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Fiber type composition of the hip abductor muscles

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Abstract

Objectives: The hip abductor muscles; gluteus medius, gluteus minimus and tensor fasciae latae, play an important role in pelvic stabilization. Morphological changes occur in these muscles as a consequence of chronic musculoskeletal conditions (e.g. osteoarthritis), aging, and following hip joint replacement. Functional studies show unique activation profiles of the different compartments of gluteus medius and gluteus minimus; however, little is known of the fiber type composition of these muscles, which is an important consideration for understanding their functional and metabolic capabilities.

Methods: Eight transverse muscle samples from each compartment of gluteus medius and gluteus minimus, and two samples from tensor fasciae latae were harvested from 11 cadavers, and processed for immunohistochemistry. Fast-twitch muscle fibers were stained with the MY-32 antibody to estimate the proportion of type II fibers comprising the muscles.

Results: Individual muscle fiber composition profiles demonstrated that gluteus medius and gluteus minimus were similar in composition, supporting a predominantly postural function. Tensor fasciae latae had a higher proportion of type II fibers, suggesting a more phasic functional role. No differences were observed between compartments for gluteus medius, but the anterior compartment of gluteus minimus had a significantly higher proportion of type II fibers than the posterior.

Conclusion: This study provides anatomical data for the fiber type composition profiles of the hip abductor muscles, contributing to the understanding of their metabolic and contractile capabilities. These data may be valuable when considering changes that occur at the cellular level in the hip abductor muscles under pathological conditions and with aging.

Keywords: fiber type; gluteus medius; gluteus minimus; skeletal muscle

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Introduction

The contribution of the hip abductor muscles, gluteus medius (GMed), gluteus minimus (GMin) and tensor fasciae latae (TFL), to pelvic and hip stability and movement has attracted increasing interest in recent years, particularly in relation to greater trochanteric pain syndrome,[1–4] hip osteoarthritis,[5–8] and total hip replacement surgery.[9,10] Changes in the morphology of these muscles are evident in individuals with these differing forms of hip dysfunction and following surgery: primarily a loss in muscle volume (atrophy), accompanied by increased intramuscular adiposity (particularly of GMin), with or without a reduction in muscle strength.[3,4,6–10]

The function of the hip abductor muscles has been assessed using a variety of methods including surface electromyography (EMG),[11–14] biomechanical modelling,[14–17] and intramuscular EMG.[13,18–20] Generally, these studies describe GMed as an important stabilizer of the pelvis during weight-bearing, and a powerful abductor of the hip. It is also likely that it contributes to contralateral forward rotation of the pelvis.[19] Likewise, the GMin is an abductor of the thigh, and also contributes to internal rotation of the hip. More recent work has shown that it is also highly active during maximum resisted thigh extension, with the hip in neutral, and at the end of hip extension during the stance phase of the gait cycle.[20] The TFL is also morphologically designed for, and active during isolated hip abduction, and its intensity of activation during mid-stance of gait suggests it assists GMed and GMin to stabilize the pelvis.[12,21–23] The TFL is also active during the initial part of the swing phase where it works with iliopsoas to assist in hip flexion.[12,22,23]

In early EMG studies, each of the hip abductors were considered as a whole muscle,[13,18] which is appropriate for TFL. However, it is now known that GMed and GMin are comprised of compartments which are morphologically[24] and functionally[19,20] unique. Semciw et al.[19,20] established an intramuscular EMG protocol utilizing fine wire electrodes that enabled the collection of data from the compartments of GMed (anterior, middle and posterior) and GMin (anterior and posterior). In healthy, young adults, distinct muscle activation profiles were demonstrated for the hip abductors during specific hip movements and gait. During gait, a compartment-specific activation profile was observed. For GMed, although all three compartments (anterior, middle and posterior) showed two bursts of activity during the stance phase of gait, the anterior compartment activated significantly later than the middle compartment at the first peak (0–20% gait), and both middle and posterior compartments at the second peak (20–60% gait cycle).[19] Comparably, while both anterior and posterior compartments of GMin are co-activated in late mid-stance (peak ~40–50% of gait cycle), posterior GMin is significantly more active during contra-lateral toe-off (~18% of gait cycle) and thus, has been specifically suggested as a major contributor of femoral head stabilization in early stance.[20–24]

Given the dynamic and stabilizing functions of the hip abductor muscles, examining their fiber type composition would provide further insight into their compartmental functions and metabolic capacity. However, despite the numerous gross morphological and functional studies of these muscles, little consideration has been afforded to fiber type. To date, one study has provided data for GMed and TFL, showing the percentage of type II fibers (described as fatigue susceptible fibers with fast-shortening speed[25]) in males was 42% for GMed and 55% for TFL,[26] and another reports on the fiber type composition of GMin.[27] In this study, samples harvested from the anterior and posterior aspects of nine cadaveric GMin muscles exhibited a predominance of type I fibers (described as fatigue-resistant fibers with a slow shortening speed[25]) (range 62% to 74%). However, it is unknown whether there are regional differences between the anatomically and functionally distinct compartments.[11,19,20,24] Such information may be valuable for not only furthering our understanding of the function (i.e. contraction velocity and fatigability[28]) of these muscles but also for providing information relevant to conditions where the morphology of the gluteal muscles is altered.

