# THERAPEUTIC EXERCISES for the GLUTEUS MEDIUS and GLUTEUS MINIMUS SEGMENTS


Submitted by

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| | |
|---|---|
| A-D | Analogue – digital conversion |
| Abd | Abduction |
| Add | Adduction |
| Ant | Anterior |
| BPM | Beats per minute |
| BMI | Body mass index |
| CMRR | Common-mode rejection ratio |
| CT | Computed tomography |
| DL | Double leg |
| EMG | Electromyography |
| ER | External rotation |
| ES | Effect size |
| Ext | Extension |
| FAI | Femoro-acetabular impingement |
| Flex | Flexion |
| GMax | Gluteus maximus |
| GMed | Gluteus medius |
| GMin | Gluteus minimus |
| Hz | Hertz |
| I | Isometric |
| Inf | Inferior |
| IQR | Interquartile range |
| IR | Internal rotation |
| Lat | Lateral |

| | |
|---|---|
| MMT | Manual muscle test |
| MR | Medial resistance |
| MRI | Magnetic resonance imaging |
| MVIC | Maximum voluntary isometric contraction |
| NS | Not stated |
| NWB | Non weight bearing |
| OA | Osteoarthritis |
| PCSA | Physiological cross-sectional area |
| Post | Posterior |
| R | Resistance |
| RCT | Randomised controlled trial |
| RE | Rear foot elevated |
| Reps | Repetitions |
| RMS | Root mean square |
| ROM | Range of movement |
| RS | Resisted squat posture |
| RTUS | Real time ultrasound |
| RU | Resisted upright posture |
| SD | Standard deviation |
| SL | Single leg |
| Sup | Superior |
| TFL | Tensor fascia latae |
| U | Unstable surface |
| WB | Weight bearing |

**ACKNOWLEDGEMENTS**

This thesis has been a marathon journey of highs and lows involving nine years of my life whilst maintaining a full-time job and family in a regional location. It has been a fine balancing act on my behalf to sustain the discipline, commitment and momentum to complete the thesis through to the end because there was plenty of occasions when I had wanted to quit from a sense of being overwhelmed with too much work and too few hours to complete it. There are a few people I want to thank in assisting and guiding me along this journey including my loyal supervisors, Dr Tania Pizzari and Dr Adam Semciw. Tania unexpectedly assumed the primary supervisor role early in my candidature and can't thank her enough for her guidance and feedback throughout the journey. This has included all the little extra things above and beyond her position description over the years such as car rides to and from the airport, and even offering a place to sleep over when I came to Melbourne. Adam also came on board in the process and can't thank him enough for his technical expertise in EMG as well as making sense of the data including statistics and EMG analysis. I appreciated the additional things that Adam provided such as car rides when I came to Melbourne, and after hours zoom meetings.

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**SUMMARY**

In hip pathology, normal ageing, and immobility there is increasing evidence of structural and functional impairments affecting individual segments of gluteus medius (GMed) and gluteus minimus (GMin). Prescribed therapeutic exercises should be targeted to address identified deficiencies. Determining the most effective therapeutic exercises for increasing activity levels in the GMed and GMin muscle segments in healthy young adults was the aim of this thesis.

At conception of this thesis (2012) a systematic review was undertaken to evaluate GMed and GMin segmental activity levels for various therapeutic exercises. The review identified investigations of muscle segments with only one study evaluating all three GMed segments with surface electromyography, and no studies identified that had evaluated GMin activity levels. The review highlighted the lack of studies measuring GMed segmental activity levels with fine-wire electromyography. An updated systematic review (2018) found a substantial increase in literature in this area with five included studies evaluating activity in all three GMed segments (anterior, middle and posterior), but only one using validated guidelines for fine-wire electromyography. Two studies (including one from this thesis) evaluated GMin segmental activity levels.

Based on the limited evidence at the time (2012), a cross-sectional study was undertaken investigating GMed and GMin segmental activity levels in healthy young adults performing simple therapeutic exercises using validated fine-wire EMG guidelines. The results identified simple therapeutic exercises that could be prescribed to target individual GMed and GMin segments for potential strengthening. The findings are featured in three

published papers; one evaluating GMin activity (Chapter 3), one evaluating GMed activity (Chapter 4), and one examining the effectiveness of adding hip internal rotation to therapeutic exercises particularly to target the anterior segments of GMed and GMin (Chapter 5).

The results of this thesis have improved the understanding and confidence in targeted exercise prescription for addressing GMed and GMin segmental dysfunction and established a good foundation for future research on the effectiveness of these therapeutic exercises in populations with lower limb pathologies.

## STATEMENT OF AUTHORSHIP

This thesis includes work by the author that has been published or accepted for publication as described in the text.

Except where reference is made in the text of the thesis, this thesis contains no other material published elsewhere or extracted in whole or in part from a thesis accepted for the award of any other degree or diploma.

No other person's work has been used without due acknowledgment in the main text of the thesis.

This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution.

With regard to the extent of collaboration with another person or persons, although the publications involve joint authorship, I have made a significant and leading contribution as the primary author to the work, equivalent to that expected for a traditional thesis.

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All research procedures reported in this thesis were approved by the relevant Ethics Committee (Ethics approval number: FHEC13-005, Appendix A).

This thesis has been written in English. The American Psychological Association (APA) referencing style (6th Edition) has been used, apart from the chapters that are presented in published format that use the formatting and citation style required by the journals they were published in.

Signed: D. Moore ........................................................Date: 29th August 2020.

**PUBLICATIONS**

Chapters 2, 3, 4 and 5 consist of manuscripts published or accepted in peer-reviewed journals. These studies are presented in the format in which they were published.

- Chapter 2 has been accepted as:

  Moore, D., Semciw, A. I., & Pizzari, T. (2020). A systematic review of common therapeutic exercises that generate the highest muscle activity in the gluteus medius and gluteus minimus segments. *International Journal of Sports Physical Therapy*

- Chapter 3 has been published as:

  Moore, D., Semciw, A. I., McClelland, J., Wajswelner, H., & Pizzari, T. (2019). Rehabilitation exercises for the gluteus minimus muscle segments: An electromyography study. *Journal of Sport Rehabilitation*, 28(6), 544-551. doi:10.1123/jsr.2017-0262

- Chapter 4 has been published as:

  Moore, D., Pizzari, T., McClelland, J., & Semciw, A. I. (2019). Rehabilitation exercises for the gluteus medius muscle segments - An electromyography study. *Journal of Sport Rehabilitation*, 1-14. doi:10.1123/jsr.2018-0340

- Chapter 5 has been published as:

  Moore, D., Semciw, A. I., Wisbey-Roth, T., & Pizzari, T. (2020). Adding hip rotation to therapeutic exercises can enhance gluteus medius and gluteus minimus segmental activity levels - An electromyography study. *Physical Therapy in Sport*, 43, 157-165. doi:10.1016/j.ptsp.2020.02.017

**PRESENTATIONS**

- Moore, D., Pizzari, T., McClelland, J., & Semciw, A. I. (October 2017). Gluteus minimus and gluteus medius muscle activity during common rehabilitation exercises in healthy young adults. Free paper presented at the Australian Physiotherapy Conference (Momentum), Sydney, Australia.

- Moore, D., Pizzari, T., McClelland, J., Wajswelner, H., & Semciw, A. I. (October 2015). Single leg bridge and single leg squat elicit high muscle activity levels in all segments of gluteus medius and gluteus minimus posterior. Free paper presented at the Australian Physiotherapy Conference (Connect), Gold Coast, Australia.

- Moore, D., Pizzari, T., McClelland, J., Wajswelner, H., & Semciw, A. I. (September 2015). Single leg bridge and single leg squat elicit high muscle activity levels in all segments of gluteus medius and gluteus minimus posterior. Mill Park Physiotherapy Lecture Series, Melbourne, Australia.

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# CHAPTER 1: INTRODUCTION

The hip joint requires adequate support and control from its surrounding muscles for optimal function in activities of daily living (Retchford, Crossley, Grimaldi, Kemp, & Cowan, 2013). The hip abductor muscle group which includes the gluteus medius (GMed) and gluteus minimus (GMin) is located around the posterolateral hip and pelvic region. For activities involving single leg stance, the GMed and GMin are considered to provide maintenance of pelvic equilibrium and hip joint stability as well as controlling hip internal rotation and adduction (Al-Hayani, 2009; Flack, Nicholson, & Woodley, 2014; Gottschalk, Kourosh, & Leveau, 1989).

## 1.1 Anatomy and function of gluteus medius

The GMed is a broad fan-shaped muscle with a large physiological cross-sectional area (PCSA) of close-packed sarcomeres in parallel arrangement with a relatively short fibre length (Neumann, 2010; Ward, Winters, & Blemker, 2010). This muscle has the potential to generate large forces over small muscle fibre length changes (Neumann, 2010; Ward et al., 2010). It originates from the upper and flared portions of the ilium between the iliac crest and posterior gluteal line above and the anterior gluteal line below, and attaches distally to the lateral and superior-posterior aspects of the greater trochanter (Al-Hayani, 2009) (Figure 1.1). The GMed can be further compartmentalised anatomically into three to four subdivisions that have unique fascicle orientations and separate innervations from the inferior division of superior gluteal nerve (Al-Hayani, 2009; Flack et al., 2014; Gottschalk et al., 1989; Soderberg & Dostal, 1978). The subdivisions are commonly considered to be the anterior, middle and posterior segments (Al-Hayani, 2009; Gottschalk et al., 1989; Soderberg & Dostal, 1978), with one study further splitting the middle segment into mid-anterior and mid-posterior (Flack et al., 2014) (Figure 1.2). These

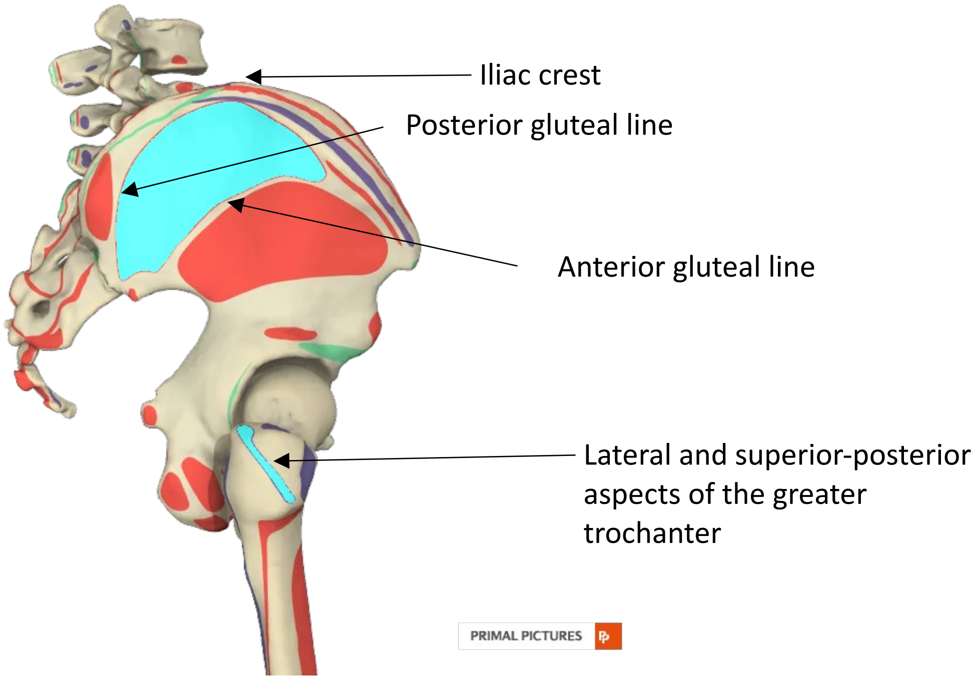


*Figure 1.1. Gluteus medius muscle attachments (turquoise shading)*

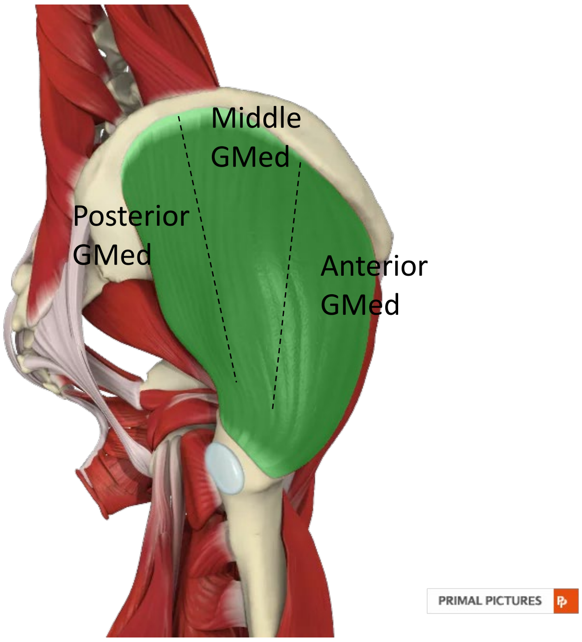


*Figure 1.2. Gluteus medius segments*

segments of GMed have been shown to have distinct functional roles during gait and maximum voluntary isometric contractions (MVIC) (Ganderton, Pizzari, Harle, Cook, & Semciw, 2017; Semciw, Pizzari, Murley, & Green, 2013; Zacharias et al., 2019).

The anterior GMed segment has a relatively large PCSA comprising of nearly vertically aligned fibres that have a large abduction moment arm and a moderate sized internal rotation moment arm (Dostal, Soderberg, & Andrews, 1986). During gait it is thought that anterior GMed stabilises the pelvis and contributes to forward rotation of the contralateral pelvis in unilateral stance (Semciw, Pizzari, Murley, et al., 2013). The middle GMed has the largest PCSA of the three segments and is well designed to stabilize the pelvis across the stance phase of gait with its vertically aligned fibres and a large abduction moment arm (Dostal et al., 1986; Semciw, Pizzari, Murley, et al., 2013). The posterior GMed has the smallest PCSA (Dostal et al., 1986) and is reported to assist with head of femur stability since its fibres are aligned parallel to the neck of femur and it has a moderately sized abduction and external rotation moment arms (Semciw, Pizzari, Murley, et al., 2013).

### 1.2 Anatomy and function of gluteus minimus

The GMin is a smaller fan-shaped muscle originating between the anterior and inferior gluteal lines of the ilium lying immediately deep and just anterior to GMed (Neumann, 2010; Ward et al., 2010). It has attachments to the anterior and superior hip capsule as well as the anterior-superior margin of the greater trochanter (Al-Hayani, 2009; Beck, Sledge, Gautier, Dora, & Ganz, 2000; Gottschalk et al., 1989; Walters, Solomons, & Davies, 2001) (Figure 1.3). The GMin contains a higher proportion of Type 1 fibers compared to GMed and tensor fascia lata suggestive of a role in hip joint stability and proprioception (Sparks, 2011). Anatomically, the GMin is segmented into two subdivisions (anterior and posterior) with separate innervations from the inferior branch of the superior gluteal nerve and distinct fascicle orientations (Al-Hayani, 2009; Beck et al., 2000; Flack et al., 2014; Gottschalk et al., 1989) (Figure 1.4).

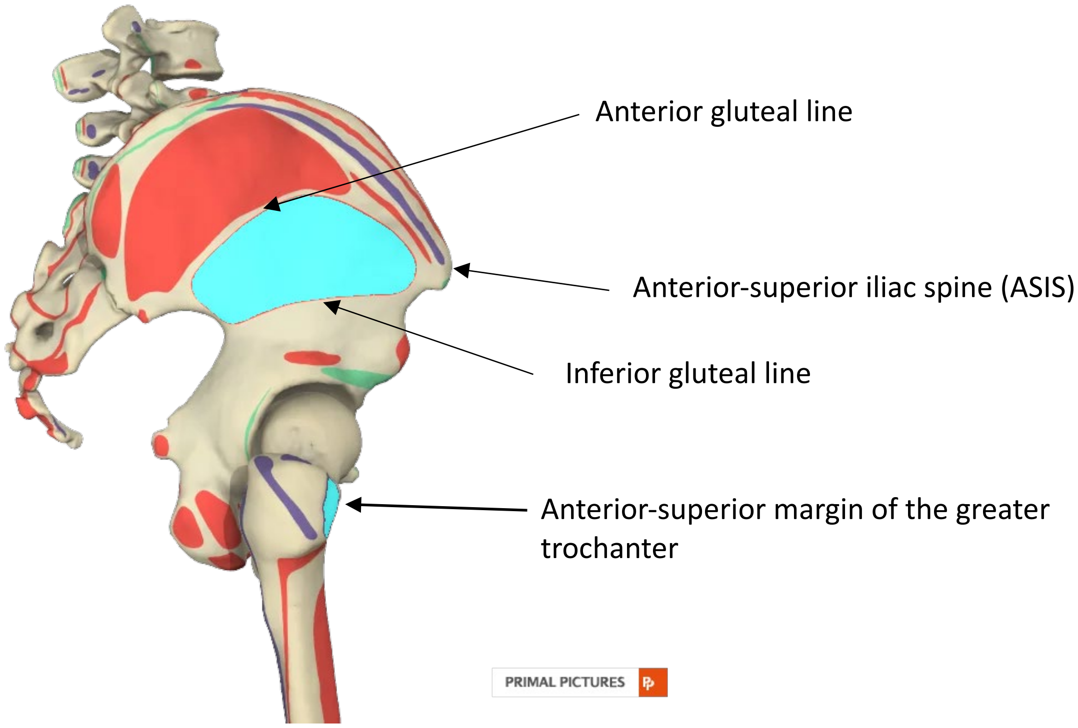


*Figure 1.3. Gluteus minimus muscle attachments (turquoise shading)*

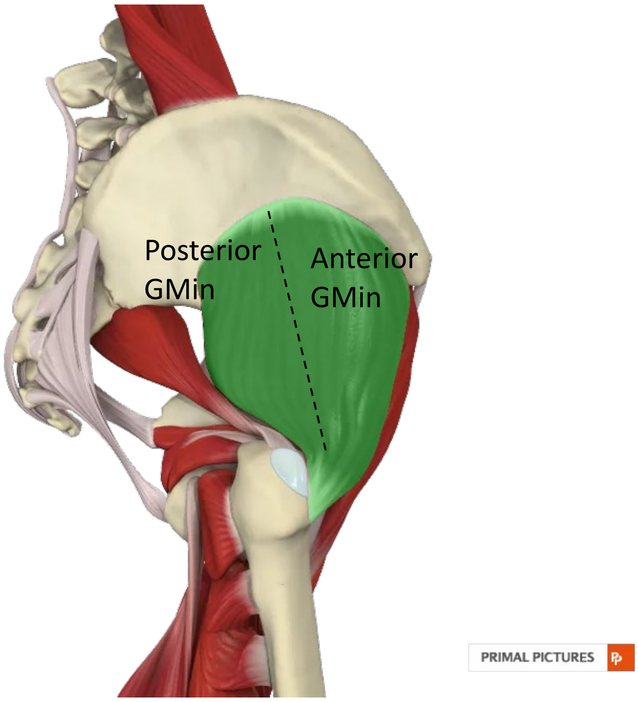


*Figure 1.4. Gluteus minimus muscle segments*

The two segments of GMin have shown potential for functional independence during MVICs and during gait (Semciw, Green, Murley, & Pizzari, 2014). The anterior GMin has vertically aligned fibres (Flack et al., 2014) that are anteriorly positioned and parallel to the neck of femur, a large abduction moment arm, and a moderate sized internal rotation moment arm (Dostal et al., 1986). These features are considered to assist the GMin to attenuate anterior hip joint forces as well as providing head of femur stability during gait (A. I. Semciw et al., 2014). The posterior GMin fibres are positioned posteriorly and parallel to the neck of femur providing hip joint stability during gait (A. I. Semciw et al., 2014) and this segment has a moderately sized abduction and external rotation moment arms.

**1.3 Dysfunction of gluteus medius and gluteus minimus**

Weakness and dysfunction of the GMed and GMin muscles are associated with musculoskeletal conditions around the ankle (Azevedo, Lambert, Vaughan, O'Connor, & Schwellnus, 2009; Franettovich, Chapman, Blanch, & Vicenzino, 2010; Friel, McLean, Myers, & Caceres, 2006), knee (Cowan, Crossley, & Bennell, 2009; Hewett et al., 2005; Hinman et al., 2010), hip (Casartelli et al., 2011; Morrissey et al., 2012; Sole, Milosavljevic, Nicholson, & Sullivan, 2012) and lower back (Bewyer, Bewyer, Messenger, & Kennedy, 2009; Cooper et al., 2016; Nelson-Wong, Gregory, Winter, & Callaghan, 2008). Structural and functional impairments of GMed and GMin are associated with hip pathology, normal ageing and bed rest evident in radiological (Bremer, Kalberer, Pfirrmann, & Dora, 2011; Grimaldi, Richardson, Stanton, et al., 2009; Kawasaki, Hasegawa, Okura, Ochiai, & Fujibayashi, 2017; Kivle et al., 2018; Kiyoshige & Watanabe, 2015; Liu, Wen, Tong, Wang, & Wang, 2012; Mendis, Wilson, Hayes, & Hides, 2020; Miokovic, Armbrecht, Felsenberg, & Belavy, 2011; Muller, Tohtz, Dewey, Springer, &

Perka, 2010; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann, Notzli, Dora, Hodler, & Zanetti, 2005; Woodley et al., 2008; Zacharias, Pizzari, English, Kapakoulakis, & Green, 2016), anatomical (Flack et al., 2014; Takano et al., 2018), biomechanical (Allison, Bennell, et al., 2016; Allison, Hall, et al., 2018; Allison, Vicenzino, Bennell, et al., 2016; Allison, Wrigley, et al., 2016) and electromyography (EMG) studies (Allison, Vicenzino, Bennell, et al., 2016; Ganderton, Pizzari, Harle, et al., 2017; Zacharias et al., 2019).

