et al., 2020a [52] | 3                      | ● T1 TSE ● DIXON                        | 1.5 (0.45)                | 3 cm below the lesser trochanter to the top of the iliac crest                            | Gmax               | ✓    |     | NA                           |
| Belzunce et al., 2020b [53] | 3                      | ● T1 TSE ● DIXON                        | 1.5 & 3 (1.95 & 3.3)      | Pelvis                                                                                   | TFL Gmax Gmed Gmin | ✓    |     | NA                           |
| Belzunce et al., 2021 [91] | 3                      | ● DIXON                                               | 1.5 (1.95)                | 1 cm below the lesser trochanter to the top of the iliac crest                            | Gmax               | ✓    | ✓   | NA                           |
| Berber et al., 2015 [122] | NA                     | ● T1 TSE ● T2 TSE                              | NR                        | NR                                                                                       | Gmax               | ✓    |     | Inter-rater k = 0.0463        |
| Bravo et al., 2013 [90]  | 1.5                    | ● T1                                                 | 5 (no gap)                | NR                                                                                       | Gmax               | ✓    |     | NA                           |
| Bremer et al., 2011 [93] | 1.5                    | ● T1 SE                                              | NR                        | NR                                                                                       | TFL Gmed Gmin      | ✓    |     | NA                           |
| Burian et al., 2020 [54] | 3                      | ● MEDIC                                           | 1.5 (NR)                  | Gluteal region                                                                           | Gmax               | ✓    |     | NA                           |
| Chi et al., 2015 [72]   | 1.5                    | ● T1 SE ● T2-FSE fat-saturated                         | 4–5 (1)                  | ASIS to the ischia (including both hips)                                                | Gmed Gmin          | ✓    |     | NA                           |
| Citation                  | Field Strength (Tesla) | Axial MRI Sequence | Slice thickness (mm) | MRI slice selection range | Muscle of interest | Size | Fat | Reliability (Kappa Score/ ICC) |
|--------------------------|------------------------|--------------------|----------------------|---------------------------|-------------------|------|-----|--------------------------------|
| Cowan et al., 2019 [19]  | 3                      | ● T1               | 4 (NR)               | Top of the iliac crest to the lesser trochanter | TFL               |      |     | ✅ Intra-rater ICC: [Size] = 0.999 |
|                          |                        | ● PD- with and without fat saturation                  |                      |                            | Gmax             |      |     |                                |
|                          |                        |                   |                      |                            | Gmed             |      |     |                                |
|                          |                        |                   |                      |                            | Gmin             |      |     | 10 randomly selected muscles, re-evaluated, 6 months apart |
| De Anta-Díaz et al., 2016 [94] | 1.5                  | ● T1 SE            | 3–4 (NR)             | NR                        | TFL              |      |     | ✅ NA                                 |
|                          |                        | ● STIR             |                      |                            | Gmax             |      |     |                                |
|                          |                        |                   |                      |                            | Gmed             |      |     |                                |
|                          |                        |                   |                      |                            | Gmin             |      |     |                                |
| Dorado et al., 2020 [51] | 1.5                    | ● NR               | 8 (2)                | Trunk and pelvis           | Gmax             |      |     | ✅ NA                                 |
| Ebert et al., 2019 [71]  | 1.5                    | ● T2 fat-saturated | 3.5 (NR)            | NR                        | Gmed             |      |     | ✅ Inter-rater k: Ranged from 0.855 (middle portion Gmed) to 0.913 (anterior portion of the Gmin) First 41 consecutive MRI scans were evaluated |
|                          | 3                      |                   |                      |                            | Gmin             |      |     |                                |
| Emery et al., 2019 [86]  | 3                      | ● PD FSE          | 4 (1.5)             | NR                        | TFL              |      |     | ✅ Intra-rater ICC (TFL) = 1.0 (CI: 1.000, 1.000) 10 randomly selected participants, re-evaluated, 6 weeks apart |
| Engelken et al., 2014 [42] | 1.5                | ● T1 SE           | 4–6 (NR)            | The pelvis                | Gmax             |      |     | ✅ Intra-rater (3 observers) Quartile classification: k = 0.90, 0.90, 0.92 Goutallier classification: k = of 0.81, 0.72, 0.77 |
| Flack et al., 2012 [73]  | 1.5                    | ● T1 PD           | 4 (NR)              | The highest point of iliac crest superiorly to the base of the lesser trochanter | TFL              |      |     | ✅ Intra-rater ICC: 0.979–0.996 (GMed), 0.886–0.995 (GMin), 0.950–0.994 (TFL) |
|                          |                        | ● T1 3D-fast field echo |                    |                            | Gmed             |      |     |                                |
|                          |                        |                   |                      |                            | Gmin             |      |     |                                |
| Franettovich-Smith et al., 2017 [33] | 3                      | ● T2 | 5 (6) | Top of the iliac crest to the inferior gluteal fold | Gmax             |      |     | ✅ NA                                 |
| Gerber et al., 2007 [123] | 1.5                    | ● T1 SE           | 8 (15)              | NR                        | Gmax             |      |     | ✅ Intra-rater ICC > 0.99 |
|                          |                        |                   |                      |                            | Gmed             |      |     |                                |
| Citation | Field Strength (Tesla) | Axial MRI Sequence | Slice thickness (mm) | MRI slice selection range | Muscle of interest | Fat Size | Reliability (Kappa Score/ICC) |
|----------|-----------------------|--------------------|---------------------|--------------------------|-------------------|---------|-------------------------------|
| Grimaldi et al., 2009 [23] | 1.5 | T2 FSE | 6 (NR) | Iliac crest to the ankle joint | TFL | NA | NA |
| Grimaldi et al., 2009 [24] | 1.5 | T2 FSE | 6 (NR) | Iliac crest to the most distal extent of the Gmax muscle | TFL | NA | NA |
| Handsfield et al., 2014 [105] | 3 | 2D multi-slice sequence utilising spiral gradient echo (NR) | 5 (NR) | Iliac crest to the ankle joint | TFL | NA | NA |
| Homma et al., 2019 [106] | NA | T1 FSE | 3 (0.5) | Iliac crest to the head of the fibula | TFL | NA | NA |
| Jaegers et al., 1992 [43] | 1.5 | SE | 5 (0.5) | Iliac crest to the ankle joint | TFL | NA | NA |
| Jaegers et al., 1995 [124] | 1.5 | T1 turbo spin echo | 6 (NR) | Iliac crest to the head of the fibula | TFL | NA | NA |
| Kawasaki et al., 2017 [75] | 1.5 | T1 turbo spin echo | 6 (NR) | Iliac crest to the ankle joint | TFL | NA | NA |
| Kheterpal et al., 2020 [44] | 3 | FSE PD | 3-4 (NR) | Pelvic region | Graud | NA | NA |
| Kim et al., 2014 [74] | 3 | T2 FSE | 5 (NR) | Pelvic region | Graud | NA | NA |
Table 1 (continued)