The aims of this study were to (a) quantify the proportion of type I and type II fibers of GMed, GMin and TFL using immunohistochemistry and stereology and (b) determine the fiber type composition of the different anatomical compartments.

Materials and Methods

Tissue was collected from 15 limbs of 11 cadavers (7 male, 4 female; 7 right, 8 left; mean age at death, 81.9 years, range 66–97 years); both hips from 4 male cadavers were therefore included in our sample.

The cadavers from which samples were taken were embalmed with Crosado Mix.[29] Each specimen was dissected as described elsewhere,[24] and two transverse muscle samples (deep and superficial) of 10 mm in length were taken from the mid-point (proximal-distal, and anterior-posterior) at four areas in each of GMed and GMin, and one area of TFL (**Figure 1**), based on the results of a previous investigation into the compartmentalisation of these muscles.[24] Although initially, the mid-anterior and mid-posterior regions of the GMed and GMin were sampled, after consideration of existing literature and in alignment with recent functional studies,[19,20] the most anterior sample of GMed was considered to be representative of the anterior compartment of GMed, the middle two samples represented the middle compartment and the most posterior sample the posterior compartment of the muscle. For GMin, the two most anteriorly located samples were re-considered to represent the anterior compartment of the muscle, while the two most posterior samples were from the posterior compartment. Following extraction of tissue, samples were immediately immersed in Bouin's solution (saturated aqueous picric acid [250 ml], 37% formalin [250 ml] and acetic acid [50 ml]), at room temperature overnight. Thereafter, samples were kept in 70% alcohol until they were processed and embedded in paraffin wax, oriented to be sectioned transversely across the muscle fibers.

Optimization of Immunohistochemical Methods

The use of Crosado-embalmed cadavers for histology has been shown to be successful and acceptable.[29,30] Mouse and human muscle tissue samples from gluteus maximus and GMed were used to optimize the immunohistochemical protocol to ensure reliable complimentary staining of the mouse monoclonal antibodies MY-32 (Anti-fast skeletal myosin heavy chain MY-32 (catalogue # M4276, Sigma-Aldrich, St. Louis, MO, USA); mouse monoclonal Ab which reacts with type II skeletal myosin (all types)(Dilution 1:200 in tris-buffered saline in 1% bovine serum albumin)) and 1a (Anti-slow skeletal myosin heavy chain NOQ7.1.1A (1a)(gifted by M Duxson); mouse monoclonal Ab hybridoma supernatant specific for type I myosin heavy chain[31] (Dilution 1:100)) (**Figure 2**). Negative control sections were incubated with an equivalent concentration of mouse immunoglobulin (IgG). Initially, both 1a and MY-32 antibodies were used to show