### 1.3.1 Structural impairments of gluteus medius and gluteus minimus

Whole muscle atrophy of the GMin and the GMed have been identified in people with advanced hip osteoarthritis (OA) (Grimaldi, Richardson, Stanton, et al., 2009; Kivle et al., 2018; Zacharias et al., 2016), lateral hip pain (Woodley et al., 2008), falls-related hip fracture in the elderly (Chi, Long, Zoga, Parker, & Morrison, 2016), after prolonged bed rest (Miokovic et al., 2011), and in normal ageing (Chi et al., 2015). The extent of the atrophy and fat infiltration in hip OA is related to clinical severity with GMin more affected in the earlier stages of OA compared to GMed (Grimaldi, Richardson, Stanton, et al., 2009; Zacharias et al., 2016). Total GMed atrophy has been found in adults with unilateral developmental hip dysplasia (Liu et al., 2012) and young to middle aged adults with acetabular labral joint pathology (Mendis et al., 2020).

In end stage OA and following total hip arthroplasty, segmental atrophy and fatty infiltrate is present in the anterior GMin and to a lesser degree the anterior GMed (Bremer et al., 2011; Kawasaki et al., 2017; Kivle et al., 2018; Muller, Tohtz, Dewey, et al., 2010; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005). Anatomical studies have identified targeted anterior GMin atrophy and fatty infiltrate with ageing (Flack et al., 2014; Takano et al., 2018), and associated with an increased risk of falls (Kiyoshige & Watanabe, 2015).

### 1.3.2 Functional impairments of gluteus medius and gluteus minimus

Hip abductor weakness, as measured by a hand-held dynamometer, has been identified across a range of hip conditions including hip dysplasia (Jacobsen et al., 2018), femoroacetabular impingement syndrome (Casartelli et al., 2011; Freke et al., 2016), hip chondrolabral pathology (Kemp et al., 2014), lateral hip pain (Allison, Vicenzino, Wrigley, et al., 2016; Ganderton, Pizzari, Harle, et al., 2017) and hip OA (Loureiro, Mills, & Barrett, 2013; Zacharias et al., 2016). Decreased hip abductor strength is also associated with numerous distal lower limb conditions including medial knee osteoarthritis (Hinman et al., 2010), patellofemoral pain (Rathleff, Rathleff, Crossley, & Barton, 2014), iliotibial band syndrome (Fredericson et al., 2000) and tibialis posterior dysfunction (Kulig, Popovich, Noceti-Dewit, Reischl, & Kim, 2011). Hip abductor weakness is considered a risk factor for sustaining various lower limb disorders such as exertional shin pain (Verrelst et al., 2014), non-contact ACL injuries (Khayambashi, Ghoddosi, Straub, & Powers, 2016) and lateral ankle sprains (Powers, Ghoddosi, Straub, & Khayambashi, 2017).

Gluteus medius and GMin muscle activation measured using EMG is altered in people with hip-related pain (Allison, Salomoni, et al., 2018; Ganderton, Pizzari, Harle, et al., 2017; Zacharias et al., 2019). During gait, people with lateral hip pain typically demonstrated greater average muscle activation across all GMin and GMed segments with decreased variability in EMG muscle activity particularly for the anterior GMed and GMin segments across the stance phase compared to controls (Allison, Salomoni, et al., 2018; Ganderton, Pizzari, Harle, et al., 2017). For people with hip OA, higher peak posterior GMin activity and earlier peak anterior GMin activity were reported as well as decreased variability in EMG muscle activity for the anterior GMed and GMin segments across the stance phase of gait compared to controls (Zacharias et al., 2019). Higher activation in the presence of pathology could be due to GMin and GMed segments requiring greater neural drive and motor unit recruitment to perform a submaximal task to compensate for weakness (Homan, Norcross, Goerger, Prentice, & Blackburn, 2013).

With structural and functional impairments demonstrating specific segment effects as a result of pathology and ageing, therapeutic exercise programs may need to consider targeting distinct GMed and GMin segments.

**1.4 Hip abductor strengthening programs**

Contemporary rehabilitation has focused on prescribing therapeutic exercise programs to strengthen the hip abductor muscles in the management and prevention of many common lower extremity musculoskeletal conditions. These exercise programs have had varying levels of efficacy for achieving good outcomes for pain, function and quality of life measures. Adding hip strengthening exercises (including hip abductors) to quadricep strengthening exercises was found to be more effective than quadricep strengthening exercises alone for patient-reported outcomes and physical function in the short-term for knee OA (Bennell et al., 2010; Hislop, Collins, Tucker, Deasy, & Semciw, 2020), and in the short and longer-term for patellofemoral pain (Barton et al., 2019; Fukuda et al., 2012; Santos, Oliveira, Ocarino, Holt, & Fonseca, 2015).

Based on recently published clinical guidelines, the benefits of hip strengthening exercises for hip OA are mixed (Bannuru et al., 2019). A systematic review (Fransen, McConnell, Hernandez-Molina, & Reichenbach, 2014), that was included in the clinical guidelines, highlighted short to medium term improvements in pain and physical function following land-based therapeutic exercise for hip OA. A randomized controlled trial (RCT) published in the same year identified that hip strengthening exercises as part of an active physiotherapy intervention was no better than a sham treatment in the short and medium term for pain, patient-reported outcomes and physical function (Bennell et al., 2014).

There may be a number of reasons for inconsistent findings of the benefits of hip abductor strengthening programs across these studies. First, the exercises prescribed to strengthen the hip muscles may not have been individually optimised throughout the intervention period in accordance with generally accepted exercise prescription principles for enhancing muscular fitness (Garber et al., 2011). Second, specific to the hip abductors, the prescribed exercises may not have generated sufficient muscle activity in GMin or GMed segments to address the structural and functional impairments, with at least 40 percent maximum voluntary isometric contraction (MVIC) required for strength gains and muscular hypertrophy (Andersen et al., 2006). No studies have based exercise selection on targeting the deeper GMin muscle.

### 1.5 Gluteus medius therapeutic exercises

Various therapeutic exercises have been recommended to target and strengthen the GMed based on EMG activity levels (Ebert, Edwards, Fick, & Janes, 2017; French, Dunleavy, & Cusack, 2013; Hamstra-Wright & Huxel Bliven, 2012; Macadam, Cronin, & Contreras, 2015; Reiman, Bolgla, & Loudon, 2012). There has been a dramatic increase in research into this area over the last few years. This is best illustrated by a review (Reiman et al., 2012) performed in May 2010 on therapeutic exercises for GMed identifying four studies suitable for inclusion. An updated systematic review (Chapter 2) performed in May 2018 with stricter inclusion criteria contained 56 studies. Some of the recommended exercises based on high GMed EMG levels have included side bridge, single leg squat, single leg deadlift, pelvic drop, side lie hip abduction, transverse lunge, single leg bridge and forward step-up (Reiman et al., 2012).

The limitation of the majority of studies evaluating GMed muscle activity is the use of a single surface electrode positioned at the middle GMed segment. This limits inferences about the best exercises for eliciting anterior and posterior GMed activity. Measuring middle GMed EMG activity using surface electrodes might also be impacted by myoelectric contamination or crosstalk from surrounding muscles (Semciw, Neate, & Pizzari, 2014).

Four studies (Heo, An, Yoo, & Oh, 2013; Ju & Yoo, 2016; O'Sullivan, Herbert, Sainsbury, McCreesh, & Clifford, 2012; O'Sullivan, Smith, & Sainsbury, 2010) have recorded activity from all three GMed segments using surface electrodes but anatomical coverage of the anterior and posterior GMed segments by the neighbouring tensor facia latae and gluteus maximus (Semciw, Green, Pizzari, & Briggs, 2013) brings into question the validity of these studies. At the inception of the research for this thesis and at the time of data collection, no studies had evaluated the activation of the three segments of GMed during exercise using intramuscular EMG.

### 1.6 Gluteus minimus therapeutic exercises

There is limited research to guide prescription of therapeutic exercises for the GMin, with there being only one recent study (Ganderton, Pizzari, Cook, & Semciw, 2017) evaluating exercises in healthy elderly women. The lack of research in this area may be due to having to use the more technically difficult and invasive method of inserting fine wire intramuscular electrodes to access and measure the GMin. Based on this one study, the exercises that generated at least high EMG activity for both GMin segments were different variations of the hip hitch exercise (hip hitch, hip hitch with toe-tap and hip hitch with hip swing) and weight bearing isometric hip abduction. The dip test (rear-foot elevated lunge) also generated at least high EMG activity for the posterior GMin segment. At the time of data collection and inception of the research for this thesis, there had been no studies that had evaluated the activation of the two segments of GMin during exercise using intramuscular EMG.

### 1.7 Summary and general aim

Considering the importance of GMed and GMin in normal hip function, the propensity for deficits with pathology and ageing, and our emerging understanding of segmental function and limited knowledge of how to target each segment, it was the aim of this thesis to determine the most effective therapeutic exercises for increasing activity levels in each of the GMed and GMin segments to guide clinicians in exercise prescription for targeted interventions.

The aim of this thesis was achieved by a series of published papers presented over the following chapters including one systematic review and three experimental studies.

Chapter 2 is a systematic review evaluating the current evidence on the effectiveness of common therapeutic exercises generating at least high EMG activity levels for individual segments of GMed and GMin. This is an updated systematic review (2018) with the original (2012) located in Appendix 3. Conception of the research studies undertaken in this thesis was based on results from the original systematic review performed in 2012 where there had been no published studies evaluating segmental activity levels for GMed and GMin using intramuscular EMG.

Chapter 3 is an experimental cross-sectional study quantifying and comparing GMin segmental activity levels for six simple therapeutic exercises.

Chapter 4 investigates GMed segmental activity levels for six simple therapeutic exercises in an experimental cross-sectional study.

Chapter 5 evaluates the effectiveness of enhancing GMed and GMin segmental activity levels by adding hip rotation to two simple therapeutic exercises in an experimental cross-sectional study.

The overall findings and clinical implications of this thesis are then summarised in Chapter 6 and recommendations are made for future research.

# CHAPTER 2: A SYSTEMATIC REVIEW OF COMMON THERAPEUTIC EXERCISES THAT GENERATE THE HIGHEST MUSCLE ACTIVITY IN THE GLUTEUS MEDIUS AND GLUTEUS MINIMUS SEGMENTS.

## Introduction

Rehabilitation programs that include hip abductor (GMed and GMin) strengthening exercises are becoming more prevalent in clinical practice for managing common local (French, Cusack, et al., 2013; Kemp, Coburn, Jones, & Crossley, 2018) and distal (Bennell et al., 2010; Khayambashi, Fallah, Movahedi, Bagwell, & Powers, 2014) lower limb conditions. With the GMed and GMin consisting of functionally unique subdivisions with different responses to pathology, there is uncertainty about whether the prescribed hip abductor exercises in these programs are targeting the specific segmental impairments with adequate intensity to stimulate hypertrophy (Kawasaki et al., 2017; Kivle et al., 2018; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005).

Previous reviews of GMed exercises (Ebert et al., 2017; French, Dunleavy, et al., 2013; Hamstra-Wright & Huxel Bliven, 2012; Macadam et al., 2015; Reiman et al., 2012) base recommendations on single electrode surface EMG measurements, and there is only one study on GMin exercises (Ganderton, Pizzari, Cook, et al., 2017). There was a need to update the evidence such that the clinician is confident in targeted exercise prescription for rehabilitation programs.

The aim of this systematic review was to evaluate the most effective therapeutic exercises for generating high activity levels in GMed and GMin segments.

The study in this chapter has been accepted as:

Moore, D., Semciw, A.I., & Pizzari, T. (2020). A systematic review of common therapeutic exercises that generate the highest muscle activity in the gluteus medius and gluteus minimus segments. *International Journal of Sports Physical Therapy.*

## 2.1 Abstract

***Background:*** The gluteus medius (GMed) and gluteus minimus (GMin) muscle segments demonstrate different responses to pathology and ageing, hence it is important in rehabilitation that prescribed therapeutic exercises can effectively target the individual segments with adequate exercise intensity for strengthening.

***Purpose:*** The purpose of this systematic review was to evaluate whether commonly evaluated therapeutic exercises generate at least high (> 40% maximum voluntary isometric contraction (MVIC)) electromyographic (EMG) activity in the GMed (anterior, middle and posterior) and GMin (anterior and posterior) segments.

***Methods:*** Seven databases (MEDLINE, EMBASE, CINAHL, AusSPORT, PEDro, SPORTdiscus and Cochrane Library) were searched from inception to May 2018 for terms relating to gluteal muscle, exercise, and EMG. The search yielded 6918 records with 56 suitable for inclusion. Quality assessment, data extraction and data analysis were then undertaken with exercise data pooled into a meta-analysis where two or more studies were available for an exercise and muscle segment.

***Results:*** For the GMed, different variations of the hip hitch/pelvic drop exercise generated at least high activity in all segments. The dip test and isometric stand hip abduction are other options to target the anterior GMed segment, while isometric stand hip abduction can be used for the posterior GMed segment. For the middle GMed segment, the single leg bridge; side-lie hip abduction with hip internal rotation; lateral step-up; stand hip abduction on stance leg or swing leg with added resistance; and resisted side-step were the best options for generating at least high activity. Standing isometric hip abduction and different variations of the hip hitch/pelvic drop exercise generated at least high activity in all GMin segments, while side-lie hip abduction, the dip test, single leg bridge and single leg squat can also be used for targeting the posterior GMin segment.

***Conclusion:*** The findings from this review provide the clinician with confidence in exercise prescription for targeting individual GMed and GMin segments for potential strengthening with ageing or following injury.

***Levels of Evidence:*** 1.

***What is known about the subject:*** Previous reviews on GMed exercises have been based on single electrode, surface EMG measures at middle GMed segment. It is not known whether these exercises effectively target the other segments of GMed or the GMin at a sufficient intensity for strengthening.

***What this study adds to existing knowledge:*** This review provides the clinician with confidence in exercise prescription of commonly reported therapeutic exercises to effectively target individual GMed and GMin segments for potential strengthening.

***Keywords:*** EMG, gluteal muscle, hip, exercise therapy, movement system

## 2.2 Introduction

Gluteal muscle dysfunction is associated with pain and symptoms at the ankle (Azevedo et al., 2009; Beckman & Buchanan, 1995; Franettovich et al., 2010), knee (Fredericson & Wolf, 2005; Hewett et al., 2005; Souza & Powers, 2009) hip (Amaro, Amado, Duarte, & Appell, 2007; Casartelli et al., 2011; Morrissey et al., 2012), and lower back (Bewyer et al., 2009; Nelson-Wong et al., 2008). There is also evidence that severity of symptoms on clinical presentation are associated with atrophied or weak muscles (Lawrenson et al., 2019; Zacharias et al., 2018). It is therefore important to understand the most effective methods of activating the gluteal muscles with therapeutic exercise for the purpose of strengthening these muscles in clinical populations (Boling, Bolgla, Mattacola, Uhl, & Hosey, 2006; Gilchrist et al., 2008; Sled, Khoja, Deluzio, Olney, & Culham, 2010).

The effectiveness of hip strengthening programs for improving symptoms and quality of life in clinical conditions is variable. While there are clear benefits of hip strengthening exercises for conditions of the knee, (Hislop et al., 2020) results for conditions such as hip osteoarthritis are less convincing with only mild benefits in the short term (Fransen et al., 2014). Two reasons that may account for variable effects are; (1) the exercises used in typical rehabilitation programs may not activate the muscles with sufficient intensity to elicit strength and/or hypertrophic adaptations, or (2) the exercises typically prescribed may not target individual segments of gluteus medius (GMed) and gluteus minimus (GMin) and/or with sufficient intensity. These muscles consist of distinct individual segments (anterior, middle and posterior for GMed; and anterior and posterior for GMin) with separate innervations, different muscle fiber orientations, and diverse functional roles (A. I. Semciw et al., 2014; Semciw, Pizzari, Murley, et al., 2013). In addition to generalized muscle atrophy of GMin and GMed in clinical presentations such as hip osteoarthritis (Zacharias et al., 2016), gluteal tendinopathy (Woodley et al., 2008), and following total hip replacement (Bremer et al., 2011; Pfirrmann et al., 2005) there is evidence of specific segmental atrophy and dysfunction (Bremer et al., 2011; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005). Understanding the role of exercises for targeting individual muscle segments of GMin and GMed may enable better tailoring of exercise interventions to people with varied underlying presentations, or those with specific conditions.

There are a number of reviews (Ebert et al., 2017; French, Dunleavy, et al., 2013; Hamstra-Wright & Huxel Bliven, 2012; Macadam et al., 2015; Reiman et al., 2012) that have reported GMed activity levels for various therapeutic exercises but have mostly contained studies that utilise a single surface electrode positioned over the middle GMed segment to record electromyographic (EMG) activity. No previous reviews have considered exercises to target the individual segments of the GMed, and none have examined therapeutic exercises for the GMin. An updated systematic review will inform clinicians of the effectiveness of exercises targeting individual GMed and GMin segments.

The aim of this review was to evaluate the effectiveness of commonly evaluated therapeutic exercises in generating at least high activity levels adequate for targeted hypertrophy of the individual GMed and GMin segments.

## 2.3 Method

### 2.3.1 Search strategy

This review was conducted in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) statement guidelines (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). A systematic literature search was conducted of MEDLINE, CINAHL, EMBASE, AUSPORT, SPORTDiscus, PEDRO and the Cochrane Library from inception to first week May 2018. These databases were searched using free-text words, keywords mapped to medical subject headings (MeSH), and filters were applied for human subjects where possible. Boolean operators were used to combine the key words with truncated search terms: (glut* OR buttock* OR hip rotat* OR hip abduct*) AND (strength* OR contract* OR electromyo* OR EMG OR electrode* OR activ* OR intensit*

OR peak amplitude* OR funct*) (Supplementary file). Further relevant studies were searched through reference scanning of included full-text studies.

From the initial search yield, articles were imported into Endnote version X8, duplicate papers were removed, and the abstracts and titles of the remaining papers were screened by two reviewers (DM and TP) independently through application of the inclusion and exclusion criteria. Full-text was obtained for the remaining studies to determine eligibility for inclusion into the review through consultation and consensus between the reviewers (DM and TP).

**2.3.2 Inclusion and Exclusion Criteria**

Inclusion and exclusion criteria were determined prior to administering the search strategy. Since most studies in this area of research are either cross-sectional or single-group pre- and post-test design, all study designs were eligible for inclusion except clinical commentary or opinion articles, and unpublished material such as theses, abstracts, and conference proceedings.

Studies comprising of only healthy participants were included in this review. A study with pathological participants was only included if there was a group of healthy controls with separate data presented.

Normalised muscle activity measured using surface or intramuscular EMG was selected as the outcome measure of interest since it has been long established and universally advocated as the method of choice in measuring and comparing muscle activity between different exercises and individuals (Burden, 2010; De Luca, 1997; Soderberg & Cook, 1984; Soderberg & Knutson, 2000). To be included, studies had to normalise EMG to a MVIC since this has been found to be the most reliable method for comparing exercises for the GMed in healthy participants (Bolgla & Uhl, 2007) and is clinically interpretable. This also allows a more meaningful comparison between studies and a logical synthesis of findings. Inappropriate normalisation procedures were considered to include no normalisation, sub-maximal isometric contraction normalisation, and dynamic contraction normalisation.

Due to the vast breadth of studies that have evaluated exercises for the GMed, only studies that evaluated the GMed and / or the GMin, and contained at least one commonly evaluated therapeutic exercise (including squats, lunges, steps, hip hitches, standing hip abduction, supine bridges, side lie hip abduction and side lie hip clam) and the different variations of these exercises were accepted into this review. A commonly evaluated exercise was one that had been examined in more than one study. Exercises using custom-made devices or commercial gym equipment were excluded from this review as were plyometric exercise activities such as hopping, running or jumping.

### 2.3.3 Quality assessment

Methodological quality of included studies in this review were assessed independently by two reviewers (DM and TP) using a standardised quality assessment tool recommended by the Non-Randomised Studies Group of the Cochrane Collaboration and previously adapted for EMG study reviews (Ganderton & Pizzari, 2013; Semciw, Neate, & Pizzari, 2016). With the scope of the tool covering external validity, performance bias and detection bias, these items are then displayed in its raw form individually for the reader to evaluate the study quality for each item rather than be determined by an overall summary score.

### 2.3.4 Data extraction

Data were extracted by one reviewer (DM) and verified by a second (TP) using a standardised form (University of York, 2001) that was modified for this review. The main study characteristics extracted included; participant characteristics; electrode placement; normalisation method; exercise characteristics; and study results. Where studies had healthy and pathological participants performing therapeutic exercises, data were extracted for the healthy participants. Data relating to muscle activity for each exercise was summarised as mean % MVIC with 95% confidence interval (CI). Data reported as medians and inter-quartile range (IQR) were converted to means and standard deviations (SD) using methods described by Wan, Wang, Liu, and Tong (2014). The meta R statistical software package (v 4.9-5) was used to convert the SD to a 95% CI. Calculations were performed in the log scale and backtransformed to raw units (% MVIC) for ease of interpretation.

Electromyographical technical data for collection, processing and analysis were also extracted from all the included studies since collection, normalisation and processing methods can influence muscle activity profiles (Kleissen, 1990).

### 2.3.5 Data analysis

Data were grouped according to muscle segment and exercise and summarised qualitatively according to level of activity. Where two or more studies were available for a specific muscle segment and exercise, data were pooled quantitatively in a meta-analysis using the meta package in R. A random effects model was used for data pooling, and statistical heterogeneity was described using the $I^2$ statistic (0-100%) where 25%, 50% or 75% was considered low, moderate or high level of heterogeneity respectively (Higgins, Thompson, Deeks, & Altman, 2003).

For simplicity in analysing the exercises for activation levels across the studies, exercise results were characterised into very-high (>60% MVIC), high (41-60% MVIC), moderate (21-40% MVIC) or low (0-20% MVIC) levels of activation as has been utilised in previous reviews (Ebert et al., 2017; Escamilla, Yamashiro, Paulos, & Andrews, 2009; Reiman et al., 2012).

## 2.4 Results

### 2.4.1 Study selection

The flow of studies through the review is illustrated in Figure 2.1. Fifty-six studies satisfied the eligibility criteria and were included in this review.