| Citation                  | Field Strength (Tesla) | Axial MRI Sequence | Slice thickness (mm) (Gap) | MRI slice selection range | Muscle of interest | Size | Fat | Reliability (Kappa Score/ ICC) |
|---------------------------|------------------------|--------------------|---------------------------|---------------------------|-------------------|------|-----|--------------------------------|
| Kivle et al., 2018 [67]   | 1.5                    | ● T1 SE ● STIR     | 5 (NR)                    | Pelvis                    | Gmed Gmin         | ✓    | ✓   | Intra-rater ICC [size]: 0.970 [CI: 0.91–0.99] (Gmed), 0.930 [CI: 0.84–0.97] (Gmin) Inter-rater ICC [size]: 0.980 [CI: 0.82–0.99] (Gmed), 0.950 [CI: 0.90–0.97] (Gmin) k [Fat]: mean score = 0.23 All participants re-evaluated, 8 weeks apart for intra-rater reliability “The interobserver reliability … were calculated on the basis of the first evaluation.” |
| Kiyoshige et al., 2015 [125] | 1.5                   | ● T1               | NR                         | NR                        | Gmax Gmed Gmin     | ✓    | NA  | Intra-rater (3 observers) k(Quartile): 0.91, 0.89, 0.85 k(Goutallier): 0.88, 0.84, 0.81 k(Bal & Lowe): 0.83, 0.77, 0.75 Inter-rater ICC (Goutallier): range 0.84–0.91 ICC (Quartile): range 0.87–0.94 ICC (Bal and Lowe): range 0.79–0.88 |
| Klemt et al., 2021 [120]  | 1.5                    | ● T1 TSE           | 4 (NR)                    | Pelvis                    | Gmax Gmed Gmin     | ✓    | ✓   | Intra-rater ICC (Size) = 0.99 [CI: 0.99–0.99] 10 participants, re-evaluated, more than 3 months apart |
| Koch et al., 2021 [26]    | 3                      | ● T1 VIBE-DIXON    | 1.1 (NR)                  | Centred at the pelvis     | Gmax Gmed Gmin     | ✓    | ✓   | Intra-rater ICC [size] = 0.99 [CI: 0.99–0.99] |
| Kovalak et al., 2018 [95] | 1.5                    | ● T1 TSE           | 3.5 (1)                   | NR                        | Gmed Gmin         | ✓    | NA  | |
| Kubo et al., 2019 [126]   | 1.5                    | ● T1 SE            | 10 (no gap)               | The anterior superior iliac spine to distal tibia | Gmax              | ✓    | NA  | |
| Loureiro et al., 2018 [76] | 3                      | ● T1 2D gradient-recall acquisition in the steady state | 10 (1)                    | Approx. 2 cm superior to the iliac crest to approx. 2 cm inferior to the proximal tibia-fibula joint | TFL Gmax Gmed Gmin | ✓    | ✓   | Intra-rater (for all muscles) ICC > 0.985 All image slices for a single randomly selected participant, re-evaluated, 2 weeks apart |
| Citation                | Field Strength (Tesla) | Axial MRI Sequence | Slice thickness (mm) (Gap) | MRI slice selection range | Muscle of interest | Size | Fat | Reliability (Kappa Score/ ICC) |
|------------------------|------------------------|--------------------|-----------------------------|--------------------------|-------------------|------|-----|-------------------------------|
| Makridis et al., 2014  | NA                     | T1                 | 4–5 (NR)                    | NR                       | Gmed Gmin         | ✓    | ✓   | NA                            |
| Malloy et al., 2019    | 1.5                    | T1 FSE             | 4 (5)                       | iliac crest to the level of the knee joint | TFL Gmax Gmed Gmin | ✓    |     | Inter-rater ICC = 0.989 (CI: 0.985–0.992) 20 MRI measurements reviewed by 2 raters* |
| Marcon et al., 2016    | 3                      | 3-point mDIXON     | NR (no gap)                 | iliac crest to ischial tuberosity | Gmax Gmed Gmin | ✓    | ✓   | Intra-rater ICC (Size) = 0.900 (CI: 0.78–0.95) "... for the first ten measurements" |
| Mastenbrook et al., 2017 | 1.5                  | 3D FS gradient-echo | 0.82 (no gap)              | Pelvis (ASIS to acetabulum) | TFL Gluteals (as a group) | ✓    |     | Intra-rater ICC(TFL) = 0.990 (CI: 0.99, 1.00) 20 participants re-evaluated, 2 weeks apart |
| Masuda et al., 2003    | 1.5                    | NR                 | 5 (15)                      | ASIS to the head of the fibula | Gmax Gmed Gmin | ✓    |     | NA                            |
| Mendis et al., 2014    | 1.5                    | T2 FISP            | 8 (8.8)                     | iliac crest to just below the lesser trochanter of the femur | TFL | ✓    |     | Intra-rater ICC Range: 0.940-1.000 (CI: 0.78, 0.99) "Assessed in 10 randomly selected subjects" |
| Mendis et al., 2016    | 1.5                    | T2 FISP            | 7 (10.5)                    | Top of the iliac crest to the hip joint | Gmed Gmin | ✓    |     | Intra-rater ICC Range: 0.970-0.990 (CI: 0.81–0.99) "Assessed in 10 randomly selected subjects" |
| Mendis et al., 2020    | 1.5                    | T2 FISP            | 8 (8.8)                     | iliac crest to below the lesser trochanter of the femur | Gmax Gmed Gmin | ✓    |     | Intra-rater ICC Range: 0.950–0.990 (CI: 0.90, 0.99) "Assessed in 5 randomly selected subjects" |
| Miller et al., 2020    | 3                      | T1                 | 5 (5)                       | abdomen, thigh, and shank | TFL Gmax Gmed Gmin | ✓    |     | NA                            |
Table 1 (continued)