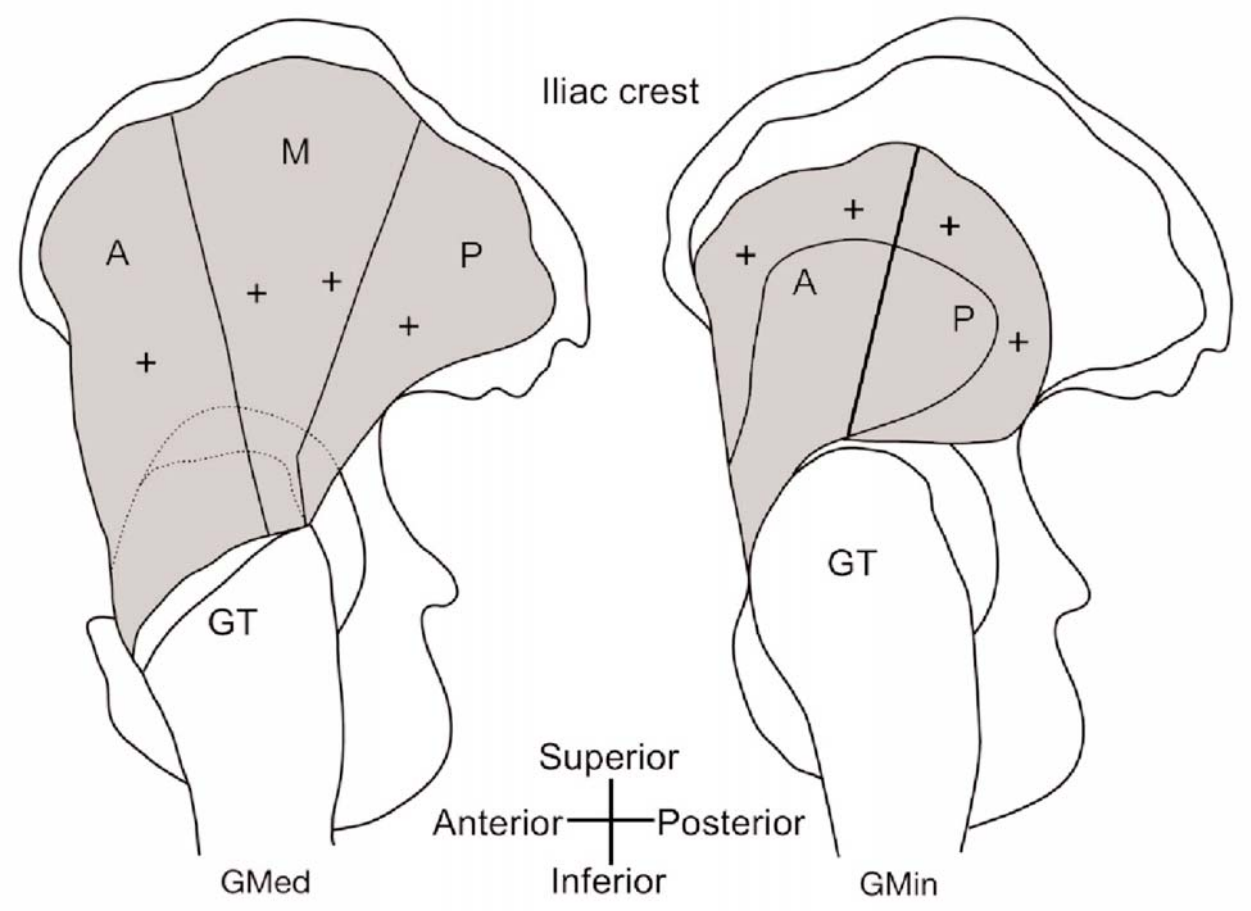

Figure 1. The regions within GMed and GMin from which samples were taken for immunohistochemical fiber typing. Samples taken for staining included a superficial and deep fascicle taken from the areas indicated by "+" in the anatomical compartments of GMed (3) and GMin (2). In total, eight fascicles were taken from each of GMed and GMin. **A:** anterior; **GMed:** gluteus medius; **GMin:** gluteus minimus, **GT**: greater trochanter; **M:** middle; **P:** posterior.

specificity and produce complimentary staining. Subsequently, only MY-32 was used as access to 1a was limited; it was therefore assumed that all non-stained fibers within these sections were type I. Sections of human gluteus maximus were used as positive controls.

Immunohistochemistry

After discarding the first 50 sections (5 µm thickness) (microtome, Leica Instruments, Wetzlar, Germany) of each sample, three serial sections were cut, mounted and left to dry overnight at 37 °C, before being stained using standard immunohistochemical procedures. Briefly, prior to staining, antigen retrieval methods required the sections to be immersed in a 10 mM citrate buffer solution, and heated to 95 °C for 10 minutes. After cooling, an endogenous peroxidase blocking step was carried out (15 minutes, 0.3% hydrogen peroxide) followed by a second blocking step using Donkey serum in 1% bovine serum albumin (catalogue # 85040C- 1K, Sigma-Aldrich, St. Louis, MO, USA) in TBS, for 2 hours, at room temperature. Sections were then incubated with the MY-32 primary antibody (or negative control, mouse IgG) overnight at 4 °C. A Dako biotinylated horseradish peroxidase kit (Dako LSAB2 system-HRP, Dako North Amerika, Inc., Carpinteria, CA, USA) was used for the secondary antibody step. Then, diaminobenzidine (Sigma-Aldrich, St. Louis, MO, USA) was applied to sections for visualization of immunoreactivity, prior to permanently mounting the slides using entellan mounting media (Merck KGaA, Darmstadt, Germany).

Stereology

Whole stained sections were scanned at a magnification of 20× using an Aperio CS2 scanner (Leica Biosystems, Nussloch, Germany) and subsequently viewed in ImageJ