### 2.4.2 Methodological quality

The risk of bias across studies is summarised in Table 2.1. All but four studies provided adequate demographic data for the study population and only one study had a blinded data analyst for raw EMG data (Poolman et al., 2007) (Table 2.1). Eighteen studies provided

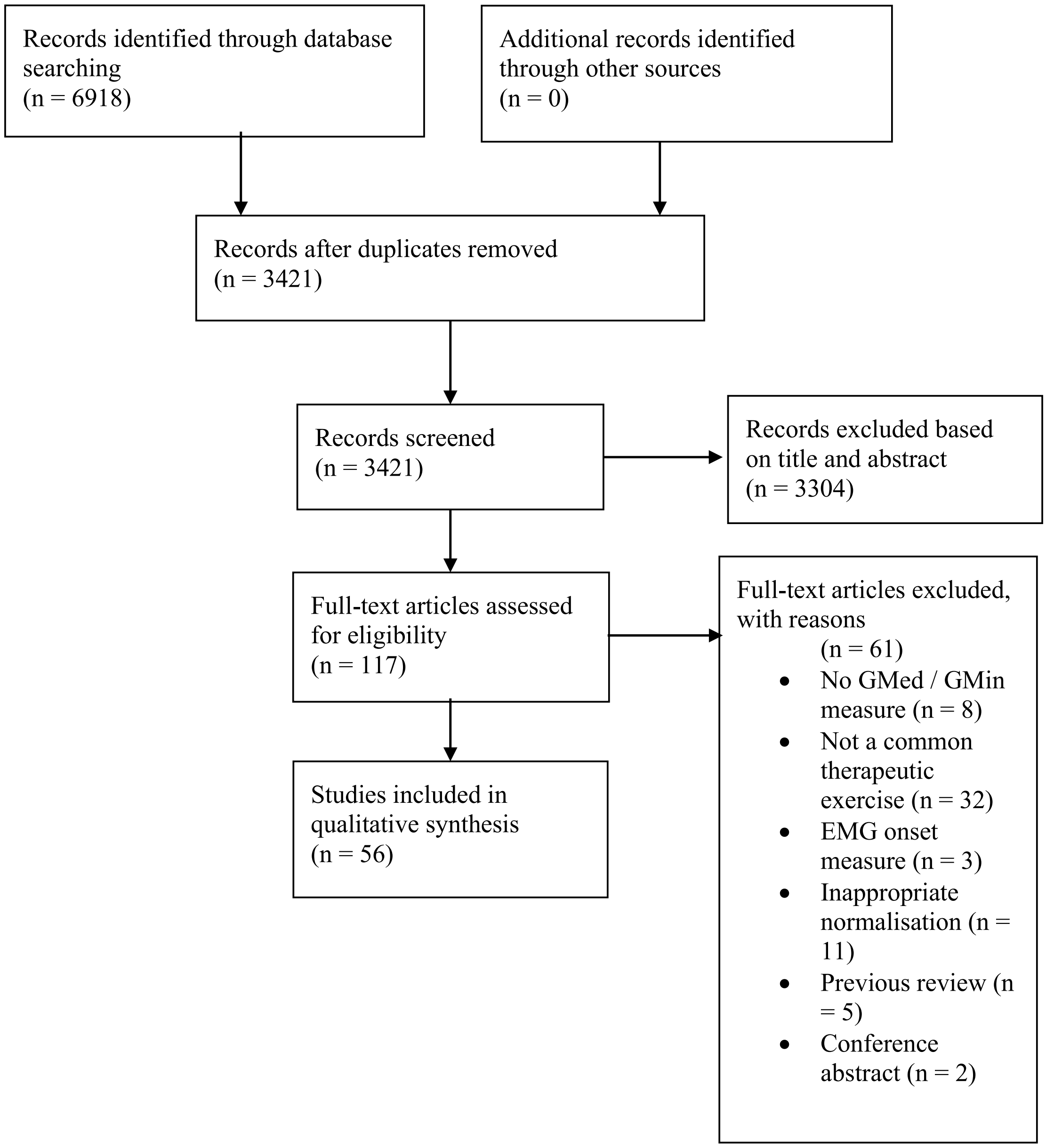


*Figure 2.1. PRISMA diagram of study selection through the review*

*Table 2.1. Methodological quality of the included studies using a risk of bias assessment*

| Study | External validity | Internal validity | | | | |
|---|---|---|---|---|---|---|
| | | Detection | Selection bias / control of confounding | | | |
| | Representative | Blinded assessors | Appropriate electrode positioning | Randomisation of exercises | Appropriate normalisation procedure | Appropriate statistical tests used to assess EMG activity |
| Ayotte et al. (2007) | ✓ | × | × | ✓ | ✓ | ✓ |
| Barton et al. (2013) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Berry et al. (2015) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Bolgla et al. (2014) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Bolgla et al. (2016) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Bolgla & Uhl (2005) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Boren et al. (2011) | × | × | ✓ | ✓ | ✓ | × |
| Boudreau et al. (2009) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Bouillon et al. (2012) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Cambridge et al. (2012) | ✓ | × | × | ✓ | ✓ | ✓ |
| Chan et al. (2017) | ✓ | × | × | ✓ | ✓ | ✓ |
| Cynn et al. (2006) | ✓ | × | ✓ | × | ✓ | ✓ |
| Distefano et al. (2009) | ✓ | × | × | ✓ | ✓ | ✓ |
| Dwyer et al. (2010) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Dwyer et al. (2016) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Ekstrom et al. (2007) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Felecio et al. (2011) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Ganderton et al. (2017) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Harput et al. (2016) | ✓ | × | ✓ | × | ✓ | ✓ |
| Hatfield et al. (2016) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Heo et al. (2013) | ✓ | × | × | × | × | ✓ |
| Hertel et al. (2005) | ✓ | × | × | ✓ | ✓ | ✓ |
| Ju & Yoo (2017) | ✓ | × | × | × | ✓ | ✓ |
| Ju & Yoo (2016) | ✓ | × | ✓ | × | ✓ | ✓ |
| Kang et al. (2014) | ✓ | × | ✓ | × | ✓ | × |
| Kim et al. (2015) | ✓ | × | × | × | ✓ | ✓ |
| Krause et al. (2018) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Krause et al. (2009) | ✓ | × | × | ✓ | ✓ | ✓ |
| Lee et al. (2013) | ✓ | × | × | ✓ | ✓ | ✓ |
| Lee et al. (2014) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Lehecka et al. (2017) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Lin et al. (2016) | ✓ | × | × | × | ✓ | ✓ |
| Lubahn et al. (2011) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| MacAskill et al. (2014) | ✓ | × | × | ✓ | ✓ | ✓ |
| Mauntel et al. (2013) | ✓ | × | × | ✓ | ✓ | ✓ |
| McBeth et al. (2013) | ✓ | × | ✓ | × | ✓ | ✓ |
| Monteiro et al. (2017) | ✓ | × | ✓ | ✓ | ✓ | ✓ |

| Study | External validity | Internal validity | | | | |
|---|---|---|---|---|---|---|
| Moore et al. (2018) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Morimoto et al. (2018) | × | × | × | × | ✓ | ✓ |
| Noh et al. (2012) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Oliver & Stone (2016) | × | × | ✓ | × | ✓ | ✓ |
| Oliver et al. (2010) | × | × | ✓ | ✓ | ✓ | ✓ |
| O'Sullivan et al. (2012) | ✓ | × | ✓ | × | ✓ | ✓ |
| O'Sullivan et al. (2010) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Petrofsky et al. (2005) | ✓ | × | × | × | ✓ | ✓ |
| Philippon et al. (2011) | ✓ | × | × | ✓ | ✓ | ✓ |
| Selkowitz et al. (2013) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Sidorkewicz et al. (2014) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Sinsurin et al. (2015) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Souza & Powers (2009) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Webster & Gribble (2013) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Willcox & Burden (2013) | ✓ | × | × | ✓ | ✓ | ✓ |
| Youdas et al. (2014) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Youdas et al. (2015) | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Youdas et al. (2013) | ✓ | × | ✓ | × | ✓ | ✓ |
| Zeller et al. (2003) | ✓ | × | ✓ | ✓ | ✓ | ✓ |

Note:✓ indicates the quality measure was addressed adequately, × indicates the quality measure was not addressed adequately or not reported clearly in the study
Representative: ✓ if the study describes demographic details (age, gender, height, weight).
Blinded assessors: ✓ if data assessed or processed by a blinded assessor.
Appropriate electrode positioning: ✓ if surface electrodes were described being placed according to SENIAM guidelines or anatomy atlas.
Appropriate normalisation procedure:✓ if procedure described tested position and contraction type.

insufficient information on appropriate electrode positioning and 14 studies did not randomise the exercise protocol to minimise the potential for bias from learning effects and fatigue (Table 2.1).

### 2.4.3 Study characteristics

The 56 included studies for this review are summarised in Tables 2.2 and 2.3. There were 55 studies included for GMed and two studies (Ganderton, Pizzari, Cook, et al., 2017; Moore, Semciw, McClelland, Wajswelner, & Pizzari, 2019) for GMin with one study

*Table 2.2. Summary of included gluteus medius studies*

| Study and type | Participant characteristics | EMG electrode type and placement | Normalisation method | Exercise characteristics | Results (% MVIC (SD)) |
|---|---|---|---|---|---|
| Ayotte et al. (2007) (Cross-sectional) | 23 (16 M) physically active Department of Defence. 31.2 (5.8) years; 173.1 (10.1) cm; 77 (13.9) kg. | Surface (33% iliac crest to greater trochanter) dominant limb. | MVIC 3 trials x 3 secs in side-lie $0^0$ abd., neutral flex. / ext. 1 min rest between trials. | Exercises – 5 randomised: wall squat; mini squat; forward step-up; lateral step-up; retro step-up. Repetitions – 3 of 1.5 secs concentric and 1.5 secs eccentric to a metronome (40 bpm). Practice reps before. Rest – 5 mins between MVIC testing and exs. | wall squat 52 (22); forward step-up 44 (17); lateral step-up 38 (18); retro step-up 37 (18); mini squat 36 (17). |
| Barton et al. (2013) (Cross-sectional) | 19 (11 M) healthy university. 28.4 (2.7) years; 172.4 (5.8) cm; 67.8 (10.4) kg. | Surface (SENIAM, 2011) on dominant limb. | MVIC 3 trials x 5 sec in side-lie $10^0$ abd, neutral hip flex. - ext. 1 min rest between reps. | Exercises – 4 randomised: wall squat; wall squat against gym ball; SL squat with contralateral leg wall support; SL squat with contralateral leg against gym ball wall support. Repetitions – 3 trials, 2 secs eccentric, 5 secs isometric, 2 secs concentric. 1 practice trial before. Rest - 30 secs between trials. | SL squat with ball 46 (15); SL squat 42 (12); squat with ball 10 (7); squat 9 (5). |
| Berry et al. (2015) (Cross-sectional) | 24 (12 M) healthy college. 22.9 (2.9) years; 171.1 (10.5) cm; 68.6 (12.9) kg | Surface (Konrad (2005)) post. portion bilaterally. | MVIC 1 trial x 3 secs in side-lie abd. 1 practice rep before. | Exercises – 2 randomised: side-step upright posture with elastic resistance; side-step squat posture with elastic resistance. Repetitions – 8 for each ex. for each direction. | squat posture stance limb 35.7 (13.8); squat posture moving limb 23.3 (11.2); upright posture stance limb 22.9 (9.5); upright posture moving limb 18.7 (8.0). |
| Bolgla et al. (2016) (Cross-sectional) | 34 (18 M) healthy active university. 24.3 (3.4) years (M), 24 (1.5) years (F); 1.8 (0.1) m (M), 1.65 (0.1) m (F); 81.2 (9.7) kg (M), 59.9 (8.8) kg (F). | Surface (33% iliac crest to greater trochanter) on dominant limb. | MVIC 2 trials x 5 sec in side-lie abd. 1 practice trial before. 30 secs rest between trials. | Exercises – 4 randomised: SL wall squat; SL mini squat; lateral step down; forward step down. Repetitions – 15 to a metronome (40 bpm), 1 beat down, 1 beat up, 1 beat rest. Practice reps before. Rest – 3 mins between exs. | SL wall squat 26.5 (12); SL mini squat 23.2 (12.2); front step down 22.8 (12.2); lateral step down 21.4 (10.7). |
| Bolgla et al. (2014) (Cross-sectional) | 34 (18M) healthy active university. 24.3 (3.4) years (M), 24 (1.5) years (F); 1.8 (0.1) m (M), 1.65 (0.1) m (F); | Surface on dominant limb. | MVIC 2 trials x 5 sec in side-lie abd. | Exercises – 4 randomised: SL wall squat; SL mini squat; lateral step down; forward step down. Repetitions – 15 to a metronome (40 bpm). | SL wall squat 21.6 (8.6) (M), 32 (13.1) (F); SL mini squat 20.3 (11.2) (M), 26.6 (12.8) (F); front step down 19 (9.2) (M), 27.2 (13.9) (F); lateral step down 18.5 (10.2) (M), 24.6 (10.6) (F). |

| | | | | | |
|---|---|---|---|---|---|
| | 81.2 (9.7) kg (M), 59.9 (8.8) kg (F). | | | Rest – 3 mins between exs. | |
| Bolgla and Uhl (2005) (Cross-sectional) | 16 (8 M) healthy university. 27 (5) years; 1.7 (0.2) m; 76 (15) kg. | Surface (33% iliac crest to greater trochanter) on (R) limb. | MVIC 3 trials x 3-5 secs in side-lie $25^0$ abd. 1 min rest between trials. | Exercises – 6 randomised: side-lie hip abd; stand hip abd NWB; stand hip abd hip flex $30^0$ NWB; pelvic drop; stand hip abd; stand hip abd with hip flex $30^0$. NWB exs had cuff weight 3% body weight on (R) leg. Repetitions – 15 to a metronome (60 bpm) of 1 beat up, 1 beat down and 1 beat rest. 8-10 practice reps 10 mins before testing. Rest - 3 mins between exs. | pelvic drop 57 (32); stand abd with hip flex $30^0$ 46 (34); stand abd 42 (27); side-lie abd 42 (23); stand abd NWB 33 (23); stand abd with hip F $30^0$ NWB 28 (21). |
| Boren et al. (2011) (Cross-sectional) (Exercise data partially extracted) | 26 healthy university and surrounds. | Surface (positioned per standard EMG protocol) on dominant limb. | MVIC 3 trials x 5 secs in-side lie abd. 1 min rest between trials. | Exercises – 22 randomised including: SL squat; clam hip flex.$45^0$; side lie abd; lateral step-up; skater squat; pelvic drop; SL bridge stable; forward step-up; SL bridge unstable. Repetitions – 8 to a metronome (60 bpm) of 1 beat up and 1 beat down including 3 practice reps. Rest – 2 mins between exs. | SL squat 82.26; side-lie abd 62.91; lateral step-up 59.87; skater squat 59.84; pelvic drop 58.43; SL bridge stable 54.99; forward step-up 54.62; SL bridge unstable 47.29; clam hip flex. $45^0$ 47.23. |
| Boudreau et al. (2009) (Cross-sectional) | 44 (22 M) healthy. 23.3 (5.1) years; 174.5 (9.1) cm; 74.6 (16.5) kg | Surface (33% iliac crest to greater trochanter ant to the GMax) bilaterally. | MVIC 3 trials x 3 secs in stand hip abd. 30 sec rest between trials. | Exercises – 3 randomised: SL squat; lunge; step-up and over. Repetitions – 3 trials for each ex. 2 practice trials before. Rest – 30 secs between trials and 2 mins between exs. | DOM: SL squat 30.1 (9.1); lunge 17.7 (8.8); step-up and over 15.2 (6.9). Non-DOM: lunge 19.0 (11.7); step-up and over 16.8 (10.4); SL squat 12.0 (7.5). |
| Bouillon et al. (2012) (Cross-sectional) | 40 (20 M) healthy active university and surrounds. 23.2 (1.9) years (M), 22.4 (1.8) years (F); 1.8 (.09) m (M), 1.6 (.07) m (F); 87.8 (20) kg (M), 42.5 (7) kg (F). | Surface (3cm inf. to iliac crest) on dominant limb. | MVIC 3 trials x 5 sec in side-lie abd., neutral rotation, slight hip ext. 3 secs rest between trials and 5 mins between MVIC and exs. | Exercises - 3 randomised: step down; forward lunge; side lunge. Repetitions – 1 trial of 10 to metronome (80 bpm) with 4 beats per repetition 10 practice reps before. Rest – 30 secs between sets | step down (M & F) 14 (3); side lunge (M) 13 (3), (F) 13 (2); lunge (M & F) 12 (2). |

| | | | | | |
|---|---|---|---|---|---|
| Cambridge et al. (2012) (Cross-sectional) (Exercise data partially extracted) | 9 healthy males university. 22.6 (2.2) years; 181.9 (9.2) cm; 85.8 (15.4) kg. | Surface bilaterally | MVIC 1 trial in side-lie abd. | Exercises – 2 randomised: sumo walks with elastic resistance band at 3 different positions for each ex. Repetitions – 3 trials for each ex. Practice reps before. | Sumo walk with feet band ~ 35 (12); sumo walk with ankle band ~ 29 (8); sumo walk with knee band ~ 24 (8.5). |
| Chan et al. (2017) (Cross-sectional) | 20 (10 M) healthy university. 21.10 (1.70) years, 166.75 (7.90) cm; 58.10 (9.20). | Surface (33% iliac crest to greater trochanter) | MVIC in side-lie abd, neutral rotation and slight ext. | Exercises – 2 randomised: clam hip flex 45$^0$; side-lie abd with normal core activation and enhanced core activation. Repetitions – 3 trials to metronome (60 bpm). 3 secs up, 3 secs hold, 3 secs down. Practice reps before. Rest – 3 sec between trials and 1 min between exs. | Enhanced core: side-lie abd 31.38 (12.02); clam hip flex 45$^0$ 18.39 (10.66). Normal core: side-lie abd 28.89 (7.92); clam hip flex 45$^0$ 15.63 (10.53). |
| Cynn et al. (2006) (Cross-sectional) | 18 (9 M) healthy university. 23.5 (3.5) years; 59.3 (5.1) kg; 167.7 (4.3) years. | Surface (33% iliac crest to greater trochanter) on dominant limb. | MVIC 3 trials in side-lie abd. | Exercises - 2: side-lie abd; side-lie abd with pressure biofeedback unit. Repetitions – 5 sec hold. Practice reps before. | Side-lie abd 25.03 (10.25); side-lie abd with pressure biofeedback unit 46.06 (21.20). |
| Distefano et al. (2009) (Cross-sectional) (Exercise data partially extracted) | 21 (9 M) healthy recreationally active. 22 (3) years; 171 (11) cm; 70.4 (15.3) kg. | Surface (33% greater trochanter to iliac crest) on dominant limb. | MVIC 3 trials x 5 secs in side-lie 25$^0$ abd. 1 practice trial before. | Exercises – 9 randomised including clam hip flex 30$^0$; clam hip flex 60$^0$; side-lie hip abd; SL squat; forward lunge; sideways lunge; transverse lunge; lateral band walk. Repetitions – 8 to metronome (60 bpm) with 2 beats up and 2 beats down. Practice reps before. Rest – 2 mins between exs. 5 mins between exs and MVIC. | Side-lie hip abd 81 (42); SL squat 64 (24); lateral band walk 61 (34); transverse lunge 48 (21); forward lunge 42 (21); clam hip flex 30$^0$ 40 (38); sideways lunge 39 (19); clam hip flex 60$^0$ 38 (29). |
| Dwyer et al. (2013) (Cross-sectional) (Exercise data extracted for healthy controls) | 17 healthy local controls. 50.8 (1.4) years; 173.1 (2.5) cm; 77.3 (3.8) kg. | Surface (33% iliac crest to greater trochanter) bilaterally. | MVIC 3 trials x 3 secs in stand hip abd on stance leg. Practice trials before. 30 sec rest between trials. | Exercises – 2 randomised: step-up; step-down Repetitions – 3 trials for each limb to a metronome (55bpm) Rest – 30 secs between trials and 2 mins between exs. | DOM step up 29.4 (2.4); non-DOM step up 28.9 (2.5); non-DOM step down 22.1 (4.5); DOM step down 19.9 (1.7). |
| Dwyer et al. (2010) (Cross-sectional) | 42 (21 M) healthy asymptomatic. 23 (5.8) years (F), 23 (4.0) years (M); 167.6 (5.1) cm (F), 181.4 (7.4) cm (M); | Surface (Cram, Kasman, and Holtz (1998)) bilaterally. | MVIC 3 trials x 3 secs in stand abd. 30 sec rest between trials. | Exercises – 3 randomised: SL squat; lunge; step-up-and-over. Repetitions – 3 trials for each ex. Practice reps before. Rest – 30 secs between trials and 2 mins between exs. | Concentric and eccentric phases DOM; SL squat 31.2 (10.9), 25.3 (11.5) (M), 29.5 (7.5), 26.6 (6.8) (F); step-up-and–over 15.5 (7.9), 14.4 (9.6) (M), 16.5 (5.7), 14.5 (4.6) (F); lunge 11.6 |

| | | | | | |
|---|---|---|---|---|---|
| | 63.7 (5.9) kg (F), 85.6 (16.5) kg (M). | | | | (8.3), 15.5 (9) (M), 11.4 (4.8), 17.8 (8.8) (F).<br>Concentric and eccentric phases non-DOM; SL squat 11.6 (6.1), 10.6 (5.8) (M), 12.5 (9.3), 12.6 (9) (F); lunge 17.2 (7.3), 14.8 (4.7) (M), 24.6 (18.1), 20.8 (15.9) (F); step-up-and-over 14.8 (3.8), 13.3 (4.6) (M), 20.7 (14.6), 18.7 (14.3) (F). |
| Ekstrom et al. (2007) (Cross-sectional) (Exercise data partially extracted) | 30 (19 M) healthy university. 27 (8) years; 176 (8) cm; 74 (11) kg. | Surface (ant-sup. to GMax and inf. to the iliac crest) applied unilaterally. | MVIC 3 trials x 5 secs in side-lie neutral hip rot, slight ext, end AROM abd. 30 sec rest between trials. | Exercises – 8 randomised including: side lie hip abd; bridge; SL bridge with opposite knee ext; lateral step-up; stand lunge.<br>Repetitions – 3 for trunk stabilisation exercises held for 5 secs; lateral step-up and lunge held 5 secs at max knee. flex; Practice reps before.<br>Rest – 30 secs between trials; 1 min between exs. | SL bridge 47 (24); lateral step-up 43 (18); side lie abd 39 (17); lunge 29 (12); bridge 28 (17). |
| Felicio et al. (2011) (Cross-sectional) | 15 healthy sedentary females with misalignment of lower limb. 22.26 (2.22) years; 161.7 (7.33) cm; 56.56 (4.68) kg. | Surface (Hermens, Freriks, Disselhorst-Klug, and Rau (2000)) bilaterally. | MVIC 3 trials x 6 secs in side-lie $20^0$ abd, $10^0$ ext. | Exercises – 3 randomised with 25% additional body weight: ball wall squat; ball wall squat with add; ball wall squat with abd.<br>Repetitions – 3 trials for each ex. held for 6 secs.<br>Rest – 2 mins between trials. | DOM: squat with add 59 (22); squat with abd 47 (20); squat 33 (27).<br>Non-DOM: squat with add 59 (27); squat with abd 52 (24); squat 26 (13). |
| Ganderton et al. (2017) (Cross-sectional) (Exercise data partially extracted) | 10 healthy post-menopausal women. 60.2 (2.7) years; 164.7 (4.3) cm; 70.0 (10.2) kg. | Fine-wire into 3 GMed segments (anterior, middle & posterior) via standardised landmarks on dominant leg. | MVICs 3 trials x 5 secs in side-lie hip abd, side-lie clam, seated hip ER / IR to determine max for each segment. 3 min rest between trials. | Exercises – 7 exercises randomised including: hip hitch; hip hitch with toe tap; hip hitch with hip swing; isometric hip abduction; dip test; clam hip flex $45^0$.<br>Repetitions – 2 sets of 6 reps to metronome 2 secs concentric and 2 secs eccentric for dynamic exs. 3 reps of 15 secs hold for isometric exs.<br>Rest – 1 min between isometric reps and dynamic sets; 2 mins between each ex. | Anterior GMed: hip hitch swing 82.18 (54.71); hip hitch 68.74 (40.98); hip hitch toe-tap 75.60 (47.82); dip test 44.75 (29.11); stand isometric hip abd 55.65 (49.65); clam 3.06 (2.81).<br>Middle GMed: dip test 71.06 (64.53); hip hitch swing 66.26 (38.37); hip hitch 65.90 (47.54); hip hitch toe tap 57.91 (43.51);; stand isometric hip abd 29.81 (18.81); clam 13.26 (16.34).<br>Posterior GMed: hip hitch 73.80 (53.89); hip hitch swing 72.15 (43.32); hip hitch toe tap 45.55 (13.10); stand isometric hip abd 40.52 (44.30); dip test 28.35 (14.29); clam 22.79 (17.03). |