| Citation                        | Field Strength [Tesla] | Axial MRI Sequence | Slice thickness (mm) | MRI slice selection range                                                                 | Muscle of interest | Size | Fat | Reliability (Kappa Score/ ICC) |
|---------------------------------|------------------------|--------------------|----------------------|------------------------------------------------------------------------------------------|-------------------|------|-----|--------------------------------|
| Miokovic et al., 2011 [62]      | 1.5                    | ● NR               | 6 (0.6)              | From the iliac crest to the inferior-most portion of the gluteus maximus with a second sequence overlapping the gluteus maximus and extending to the knee joint line | Gmax Gmed Gmin    | ✓    | NA  |                                |
| Montefiori et al., 2020 [55]    | 1.5                    | ● TI               | 3 (NR)               | NA                                                                                        | TFL Gmax Gmed Gmin| ✓    | NA  |                                |
| Muller et al., 2010 [56]        | 1.5                    | ● T1 TSE           | 6 (NR)               | From the iliac crest to the inferior-most portion of the gluteus maximus with a second sequence overlapping the gluteus maximus and extending to the knee joint line | Gmin              | ✓    | NA  |                                |
| Muller et al., 2011a [58]       | 1.5                    | ● T1 TSE ● TIRM    | 6 (NR)               | Gmed Gmin                                                                                 |                   |      |     |                                |
| Muller et al., 2011b [57]       | 1.5                    | ● TI               | 6.5 (1.8)            | From the most proximal aspect of the femoral head to the distal-most aspect of the greater trochanter | Gmed              | ✓    | NA  |                                |
| Niinimäki et al., 2016 [129]    | 1.5                    | ● T1 VIBE          | 1 (no gap)           | Gmax                                       |                   |      |     |                                |
| Niinimäki et al., 2019 [130]    | 1.5                    | ● T1 VIBE          | 1 (no gap)           | From the most proximal aspect of the femoral head to the distal-most aspect of the greater trochanter | Gmax              | ✓    | NA  |                                |
| Peiris et al., 2020 [46]        | 3                      | ● T1 2D FSE        | 10 (NR)              | Gmax Gmed Gmin                              |                   |      |     |                                |
| Pfirrmann et al., 2005 [69]     | 1.5                    | ● STIR ● T1 SE     | 3–4 (NR)             | Gmed Gmin                                   |                   |      |     |                                |
| Reito et al., 2016 [131]        | 1.5                    | ● T1 FSE ● STIR    | 6.5 (1.8)            | Gmax Gmed Gmin                              |                   |      |     |                                |
| Rodríguez-Roiz et al., 2017 [70]| 1.5                    | ● T1               | 5 (NR)               | TFL                                         |                   |      |     |                                |
| Citation                 | Field Strength (Tesla) | Axial MRI Sequence | Slice thickness (mm) (Gap) | MRI slice selection range | Muscle of interest | Size | Fat | Reliability (Kappa Score/ ICC) |
|-------------------------|------------------------|--------------------|---------------------------|--------------------------|-------------------|------|-----|-------------------------------|
| Rothwell et al., 2019 [132] | 3                      | ● T1 SE            | 5 (no gap)                | NR                       | TFL Gmax Gmed Gmin | ✓    |     | intra-rater (for all muscles) ICC (within session): 0.970 ± 0.030 ICC (between sessions): 0.960 ± 0.030 ICC (> 6 months): 0.91 ± 0.09 Multiple occasions, both within- and between sessions, minimum 12h apart and up to 6 months |
| Ruckenstuhl et al., 2020 [49] | NR                     | ● MARS             | NR                        | NR                       | Gmed              | ✓    | NA  |                               |
| Rykov et al., 2021 [92]   | 1.5                    | ● T1               | NR                        | NR                       | Gmed              | ✓    | NA  |                               |
| Rykov et al., 2021 [92]   | 1.5                    | ● STIR             | NR                        | NR                       | Gmed              | ✓    | NA  |                               |
| Sakamaki et al., 2011 [133] | 1.5                    | ● T1 SE            | 10 (no gap)               | From the first cervical vertebra to the ankle joint | Gmax              | ✓    | NA  |                               |
| Semoiwet et al, 2016 [63] | 1.5                    | ● T1               | 6 (no gap)                | From above the iliac crest to just below the distal aspect of the TFL | Gmed Gmin | ✓    | NA  |                               |
| Skorupska et al, 2016 [65] | 1.5                    | ● T2               | 4 (no gap)                | From the lumbar spine down to pelvis and upper thigh | Gmax              | ✓    | Inter-rater ICC: > 0.900 for all muscles except (R) Gmed = 0.848 |
| Springer et al, 2012 [59] | 1.5                    | ● T1 TSE           | 6 (NR)                    | NR                       | Gmed Gmin         | ✓    | NA  |                               |
| Sugisaki et al, 2018 [106] | 1.5                    | ● T1 echo          | 7 (15)                    | From the first lumbar vertebra (L1) to the lateral malleolus of the fibula | TFL Gmax Gmed Gmin | ✓    | Intra-rater ICC = 0.999 Repeated twice for 7 participants |
| Sutter et al, 2013 [85]   | 1.5                    | ● T1               | NR                        | NR                       | TFL Gmed Gmin     | ✓    | ✓   | inter-rater ICC [Size & Fat] Range: 0.700–0.980 |
| Takada et al, 2018 [80]   | 1.5                    | ● T1               | NR                        | NR                       | TFL Gmed Gmin     | ✓    | ✓   | inter-rater ICC [Size & Fat] Range: 0.700–0.980 |
| Citation                | Field Strength (Tesla) | Axial MRI Sequence | Slice thickness (mm) | MRI slice selection range | Muscle of interest | Size | Fat | Reliability (Kappa Score/ ICC) |
|------------------------|------------------------|--------------------|----------------------|---------------------------|-------------------|------|-----|--------------------------------|
| Takada et al., 2021 [81] | 1.5                    | ● T1               | 1.5 (NR)             | Lower pelvis & hips       | TF                |     | ✓  | Intra-rater ICC [Size & Fat] Range: 0.750–0.980 Inter-rater ICC [Size & Fat] Range: 0.750–0.980 |
| Takahashi et al., 2019 [79] | 1.5                    | ● T1               | 6 (4)                | Trunk and hip             | Gmax              |     | ✓  | Intra-rater for all muscles ICC > 0.987 |
| Tesch et al., 2005 [88] | 1, 1.5                 | ● NR               | 10 (NR)              | NR                        | Gmax              |     | ✓  | NA |
| Thaunat et al., 2018 [96] | NA                     | ● T1 non-FS        | NR                   | NR                        | Gmed              |     | ✓  | NA |
| Tran et al., 2021 [121] | 3                      | ● T1 2-point Dixon | 4 (NR)              | T11 vertebral level to the inferior-most portion of the Gmax | Gmax              |     | ✓  | Intra-rater ICC Range [Size]: 0.938–0.994 (CI: 0.905–0.999) All participants, re-evaluated, at least 7 days apart |
| Unis et al., 2013 [87]  | 1.5                    | ● STIR             | NR                   | Lower pelvis and both hips | TFL               |     | ✓  | NA |
| Vasarhelyi et al., 2020 [48] | NR                  | ● T2               | NR                   | NR                        | TFL               |     | ✓  | NA |
|                          |                        | ● STIR             |                       |                           |                   |     |     |                                |
| von Roth et al., 2014 [60] | 1.5                    | ● T1 TSE           | 6 (NR)               | NR                        | Gmed              |     | ✓  | NA |
| Winkler et al., 2018 [61] | NA                     | ● T1               | 5 (NR)               | NR                        | Gmed              |     | ✓  | NA |
| Yang et al., 2021 [83]   |                        | ● T2 FS PD         | 3.5 (NR)             | Hip                       | TFL               |     | ✓  | Intra-rater ICC [Gmax- pre-op]: 0.985 (CI: 0.974–0.991) ICC [Gmax post-op]: 0.934 (CI: 0.885–0.963) ICC [Gmin pre-op]: 0.910 (CI: 0.862–0.953) ICC [Gmin post-op]: 0.951 (CI: 0.915–0.972) Re-evaluated, 2 months apart |
| Yasuda et al., 2014 [84] | 1.5                    | ● T1 SE            | 10 (no gap)          | From the top edge of the great trochanter to the lateral condyle of femur | Gmax              |     | ✓  | NA |
| Citation                          | Field Strength (Tesla) | Axial MRI Sequence | Slice thickness (mm) (Gap) | MRI slice selection range          | Muscle of interest | Size | Fat | Reliability (Kappa Score/ ICC) |
|----------------------------------|------------------------|--------------------|---------------------------|-----------------------------------|-------------------|------|-----|-------------------------------|
| Yuksel et al., 2009 [134]        | 1.5                    | ● T1               | NR NR                     | TFL Gmax                          | ✓                 |      |     | NA                            |
| Zacharias et al., 2016 [22]      | 3                      | ● T1 FSE           | 6 (no gap)                | Iliac crest to distal insertion of TFL | ✓                 | ✓    |      | Inter-rater ICC [Size] Range: 0.800–0.980 ICC [Fat] = 0.900 5 participants, 2 observers |
| Zacharias et al., 2018 [21]      |                        |                    |                           |                                   |                   |      |     |                               |
| Zhao et al. 2020 [47]            | 3                      | ● T2               | NR NR                     | TFL Gmax Gmed Gmin                | ✓                 | ✓    |     | NA                            |