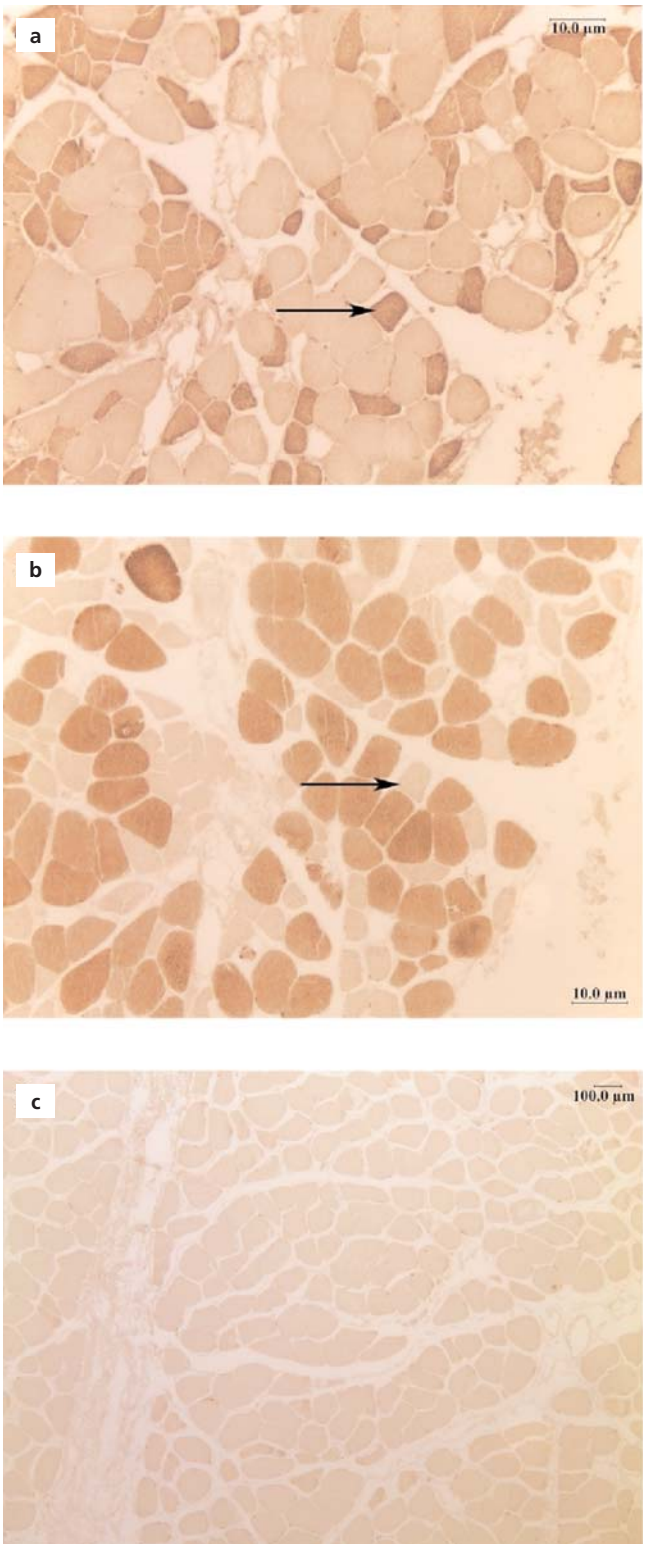

Figure 2. Complimentary staining of Ab MY-32 (type II fibers) and 1a (type I fibers) within GMed. Those fibers that were darkly stained by the MY-32 Ab (**a**), were not stained by the 1a Ab (**b**) (**arrows**). No fibers were stained in the control section (**c**), where a mouse IgG replaced the primary Ab. Magnification: (**a**, **b**) 20×, (**c**) 10×. **Ab:** antibody; **GMed:** gluteus medius; **IgG:** immunoglobulin G.

(NIH, Bethesda, MD, USA, v1.51s) as both a reference for determining counting sample squares and for counting the individual fibers. A grid with squares measuring 20 mm by 20 mm, was laid over the reference image and using a random number generator, selected squares on this grid were chosen for analysis. The number of whole cells within the square, of each fiber type was counted. A total of approximately 100 cells were required to be counted from each section,[32] so depending on the density of cells within each sample square, the number of sample squares that were chosen for counting cells varied (range 5–94). For some sections, it was necessary to count all cells in the section. The mean number of type I and type II fibers was calculated from the two superficial areas, and the two deep areas sampled in the middle compartment of GMed, as were the two areas for the two superficial areas and the two deep areas sampled in the anterior, and posterior compartments of GMin (**Figure 1**). Thus, an average fiber type composition for the superficial samples, and the deep samples, in each of the three compartments of GMed and the two of GMin was attained.

Atrophy Assessment

Each section was assessed for the amount of atrophy present in the sample, using the Goutallier system.[33] Sections with considerable amounts of atrophy (i.e. less muscle than adipose), were excluded from the statistical analysis of the fiber type composition, as data for those sections were insufficient.