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| Harput et al. (2016) (Cross-sectional) (Exercise data partially extracted for healthy controls) | 15 (8 M) healthy controls 26.3 (6.6) years; 171.6 (10.8) cm; 75.1 (9.2) kg. | Surface (50% iliac crest to greater trochanter) on dominant leg. | MVIC 3 trials x 5 secs in stand hip abd on stance leg. 1 practice trial before. 30 secs between trials. | Exercises - 3 exercises including step down.<br>Repetitions – 3 reps in 2 directions for SEBT (4 practice reps); 5 for step down to metronome (75bpm) (1 practice rep). | Step down ascending 28.2 (10.4), descending. 27.5 (11.4). |
| Hatfield et al. (2016) (Cross-sectional) | 20 (10 M) healthy university. 26.6 ± 5.1 years; 1.73 ± 0.08 m; 66.1 ± 9.2 kg. | Surface (SENIAM, 2011) randomly allocated to a side. | MVIC 2 trials x 3 secs in prone hip abd. Practice trials before. | Exercises – 4 randomised: SL squat; step down; half step down; step up.<br>Repetitions – 5 reps to metronome (1Hz) 4 sec count. Practice reps before. | Step down 27.42 (7.37); (2) half step down 21.23 (6.2); SL squat 23.71 (5.98); step up 16.87 (4.34). |
| Heo et al. (2013) (Exercise data partially extracted) | 15 healthy females. 23.53 (3.15) years; 162.06 (4.78) cm; 52.60 (4.84) kg. | Surface for 3 GMed segments: anterior (50% ASIS to greater trochanter); middle (50% iliac crest to greater trochanter); and posterior. (33% posterior ilium to greater trochanter) | MVIC hip abd. | Exercises – 4 including SL wall squat with abd; SL wall squat with add; SL squat with abd; SL squat with add.<br>Repetitions – 3 reps for 5 sec holds for each ex.<br>Rest - 30 secs between reps and 1 min between exs. | Anterior GMed: SL squat with add 42.11 (20.63); SL wall squat with abd 28.72 (14.7); SL squat with abd 19.36 (13.32); SL wall squat with add 15.66 (10.50).<br>Middle GMed: SL wall squat with abd 32.95 (10.86); SL squat with add 31.32 (17.38); SL squat with abd 26.84 (13.20); SL wall squat with add 20.69 (9.56).<br>Posterior GMed: SL wall squat with abd 43.81 (19.42); SL squat with abd 32.99 (10.84); SL wall squat with add 27.97 (19.78); SL squat with add 22.43 (10.10). |
| Hertel et al. (2005) (Cross-sectional) (Exercise data extracted for no orthotic condition) | 30 (15 M) healthy recreationally active equally divided into 3 groups depending on foot-type (pes planus, pes cavus, pes rectus). 21.1 (1.6) years; 170.2 (6.1) cm; 69.1 (13.9) kg. | Surface (50% iliac crest to greater trochanter) on leg contralateral to dominant throwing arm. | MVIC 3 trials in SL stance in a custom-made device. 90 secs rest between trials. | Exercises – 2 randomised: SL squat; lateral step-down.<br>Repetitions – 3 trials for each ex. Metronome (60 bpm) 2 secs down, 2 secs up for lateral step down.<br>Rest – 5 mins between each orthotic condition. | SL squat ~ 77 (5); lateral step down ~ 74 (6). |
| Ju & Yoo (2017) (Cross-sectional) (Exercise data partially extracted) | 15 healthy males. 29.1 (2.9) years; 173.4 (7.1) cm; 71.7 (8.5) kg. | Surface anterior segment (50% ASIS to greater trochanter). | MVIC in side-lie abd. | Exercises – 4 including pelvic drop.<br>Repetitions – 5 secs contraction. | Pelvic drop 25.40. |

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| Ju & Yoo (2016) (Cross-sectional) (Exercise data partially extracted) | 15 healthy males. 29.13 (2.85) years, 173.4 (7.08) cm, 71.73 (8.52) kg. | Surface for 3 GMed segments: anterior (50% ASIS to greater trochanter); middle (50% iliac crest to greater trochanter); posterior (33% distance posterior ilium to greater trochanter). | MVIC in side-lie abd, prone hip ER, and prone hip IR to determine max. for each segment. 30 secs rest between trials. | Exercises – 4 including pelvic drop. Repetitions – 3 trials for each ex. 2 secs up, 2 secs down. Rest – 30 secs between trials and 1 min between exs. | Anterior GMed: pelvic drop 25.40 (7.77). Middle GMed: pelvic drop 23.43 (8.65). Posterior GMed: pelvic drop 21.63 (9.06). |
| Kang et al. (2014) | 17 healthy males. 23.06 (1.47) years; 172.88 (5.65) cm; 68.29 (4.69) kg. | Surface (Criswell E., 2011) on dominant limb. | MVIC 2 trials x 5 secs in side-lie abd. 1 min rest between trials. | Exercises – 2: squat; squat with resisted shoulder flex. Repetitions – 3 trials to metronome (3 secs down and 3 secs up). | Eccentric phase: squat with resisted shoulder flex 12.09 (6.29); squat 8.82 (3.91). Concentric phase: squat with resisted shoulder flex 11.58 (5.96); squat 8.44 (3.59). |
| Kim et al. (2015) (Cross-sectional) (Exercise data partially extracted) | 10 healthy males 31 (4.2) years; 176.8 (8.3) cm; 76.7 (8.1) kg. | Surface (33% iliac crest to greater trochanter) bilaterally. | MVIC 3 trials in side-lie $5^0$ abd. | Exercise – 2 including side-lie abd. Repetitions – 3 trials, 5 secs hold. Rest – 30 secs between trials. | Side-lie abd. 24.30 (5.45). |
| Krause et al. (2018) (Cross-sectional) (Exercise data partially extracted) | 30 (15 M) healthy. 23.9 (1.7) years, BMI 24.21 (2.88). | Surface (33% iliac crest to greater trochanter) on dominant limb. | MVIC 1 trial x 5 secs in side-lie abd $5^0$. 1 submaximal practice trial before. | Exercise – 2 including lunge. Repetitions – 3 to a metronome, 3 secs down, 1-2 secs hold, 3 secs up. Practice trials before. | Lunge 15.3 (11.4) |
| Krause et al. (2009) (Cross-sectional) (Exercise data partially extracted) | 20 (6 M) healthy recreationally active. 23.6 (1.7) years (F), 26.3 (2.5) years (M); 169.3 (9.5) cm (F), 172.2 (12.9) cm (M); 65 (9.2) kg (F), 85 (10.1) kg (M). | Surface (50% greater trochanter to iliac crest) on dominant limb. | MVIC 3 trials in side-lie abd $30^0$, slight hip ext. Adequate rest between trials. | Exercises – 5 randomised including SL squat; SL squat on Airex cushion. Repetitions – 3 trials for each ex. Stance exs held for 10 secs and squats for 3 reps. Practice reps before. Rest – adequate rest between each set of exs. | SL squat on Airex 58.5 (35.32); SL squat 47.79 (22.61). |
| Lee et al. (2013) (Cross-sectional) | 20 healthy with normal ITB length and BMI < 25. 22.3 (1.9) years, 168.7 (7.2) cm; 65.5 (12.4) kg. | Surface (33% iliac crest to greater trochanter) on dominant limb. | MVIC 2 trials x 5 secs in side-lie abd 50% AROM, slight ext and ER. 30 secs rest between trials. | Exercises – 3 randomised: side-lie abd.; side-lie abd. + IR; side-lie abd + ER. Repetitions – 3 trials x 5 sec hold. Rest – 3 mins between exs. | Side-lie abd. + IR 45.3 (20.5); side-lie abd + ER 35.3 (12.5); side-lie abd 34.2 (11.8). |

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| Lee et al. (2014) (Cross-sectional) | 19 (8 M) healthy with weak GMed and BMI < 25. 21 (1.73) years; 166 (.07) cm; 59.79 (9.61) kg. | Surface (33% iliac crest to greater trochanter) on dominant limb. | MVIC 2 trials x 5 secs in side-lie abd 50% AROM, slight ext and ER. 3 mins rest between trials. | Exercises – 3 randomised: side-lie abd; side-lie abd + IR; side-lie abd + ER.<br>Repetitions – 3 trials x 5 sec hold.<br>Rest – 3 mins between exs. | Side-lie abd + IR ~ 61.34 (4); side-lie abd + ER ~ 48.96 (7); side-lie abd ~ 45.22 (6). |
| Lehecka et al. (2017) (Cross-sectional) | 28 (12 M) healthy. 23.43 (2.28) years; 1.73 (0.11) m; 72.57 (13.93) kg. | Surface (inf. to lat. aspect of iliac crest on a line to greater trochanter) on dominant limb. | MVIC 3 trials x 7 secs in side-lie abd end range, slight ext. 30 secs rest between trials. | Exercises – 5 randomised: SL bridge with knee flex $90^0$; SL bridge with knee flex. $135^0$; SL bridge with knee flex $90^0$ opposite leg bent; SL bridge with knee flex $90^0$ ankle DF, opposite leg bent; SL bridge with knee flex $135^0$ ankle DF, opposite leg bent.<br>Repetitions – 8 to metronome (60 bpm) for each including 2 practice reps before. | SL bridge with knee flex $90^0$ 57.81 (20.72); SL bridge knee flex $135^0$ 57.23 (27.82); SL bridge knee flex $90^0$, opposite leg bent 55.05 (20.71); SL bridge knee flex $90^0$ ankle DF, opposite leg bent 54.27 (20.01); SL bridge knee flex $135^0$ ankle DF, opposite leg bent 41.63 (18.19). |
| Lin et al. (2016) (Cross-sectional) (Exercise data partially extracted) | 12 (6 M) healthy. 26.1 (4.7) years; 168.8 (2.7) cm; 63.6 (9.6) kg. | Surface (33% greater trochanter to iliac crest) on dominant limb. | MVIC 2 trials x 5 secs in side-lie hip abd. 30 secs rest between trials. | Exercises – 3: clam hip flex $60^0$; SL squat; lunge.<br>Repetitions – 5 for each ex. to a metronome (1 rep per 2 secs). | Clam 19.1 (8.8); SL squat 18.4 (7.9); lunge 8.2 (3.8). |
| Lubahn et al. (2011) (Cross-sectional) | 18 healthy females; 22.3 (2.3) years; 166.82 (9.2) cm; 61.1 (7.1) kg. | Surface (Cram et al. (1998)) on dominant limb. | MVIC 3 trials x 5 secs in side-lie abd. with neutral hip. | Exercises – 4 randomised: squat; squat with lateral resistance band; step-up; SL squat.<br>Repetitions – 5 for each ex. to a metronome (40 bpm) with 1 beat for start of rep. then beat 2 at midpoint then beat 3 for end of rep. Several practice reps before.<br>Rest - 10-15 secs between reps. 45-60 secs rest between each ex. | SL squat 65.6 (23.8); step-up 48.2 (20.4); squat with lateral resistance band 23.7 (16.3); squat 20.8 (14.7). |
| MacAskill et al. (2014) (Cross-sectional) (Exercise data partially extracted) | 34 (14 M) healthy. 21.2 (1.8) years (M), 21.7 (1.6) years (F); 177.8 (15.3) cm (M), 163.2 (6.7) cm (F); 77.1 (8.9) kg (M), 58.1 (6.2) kg (F). | Surface (2-3 cm distal to midpoint iliac crest) on dominant limb. | MVIC 3 trials x 5 secs in side-lie abd 50% AROM. 1 sec rest between trials. | Exercises – 4 randomised including forward step-up; lateral step-up; 10 RM side-lie abd with cuff weight.<br>Repetitions – 3 trials of 5 reps, 2 secs for each rep<br>Rest – 3 mins between sets | 10 RM side-lie abd ~ 100 (23); lateral step-up ~ 63 (21); forward step-up ~ 62 (19). |

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| Mauntel et al. (2013) (Cross-sectional) | 40 (20 M) healthy active divided equally into 2 groups – control and medial knee displacement (MKD). 20.2 (1.5) years, 20.2 (1.8) years (MKD); 173.1 (10.1) cm, 173.8 (8.8) cm (MKD); 71 (14.6) kg, 71.8 (14.7) kg (MKD). | Surface on dominant limb. | MVIC 3 trials x 5 secs in side-lie abd. 1 min rest between trials. | Exercise – 1: SL squat<br>Repetitions – 5 trials to a metronome (60 bpm). 2 beats down, 2 beats up.<br>Rest – 1 min between trials. | Control group: SL squat 37.1 (17.3). MKD group: SL squat 32.9 (17.2). |
| McBeth et al. (2012) (Cross-sectional) | 20 (9 M) healthy community runners (> 40 km / week). 25.45 ± 5.8 years (M), 26.1 ± 5.2 years (F); 1.75 ± 0.08 m (M), 1.68 ± 0.03 m (F); 69.3 ± 7.1 kg (M), 61.3 ± 6.6 kg (F). | Surface (33% iliac crest to greater trochanter) on dominant limb. | MVIC 3 trials x 5 secs in side-lie abd 35$^0$, slight ext. and ER. 10 sec rest between trials. | Exercises – 3: side-lie abd; side-lie abd + ER; clam hip flex 45$^0$.<br>All performed with 5% body weight cuff weight.<br>Repetitions – 7 set to a metronome (60 bpm) of 1 beat up, 1 beat down, and 4 beat rest. 4 practice sets of 5 reps before.<br>Rest - 1 min between exs. 2 mins between MVIC testing and exs. | Side-lie abd 79.1 (29.9); side-lie abd + ER 53.03 (28.4); clam hip flex 45$^0$ 32.6 (16.9). |
| Monteiro et al. (2017) (Cross-sectional) | 17 (6 M) healthy sedentary, BMI (19-25 kg/m$^2$). 25.6 (1.4) years; 168.29 (8.64) cm; 70 (9.98) kg. | Surface (50% iliac crest to greater trochanter) on dominant limb. | MVIC 3 trials x 3 secs in side-lie abd 30$^0$. 1 min rest between trials. | Exercises – 3 randomised: pelvic drop; pelvic drop + hip IR; pelvic drop + hip ER.<br>Repetitions – 2 trials of 4 to metronome (60 bpm). 60 practice reps for each ex before. | pelvic drop + IR 42.43 (15.45); pelvic drop 42.11 (18.39); pelvic drop + ER 32.77 (14.01). |
| Morimoto et al. (2018) (Cross-sectional) (Exercise data partially extracted) | 11 healthy. 22 (2) years; 174 (7.5) cm; 71,7 (13.5) kg. | Surface on dominant limb. | MVIC in side-lie abd. | Exercises – 7 including side-lie abd; side-lie abd + hip ER; side-lie abd + hip IR. | Side-lie abd + ER 40.5 (16.9); side-lie abd 38 (14.2); side-lie abd + IR 36.3 (16.7). |
| Noh et al. (2012) (Cross-sectional) | 15 (10 M) healthy. 25.07 (3.59) years; 172.07 (5.03) cm; 65.93 (6.31) kg. | Surface (33% iliac crest to greater trochanter) on dominant limb. | MVIC 2 trials x 5 secs in side-lie abd. | Exercises – 3 randomised: lateral step-up; lateral step-up + hip IR; lateral step-up + hip ER.<br>Repetitions – 3 trials for 2 secs up to a metronome.<br>Rest – 1 min between trials and 5 mins between exs. | lateral step-up + IR 41.27 (13.16); lateral step-up 38.81 (13.01); lateral step-up + ER 30.17 (9.81). |

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| Oliver et al. (2010) (Cross-sectional) (Exercise data partially extracted) | 30 healthy active college students. 23.4 (1.4) years; 171.3 (10.3) cm; 73.3 (16.2) kg. | Surface (Basmajian and De Luca (1985)) bilaterally. | MVIC 2 trials x 5 secs in side-lie abd. | Exercises – 4 randomised including bridge and SL bridge. Repetitions – 3 for each ex. Held for 10 secs. Practice reps before. | (L) side: (R) SL bridge ~ 35 (17); bridge ~ 17 (11); (L) SL bridge ~ 10 (13). (R) side: (L) SL bridge ~ 33 (16); bridge ~ 17 (9); (R) SL bridge ~ 14 (14). |
| Oliver & Stone (2016) (Cross-sectional) (Exercise data partially extracted) | 28 healthy active college students. 22 (2) years; 168 (8) cm; 66 (10) kg. | Surface (Cram et al. (1998)) on dominant limb. | MVIC 3 trials x 5 secs in side-lie abd. | Exercises – 2 including SL step down. | SL step down 187 (80). |
| O'Sullivan et al. (2013) (Cross-sectional) (Exercise data partially extracted for control group) | 12 healthy active women. 21 (1) years; 164.6 (7.9) cm; 62.6 (9.9) kg. | Surface for 3 GMed segments: anterior (50% ASIS to greater trochanter); middle (50% greater trochanter to iliac crest); posterior (33% posterior ilium to greater trochanter) on dominant limb. | MVIC 3 trials x 5 secs in side-lie abd including 2 practice trials. 30 sec rest between trials | Exercises – 4 non-randomised including pelvic drop; step up and over; SL squat. Repetitions – 3 for each ex. Step up and over held for 5 secs. Pelvic drop and SL squat 2 secs down, 2 secs up to a metronome (60 bpm). 3 practice trials before. Rest – 30 secs between trials and 2 min rest between exs. | Anterior GMed: SL squat 89.6 (24.6); step up and over 88.4 (19.6); pelvic drop 79.9 (24.8). Middle GMed: SL squat 91.7 (36.9); pelvic drop 87.6 (32.6); step up and over 85.4 (29.6). Posterior GMed: pelvic drop 87.9 (23.9); SL squat 86.7 (16); step up and over 81.2 (28.8). |
| O'Sullivan et al. (2010) (Cross-sectional) (Exercise data partially extracted) | 15 (7 M) healthy university. 22 (4) years; 170 (12) cm; 68 (12) kg. | Surface for 3 GMed segments: anterior (50% ASIS to greater trochanter); middle (50% greater trochanter to iliac crest); posterior (33% posterior ilium to greater trochanter) on (R) limb. | MVIC 3 trials x 5 secs in stand hip $30^0$ abd, neutral flex / ext / ER / IR; prone hip ER; and prone hip IR to determine max for each segment. 30 sec rest between trials. | Exercises – 3 randomized including SL wall squat; pelvic drop. Repetitions – 3 for each ex. with wall squat held for 5 secs. Pelvic drop 2 secs down and 2 secs up. 3 practice reps for each ex. before. Rest – 30 secs between reps and 1 min between exs. | Anterior GMed: pelvic drop 21.12 (6.80); SL wall squat 13.30 (7.50). Middle GMed: pelvic drop 28.45 (8.49); SL wall squat 24.60 (8.89). Posterior GMed: pelvic drop 38.17 (16.76); SL wall squat 34.82 (19.86). |
| Petrofsky et al. (2005) (Cross-sectional) (Exercise data partially extracted) | 6 (4 M) healthy. 25.3 (1.5) years; 169.9 (6.7) cm; 69.8 (9.6) kg. | Surface (over muscle belly and 2 cm distal) on (R) limb. | MVIC 3 trials x 3 secs in side-lie hip abd 1 min rest between trials. | Exercises – 6 including $45^0$ squat; $90^0$ squat. | $90^0$ squat 28.4 (6.7); $45^0$ squat 22.1 (9.3). |
| Philippon et al. (2011) (Cross-sectional) (Exercise data partially extracted) | 10 (5 M) healthy. 28.7 (2.0) years; 1.72 (0.04) m; 67 (4.3) kg | Fine-wire (2.5 cm distal to midpoint of iliac crest under US guidance). | MVIC 3 trials x 3 secs in stand hip abd, slight hip ER. 3-5 sec rest between trials. | Exercises – 13 randomised including bridge; clam hip – knee flex $45^0$; clam hip neutral, knee flex $90^0$; side-lie abd with hip IR; side-lie abd with hip ER; side-lie abd with hip ext; SL bridge. | Concentric phase: SL bridge 35.1 (33.8); side-lie abd. + IR 33.3 (27.2); side-lie abd + ext 31.4 (22.5); side-lie abd + ER 23.3 (17.7); clam flex $45^0$ 16.7 (13.6); bridge 10.8 (8.9). |