CI 95% Confidence Interval, FISP true Fast Imaging with Steady State Precission, FS Fat Supressed, FSE Fast Spin Echo, Gmax Gluteus maximus, Gmed Gluteus medius, GMin Gluteus Minimus, MARS Metal Artifact Reduction Sequence, MEDIC Multi-echo Data Image Combination, NA Not Assessed, NR Not Reported, PD Proton Density, Pre-op Pre-operative, Post-op Post-operative, SE Spin Echo, SPAIR Spectral Attenuated Inversion Recovery, STIR Short Tau Inversion Recovery, T1 T1 weighted, T2 T2 weighted, TFL Tensor Fascia Latae, TSE Turbo Spin Echo, TIRM Turbo-inversion Recovery Magnitude, VIBE gradient echo Volumetric Interpolated Breath-hold
### Table 2: Volume measurement outcomes for individual studies

| Citation | Muscle segmentation: Manual/ automatic | Volume Full/partial | Software used | Equation |
|----------|---------------------------------------|---------------------|---------------|----------|
| Ackland et al. 2019 [66] | Semi-automatic | Full (excl. fat) | Amira FEI (V 5.3.3, FEI Visualization Sciences Group) | Estimated from CSAs, multiplied by slice thickness, normalised to body weight |
| Amabile et al. 2017 [104] | Manual | Full | Imaging software developed by researchers' institution | “Volume” was normalized to subject height |
| Belzunce et al., 2020 [52] | Automatic & Manual | Partial (excl. top & bottom extremes, & fat) | Simpleware ™ (V 2018.12, ScanIP) | Estimated from CSAs |
| Belzunce et al., 2021 [91] | Automatic | Full | Simpleware ™ (V 2020.6, ScanIP) | Estimated from CSAs, normalised to body weight |
| Cowan et al., 2019 [19] | Manual | Full | 3D-DOCTOR (Able Software Corp.) | Estimated from CSAs, multiplied by slice thickness |
| Dorado 2020 et al., 2020 [51] | Manual | Full | Slice O’matic (V 4.3, Tomovision Inc) | Estimated from CSAs |
| Flack et al., 2012 [73] | Semi-automatic | Full (excl. fat) | OsiriX package (V 2.7.5) | Estimated from CSAs, multiplied by slice thickness |
| Franettovich Smith et al., 2017 [135] | Manual | Full | OsiriX package (V 5.7) | Estimated from CSAs, multiplied by slice thickness |
| Grimaldi et al., 2009a [23] | Manual | Full | Osiris package (V 4.19) | Estimated from CSAs, multiplied by slice thickness |
| Handsfield et al., 2014 [105] | Manual | Full | Software written in Matlab (The Math works Inc.) | Estimated from CSAs with normalised to body mass & height |
| Homma et al., 2019 [107] | Manual | Full | ZedHip (Lexi Co., Ltd) | Estimated from CSAs, multiplied by slice thickness |
| Jaegers et al., 1992 [43] | Manual | Full | Obex (Cerebrum) | Estimated from CSAs |
| Jaegers et al., 1995 [124] | Manual | Full | Obex (Cerebrum) | Estimated from CSAs |
| Koch et al., 2021 [26] | Manual | Partial | ITK-Snap Software (V 3.6) | Estimated from CSAs |
| Kubo et al., 2019 [126] | Manual | Full | OsiriX package (DICOM image analysis) | Estimated from CSAs, multiplied by slice thickness |
| Loureiro et al., 2018 [76] | Semi-automatic | Full | Mimics | Estimated from CSAs |
| Makridis et al., 2014 [127] | Manual | Full | NR | Estimated from CSAs, multiplied by slice thickness |
| Marcon et al., 2016 [89] | Semi-automatic | Full (excl. artifacts) | Myrian 1 (Intrasense) | Estimated from CSAs |
| Mastenbrook et al., 2017 [128] | Semi-automatic | Full | Analyze 11.0 (AnalyzeDirect, Inc.) | Estimated from CSAs |
| Miller et al., 2020 [50] | Manual | Full | DICOM software (V 2.2.0, Horos) | Estimated from CSAs, multiplied by slice thickness, normalised to body mass |
| Mio Kovacic et al., 2011 [62] | Manual | Full | ImageJ (V 1.38x) | Estimated from CSAs |
| Montefiori et al., 2020 [55] | Semi-automatic | Full | Mimics (V 2.0, Materialise) | Estimated from CSAs |
| Reito et al., 2016 [131] | Manual | NR | NR | “Muscle atrophy was assessed as a decrease in volume and the appearance of fatty change relative to the contralateral, non-operated side.” |
| Rothwell et al., 2019 [132] | Manual | Full | OsiriX Lite (V 8.0.1, Pixmeo) | Estimated from CSAs, multiplied by slice thickness, normalised to body mass & height |
| Sakamaki et al., 2011 [133] | Manual | Full | NR | Estimated from CSAs, multiplied by slice thickness |
| Semciw et al., 2016 [63] | Manual | Full | Sante DICOM Editor (Santesoft) | Estimated from CSAs, multiplied by slice thickness |
reliability. However, kappa coefficient scores were only performed for fatty infiltrate and demonstrated a greater variety of scores spanning from fair to almost perfect agreement among studies. Kappa scores ranged from 0.72 to 0.93 for intra-rater and 0.23 to 0.94 for inter-rater reliability (Table 2). No study reported scan to rescan reliability.