Statistics

All data were analysed using Excel (Microsoft Excel for Mac, v16.54, 2021). Descriptive statistics (means, standard errors) of the percentage of type II fibers found in each muscle (GMed, GMin and TFL), and the individual compartments (GMed and GMin only) were determined. A paired Student's t-test was used to determine differences between superficial and deep fascicle fiber types within each compartment of GMed, GMin and TFL (**Table 1**). As no differences were observed, the samples were combined, and the percentage of type II fibers for each compartment was calculated for each muscle; e.g., anterior, middle and posterior for GMed, anterior and posterior for GMin, and the whole of TFL. All samples were then combined to obtain whole muscle type II fiber percentages, for each of the three muscles. Differences across the three muscles were determined using a one-way analysis of variance (ANOVA) as well as to explore differences between the three compartments of GMed. A paired-samples t-test was used for differences between the two compartments of GMin. Significance was taken as $p<0.05$.

Table 1

Mean percentage and differences between means of type II fibers found in superficial and deep regions for all muscles, and each compartment for gluteus medius and gluteus minimus.

	Gluteus medius			
Sample region	Anterior mean (%) SEM n=14	Middle mean (%) SEM n=27	Posterior mean (%), SEM n=12	Difference between compartments (ANOVA)
Superficial	40.8±20.7	41.1±19.4	44.6±18	
Deep	44±27.9	36.8±20.3	38.75±15.7	
Difference	p=0.6	p=0.1	p=0.3	
Combined superficial and deep	42.4±4.6	38.9±2.7	41.7±3.4	$F_{(2,103)}$=0.31, p=0.73
	Gluteus minimus			
Sample region	Anterior mean (%) SEM n=22		Posterior mean (%) SEM n=24	Mean difference between compartments (Paired samples t-test)
Superficial	48.4±25.9		37.4±26.5	
Deep	50.9±26.4		35.7±24.8	
Difference	p=0.3		p=0.5	
Combined superficial and deep	49.7±3.9		36.6±3.7	t(89)=2.5, p=0.02
	Tensor fasciae latae			
Sample region	Whole muscle mean (%) SEM n=12			
Superficial	52.2±17.9			
Deep	55.6±19.6			
Difference	p=0.1			
Combined superficial and deep	53.9±3.8			

Sample size differences between compartments are due to the loss/damage of sections during immunohistochemistry; as more areas were sampled for the middle GMed compartment, and the compartments of GMin, larger sample sizes were available for this compartment. **F:** F-statistic; **SEM:** standard error of means; **t:** t-statistic. Significance taken as p<0.05.

Results

Differences between compartments: **Table 1** shows the mean percentage of type II fibers found within each compartment of GMed, and GMin. There were no statistically significant differences in the percentage of type II fibers across the compartments for GMed ($F_{(2,103)}$=0.31, p=0.73). However, there was a significantly higher mean percentage of type II fibers in the anterior compartment of GMin (49.7±3.9) when compared to the posterior compartment (36.6±3.7, p=0.02).

Differences Between Muscles

The descriptive statistics of the three hip abductor muscles are summarized in **Figure 3**. There was a significant difference between the mean type II fiber type percentage across the three muscles ($F_{(2,219)}$=3.37, p=0.03). Post-hoc analyses using the Bonferroni's correction revealed that there was a significantly higher mean percentage of type II fibers in TFL (53.9±3.8) when compared to GMed (40.5±2.0, p=0.03). No differences were observed between TFL and GMin, nor between GMed and GMin.

Fatty Infiltration

Each specimen showed variable amounts of adipose tissue, but ratings mostly ranged between 0 (normal muscle tissue) and 2 (fat evident, but less fat than muscle),[33] with a few rated 4 (more fat than muscle tissue) for GMin only. For the compartments of GMed, mean fatty infiltration ratings ranged from 0.6 to 0.8 (range 0 to 3), with a median rating of 1 for all three compartments. For GMin, mean fatty infiltration ratings were slightly higher, at 1.6 (anterior) and 1.5 (posterior) (range 0 to 4), with median ratings of 2.0 for both compartments. Little fatty infiltration was observed in TFL, with a mean rating of 0.7, and a median rating of 0 (range 0 to 2) (**Figure 4**).

Although fiber dimensions were not quantified in this study, it was anecdotally observed that the diameters of both muscle fiber types were variable between muscles and

across specimens. There were also differences in size and shape between type I and type II fibers within the same muscle. In general, type I fibers appeared larger and rounder, while type II fibers were smaller and shrunken. Type II fibers also often appeared "spiked" in shape.

Discussion

Insight into the fiber type composition of the hip abductor muscles may contribute to a comprehensive understanding of their function, and provide an anatomical understanding for changes that may occur as a consequence of musculoskeletal conditions such as hip osteoarthritis, greater trochanteric pain syndrome or following hip joint replacement.