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| Selkowitz et al. (2013) (Cross-sectional) (Exercise data partially extracted) | 20 (10 M) healthy university. 27.9 (6.2) years. | Fine-wire (2.5 cm distal to midpoint of iliac crest) on dominant limb. | MVIC 1 trial X 5 secs in side-lie abd $30^0$, neutral flex. | Exercises – 11 randomised including side-lie abd; bridge; elastic resistance clam hip flex $45^0$; hip hike; lunge; elastic resistance side-step; squat; step up; SL bridge. Repetitions – 5 for each ex to a metronome (40bpm). Side-step 3 trials x 2 strides in each direction to metronome (80 bpm). Rest – 2 mins between exs. | Side-lie abd 43.5 (14.7); hip hike 37.7 (15.1); SL bridge 30.9 (20.7); side step 30.2 (15.7); step up 29.5 (14.9); clam flex $45^0$ 26.7 (18); lunge 19.3 (12.9); bridge 15 (10.5); squat 9.7 (7.3). |
| Sidorkewicz et al. (2014) (Cross-sectional) | 13 healthy males. 24.8 (4.2) years; 179.7 (5.4) cm; 75.9 (9.8) kg. | Surface (SENIAM, 2011) on (R) limb. | MVIC 3 trials in side-lie abd. 2 mins rest between trials. | Exercises – 6 randomised: side-lie abd; side-lie abd + hip IR; side-lie abd + hip ER; clam hip flex $30^0$; clam hip flex $45^0$; clam hip flex $60^0$. Repetitions – 3 trials for each ex. Practice reps before. | Side-lie abd + IR 48.67 (20.21); side-lie abd 36.70 (14.55); side-lie abd + ER 36.50 (16.46); clam hip flex $60^0$ 36.49 (33.06); clam hip flex $45^0$ 35.55 (34.25); clam hip flex $30^0$ 26.80 (24.08). |
| Sinsurin et al. (2015) (Cross-sectional) (Exercise data partially extracted) | 9 healthy sedentary males. (18-25 years); BMI (18.5-23 kg/m$^2$); dominant (R) limb. | Surface (50% iliac crest to greater trochanter) bilaterally. | MVIC 3 trials x 3 secs in side-lie abd, neutral hip. 3 submaximal practice trials before. 90 secs rest between trials. | Exercises – 7 randomised including (L) stance, (R) hip abd Repetitions – 3 trials Rest – 30 secs between trials. 2 mins between exs. | (L) stance limb: hip abd 43.71 (15.05); (R) swing limb: hip abd 63.59 (41.16); |
| Souza & Powers (2009) (Cross-sectional) Exercise data partially extracted for controls) | 20 healthy females. 26 (5) years; 1.7 (0.6) m; 62.9 (6.6) kg. | Surface (2.5cm inferior to iliac crest) on 13 matched (R) and 7 matched (L) limbs. | MVIC 1 trial x 5 secs in side-lie abd $20^0$, $5^0$ ext. | Exercise – 3 including step down Repetitions – 3 trials, 2 secs down, 2 secs up to a metronome. | Step down ~ 17 (5). |
| Webster & Gribble (2012) (Cross-sectional) (Exercise data partially extracted for controls) | 9 healthy active controls. 22.9 (4.6) years; 164.5 (6.5) cm; 65.4 (10) kg. | Surface (2.5 cm below iliac crest) on matched assigned limb. | MVIC 3 trials x 10 secs in side-lie abd. 1 min rest between trials. 2 mins rest before exs. | Exercises – 2 randomised: rotational lunge; SL squat with rotational reach. Repetitions – 10 to metronome (72 bpm) – 2 beats out, 2 beats back. Rest – 2 mins between exs. | rotational lunge ~ 68 (32); rotational squat ~ 66 (55). |

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| Willcox & Burden (2013) (Cross-sectional) | 17 (10 M) healthy active. 25 (5) years (M), 23 (4) years (F); 182 (8) cm (M), 165 (4) cm (F); 77 (13) kg (M), 60 (11) kg (F). | Surface (33% greater trochanter to iliac crest) on dominant limb. | MVIC 5 secs in side-lie abd. | Exercises – 6 randomised: clam hip flex $0^{0;}$ clam hip flex $30^{0}$; clam hip flex $60^{0}$. Exs were then repeated with pelvis reclined $35^{0}$. Repetitions – 10 for each ex. holding for 6 secs. Rest – 3 mins between exs. | Pelvis neutral: clam hip flex $60^{0}$ ~ 22.5 (4.5); clam hip flex $30^{0}$ ~ 21 (5); clam hip flex $0^{0}$ ~ 17 (4). Pelvis reclined: clam hip flex $60^{0}$ ~ 17.5 (4.5); clam hip flex $30^{0}$ ~ 13 (3.5); clam hip flex $0^{0}$ ~ 12.5 (3). |
| Youdas et al. (2012) (Cross-sectional) | 21 (10 M) healthy active university. 25 (3.1) years (M), 24.5 (1.4) years (F); 1.8 (0.1) m (M), 1.7 (0.1) m (F); 82.2 (7.9) kg (M), 69.1 (4.9) kg (F). | Surface (Criswell E. (2011)) bilaterally. | MVIC 1 trial x 5 secs in side-lie abd $30^{0}$. | Exercises – 3 randomised: lateral step against elastic resist, hips neutral; lateral step against elastic resist, hips ER; lateral step against elastic resist, hips IR. Repetitions- 3 for each ex. to metronome (40bpm). Several practice trials before. Rest – 30 – 45 secs between exs. | Stance limb: lateral step hips IR 57.8 (24.3); lateral step hips neutral 49.9 (21.9); lateral step hips ER 47.6 (21.5). Moving limb: lateral step hips IR 43.8 (27); lateral step hips neutral 32.8 (21.9); lateral step hips ER 27.3 (18.1). |
| Youdas et al. (2014) (Cross-sectional) (Exercise data partially extracted) | 26 (13 M) healthy active. 25.3 (3.1) years (M), 23.7 (1.3) years (F). | Surface (Criswell E. (2011)) bilaterally. | MVIC 1 trial x 2-3 secs in side-lie abd $30^{0}$. Practice reps before. | Exercises – 4 randomised including reverse cross over pull against elastic resist. Repetitions – 3 reps to metronome (40 bpm). Practice reps before. Rest – 2-3 mins between exs. | Stance limb: reverse cross over pull 50.0 (25.1). Moving limb: reverse cross over pull 52.9 (17.6). |
| Youdas et al. (2015) (Cross-sectional) (Exercise data partially extracted) | 26 (13 M) healthy active. 23.4 (1.3) years (M), 23.5 (1.2) years (F); 1.8 (0.1) m (M), 1.7 (0.1) m (F); 79.7 (10.6) kg (M), 63.7 (7.4) kg (F). | Surface (Criswell E. (2011)) on (R) limb. | MVIC 5 sec in side-lie abd $20^{0}$. | Exercises – 6 randomised including DL bridge; DL bridge unstable; SL bridge; SL bridge unstable. Repetitions – 3 reps to metronome (40 bpm). Rest – 1 min between exs. | SL bridge unstable 42 (10.2); SL bridge 40 (11.6); DL bridge 21.4 (7.4); DL bridge unstable 19.9 (10) |
| Zeller et al. (2003) (Cross-sectional) | 18 (9 M) healthy college athletes. 20.33 (1) years (M), 20 (1.5) years (F); 72.44 (2.01) in (M), 67.44 (2.4) in (F); 173.89 (8.94) lbs (M), 141.89 (12.33) lbs (F). | Surface (Cram et al. (1998)) on dominant limb. | MVIC 2 trials x 3 secs in side-lie abd. | Exercises – 1: SL squat Repetitions – 5 with 5 sec duration. Practice reps before. | SL squat 77.3 (64.3) (M), 41 (29.5) (F). |

Key: abd – abduction; add – adduction; ant – anterior; ASIS – anterior superior iliac spine; BMI – body mass index; bpm – beats per minute; cm – centimeters; DL – double leg; DOM – dominant limb; ER – external rotation; exs – exercises; ext – extension; F – females; flex – flexion; GMed – gluteus medius; in – inches; inf – inferior; IR – internal rotation; kg – kilograms; $kg/m^2$ – kilograms per metres squared; lat – lateral; lbs – pounds; M – males; max – maximum; m – metres; mins – minutes; MVIC – maximum voluntary isometric contraction; non-DOM – non dominant limb; NWB – non-weight-bearing; PBU – pressure biofeedback unit; post – posterior; reps – repetitions; resist – resistance; secs – seconds; SL – single leg; sup – superior; WB – weight-bearing

*Table 2.3 Summary of included gluteus minimus studies*

| Study and type | Participant characteristics | EMG electrode type and placement | Normalisation method | Exercise characteristics | Results (% MVIC (SD)) |
|---|---|---|---|---|---|
| Ganderton et al. (2017) (Cross-sectional) | 10 healthy post-menopausal women. 60.2 (2.7) years; 164.7 (4.3) cm; 70.0 (10.2) kg | Fine-wire into 2 segments (anterior & posterior) of GMin via standardised landmarks on dominant limb. | MVICs 3 trials x 5 secs in side-lie abd, side-lie clam, seated hip ER, seated hip IR to find max for each segment. 3 min rest between trials. | Exercises – 7 randomised including hip hitch; hip hitch with toe tap; hip hitch with hip swing; isometric hip abduction; dip test; clam hip flex $45^0$.<br>Repetitions – 2 sets of 6 reps to metronome 2 secs concentric and 2 secs eccentric for dynamic exs. 3 reps of 15 secs hold for isometric exs.<br>Rest – 1 min between isometric reps and dynamic sets; 2 mins between each ex. | Anterior GMin: hip hitch 68.77 (21.74); hip hitch swing 59.70 (17.26); isometric stand hip abd 54.79 (33.49); hip hitch toe tap 48.30 (16.07); dip test 21.33 (12.30); clam 7.31 (8.94).<br>Posterior GMin: hip hitch swing 78.64 (20.93); hip hitch 83.71 (40.17); hip hitch toe tap 66.73 (25.99); dip test 64.41 (35.54); isometric hip abd 48.62 (30.58); clam 19.59 (20.38). |
| Moore et al. (2018)<br><br>(Cross-sectional) | 10 (6 M) healthy active university. 23.8 (1.6) years; 177.5 (10) cm; 79.9 (18.5) kg. | Fine-wire into 2 segments (anterior & posterior) of GMin via standardised landmarks on dominant limb. | MVICs 3 trials x 5 secs in side-lie abd, side-lie abd + IR, side-lie clam, side-lie hip flex, side-lie hip IR, prone hip ext to find max for each segment. 3 mins rest between trials. | Exercises – 6 randomised including SL squat; SL bridge; side-lie abd; clam hip flex $45^0$.<br><br>Repetitions – 3 trials of 6 for each ex to a metronome (ranging from 40 – 90 bpm depending on ex). Practice reps before.<br><br>Rest- 1 – 2 mins between exs and trials. 3 mins between exs and MVIC. | Anterior GMin: side-lie abd 37.62 (14.07); SL squat 25.42 (9.49); SL bridge 13.62 (11.36); clam 2.98 (2.91).<br><br>Posterior GMin: SL bridge 46.04 (27.83); side-lie abd 43.49 (15.96); SL squat 45.76 (29.99); clam 8.00 (6.44). |

Key: abd – abduction; add – adduction; ant – anterior; bpm – beats per minute; cm – centimeters; DL – double leg; DOM – dominant limb; ER – external rotation; ext – extension; flex – flexion; GMed – gluteus medius; GMin - gluteus minimus; inf – inferior; IR – internal rotation; kg – kilograms; lat – lateral; MVIC – maximum voluntary isometric contraction; mins – minutes; non-DOM – non dominant limb; NWB – non-weight-bearing; post – posterior; reps – repetitions; secs – seconds; SL – single leg; sup – superior; WB – weight-bearing.

(Ganderton, Pizzari, Cook, et al., 2017) evaluating both GMed and GMin. All the studies were cross-sectional with six including a comparison group (Dwyer, Stafford, Mattacola, Uhl, & Giordani, 2013; Harput, Howard, & Mattacola, 2016; Hertel, Sloss, & Earl, 2005; O'Sullivan et al., 2012; Souza & Powers, 2009; Webster & Gribble, 2013). These comparison groups included a specific lower limb pathology (including patellofemoral pain, chronic ankle instability, hip osteoarthritis and anterior cruciate ligament reconstruction) or various orthotic conditions. Sample sizes of the included studies ranged from 6 to 44 participants. Most studies contained a mixture of men and women aged 20-30 years with 13 studies (Cambridge, Sidorkewicz, Ikeda, & McGill, 2012; Felício, Dias, Silva, Oliveira, & Bevilaqua-Grossi, 2011; Ganderton, Pizzari, Cook, et al., 2017; Heo et al., 2013; Ju & Yoo, 2016, 2017; Kang, Jang, Kim, & Oh, 2014; Kim et al., 2015; Lubahn et al., 2011; O'Sullivan et al., 2012; Sidorkewicz, Cambridge, & McGill, 2014; Sinsurin, Pluemjai, Srisangboriboon, Suanshan, & Vachalathiti, 2015; Souza & Powers, 2009) comprising of a single gender population, and one study (Ganderton, Pizzari, Cook, et al., 2017) recruiting healthy elderly participants.

A single surface electrode positioned at the middle segment of GMed on the dominant limb was used in most GMed studies with six different electrode positions described (Table 2.2). Five studies (Ganderton, Pizzari, Cook, et al., 2017; Heo et al., 2013; Ju & Yoo, 2016; O'Sullivan et al., 2012; O'Sullivan et al., 2010) recorded EMG measurements for the anterior, middle and posterior segments of GMed with only one study (Ganderton, Pizzari, Cook, et al., 2017) using fine wire electrodes. Two studies (Ganderton, Pizzari, Cook, et al., 2017; Moore, Semciw, et al., 2019) recorded the anterior and posterior segments of GMin using fine wire electrodes.

Normalisation of the EMG signal was typically performed with side-lie hip abduction MVIC for GMed (Table 2.2). Standing hip abduction (Boudreau et al., 2009; Dwyer, Boudreau, Mattacola, Uhl, & Lattermann, 2010; Hertel et al., 2005; Krause et al., 2009; O'Sullivan et al., 2010; Philippon et al., 2011) was used in other studies, while one study (Hertel et al., 2005) used an isometric single leg wall squat in a custom-made apparatus to determine MVIC. Two studies (Ganderton, Pizzari, Cook, et al., 2017; O'Sullivan et al., 2010) for GMed and two studies (Ganderton, Pizzari, Cook, et al., 2017; Moore, Semciw, et al., 2019) for GMin determined each segments' maximum value from performing MVICs for different hip actions.

Therapeutic exercise characteristics were diverse across the included studies (Tables 2.2 and 2.3). All included studies attempted to standardize exercise performance and control EMG signal variability between participants by employing strategies such as allowing practice repetitions before testing; controlling exercise ROM; and using a metronome to control contraction speed (Tables 2.2 and 2.3). For most studies, the potential impact of fatigue was minimised by randomising the exercise order; having rest periods between exercises and trials; and restricting numbers of trials (Tables 2.2 and 2.3).

Only two studies (Dwyer et al., 2010; Dwyer et al., 2013) reported on all technical parameters for collection, processing and analysis of the EMG signal (Table 2.4).

*Table 2.4. Electromyographic technical aspects of included studies*

| Study | EMG unit type | Electrode size and skin preparation | Inter-electrode distance (mm) | Input impedance (Ω) | Common mode rejection ratio (dB) | Amplifier gain | Data filtering (Hz) | Sampling frequency (Hz) | Rectification (full or half wave) | Data processing (ms) |
|---|---|---|---|---|---|---|---|---|---|---|
| Ayotte et al. (2007) | Nicolet Viking IV | NS; skin debrided and cleansed | 30 | NS | >110 @ 50-60 Hz | NS | Band pass 30 – 10000 | 20000 | Full | Integrated over 1.5sec |
| Barton et al. (2013) | Noraxon Telomyo 2400 G2 | SENIAM, 2011 | 20 | NS | NS | NS | Band pass 10 – 500 RMS smoothing 100 epoch | 1500 | Full | Mean amplitude |
| Berry et al. (2015) | Bagnoli Delsys | 10x1mm; skin scrubbed | 10 | $10^{15}$ | 100 | NS | Band pass 20 - 390 4th order Butterworth RMS smoothing 100ms | 1000 | Full | Average RMS |
| Bolgla et al. (2016) | 8 channel Run Technologies | 5 mm diameter; skin shaved and cleaned | 20 | 1M | 90 | 2000 | Band pass 20 - 500 | 2000 | Full | Average RMS for each repetition |
| Bolgla et al. (2014) | 8 channel Run Technologies | 5 mm diameter; skin shaved and cleaned | 20 | 1M | 90 | 2000 | Band pass 20 - 500 | 2000 | Full | Average RMS for each repetition |
| Bolgla and Uhl (2005) | 16 channel Run Technologies | 5 mm diameter; skin prepared in standard manner | 20 | NS | 90 | 2000 | Band pass 20-500 RMS smoothing 15ms | 1000 | Full | Average RMS for each repetition |
| Boren et al. (2011) | Schiller America | NS; skin cleansed | NS | NS | NS | NS | RMS smoothing 50ms | NS | Full | Average amplitude: surround peak activity (100 ms of time) |
| Boudreau et al (2009) | 16 channel Run Technologies | 5 mm diameter; skin debrided and cleansed | 20 | NS | 90 | 2000 | Band pass 20-500 RMS smoothing 20ms | 1339 | Full | Average amplitude |
| Bouillon et al (2012) | 8 channel Noraxon myosystem 900 12 bit A-D converter | NS; skin shaved, abraded and cleaned | 20 | 10M | 115 | 1000 | Band pass 10-500 RMS 300 | 1000 | Full | Average activity per repetition |
| Cambridge et al. (2012) | 16 channel AMT 8 Bortec A-D converter | NS | NS | 1M | 115 @ 60 Hz | NS | Band pass 30-500 Low-pass smoothing: | 2160 | Full | Peak amplitude |

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|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Butterworth 2.5Hz Sampled at 60Hz (synchronisation with kinematic data) | | | |
| Chan et al. (2017) | Myomuscle Noraxon | Skin shaved, abraded and cleaned | 10 | NS | 80 | NS | Band pass 10-500 Butterworth 4th order RMS smoothing 500ms | 1024 | Full | Average amplitude for each repetition |
| Cynn et al. (2006) | Bagnoli | Skin cleansed | 20 | NS | NS | NS | Band pass 20-450 Backstop filter (60Hz) | NS | Full | Average amplitude (RMS) |
| Distefano et al. (2009) | Bagnoli 8 Delsys | NS; skin cleansed | 10 | NS | >80 @ 60 Hz | 10000 | Band pass 20-350 RMS smoothing (20ms) | 1000 | Full | Average amplitude of each repetition |
| Dwyer et al. (2013) | 16 channel Run Technologies | 5 mm diameter; skin prepared | 20 | 1M | 90 | 2000 | Band pass 20-500 RMS smoothing (30ms) | 1000 | Full | Average amplitude |
| Dwyer et al. (2010) | 16 channel Run Technologies | 5 mm diameter; skin debrided and cleansed | 20 | 1M | 90 | 2000 | Band pass 20-500 RMS smoothing (20ms) | 1339 | Full | Average amplitude for each phase (concentric and eccentric) |
| Ekstrom et al. (2007) | 8 channel Noraxon myosystem 1200 | NS; skin debrided and cleansed | 20 | 10M | >100 @ 60 Hz | 1000 | Band pass 10-500 Butterworth (1st order high-pass, 4th order low-pass) RMS smoothed (20ms) | 1000 | Full | Average activity of 1 secs surrounding peak amplitude |
| Felicio et al. (2011) | Myosystem BR 1P84 | 23x21x5 mm; skin prepared | 10 | 10G | 130 | 20 | Band pass 20-500 | 2000 | Full | Average activity (RMS) across |

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|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | the whole repetition |
| Ganderton et al. (2017) | Delsys Trigno EMG | Stainless steel,teflon-coated 20 cm and 25 cm lengths | | NS | >80 @ 60 Hz | 1000 | Band pass 20-900 Butterworth high-pass, 4th order, 50Hz<br><br>Butterworth low-pass smoothed, 4th order, 6Hz | 2000 | Full | Average activity for each repetition |
| Harput et al. (2016) | Telemyo DTS Noraxon | 10 mm width; skin shaved, abraded and cleaned | 20 | 10m | 80 | NS | Band pass 10-500 RMS smoothed (25ms) | 1000 | Full | Average activity in each phase (concentric, eccentric) |
| Hatfield et al. (2016) | Delsys Trigno | NS | NS | NS | 80 | NS | Band pass 20-450 Low pass filtered, Butterworth, 4th order, 25 Hz | 2000 | Full | Integrated activity over entire task |
| Heo et al. (2013) | Biopac MP150WSW | 3 mm diameter; skin shaved and cleaned | NS | NS | NS | NS | Band pass 20 – 500 | 1000 | Full | Average activity (RMS) |
| Hertel et al. (2005) | Biopac MP 100 | 10 mm contact area; skin debrided and cleansed | 20 | 2M | 11 | 1000 | 10-500<br><br>RMS smoothing (500ms moving window) | 1000 | Full | Peak RMS activity within trials |
| Ju & Yoo (2017) | Biopac MP 150 | NS | NS | NS | NS | NS | NS | NS | NS | NS |
| Ju & Yoo (2016) | EL503 Biopac | 3mm diameter | NS | NS | NS | NS | Band pass 20 - 500 RMS of 250 samples | 1000 | Full | Average (RMS) of the middle 3 seconds of a 5 secs trial |
| Kang et al. (2014) | Delsys surface EMG | NS | NS | NS | NS | NS | Band pass 20-450 | 2000 | NS | Average activity of each phase (descend and ascend components) |
| Kim et al. (2015) | Telemyo 2400 T2 | NS; skin shaved and scrubbed | 20 | NS | NS | 500 | Band pass 30 – 500 RMS smoothed (100ms window) | 1500 | Full | Average (RMS) for each trial |