**MRI parameters**

The MRI parameters of all studies are summarised in Table 1. Two MRI field strengths were reported, 1.5 Tesla and 3 Tesla. A wide range of MRI sequences were used across the studies, with many incorporating several sequence types, both T1- and T2-weighted, with and without fat suppression. Slice thickness ranged from 0.5 mm to 15 mm, with 16 studies (20.3%) not reporting slice thickness. Acquisition time ranged from 2 h 32 min [75] to 1 min 29 s [76].

All studies that reported patient positioning specified a supine position with legs extended and hips in neutral, except three studies [45, 62, 77] that used pillows under the knees for comfort, and two studies [44, 46] placing the hips into internal rotation.

**Muscle size measures**

Lateral hip muscle volume was measured in 31 studies and CSA was measured in 24 studies, (Tables 2 and 3). For volume measures, manual segmentation techniques were most frequently used (77.4%) compared to automated. For CSA, all studies used manual segmenting techniques.

**Volume measurement outcomes**

Whole muscle volume was calculated for 28 studies (90.3%), while two [26, 52] measured partial muscle volume. To calculate volume, all studies incorporated sums of CSA estimates. Seventeen (54.8%) studies also incorporated slice thickness and five (16.1%) normalised calculations to either individual height or mass (Table 2).

**Cross-sectional area measurement outcomes and axial anatomical slice location**

Five studies calculated CSA from multiple slices either by using the mean derived from several consecutive slices or assessing CSA at two predetermined locations (Table 3). Single axial slices were chosen at a pre-determined anatomical locations for all other studies except for two studies [78, 79], which measured at the single slice with the greatest CSA for the individual muscle.

Seven anatomical levels were identified as locations where CSA can be measured for the lateral hip muscles (Figs. 2, 3 and 4). These include i) anterior superior iliac spine (ASIS) [59, 80, 81] ii) half way between the iliac crest and the superior tip of the greater trochanter [67] iii) anterior inferior iliac spine (AIIS) [59] iv) upper border of the acetabulum [46, 82, 83] v) superior tip of the greater trochanter [45, 70, 77, 84–87] vi) lower border of the acetabulum [25, 82, 83] and vii) lesser trochanter [57, 81].

When comparing MRI images to E-12 anatomical plastinates (Figs. 3 and 4), the E-12 anatomical plastinates provide better visualisation of muscle borders. At levels AIIS and the upper border of the acetabulum, the muscle borders between gluteus medius and piriformis are better visualised on the E-12 anatomical plastinates with detail of individual muscle fibre directions demarcating the individual muscles (Fig. 5). For levels at superior tip of greater trochanter and below, the TFL border is better visualised on the E-12 anatomical plastinates against neighbouring muscle borders including the gluteus medius and rectus femoris.

### Table 2 (continued)

| Citation                   | Muscle segmentation: Manual/ automatic | Volume Full/partial | Software used | Equation                                           |
|----------------------------|----------------------------------------|---------------------|---------------|---------------------------------------------------|
| Skorupska et al., 2016 [65]| Manual                                 | Full                | ITK-SNAP (V 2.2.0) | Estimated from CSAs, multiplied by slice thickness |
| Springer et al., 2012 [59] | Manual                                 | Full                | Vtrea 2 (V 4.1.2.0) | Estimated from CSAs                               |
| Sugisaki et al., 2018 [106]| Manual                                 | Full                | OsiriX (V 2.4) | Estimated from CSAs, multiplied by slice thickness, normalised to body mass |
| Tran et al., 2021 [121]    | Manual                                 | Full                | The MathWorks, Inc., Natick, MA, United States | Estimated from CSAs, multiplied by slice thickness |
| Winkler et al., 2018 [61]  | Manual                                 | Full                | PACS workstation OsiriX | Estimated from CSAs                               |
| Zacharias et al., 2016 [22]| Manual                                 | Full (excl. fat)    | Sante DICOM editor | Estimated from CSAs, multiplied by slice thickness |

CSA Cross-Sectional Area, Excl. Excluding, GMax Gluteus Maximus, NR Not Reported, V Version
### Table 3 Cross sectional area measurement outcomes for individual studies

| Citation               | Muscles          | Manual/ automatic | Single/multiple slice | Software used                                                                 |
|-----------------------|------------------|-------------------|-----------------------|-------------------------------------------------------------------------------|
| Arokoski et al., 2002 [82] | TFL GMax GMed GMin | Manual            | Single slice          | NR                                                                             |
| Emery et al., 2019 [86]   | TFL              | Manual            | Multiple              | DICOM                                                                         |
| Homma et al., 2019 [107]  | GMax GMed        | Manual            | Multiple              | ZedHip (Lexi Co., Ltd)                                                        |
| Kawasaki et al., 2017 [75] | TFL GMed GMMin   | Manual            | Single slice          | NR                                                                             |
| Kivle et al., 2018 [67]   | GMed GMMin       | Manual            | Single slice          | PACS Sectra (V 16)                                                            |
| Malloy et al., 2019 [25]  | TFL GMax GMed GMMin | Manual           | Single slice          | Picture archiving and communication system workstation software               |
| Masuda et al., 2003 [78]  | GMax GMed GMMin  | Manual            | Single slice          | Public domain imaging software package (NIH image)                            |
| Mendis et al., 2014 [77]  | TFL              | Manual            | Multiple              | ImageJ (V 1.43u)                                                              |
| Mendis et al., 2016 [64]  | GMed GMMin       | Manual            | Multiple              | ImageJ (V 1.4)                                                                |
| Mendis et al., 2020 [45]  | GMax GMed GMMin  | Manual            | Multiple              | ImageJ (V 1.43u)                                                              |
| Ninimaki et al., 2016 [129] | GMax             | Manual            | Single slice          | Osirix program                                                                |
| Ninimaki et al., 2019 [130] | GMed GMMin       | Manual            | Single slice          | Osirix program                                                                |
| Peiris et al., 2020 [46]  | GMax GMed GMMin  | Manual            | Single slice          | NR                                                                             |
| Rodriguez-Roiz et al., 2017 [70] | TFL              | Manual            | Single slice          | NR                                                                             |
| Springer et al., 2012 [59] | GMed GMMin       | Manual            | Single slice          | Vitrea 2 (V 4.1.2.0)                                                          |
| Sutter et al., 2013 [83]  | TFL GMax GMed GMMin | Manual         | Single slice          | NR                                                                             |
| Takada et al., 2018 [80]  | TFL GMed GMMin   | Manual            | Single slice          | ImageJ software (National Institute of Mental Health)                         |
| Takada et al., 2021 [81]  | TFL GMed GMMin   | Manual            | Single slice          | ImageJ software (National Institute of Health, USA)                           |
| Takahashi et al., 2019 [79] | GMax GMed GMMin  | Manual            | Single slice          | ImageJ software (National Institute of Health)                                |
| Tesch et al., 2005 [88]   | GMax             | Manual            | Single slice          | Computerized planimetry                                                        |
| Unis et al., 2013 [87]    | TFL              | Manual            | Single slice          | NR                                                                             |
| Yang et al., 2021 [83]    | TFL GMax GMed GMMin | Manual          | Single slice          | ImageJ software (National Institutes of Health)                               |
| Yasuda et al., 2014 [84]  | GMax             | Manual            | Single slice          | SliceOmatic software (Tomovision Incorporated)                                |
| Yuksei et al., 2009 [134] | TFL GMax         | Manual            | Single slice          | NR                                                                             |
| Zhao et al., 2020 [47]     | TFL              | NR                | Single slice          | NR                                                                             |