The results of this study indicate differences in the fiber type composition of the hip abductor muscles; GMed and GMin are comprised of similar percentages of type II fibers, but contain less than that observed for TFL. Based

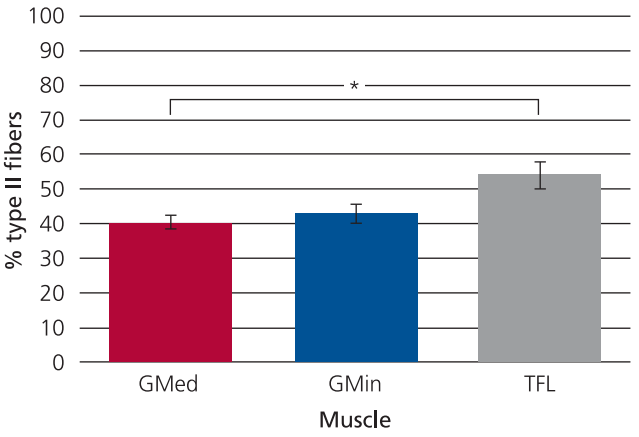

Figure 3. Mean percentage (±SEM) of type II fibers comprising the whole hip abductor muscles: GMed, GMin and TFL. A statistically significant difference in the percentage of type II fibers was observed between GMed and TFL (p=0.03), but not between GMin and TFL nor between GMed and GMin. **GMed:** gluteus medius; **GMin:** gluteus minimus; **TFL:** tensor fasciae latae.

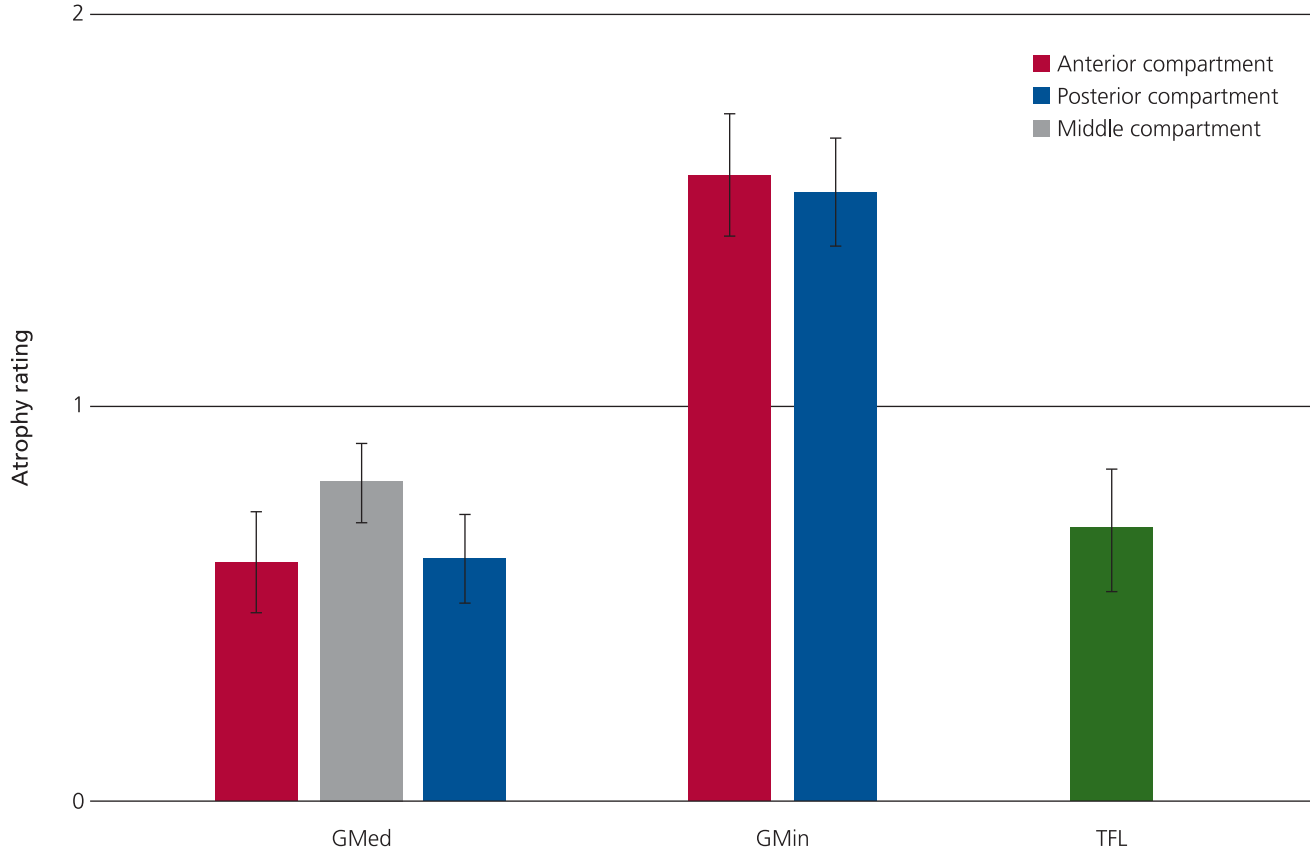

Figure 4. Mean (and SEM) atrophy ratings of each compartment for gluteus medius and gluteus minimus, and for the whole muscle of TFL as determined by using the Goutallier's scoring system. More severe fatty infiltration was observed in sections taken from GMin, with severe atrophy (rated as "4") being found only in sections taken from GMin. **A:** anterior; **GMed:** gluteus medius; **GMin:** gluteus minimus; **M:** middle; **P:** posterior; **TFL:** tensor fasciae latae.