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| Krause et al. (2018) | 16 bit NI-DAQ PCI-6 220 A-D card<br>Bagnoli 16 amplifier | 10 mm; skin scrubbed | 10 | >1015 @ 100 Hz | 92 @ 60 Hz | 100 - 10000 | Band pass 20 – 450 (Butterworth, 4th order)<br>RMS smoothing (200ms) | 1000 | Full | Average activity of 1 secs surrounding peak activity of the ascending phase |
| Krause et al. (2008) | GCS67 Therapeutics unlimited | NS; skin cleansed | 22 | >15M @ 100 Hz | 87 @ 60 Hz | 35 | RMS smoothed (55ms) | 1000 | Full | Peak activity over three squats |
| Lee et al. (2013) | Telemyo DTS | NS; skin shaved and cleansed | NS | NS | NS | NS | Band pass 20 - 450<br>RMS smoothed (50ms) | 1000 | Full | Average activity of middle 3 secs of the isometric phase |
| Lee et al. (2014) | Telemyo DTS | NS; skin shaved and cleaned | 20 | NS | 92 @ 60 Hz | | Band pass 20 – 450<br>RMS smoothed (50ms) | 1000 | Full | Average activity of middle 3 secs of the isometric phase |
| Lehecka et al. (2017) | Noraxon telemyo 2400T GT | NS; skin shaved, abraded | NS | NS | NS | NS | Band pass 15 - 500<br>High-pass filtered (Butterworth, 4th order, 15Hz)<br>Low-pass filtered (Butterworth, 4th order, 500Hz)<br>Moving average smoothed (50ms) | 3000 | Full | NS |
| Lin et al. (2016) | Bagnoli Delsys | 10x1 mm; skin shaved and cleaned | 10 | NS | NS | NS | Band pass 20 – 450<br>Low-pass filtered (12Hz) | 1000 | Full | Average activity from 5 repetitions |
| Lubahn et al. (2011) | Bagnoli 8 Delsys | NS; skin debrided and cleansed | NS | NS | NS | 1000 | Band pass 20 - 450<br>High-pass filtered (Butterworth, 4th order, 30Hz)<br><br>Low-pass filtered | 960 | NS | Integrated activity over the duration of the exercise |

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| | | | | | | | (Butterworth, 4th order, 6Hz) | | | |
| MacAskill et al. (2014) | 16 channel Motion Lab | 15 mm diameter; skin shaved and scrubbed | 20 | 1M | 90 | 50 | Band pass 20 – 450 RMS smoothing (50ms) | 4000 | Full | Integrated EMG activity across a repetition. |
| Mauntel et al. (2013) | Delsys Bagnoli | Skin shaved, abraded and cleaned | NS | NS | NS | NS | Band pass 10 - 350 Low-pass (Butterworth, 4th order, 14.5 Hz) Notch filtered 59,5-60.5 Hz RMS smoothed (25ms) | 1000 | Full | Average activity from the descent phase |
| McBeth et al. (2012) | 16 channel Run Technologies | NS; skin debrided and cleansed | 26 | NS | NS | 1000 | Band pass 10 - 499 (Butterworth filter) RMS smoothed (20ms) | 1000 | Full | Average activity from 3 trials |
| Monteiro et al. (2017) | 8 channel EMG system Brazil 16 bit resolution | 10 mm diameter; skin shaved, abraded and cleaned. | 20 | NS | NS | NS | Band pass 10 - 500 | NS | Full | Average (RMS) of the concentric phase |
| Morimoto et al. (2018) | Biolog DL 5000 | NS | NS | NS | NS | NS | Band pass 20 – 500 | 1000 | Full | Average (RMS) |
| Noh et al. (2012) | Delsys Trigno | NS; skin rubbed and cleaned | NS | NS | NS | NS | Band pass 20 – 450 | 1000 | Full | Average (RMS) of three trials |
| Oliver et al. (2010) | Noraxon myopic 1400L 8 channel | NS; skin cleansed and debrided | 25 | NS | NS | NS | Band pass 20-350 RMS smoothed (100ms) Notch filtered: 59.5Hz – 60.5Hz | 1000 | Full | Average EMG activity |
| Oliver & Stone (2016) | Delsys Bagnoli 8 channel | NS; skin shaved, abraded and cleaned | 10 | NS | NS | NS | RMS smoothed (100ms) | 1000 | Full | Average EMG activity |
| O'Sullivan et al. (2013) | Motionlab system MA-300 multichannel | 144 $mm^2$; skin cleansed, abraded and shaved | 18 | NS | NS | 2000 | RMS smoothed (150ms) | 1000 | Full | Average (RMS) per trial |

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| O'Sullivan et al. (2010) | Motionlab system MA-300 multichannel | 144 mm$^2$; skin cleansed and debrided | 18 | NS | >100 @ 60 Hz | 2000 | Band-pass 5-500 RMS smoothed (150ms) | 1250 | Full | Average (RMS) per trial |
| Petrofsky et al. (2005) | 12 bit A-D card | NS | 20 | NS | NS | 5000 | RMS | 2000 | Full | Average over a 1 second period |
| Philippon et al. (2011) | Delsys Bagnoli | .07 mm fine-wire | NS | >10M | >84 | NS | RMS (50ms) Low pass 10 Hz | 1200 | Full | Average and peak amplitude |
| Selkowitz et al. (2013) | Motionlab system MA-300 multichannel 16 channel | 50 µm fine wire | NS | > 1M | >110 @ 65 Hz | 1.2 k | Band pass 35 - 750 (Butterworth) RMS smoothing (75ms) | 1560 | Full | Average activity for each repetition |
| Sidorkewicz et al. (2014) | AMT 8 Bortec 16 Bit converter | NS; skin shaved, rubbed and cleaned | 30 | 10G | 115 @ 60 Hz | NS | Band pass 10 – 500 Low-pass (Butterworth 2nd order, 3 Hz) | 2160 | Full | Peak amplitude |
| Sinsurin et al. (2015) | Noraxon Myosystem | NS; skin shaved, abraded and cleaned | 20 | 10k | NS | NS | Bandpass 20 – 450 (Butterworth) | 1500 | Full | Average activity |
| Souza & Powers (2009) | Motion Control | Skin shaved, abraded and cleaned. | NS | NS | NS | 2000 | Band pass 35-500 Notch filter: 60Hz Moving average smoothing (75ms) | 1560 | Full | Average activity |
| Webster & Gribble (2013) | Noraxon 2000 telemyer system. | 38x28 mm; skin shaved, abraded and cleaned | NS | 100m | >100 | NS | RMS smoothing (50ms) Butterworth 3rd order filter | 1000 | Full | Average activity over 0.4 secs surrounding maximum excursion |
| Willcox & Burden (2013) | Delsys | 10x1 mm; skin shaved and cleaned | 10 | 100M | > 80 | NS | Band pass 20 – 500 RMS smoothing (150ms window, 62ms overlap) | 1080 | Full | Average activity per repetition |
| Youdas et al. (2012) | Delsys Bagnoli | 41x20x5 mm; skin shaved and cleaned. | 10 | $10^{15}$ | 92 @ 60 Hz | 100-10000 | Band pass 20 – 450 RMS smoothing (125ms) | 1000 | Full | Peak activity |
| Youdas et al (2014) | Delsys Bagnoli 16 bit A-D card | 41x20x5 mm; skin abraded and cleaned | 10 | $10^{15}$ | 92 @ 60 Hz | 100-10000 | Band pass 20 – 450 | 1000 | Full | Average activity of 500ms interval |

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|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | (Butterworth 4th order) | | | surrounding peak |
| Youdas et al. (2015) | Delsys Bagnoli 16 bit A-D card | 41x20x5 mm; skin abraded and cleaned | 10 | $10^{15}$ | 92 @ 60 Hz | 100-10000 | Band pass 20 – 450 RMS smoothing (125ms) | 1000 | Full | Average activity of 400ms interval surrounding peak |
| Zeller et al. (2003) | NS | Skin shaved and cleansed. | NS | NS | NS | NS | Low pass filtered (Butterworth, 4th order 15Hz) | 960 | Full | Average activity |

Key: A-D – analogue-digital conversion; cm – centimeters; EMG – electromyography; Hz – hertz; mm – millimeters; ms – milliseconds; NS – not stated; RMS – root mean square; secs – seconds; µs – microseconds.

### 2.4.4 Non-weight bearing exercises

***Side-lie hip abduction***

*Gluteus medius*

Side lie abduction was the most commonly investigated exercise in the non-weight bearing position for GMed (Bolgla & Uhl, 2005; Boren et al., 2011; Chan et al., 2017; Cynn, Oh, Kwon, & Yi, 2006; Distefano, Blackburn, Marshall, & Padua, 2009; Ekstrom, Donatelli, & Carp, 2007; Kim et al., 2015; Lee, Cynn, Choi, Yoon, & Jeong, 2013; Lee et al., 2014; MacAskill, Durant, & Wallace, 2014; McBeth, Earl-Boehm, Cobb, & Huddleston, 2012; Morimoto, Oshikawa, Imai, Okubo, & Kaneoka, 2018; Philippon et al., 2011; Selkowitz, Beneck, & Powers, 2013; Sidorkewicz et al., 2014). Moderate mean activity levels (40.10 (95% CI (33.37, 48.21)) % MVIC) were generated for middle GMed when the results were pooled for 8 studies (Figure 2.2) (Table 2.5). The addition of external resistance further increased activity levels to very high, although there was a high degree of heterogeneity ($I^2$ = 95%).

High mean GMed middle activity levels were generated by hip abduction with internal rotation (44.73 (32.99, 60.65) % MVIC), while moderate activity levels were elicited for hip abduction with external rotation (38.01 (29.54, 48.91)% MVIC) (Lee et al., 2013; Lee et al., 2014; Morimoto et al., 2018; Philippon et al., 2011) (Figure 2.2).

*Gluteus minimus*

One study (Moore, Semciw, et al., 2019) evaluated GMin activity for side lie abduction and found moderate activity (38% MVIC) for the anterior segment and high activity (44% MVIC) for the posterior segment (Figures 2.3 and 2.4) (Table 2.6).

*Table 2.5. Segmental mean gluteus medius activity levels (% MVIC) for exercises*

| Exercise category | Exercise | Muscle segment (middle unless indicated) | Low (0-20% MVIC) | Moderate (21-40% MVIC) | High (41-60% MVIC) | Very High (> 60% MVIC) |
|---|---|---|---|---|---|---|
| Side-lie | Hip abduction | | | 39 (Ekstrom et al., 2007); 34 (Lee et al., 2013); 37 (Sidorkewicz et al., 2014); 29-31 (Chan et al., 2017); 38 (Morimoto et al., 2018); 25-46 (Cynn et al., 2006); 24 (Kim et al., 2015) | 42R (Bolgla & Uhl, 2005); 45 (Lee et al., 2014); 44 (Selkowitz et al., 2013) | 63 (Boren et al., 2011); 81 (Distefano et al., 2009); 79R (McBeth et al., 2012); 100R (MacAskill et al., 2014) |
| | Hip abduction + ER | | | 35 (Lee et al., 2013); 37 (Sidorkewicz et al., 2014); 23 (Philippon et al., 2011) | 53R (McBeth et al., 2012); 41 (Morimoto et al., 2018); 49 (Lee et al., 2014) | |
| | Hip abduction + IR | | | 36 (Morimoto et al., 2018); 33 (Philippon et al., 2011) | 45 (Lee et al., 2013); 49 (Sidorkewicz et al., 2014) | 61 (Lee et al., 2014) |
| | Hip abduction + Ext | | | 31 (Philippon et al., 2011) | | |
| | Clam hip flex $0^0$ | | 13-17 (Willcox & Burden, 2013); 17 (Philippon et al., 2011) | | | |
| | Clam hip flex $30^0$ | | 13-21 (Willcox & Burden, 2013) | 40 (Distefano et al., 2009); 27 (Sidorkewicz et al., 2014) | | |
| | Clam hip flex $45^0$ | Anterior | 3 (Ganderton, Pizzari, Cook, et al., 2017) | | | |
| | | Middle | 13 (Ganderton, Pizzari, Cook, et al., 2017); 16-18 (Chan et al., 2017); 17 (Philippon et al., 2011) | 33 (McBeth et al., 2012); 27R (Selkowitz et al., 2013); 36 (Sidorkewicz et al., 2014) | 47 (Boren et al., 2011); | |
| | | Posterior | | 23 (Ganderton, Pizzari, Cook, et al., 2017) | | |
| | Clam hip flex $60^0$ | | 19 (Lin et al., 2016) | 36 (Sidorkewicz et al., 2014); 38 (Distefano et al., 2009); 18-23 (Willcox & Burden, 2013) | | |
| Squat | Single leg squat | Anterior | | | | 90 (O'Sullivan et al., 2012) |
| | | Middle | 18 (Lin et al., 2016) | 36 (Ayotte, Stetts, Keenan, & Greenway, 2007); 30 (Boudreau et al., 2009); 30-31 (Dwyer et al., 2010); 23 (Bolgla, Cruz, Roberts, Buice, & Pou, 2016); 24 (Hatfield et al., 2017); 20-27 (Bolgla, Cook, Hogarth, Scott, & West, 2014); 33-37 (Mauntel et al., 2013) | 59U (Krause et al., 2009); 48 (Krause et al., 2009); 41-77 (Zeller, McCrory, Kibler, & Uhl, 2003) | 82 (Boren et al., 2011); 64 (Distefano et al., 2009); 77 (Hertel et al., 2005); 66 (Lubahn et al., 2011); 92 (O'Sullivan et al., 2012) |

| Exercise category | Exercise | Muscle segment (middle unless indicated) | Low (0-20% MVIC) | Moderate (21-40% MVIC) | High (41-60% MVIC) | Very High (> 60% MVIC) |
|---|---|---|---|---|---|---|
| | | Posterior | | | | 87 (O'Sullivan et al., 2012) |
| | Single leg squat + Abd | Anterior | 19 (Heo et al., 2013) | | | |
| | | Middle | | 27 (Heo et al., 2013) | 42-46 (Barton et al., 2014) | |
| | | Posterior | | 33 (Heo et al., 2013) | | |
| | Single leg squat + Add | Anterior | | | 42 (Heo et al., 2013) | |
| | | Middle | | 31 (Heo et al., 2013) | | |
| | | Posterior | | 22 (Heo et al., 2013) | | |
| | Single leg wall squat | Anterior | 13 (O'Sullivan et al., 2010) | | | |
| | | Middle | | 25 (O'Sullivan et al., 2010); 27 (Bolgla et al., 2016); 22-32 (Bolgla et al., 2014) | 52 (Ayotte et al., 2007) | |
| | | Posterior | | 35 (O'Sullivan et al., 2010) | | |
| | Single leg wall squat + Abd | Anterior | | 29 (Heo et al., 2013) | | |
| | | Middle | | 33 (Heo et al., 2013) | | |
| | | Posterior | | | 44 (Heo et al., 2013) | |
| | Single leg wall squat + Add | Anterior | 16 (Heo et al., 2013) | | | |
| | | Middle | | 21 (Heo et al., 2013) | | |
| | | Posterior | | 28 (Heo et al., 2013) | | |
| | Single leg skater squat | | | | 60 (Boren et al., 2011) | |
| | Single leg squat + rotation | | | | | 66 (Webster & Gribble, 2013) |
| | Squat | | 10 (Selkowitz et al., 2013); 9-12R (Kang et al., 2014) | 26-33 (Felício et al., 2011); 21 (Lubahn et al., 2011); 22-28 (Petrofsky et al., 2005) | | |
| | Wall squat | | 9-10 (Barton et al., 2014) | | | |
| | Squat + Abd | | | 24 (Lubahn et al., 2011) | 47-52 (Felício et al., 2011) | |
| | Squat + Add | | | | 59 (Felício et al., 2011) | |
| Step | Lateral step-up | | | 38 (Ayotte et al., 2007); 39 (Noh et al., 2012) | 60 (Boren et al., 2011); | 63 (MacAskill et al., 2014) |
| | Lateral step-up + IR | | | | 41 (Noh et al., 2012) | |
| | Lateral step-up + ER | | | 30 (Noh et al., 2012) | | |
| | Lateral step-down | | | 21 (Bolgla et al., 2016); 19-25 (Bolgla et al., 2014) | | 74 (Hertel et al., 2005) |
| | Lateral step | Anterior | | | | |
| | | Middle | | 24-35RS (Cambridge et al., 2012) ; 30RS (Selkowitz et al., 2013); 33-50RS (Youdas et al., 2013) | | |
| | | Posterior | | 19-23RU (Berry, Lee, Foley, & Lewis, 2015); 23-36RS (Berry et al., 2015) | | |
| | Lateral step + IR | | | | 44-58RS (Youdas et al., 2013) | |

| Exercise category | Exercise | Muscle segment (middle unless indicated) | Low (0-20% MVIC) | Moderate (21-40% MVIC) | High (41-60% MVIC) | Very High (> 60% MVIC) |
|---|---|---|---|---|---|---|
| | Lateral step + ER | | | 27-48RS (Youdas et al., 2013) | | |
| | Forward step-up | | 17 (Hatfield et al., 2017) | 29 (Dwyer et al., 2013); 30 (Selkowitz et al., 2013) | 44 (Ayotte et al., 2007); 55 (Boren et al., 2011); 48 (Lubahn et al., 2011); 45MR (Lubahn et al., 2011) | 62 (MacAskill et al., 2014) |
| | Forward step-down | | 14 (Bouillon et al., 2012); 17 (Souza & Powers, 2009) | 23 (Bolgla et al., 2016); 20-22 (Dwyer et al., 2013); 28 (Harput et al., 2016); 21-27 (Hatfield et al., 2017); 19-27 (Bolgla et al., 2014) | | |
| | Forward step-up and over | Anterior | | | | 88 (O'Sullivan et al., 2012) |
| | | Middle | 15-17 (Boudreau et al., 2009); 15-21 (Dwyer et al., 2010) | | | 85 (O'Sullivan et al., 2012) |
| | | Posterior | | | | 81 (O'Sullivan et al., 2012) |
| | Retro step-up | | | 37 (Ayotte et al., 2007) | | |
| Lunge | Forward lunge | Anterior | | | 45RE (Ganderton, Pizzari, Cook, et al., 2017) | |
| | | Middle | 18-19 (Boudreau et al., 2009); 12-25 (Dwyer et al., 2010); 12 (Bouillon et al., 2012); 19 (Selkowitz et al., 2013); 15 (Krause et al., 2018); 8 (Lin et al., 2016) | 29 (Ekstrom et al., 2007) | 42 (Distefano et al., 2009) | 71RE (Ganderton, Pizzari, Cook, et al., 2017) |
| | | Posterior | | 28RE (Ganderton, Pizzari, Cook, et al., 2017) | | |
| | Transverse lunge | | | | 48 (Distefano et al., 2009) | 68 (Webster & Gribble, 2013) |
| | Sideways lunge | | 13 (Bouillon et al., 2012) | 39 (Distefano et al., 2009) | | |
| Stand | Hip hitch/ pelvic drop | Anterior | | 21 (O'Sullivan et al., 2010); 25 (Ju & Yoo, 2016); 25 (Ju & Yoo, 2017) | | 69 (Ganderton, Pizzari, Cook, et al., 2017); 80 (O'Sullivan et al., 2012) |
| | | Middle | | 28 (O'Sullivan et al., 2010); 23 (Ju & Yoo, 2016); 38 (Selkowitz et al., 2013) | 57 (Bolgla & Uhl, 2005); 58 (Boren et al., 2011); 42 (Monteiro, Facchini, de Freitas, Callegari, & Joao, 2017) | 66 (Ganderton, Pizzari, Cook, et al., 2017); 88 (O'Sullivan et al., 2012) |
| | | Posterior | | 38 (O'Sullivan et al., 2010); 22 (Ju & Yoo, 2016) | | 74 (Ganderton, Pizzari, Cook, et al., 2017); 88 (O'Sullivan et al., 2012) |
| | Hip hitch/ pelvic drop + IR | | | | 42 (Monteiro et al., 2017) | |
| | Hip hitch/ pelvic drop + ER | | | 33 (Monteiro et al., 2017) | | |
| | Hip hitch/ pelvic drop + leg swing | Anterior | | | | 82 (Ganderton, Pizzari, Cook, et al., 2017) |

| Exercise category | Exercise | Muscle segment (middle unless indicated) | Low (0-20% MVIC) | Moderate (21-40% MVIC) | High (41-60% MVIC) | Very High (> 60% MVIC) |
|---|---|---|---|---|---|---|
| | | Middle | | | | 66 (Ganderton, Pizzari, Cook, et al., 2017) |
| | | Posterior | | | | 72 (Ganderton, Pizzari, Cook, et al., 2017) |
| | Hip hitch/ pelvic drop + toe tap | Anterior | | | | 76 (Ganderton, Pizzari, Cook, et al., 2017) |
| | | Middle | | | 58 (Ganderton, Pizzari, Cook, et al., 2017) | |
| | | Posterior | | | 46 (Ganderton, Pizzari, Cook, et al., 2017) | |
| | Hip abduction | Anterior | | | 56(Ganderton, Pizzari, Cook, et al., 2017) I | |
| | | Middle | | 30I (Ganderton, Pizzari, Cook, et al., 2017) | 42-46R (Bolgla & Uhl, 2005); 44 (Sinsurin et al., 2015); 50R (Youdas et al., 2014) | |
| | | Posterior | | | 41I (Ganderton, Pizzari, Cook, et al., 2017) | |
| | Hip abduction (moving limb) | | | 28-33 (Bolgla & Uhl, 2005) | 53R (Youdas et al., 2014) | 64 (Sinsurin et al., 2015) |
| Supine | Single leg bridge | | | 33-35 (Oliver, Stone, & Plummer, 2010); 31 (Selkowitz et al., 2013); 35 (Philippon et al., 2011) | 40-42 (Youdas et al., 2015); 55 (Boren et al., 2011); 47U (Boren et al., 2011); 47 (Ekstrom et al., 2007); 42-58 (Lehecka et al., 2017) | |
| | Double leg bridge | | 17 (Oliver et al., 2010); 15 (Selkowitz et al., 2013); 11 (Philippon et al., 2011) | 20-21 (Youdas et al., 2015); 28 (Ekstrom et al., 2007); | | |

Key: Abd – abduction; Add – adduction; ER – hip external rotation; Ext – extension; Flex – flexion; IR – hip internal rotation; I – isometric exercise; MR – added medial resistance; R – added external resistance; RE – rearfoot elevated; RS – resisted squat posture; RU – resisted upright posture; U – unstable surface.