CSA Cross Sectional Area, TFL Tensor Fascia Latae, GMax Gluteus maximus, GMed Gluteus Medius, GMin Gluteus Minimus, NR Not Reported, V Version
Some same slice locations were described in multiple ways as these levels contained multiple identifying features. For example the slice location at the level of the tip of the greater trochanter (level vi) is consistent with the level described as the centre of the femoral head [70, 85, 86], and the level where the femoral head has the greatest CSA [45], depending on slice thickness. Other slice locations were at a pre-set distance from an anatomical feature including 20 mm distal to the proximal aspect of the femoral head [88] for gluteus maximus and 15 mm from the superior margin of the acetabulum [75] for gluteus medius and minimus.

**Intramuscular fatty infiltration measurement outcomes and axial anatomical slice location**

Forty studies measured intra-muscular fatty infiltration (Table 4). Qualitative measures of fatty infiltrate were used by 30 studies with the Goutallier classification being the most frequently used. Quantification methods, using a ratio of pixel intensity from fat and water images were used by 10 studies. This technique has become more utilised over recent years.

Gluteus medius and/or gluteus minimus were further divided into compartments in 11 studies. Gluteus medius was divided into three equal compartments (anterior, middle and posterior) by nine studies and two equal compartments (anterior, posterior) by one study. Similarly, gluteus minimus was divided into three equal compartments (anterior, middle and posterior) by seven studies and into two equal parts (anterior and posterior) by two studies. The TFL and gluteus maximus were not divided into compartments for intramuscular fatty infiltration measurement.

Six anatomical levels were identified as locations for fatty infiltration measurement of the lateral hip muscles (Fig. 6). Two levels were identified for TFL, four levels were identified for gluteus maximus, gluteus medius and gluteus minimus muscles. Four studies [53, 89–91] described quantitative measures of fatty infiltration for whole muscle.

**Tensor fascia latae**

The two anatomical levels for TFL fatty infiltration assessment included the superior tip of the greater trochanter [85, 87] and the lesser trochanter [75, 80, 81]. The level at the greater trochanter was consistent with other anatomical features including the centre of the femoral head [85] and the fovea capitis [19, 21, 22]. The ischial tuberosity was
described in one study [92] and can span multiple slices. The greatest axial CSA was described in one study [93].

Gluteus maximus
The four levels for gluteus maximus fatty infiltration assessment are i) the distance at one third the distance from the iliac crest to the superior tip of the greater trochanter [19] ii) greater sciatic foramen (superior most part) [19, 21, 22, 42] iii) two thirds the distance from the iliac crest to the superior tip of the greater trochanter [19] iv) the superior tip of the greater trochanter [19, 94]. The level where the femoral head has a round configuration [74] and where it has the greatest circumference [19] was deemed similar to the level at the greater trochanter.

Gluteus medius and minimus
Gluteus medius and gluteus minimus were frequently assessed individually at the same level within a study. The four levels for gluteus medius and gluteus minimus
fatty infiltration assessment are i) the distance at one third the distance from the iliac crest to the superior tip of the greater trochanter [19, 67, 69, 85, 93] ii) anterior superior iliac spine [80, 81] iii) greater sciatic foramen (superior most part) [19, 21, 22, 42] and iv) two thirds the distance from the iliac crest to the superior tip of the greater trochanter[19, 56–58, 67, 69, 85, 93, 95]. Other levels described included pre-determined distances from anatomical features and included 15 mm superior to the upper margin of the acetabulum [75], three and six slices proximal to greater trochanter with slice thickness set at 6 mm [60], 30 mm proximal to greater trochanter [61]. Descriptions of levels that could span multiple axial slices included the level of the acetabulum [75, 94] and the ipsilateral sacroiliac joint [96].

Machine learning
Overall machine learning was incorporated in 16 (20.3%) of the studies. For size measures, eight (25.8%) studies reporting volume either used automatic or semi-automatic tracing methods while no study reporting CSA incorporated machine learning. For fatty infiltration, 10 (25.0%) studies used machine learning to identify and quantify water and fat value pixels within regions of interest.

Discussion
This scoping review aimed to define standardised MRI methods for assessing lateral hip muscle size and fatty infiltration. When measuring size and fatty infiltration, a lack of detail and heterogeneity in reporting MRI parameters highlights the need for a consistent approach to reporting methods in future MRI research. We report seven identifiable anatomical locations for measurement of lateral hip muscle CSA and six identifiable anatomical locations for fatty infiltration at single slice measurement. We also identified new and emerging technology in machine learning for automated muscle segmentation techniques for size and fatty infiltration measures.

MRI acquisition parameters and methodology
MRI parameters determine the quality of images that can influence the results of a study. The use of heterogeneous MRI parameters, as found in this review, can complicate comparisons and future pooling of data between studies. Global, multi-centred collaborations aimed to provide MRI protocol consensus have been undertaken for other body regions and could be developed around the hip and pelvis with the aim of reducing the large variability in imaging parameters and wasted time on pilot research [97].

Measurement
Previous studies have examined the influence of rater’s experience in reading and interpreting MRI [98, 99]. In this review, radiologists were most frequently cited professionals reading and interpreting results, with some studies specifying musculoskeletal radiologists to reflect greater experience in musculoskeletal presentations. Previous research has demonstrated MRI to be reliable for muscle size and fatty infiltration measures [6, 100]. Although the majority of studies, reporting ICC or kappa scores, stated good to excellent reliability, some studies reported fair to moderate reliability. One study [59] assessing size measures in a total hip arthroplasty population found poor reliability for measuring gluteus minimus size with analysis limited by prosthesis artifacts and poor visualisation. To overcome this limitation specific MRI techniques have since been developed for improving imaging around and near metal [101–103]. There also remains a large proportion of studies that did not report on reliability measures. This may reflect reporting bias, since poor scores would be less likely reported, and potentially inflate our estimate of reliability across the body of literature. It is recommended that future studies continue to measure and report reliability of