on the metabolic property differences between type I and type II fibers,[34] the lower percentage of type II fibers comprising GMed (40.4±2%) and GMin (42.8±2.7%), and therefore higher percentage of type I fibers, (fatigue-resistant with slow-shortening speed[25]) hints at a more "postural" or stabilising role for these two muscles. In contrast, the higher composition of type II fibers (fatigue susceptible, fast-shortening speed[25]) in TFL (53.8±3.8%) suggests this muscle is potentially involved in more "phasic" activities. These data corroborate those presented by Sirca and Susec-Michieli[26] for GMed and TFL from "normal adult males" (n=11, age range 22 – 44 years), and those data for GMin, as identified more recently by Takano et al.[27]

Despite these observations, the relative percentages of type I and type II fibers within each muscle are not dissimilar, especially when compared with muscles recognized as having a predominantly postural function, such as the thoracolumbar transversospinal muscles (mean 88.6% type I)[35] or the palmaris brevis (72.2% type I).[25] Similar heterogeneity is observed in a number of other muscles within the body and reflects the ability of the skeletal muscle to adapt to a variety of functional demands.[36] Physiologically, GMed, GMin and TFL probably participate in both tonic activity (to maintain posture) as well as phasic activity (creating movement of joints).[37] This hypothesis is supported by the functional-based literature which states that both gluteal muscles are important stabilisers of the pelvis,[11,12,16,18,21,38,39] and also have the ability to move the lower limb through hip abduction and internal rotation.[11,14,15,38] Similarly, while TFL is considered to be involved in contributing towards flexion and abduction of the hip joint,[11,12,14,15,22,39] some authors attribute to it a role in pelvic stabilization[21,22,39] especially during the stance phase of the gait cycle.[23]

As has been previously reported, the fiber type composition of a muscle can vary depending on where the sample is taken (i.e. superficial vs deep,[37] or between anatomically distinct compartments[28]). The current study observed statistically significant compartmental differences for the percentage of type II fibers comprising GMin, but the same was not observed for GMed. As the functional profiles of the different compartments of GMed and GMin are unique, we anticipated that there would be differences between compartments, for both muscles. However, the results of our study support this hypothesis, particular to GMin only. Functionally this makes sense based on the extended length of time for which GMin posterior is required to provide stabilization through the early and midstance phases of gait,[20] it is expected that the characteristics of this region of the muscle support a slower maximum shortening velocity and are more resistant to fatigue, and thus, would contain a higher proportion of type I fibers. However, it is also likely that the observed difference in fiber type composition between compartments of GMin is attributable to the atrophic changes that appear to affect GMin preferential to GMed,[6,7,10,24,27] explaining why we did not observe a similar difference for the larger, more active muscle of GMed. Although it is known that the individual compartments of the GMed are activated at different times during gait and isolated hip movements,[19,20] the overall metabolic capacity of the different regions of the muscle may be too similar to detect a difference.

The current study also observed a tendency towards the predominance of fatty infiltration (and thus atrophy) of the muscle in GMin compared to GMed and TFL, corroborating observations made in previous studies.[6,7,10,24,27] As shown by Semciw et al.[19,20] GMin is an important pelvic stabilizer, so the predominance of atrophy in this muscle could significantly affect hip stability during gait and standing. However, the current study did not indicate that fatty infiltration was constrained to anterior GMin as shown in recent morphological studies.[7,24,27] It is possible that the advanced age of the specimens in the current study (mean age, ~81 years) can explain this absence. It has been recently observed that the preferential location of fatty muscular atrophy in GMin could be dependent upon age; individuals younger than 70 years of age are more commonly observed to have atrophic changes located in the anterior compartment of GMin, while those older more commonly experience changes throughout the whole muscle (i.e. in both compartments).[40]