*Table 2.6. Segmental mean gluteus minimus activity levels (% MVIC) for exercises*

| Exercise category | Exercise | Muscle segment | Low (0-20% MVIC) | Moderate (21-40% MVIC) | High (41-60% MVIC) | Very High (> 60% MVIC) |
|---|---|---|---|---|---|---|
| Side-lie | Hip abduction | Anterior | | 38(Moore, Semciw, et al., 2019) | | |
| | | Posterior | | | 43 (Moore, Semciw, et al., 2019) | |
| | Clam hip flex 45$^0$ | Anterior | 7 (Ganderton, Pizzari, Cook, et al., 2017); 3 (Moore, Semciw, et al., 2019) | | | |
| | | Posterior | 20 (Ganderton, Pizzari, Cook, et al., 2017); 8 (Moore, Semciw, et al., 2019) | | | |
| Squat | Single leg squat | Anterior | | 25 (Moore, Semciw, et al., 2019) | | |
| | | Posterior | | | 46 (Moore, Semciw, et al., 2019) | |
| Lunge | Forward lunge | Anterior | | 21RE (Ganderton, Pizzari, Cook, et al., 2017) | | |
| | | Posterior | | | | 66RE (Ganderton, Pizzari, Cook, et al., 2017) |
| Stand | Hip hitch/pelvic drop | Anterior | | | | 69 (Ganderton, Pizzari, Cook, et al., 2017) |
| | | Posterior | | | | 84 (Ganderton, Pizzari, Cook, et al., 2017) |
| | Hip hitch/pelvic drop + leg swing | Anterior | | | 60 (Ganderton, Pizzari, Cook, et al., 2017) | |
| | | Posterior | | | | 79 (Ganderton, Pizzari, Cook, et al., 2017) |
| | Hip hitch/pelvic drop + toe tap | Anterior | | | 48 (Ganderton, Pizzari, Cook, et al., 2017) | |
| | | Posterior | | | | 67 (Ganderton, Pizzari, Cook, et al., 2017) |
| | Hip abduction | Anterior | | | 55I (Ganderton, Pizzari, Cook, et al., 2017) | |
| | | Posterior | | | 49I (Ganderton, Pizzari, Cook, et al., 2017) | |
| Supine | Single leg bridge | Anterior | 14 (Moore, Semciw, et al., 2019) | | | |
| | | Posterior | | | 46 (Moore, Semciw, et al., 2019) | |

Key: I – isometric exercise; RE – rear-foot elevated

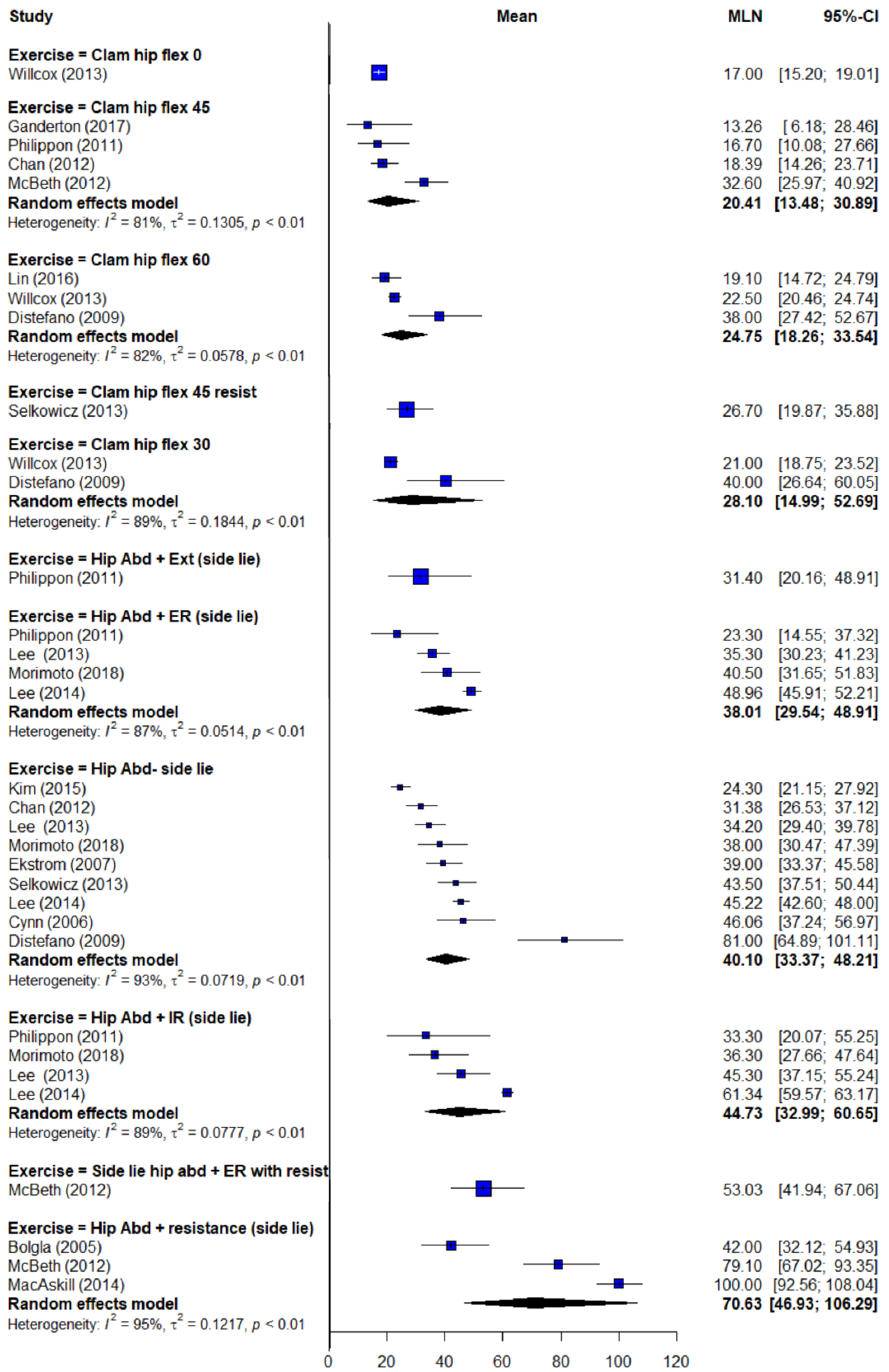


*Figure 2.2. Gluteus medius middle - side lie clam and hip abduction exercises*

***Side-lie hip clam***

*Gluteus medius*

The side-lie hip clam was evaluated in 10 studies (Boren et al., 2011; Chan et al., 2017; Distefano et al., 2009; Ganderton, Pizzari, Cook, et al., 2017; Lin et al., 2016; McBeth et al., 2012; Philippon et al., 2011; Selkowitz et al., 2013; Sidorkewicz et al., 2014; Willcox & Burden, 2013) with varying positions of hip flexion. Low to moderate activity levels (17-28% MVIC) were reported across the studies for middle GMed (Figure 2.3) (Table 2.5). There were wide variations between studies for exercise technique; angle of hip and knee flexion; repetitions; and use of external loading. One study (Ganderton, Pizzari, Cook, et al., 2017) recorded segmental GMed activity levels using fine wire EMG and found low activity levels for the anterior (3% MVIC) and middle segments (13% MVIC), and moderate activity (23% MVIC) for the posterior segment (Figures 2.5 and 2.6). Altering the angle of hip flexion or trunk position had minimal effect on mean GMed activity levels generated for this exercise (Willcox & Burden, 2013) (Figure 2.2).

*Gluteus minimus*

Two studies (Ganderton, Pizzari, Cook, et al., 2017; Moore, Semciw, et al., 2019) evaluated segmental activity levels for GMin. When pooled together, low activity was recorded for anterior (4.53 (95% CI (1.88, 10.89))% MVIC) and posterior (12.22 (5.09, 29.35)% MVIC) segments (Figures 2.3 and 2.4) (Table 2.6).

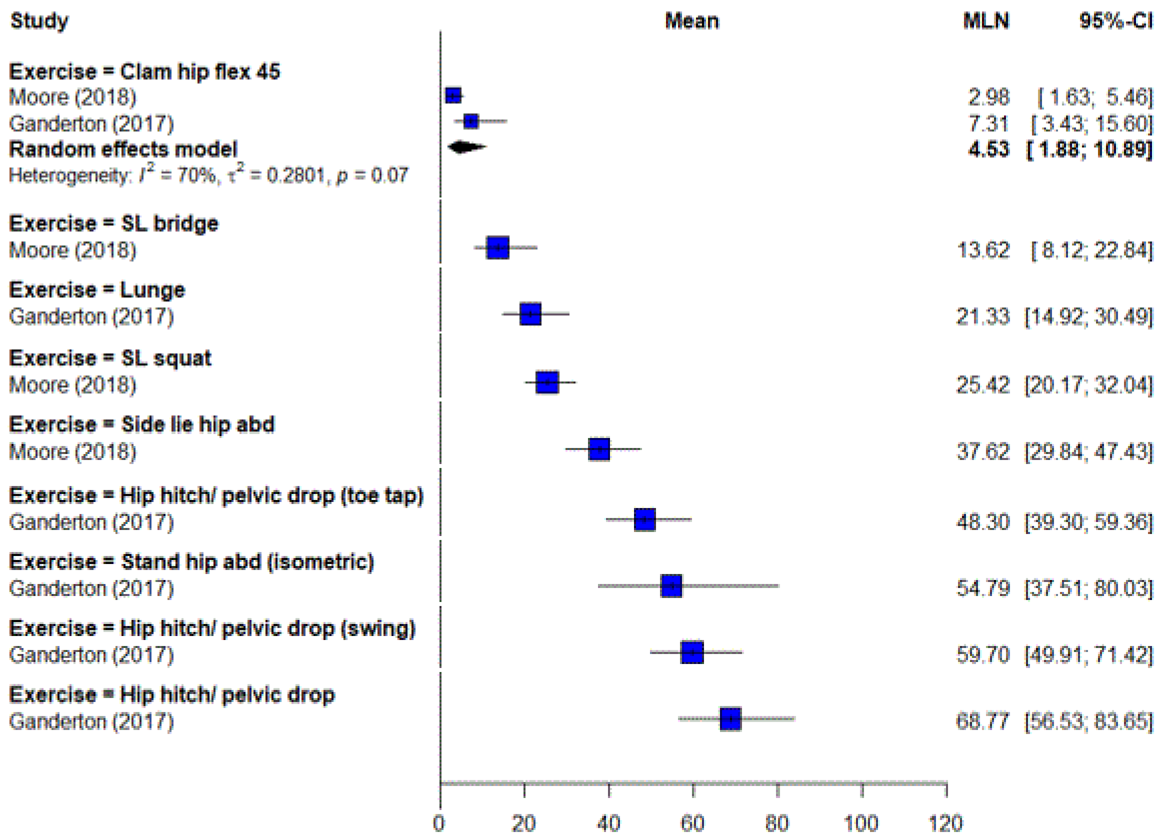


*Figure 2.3. Gluteus minimus anterior exercises*

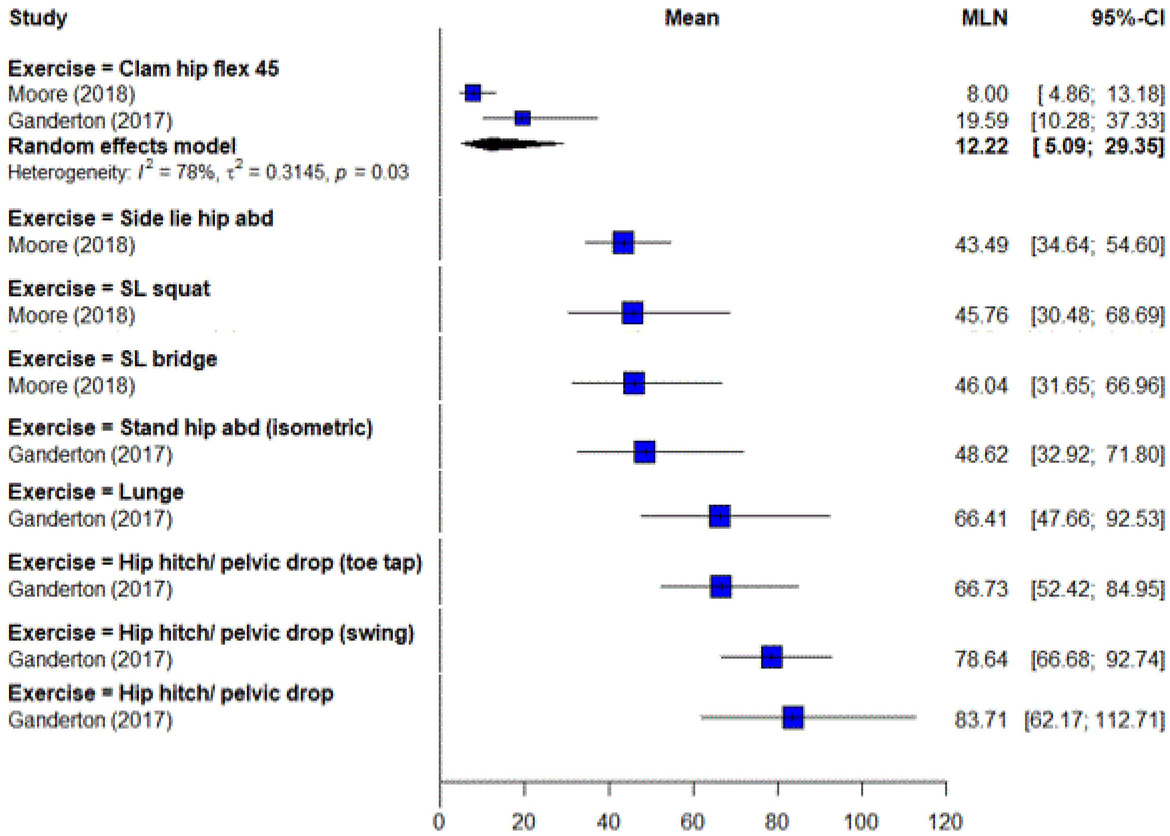


*Figure 2.4. Gluteus minimus posterior exercises*

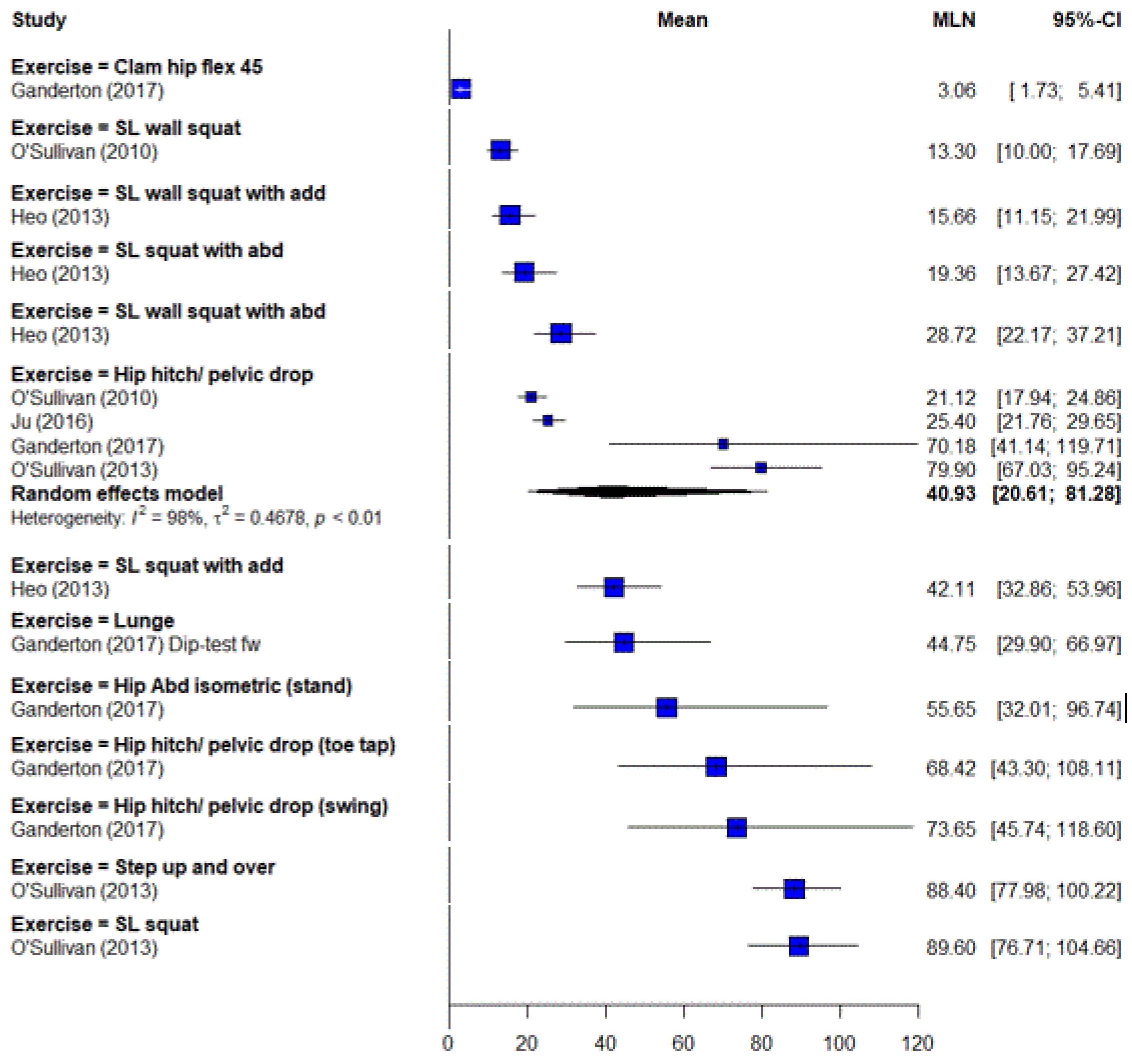


*Figure 2.5. Gluteus medius anterior exercises*

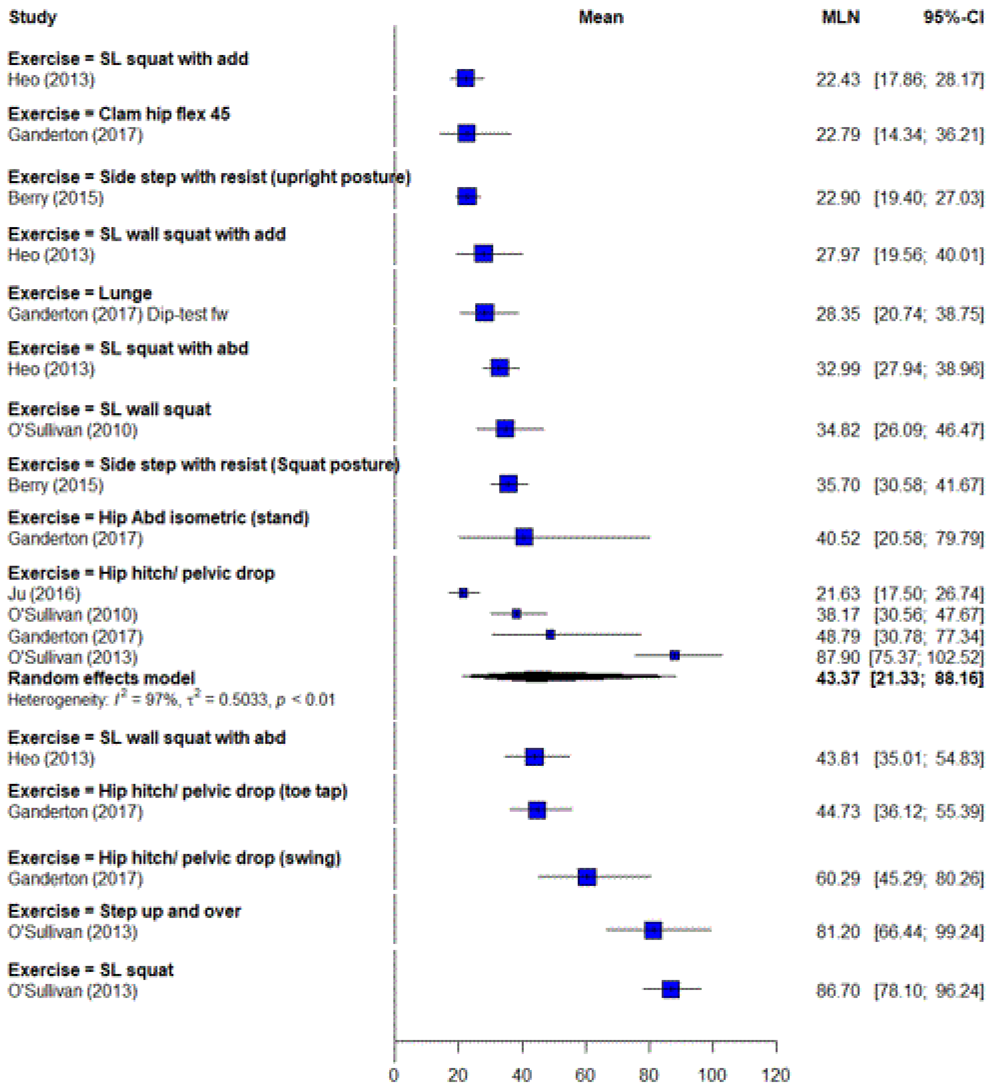


*Figure 2.6. Gluteus medius posterior exercises*

### *Standing hip abduction (open chain)*

*Gluteus medius*

Standing hip abduction on the swing leg was evaluated in three studies (Bolgla & Uhl, 2005; Sinsurin et al., 2015; Youdas et al., 2014) (Table 2.5). Two studies had added external resistance and could be pooled together generating high middle GMed activity levels (42.95 (95% CI (27.14, 67.99))% MVIC) (Figure 2.7). There was however a high degree of heterogeneity ($I^2$ = 84%). The one study (Sinsurin et al., 2015) without added resistance recorded very high activity levels (64% MVIC).