![Fig. 5](image-url) Enlarged region of interest at the level of anterior inferior iliac spine. A Axial DIXON sequence MRI B E-12 anatomical plastinate C Schematic illustration; round circle indicates feature of interest; Red line- gluteus minimus; Green line- gluteus medius; Dashed red line- partition between gluteus medius and piriformis; Dashed grey line- partition between gluteus maximus with both gluteus medius and piriformis; Red circle- highlights angles between partitions to help identify separation between piriformis and gluteus medius; Blue line- scale bar represents relative scale between images
Table 4  Fatty infiltration measurement outcomes for individual studies

| Citation                  | Fat Infiltration                                  | Divided into compartments |
|---------------------------|---------------------------------------------------|-----------------------------|
|                           | Qualitative/Quantitative                          |                             |
|                           | Classification system                             |                             |
| Divided into compartments | Yes/No                                            |                             |
| Agten et al., 2017 [68]   | Qualitative                                       | N                           |
| Belzunce et al., 2020 [53]| Quantitative                                      | N                           |
| Belzunce et al., 2021 [91]| Quantitative                                      | N                           |
| Berber et al., 2015 [122]| Qualitative                                       | N                           |
| Bravo et al., 2013 [90]   | Quantitative                                      | N                           |
| Bremer et al., 2011 [93]  | Qualitative                                       | Y                           |
| Burian et al., 2020 [54]  | Quantitative                                      | N                           |
| Chi et al., 2015 [72]     | Qualitative                                       | N                           |
| Cowan et al., 2019 [19]   | Qualitative                                       | N                           |
| De Anta-Diaz et al., 2016 | Qualitative                                       | N                           |
|                         | Grade 1: no fat or mild atrophy                   |                             |
|                         | Grade 2: moderate or severe fatty atrophy         |                             |
| Ebert et al., 2019 [71]   | Qualitative                                       | Y                           |
|                         | Grade 1: no fat or mild atrophy                   |                             |
|                         | Grade 2: moderate or severe fatty atrophy         |                             |
| Engelen et al., 2014 [42] | Qualitative                                       | N                           |
| Kawasaki et al., 2017 [75]| Qualitative                                       | N                           |
| Kheterpal et al., 2020 [44]| Qualitative                                      | N                           |
| Kim et al., 2014 [74]    | Qualitative                                       | N                           |
| Kivle et al., 2018 [67]   | Qualitative                                       | Y                           |
| Klemt et al., 2021 [120]  | Quantitative                                      | N                           |
| Koch et al., 2021 [26]    | Quantitative                                      | Y                           |
|                         | Pixel intensity values from the fat only images   |                             |
|                         | and the water only images                         |                             |
|                         | Muscle fat index = fat/(fat + water)               |                             |
| Kovalak et al., 2018     | Qualitative                                       | N                           |
| Makridis et al., 2014 [127]| Qualitative                                     | N                           |
| Marcon et al., 2016 [89] | Quantitative                                      | N                           |
|                         | Fat Signal Fraction % = 100 × fat/(water + fat)   |                             |
| Muller et al., 2010 [56]  | Qualitative                                       | Y                           |
|                         | G                                                  |                             |
| Muller et al., 2011a [58] | Qualitative                                       | Y                           |
|                         | G                                                  |                             |
| Muller et al., 2011b [57] | Qualitative                                       | Y                           |
|                         | G                                                  |                             |
| Peiris et al., 2020 [46]  | Qualitative                                       | N                           |
|                         | Grade 0: no fat infiltration                       |                             |
|                         | grade 1: 1–10% fat infiltration                    |                             |
|                         | grade 2: 11–50% fat infiltration                   |                             |
|                         | grade 3: > 50% fat infiltration                    |                             |
measurement to help guide and update the development of standardised MRI methods.

Size measures

Seven single level axial slices were identified that provided consistent CSA measurement, including three for both gluteus maximus and TFL, and four for both gluteus medius and minimus. There was no consensus on which axial slice best represents size and/or location where size changes are most likely to occur. E-12 anatomical plastinates did make visualisation of muscle borders clearer, particularly around neighbouring gluteus medius and piriformis, TFL and gluteus medius and TFL and rectus femoris. The use of E-12 anatomical plastinates in understanding and defining muscle borders at certain single level slices can aid future studies to correctly trace muscle borders and could help develop more accurate automatic, machine learning techniques.

Anatomical slice levels used in some of the included studies, where located at the very proximal or distal insertions of the target muscle which may not be representative of the muscle’s overall size. For example, the level of the anterior superior iliac spine for gluteus minimus measurement may not be the best representation for size as the muscle may not even appear at this level in some individuals. Interestingly, four studies [66, 104–106] reported size measurements from maximum CSA. This is supported by a recent study [107] in healthy individuals, which compared greatest CSA and volume and found a positive correlation for gluteus maximus and gluteus medius muscles. However greatest CSA may be quite different between individuals, pathologies and across studies. It is unclear

Table 4 (continued)

| Citation | Fat Infiltration Qualitative/Quantitative Classification system | Divided into compartments Yes/No |
|----------|---------------------------------------------------------------|----------------------------------|
| Pfirrmann et al., 2005 [69] | Qualitative G | Y Gmed & Gmin: AMP |
| Ruckenstuhl et al., 2020 [49] | Qualitative G | N |
| Rykov et al., 2021 [92] | Qualitative G | N |
| Sutter et al., 2013 [85] | Qualitative G | N |
| Takada et al., 2018 [80] | Qualitative G | N |
| Takada et al., 2021 [81] | Qualitative G | N |
| Thaunat et al., 2018 [96] | Qualitative G | Y Gmed: AMP |
| Tran et al., 2021 [121] | Quantitative Intramuscular lipid concentration | N |
| Unis et al., 2013 [87] | Qualitative Presence/absence | N |
| Vasarhelyi et al., 2020 [48] | Quantitative Muscle/fat intensity scores | N |
| von Roth et al., 2014 [60] | Quantitative % fat content: “…the quotient of the number of fat-value-pixels and the number of fat-value-pixels added to the number of muscle-value pixels.” | Y Gmed: AMP |
| Winkler et al., 2018 [61] | Quantitative % fat content = ratio of pixels of fat-value and muscle value pixels | N |
| Zacharias et al., 2016 [22] | Qualitative G | N |
| Zacharias et al., 2018 [21] | Qualitative G | N |
| Zhao et al., 2020 [47] | Qualitative G | N |

AMP equal Anterior, Middle and Posterior thirds, AP equally divided into Anterior and Posterior, FSF Fat Single Fraction, G Goutallier classification, Gmax Gluteus maximus, Gmed Gluteus medius, Gmin Gluteus minimus, GSF Greater Sciatic Foramen, GT Greater Trochanter, Ifat Mean signal fat intensity, Iwater Mean signal water intensity, N No, Q The Quartile classification, TFL Tensor Fascia Latae, Y Yes
at what level CSA should be calculated for the lateral hip muscles.