Although atrophy of individual muscle fibers and the muscle overall was not quantitatively determined, the descriptions afforded to its appearance and occurrence may be important in understanding the pathology of these muscles. In the present study, type II fibers appeared smaller and less rounded in shape, compared to type I fibers. This change in shape may indicate that type II fibers undergo selective atrophy. A selective decrease in the size of type II fibers or type II fiber area,[26,40,41] as well as changes in shape,[41] attributed to aging, have been previously described in a number of different muscles including vastus lateralis, GMed, gluteus maximus, and TFL. Additionally, photographs published in some of these studies[26,41] showed a similar histological appearance to the fibers observed in the present study. Furthermore, Lexell et al.,[41] and Sirca and Susec-Michieli,[26] both observed an alteration in size and/or shape of type II fibers (angulated and atrophic type II fibers) in the older participants (aged between 70 and 80 years), when compared to younger par-

ticipants (aged 19–44 years). The mean age of the cadaveric specimens used in the current study is similar to those of the older participant groups in these studies, so it is possible that the observations of atrophy can be explained in the same way. The evidence outlined above, supports the suggestion that the atrophy observed in the current study is due to aging, but in the current study TFL was shown to have more type II fibers than both GMed and GMin, but it was the least atrophied muscle. The impact that use, or rather, disuse of these muscles also needs to be considered when trying to explain the disparity between atrophy of the different muscle fiber types. Further quantitative analysis on fiber type dimensions are needed to provide conclusive information for GMed, GMin and TFL.

Limitations

It is generally accepted that the aging process affects the fiber composition of a muscle,[42] but how and to what extent is still largely unknown. Historically, there was agreement that with age, there was a preferential atrophy of type II fibers.[26] However, with advancements in histological methods and the understanding of co-expressions of different MHC isoforms and thus muscle fiber characteristics, this "preferential atrophy" theory is being contested, especially for the elderly.[43] It is also difficult to ascertain the full amount to which age plays a role in the changing characteristics of the muscle fiber as physical activity also impacts on fiber type composition,[26] and different muscles may behave differently (i.e. gastrocnemius versus soleus) with aging.[43] As there is no existing information addressing a changing fiber type composition specifically for GMed, GMin and TFL, with age or activity, and we also do not have the data from a younger sample to compare results, we cannot comment on to what extent these factors may have influenced our data, if at all.

Unfortunately, the limited sample size utilised for the current study did not allow analysis for differences between males and females. Within the existing studies that have investigated sex difference in fiber type composition, no data for the hip abductor muscles are available, and results for other muscles are variable. Some studies have found males to have a higher proportion of type II fibers than females (e.g. vastus laterals, biceps brachii[44] (but statistical analysis was not undertaken), some report the opposite,[45] and others show no differences (e.g. longus colli and multifidus[46]). This possibly indicates that the composition of fiber types is influenced in a number of ways. For example, fiber composition may be muscle-dependent, affected by age, physical activity levels and hormones, or there are methodological limitations such as the use of fresh or fixed tissue and the subsequent histological investigation that can be used.[37,43] The current study is further limited by the lack of medical history information that is provided as part of the bequest programme at the University of Otago. Further work to address these limitations and provide a comprehensive overview of the existence of sex differences in fiber type composition is advised.

Differentiation was made between type I and type II muscle fiber types but not between the sub-types of type II fibers. Identification of these fiber sub-types in the hip abductor muscles could contribute to a better understanding of the functional capabilities of GMed, GMin and TFL. As the MY-32 monoclonal Ab does not differentiate between fiber sub-types,[47] the ATPase method of detection would need to be employed, for which, the acquisition of fresh tissue is necessary. Additionally, investigation into the diameter size of these muscle fibers in this age group and a quantification of differences would help to explain any unexpected differences in fiber type composition, and contribute to the understanding of what might happen to different fibers comprising the hip abductor muscles as the aging process occurs.

Conclusion

The hip abductor muscles are considered to play an important role in pelvic stabilization during gait and abduction and rotation of the hip. This study has provided an account of the fiber type composition of each of the hip abductor muscles, using immunohistochemistry. Our findings suggest in general, that there are unequal distributions of type I and type II fibers within GMed, GMin and TFL, suggesting a more postural role for GMed and GMin (slower contraction, more fatigue resistant) and a more phasic role for TFL (faster contraction, more prone to fatigue), although it is likely that all three muscles participate in both actions. Furthermore, this study has shown differences in fiber type composition between the anterior and posterior compartments of GMin. Overall, such knowledge is of significance when addressing the functional capabilities of these muscles; these data provide anatomical evidence for the verification of the functions of these muscles, and a comparison for what changes might occur under pathological conditions.

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Conflict of Interest

The authors declare that there are no conflicts of interest to report.

Author Contributions

NAMSF: Protocol/project development, data collection or management, manuscript writing/editing; SJW: Protocol/project development, data analysis, manuscript writing/editing; HDN: Protocol/project development, data analysis, manuscript writing/editing.

Ethics Approval

All cadavers were from a New Zealand European population and had been bequeathed to the Department of Anatomy, in accordance with the New Zealand Human Tissue Act (2008). Ethical approval was granted by the Department of Anatomy, University of Otago, Dunedin, New Zealand. As the undertaking of this study was prior to the establishment of a university-governed ethical approval process for the use of cadavers in research, internal approval for the use of cadavers in this research project was granted by the Department of Anatomy, University of Otago, Dunedin, New Zealand in 2008 and 2014.

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