Compared to CSA, volume has a stronger correlation to muscle strength [12, 108], power [109], and can better reflect muscle size for the entire muscle in both healthy and musculoskeletal pain populations [7, 12]. Additionally assessing whole muscle, volume can better identify regions more susceptible to change and can inform most appropriate levels for CSA [7, 110]. For example in the thigh, after a bout of strength training in healthy individuals, muscle size changes have been observed in proximal portions of a muscle but not around distal portions [111]. Single CSA measures may therefore miss potential changes, depending on where measurements are taken. However compared to CSA, volume calculations can be more time consuming when manually derived. Supported by the results of this review, there has been an increase in interest and development of automatic calculations through machine learning. This increase will lead to greater availability of studies for future pooling of data.

Fatty infiltration

For assessment of fatty infiltration, six axial slice locations were identified including two for TFL, four for each of the gluteal muscles. There was no consensus which axial slice best represents fatty infiltration and/or location where changes are most likely to occur. We found that 86% of studies measuring fatty infiltration used qualitative, five-point Likert scales, often at a single slice. The most frequent Likert scale used was the Goutalier classification system [41]. All studies incorporating quantitative methods for fatty infiltration studies have been published within the last 10 years reflecting it as an emerging technique.

We feel it is important to quantify muscle fat across the entire length of the muscle. This will help to identify locations where muscle fat accumulates in symptomatic groups, how it compares to asymptomatic groups, and where interventions like exercise may have the greatest effect. For example, in a study by Koch et al. [26], muscle fat was quantified on every slice from proximal to distal, and normalised to muscle length. They found that exercise had a significant effect on reducing muscle fat of gluteus

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**Fig. 6** 3-D representation of anatomical levels for intramuscular fatty infiltration measurement; 1- 1/3rd from iliac crest and greater trochanter; 2- Anterior superior iliac spine; 3- Greater sciatic foramen; 4- 2/3rd from iliac crest and greater trochanter; 5- GT; 6- Lesser trochanter; Aqua- TFL; Blue- Gluteus maximus; Green- Gluteus medius; Red- Gluteus minimus; IC- Iliac crest, GT- Greater trochanter
minimus at the proximal portion of the muscle. If muscle fat was only measured in the distal portion, then the authors may have falsely concluded that exercise had no effect on muscle fat. In other regions of the body, Crawford and colleagues [112] have shown that the fat content at lumbar segment four (L4) best represents fatty infiltration measures that reflects the entire lumbar region in healthy participants. Further work is needed on the hip muscles to clarify if specific locations are representative of whole muscle changes.

In addition to the specific anatomical level of location, recent cadaver and electromyography studies have identified different anatomical and functional regions within the lateral hip muscles [30, 113, 114]. These compartments or regions within the individual muscle may be uniquely impacted by specific movements or muscle actions, which has relevance in musculoskeletal pathology. For example, some studies in this review divided the gluteus medius and minimus muscles into either three equal parts (anterior, middle and posterior) or two equal parts (anterior/posterior) while the gluteus maximus was divided into upper and lower portions. Investigation and understanding of muscle size and fatty infiltration within these functional regions and portions has the potential to guide future interventional studies. In spinal studies such divisions can allow for a more specific quantification to map the spatial distribution of fat content, which is increasingly showing clinical relevance as a meaningful parameter [112, 115–118].

MRI advances
Manual tracing techniques were used for the majority of size studies but can be time consuming, involving several hours per participant. Recent advances in MRI technology include the development of automated tracing techniques through machine learning [52]. Machine learning for muscle tracing as well as for automatic fatty infiltration calculation has shown to be reliable and accurate in other regions [119]. Automated analysis incorporating machine learning is more time efficient than manual tracing, reducing analysis time from hours to seconds while still maintaining near human-level performance. However with limited valid and reliable automated methods, manual methods for labelling muscles for size and fatty infiltration are currently the gold standard [52, 91]. However, machine learning has the potential to make the analyses of larger data sets more feasible, increasing the statistical power of future research and facilitating the translation of these measures to clinical practice. Although in their infancy, automated, machine learning methods around the lateral hip muscles have shown to provide reliable data for size and the ability to quantify fatty infiltration and will aid future research [26, 48, 52, 61, 91, 120, 121].

Limitations
This scoping review has limitations that should be considered. Firstly, this review focused on people with hip-related musculoskeletal pain and healthy populations, therefore the findings may not be generalisable to other populations such as those with neurological or muscle disease. Secondly, we acknowledge that by focusing on hip-related pain and healthy populations, additional fatty infiltration classification systems described in other populations were not included in this review. Thirdly, in addition to low reporting of reliability results, multiple studies were from single institutions which may make overall methods seem more homogeneous. Therefore, caution should be taken when generalising our findings.

Lastly, we acknowledge that a quality assessment of individual studies was not conducted. This is optional when undertaking a scoping review [34]. Reporting study quality would have a greater impact on describing the risk of bias of outcomes, rather than informing our understanding of muscle size and fat measures, which was the primary aim of this review.

Conclusion
Whilst no consistency was found for which anatomical location(s) is(are) most appropriate and clinically meaningful to measure lateral hip muscle size and fatty infiltration, we report several identifiable anatomical levels for single axial slice muscle size and fatty infiltration. Further studies into whole muscle measures are required before strong recommendations can be made about the most suitable anatomical locations for standardised MRI single slice muscle measures and within muscle regions susceptible to change. Whilst automated machine learning technology is rapidly emerging with associated improvements in time efficiency, widespread implementation remains a challenge. Accordingly, there remains a need to optimise manual segmentation. Overall, the findings of this scoping review will assist in the future establishment of a standardised method for examination of and measurement for lateral hip musculature using MRI.

Implications
Establishing a standardised method for MRI assessment of lateral hip muscles will contribute to greater understanding of muscle size and fatty infiltration for people with musculoskeletal conditions and the development of standardised MRI protocols. The findings of this scoping review will inform research in other clinical populations such as people with neuromuscular disease.
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Authors’ contributions
Z.P., A.I.S., A.B.M., and P.L. conceived the study, while J.M.E., K.A.W., N.A.M.S.F., J.C., and J.M.E. each made substantial contributions to its design. Z.P., N.A.M.S.F., C.S., and A.I.S. were involved in screening of results and data extraction. Z.P., A.I.S., A.B.M., N.A.M.S.F., J.C., and J.M.E. have been involved in drafting the manuscript. All authors have been involved in revising manuscript critically for important intellectual content and each given final approval of the version to be published. Z.P., A.I.S., A.B.M. and PL agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Declarations
Ethics approval and consent to participate
Departmental ethical approval to use images of the E12 plastinate sections was granted by the Department of Anatomy, University of Otago, in accordance with University of Otago ethics procedures. The preparation of the E-12 plastinated sections took place in accordance with the New Zealand Human Tissue Act (2008) and University of Otago institutional guidelines.

Consent for publication
Approval to use images of the E-12 anatomical plastinate sections was granted by the Department of Anatomy, University of Otago. All MRIs were derived from the same informed and consenting adult subject.

Availability of data and materials
All the data supporting the findings are contained within the manuscript.

Competing interests
The authors declare that they have no competing interests.

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