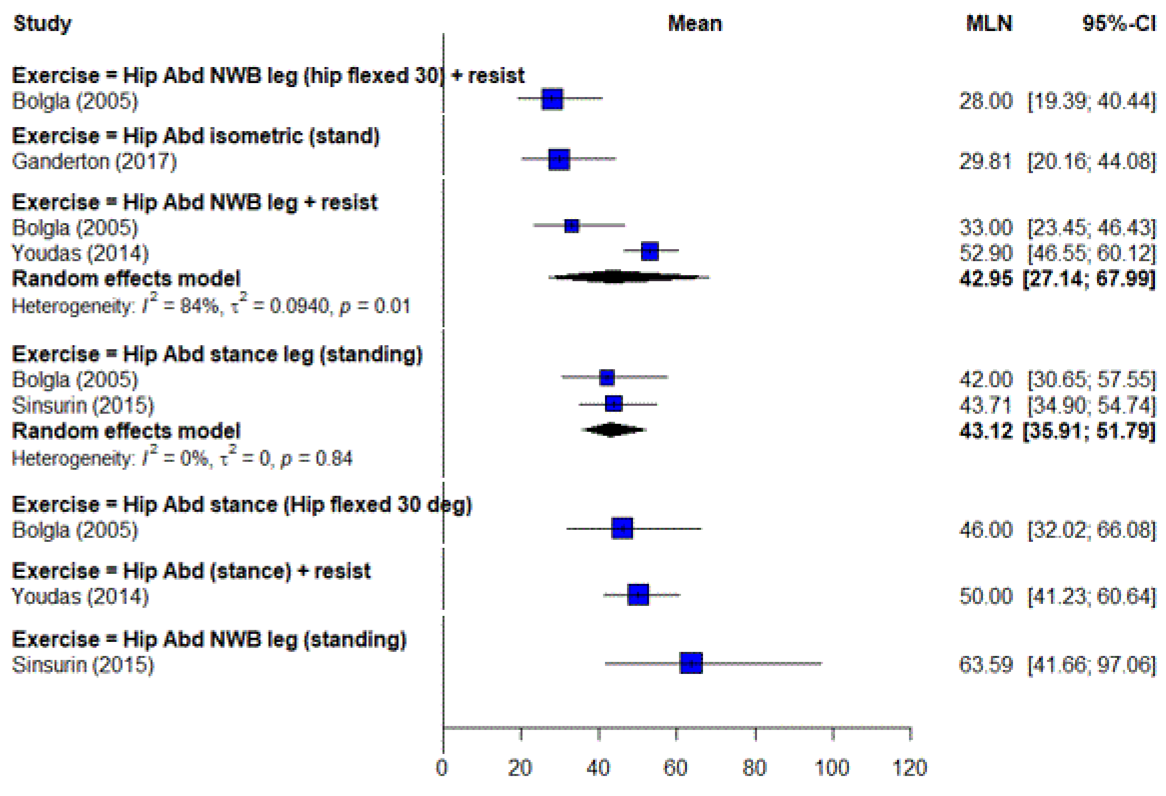


*Figure 2.7. Gluteus medius middle - stand hip abduction*

### 2.4.5 Weight-bearing exercises

***Squat exercises***

*Gluteus medius*

Single leg squats were evaluated in 15 studies (Ayotte et al., 2007; Bolgla et al., 2014; Bolgla et al., 2016; Boren et al., 2011; Boudreau et al., 2009; Distefano et al., 2009; Dwyer et al., 2010; Hatfield et al., 2017; Hertel et al., 2005; Krause et al., 2009; Lin et al., 2016; Lubahn et al., 2011; Mauntel et al., 2013; O'Sullivan et al., 2012; Zeller et al., 2003) using predominantly single surface electrode measures at middle GMed (Table 2.5). Moderate activity (39.03 (95% CI (31.21, 48.82))% MVIC) was reported when 13 studies were pooled together (Figure 2.8). Large variations did however exist between the studies including squat depth, exercise technique and number of repetitions. One study (O'Sullivan et al., 2012) recorded activity in all three GMed segments using surface electrodes and found

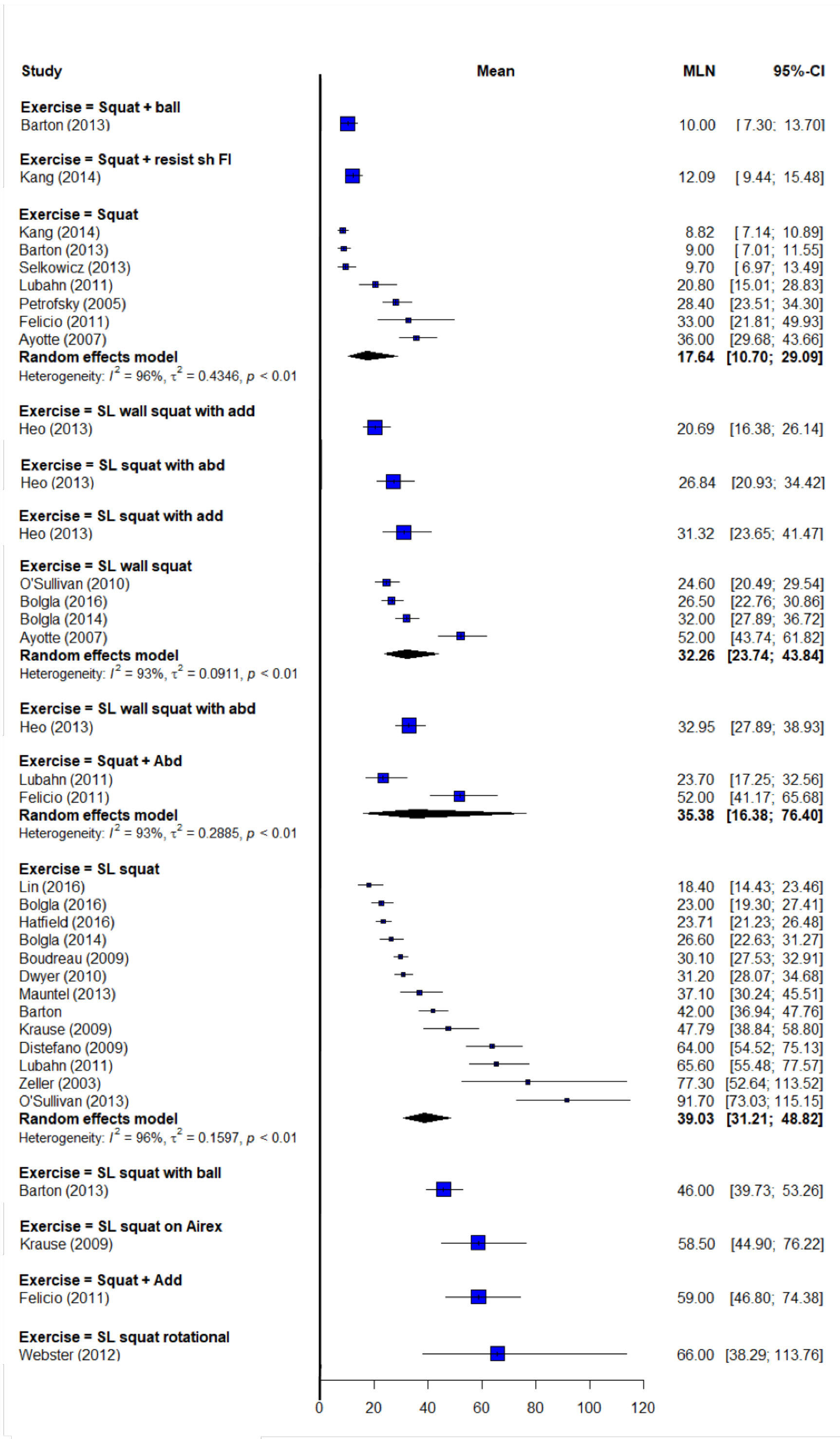


*Figure 2.8. Gluteus medius middle - squat exercises*

very high activity in all three segments (90% MVIC anterior, 92% MVIC middle, and 87% MVIC posterior). Another study (Heo et al., 2013) measured GMed segmental activity for the single leg squat with isometric hip abduction and with isometric hip adduction. They found moderate activity for both exercises for the middle (27-31% MVIC) and posterior (22-33% MVIC) segments but high anterior segmental activity (42% MVIC) for isometric adduction, and low anterior segmental activity (19% MVIC) for isometric abduction.

Single leg wall squats were evaluated in four studies. (Ayotte et al., 2007; Bolgla et al., 2014; Bolgla et al., 2016; O'Sullivan et al., 2010) When pooled together for the middle GMed segment were found to generate moderate activity (32.26 (23.74, 43.84)% MVIC) (Figure 2.8) (Table 2.5). Two studies (Heo et al., 2013; O'Sullivan et al., 2010) recorded segmental GMed activity using surface electrodes with one of the studies (Heo et al., 2013) having the single leg wall squat performed using either isometric hip abduction or isometric hip adduction. Low to moderate activity (13-29% MVIC) was reported in the anterior segment and moderate to high activity (28-44% MVIC) in the posterior segment (Figures 2.5 and 2.6).

Squats with or without medial or lateral resistance, or wall support were evaluated in six studies (Barton et al., 2014; Felício et al., 2011; Kang et al., 2014; Lubahn et al., 2011; Petrofsky et al., 2005; Selkowitz et al., 2013) using single surface electrodes placed on middle GMed (Table 2.5). When pooled together, squats generated low activity levels (17.64 (10.70, 29.09)% MVIC) and squats with resisted abduction moderate activity levels (35.38 (16.38, 76.40)% MVIC) for the middle GMed segment (Figure 2.8).

*Gluteus minimus*

Moderate (25% MVIC anterior) to high (46% MVIC posterior) activity was generated for both segments of GMin during the single leg squat in one study (Moore, Semciw, et al., 2019) (Figures 2.3 and 2.4) (Table 2.6).

***Step exercises***

*Gluteus medius*

Step exercises were evaluated in 21 studies (Ayotte et al., 2007; Berry et al., 2015; Bolgla et al., 2014; Bolgla et al., 2016; Boren et al., 2011; Boudreau et al., 2009; Bouillon et al., 2012; Cambridge et al., 2012; Dwyer et al., 2010; Dwyer et al., 2013; Ekstrom et al., 2007; Harput et al., 2016; Hatfield et al., 2017; Hertel et al., 2005; Lubahn et al., 2011; MacAskill et al., 2014; Noh et al., 2012; O'Sullivan et al., 2012; Selkowitz et al., 2013; Souza & Powers, 2009; Youdas et al., 2013) for predominantly single electrode surface measures of middle GMed (Table 2.5). For studies that could be pooled together, high mean activity levels (44.98 (95% CI (34.54, 58.58))% MVIC) were generated for the lateral step-up and moderate mean activity levels (35.23 (24.52, 50.60)% MVIC) were elicited for the forward step-up (Figure 2.9).

Adding resistance to a side-step exercise also generated high mean activity levels (40.04 (26.53.29, 60.43)% MVIC) for middle GMed (Figure 2.9). There were wide methodological variations across the studies including exercise technique; step height; step distance; concentric and eccentric phase measures; stepping or supporting leg measures; and addition of external resistance. One study (O'Sullivan et al., 2012) measured segmental surface GMed activity and found very high activity (88% MVIC anterior, 85% MVIC middle, and 81% MVIC posterior) for all three segments for the forward step up and over exercise.

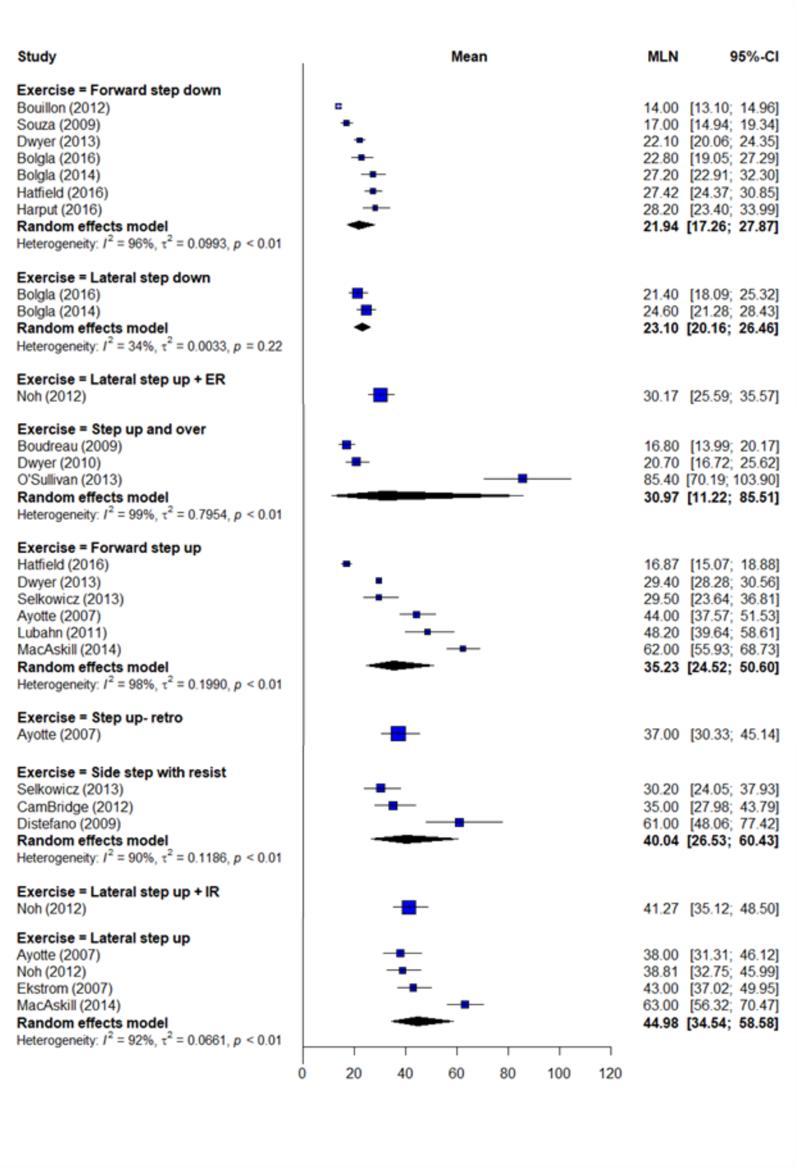


*Figure 2.9. Gluteus medius middle - step exercises*

### ***Lunge exercises***

*Gluteus medius*

The lunge was evaluated in GMed across 10 studies (Boudreau et al., 2009; Bouillon et al., 2012; Distefano et al., 2009; Dwyer et al., 2010; Ekstrom et al., 2007; Ganderton, Pizzari, Cook, et al., 2017; Krause et al., 2018; Lin et al., 2016; Selkowitz et al., 2013; Webster & Gribble, 2013) (Table 2.5). For middle GMed, pooled results suggest moderate activity is recorded during the forward (21.43 (95% CI (14.83, 30.97))% MVIC) and side lunge (22.41 (7.64, 65.78)% MVIC) (Figure 2.10). One study (Ganderton, Pizzari, Cook, et al., 2017) measured segmental GMed activity with a rear-foot elevated lunge (dip test) and found high anterior (45% MVIC), very high middle (71% MVIC) and moderate posterior (28% MVIC) GMed segmental activity. There was some variation between the studies on lunge technique, active range of movement and movement plane.

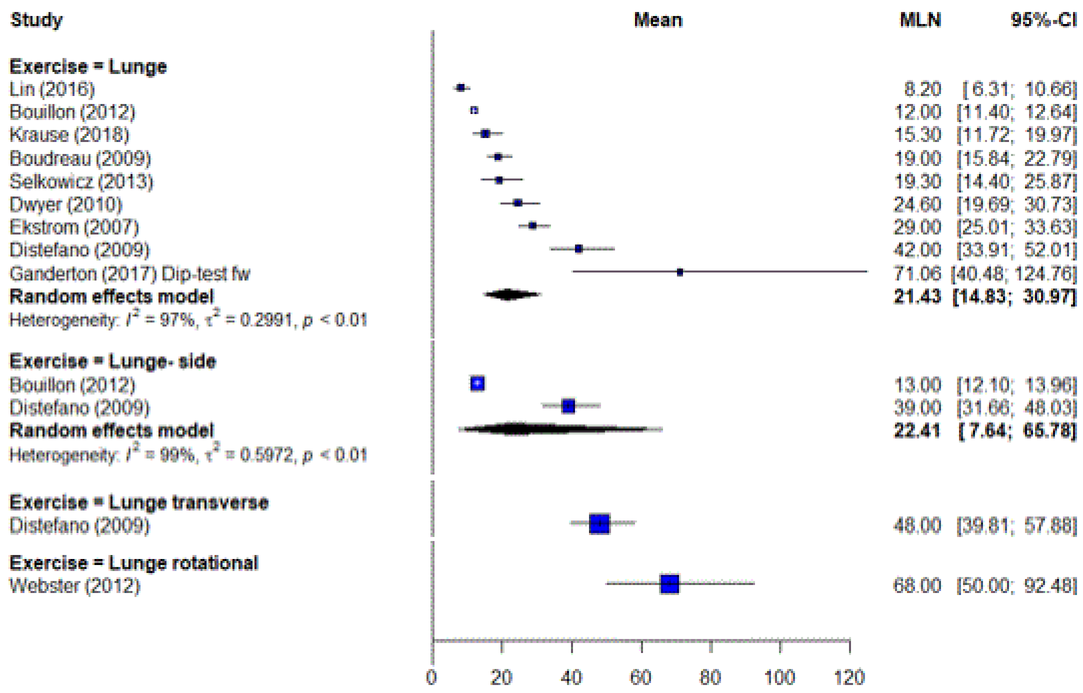


*Figure 2.10. Gluteus medius middle - lunge exercises*

*Gluteus minimus*

One study (Ganderton, Pizzari, Cook, et al., 2017) found the dip test generated moderate activity (21% MVIC) for the anterior GMin segment and very high activity (66% MVIC) for the posterior GMin segment (Figures 2.3 and 2.4) (Table 2.6).

***Hip hitch /pelvic drop***

*Gluteus medius*

The hip hitch/pelvic drop exercise were evaluated in eight studies (Bolgla & Uhl, 2005; Boren et al., 2011; Distefano et al., 2009; Ganderton, Pizzari, Cook, et al., 2017; Ju & Yoo, 2016; Krause et al., 2009; Monteiro et al., 2017; O'Sullivan et al., 2012; O'Sullivan et al., 2010; Petrofsky et al., 2005; Selkowitz et al., 2013) (Table 2.5). For studies that could be pooled together, the hip hitch/pelvic drop generated high GMed anterior activity (40.93 (95% CI (20.61, 81.28))% MVIC), GMed middle (42.64 (30.17, 60.00) % MVIC) and GMed posterior (43.37 (21.33, 88.16) % MVIC) activity (Figures 2.5, 2.6 and 2.11). Three different variations of the hip hitch/pelvic drop exercise (hip hitch, hip hitch + leg swing, and hip hitch + toe-tap) were evaluated in one study (Ganderton, Pizzari, Cook, et al., 2017) and found very high activity (68-74% MVIC) for the anterior GMed, and high to very high activity for the middle (41-65% MVIC) and posterior (45-60% MVIC) GMed segments.

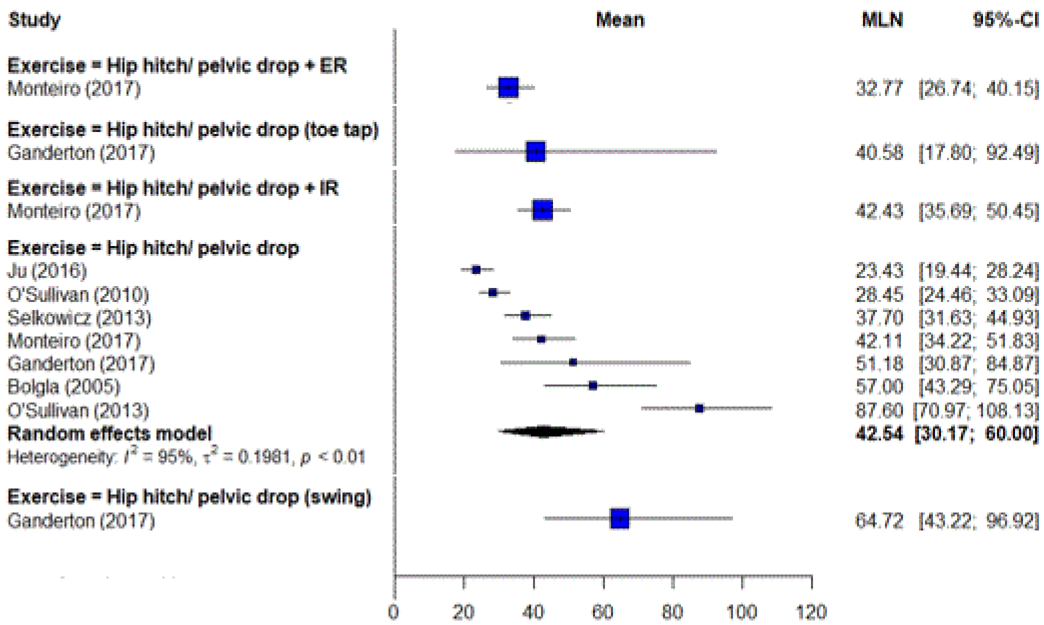


*Figure 2.11. Gluteus medius middle - hip hitch/pelvic drop exercises*

*Gluteus minimus*

Gluteus minimus activity was evaluated in one study (Ganderton, Pizzari, Cook, et al., 2017) for three different variations of the hip hitch/ pelvic drop exercise and found to generate high to very high activity (48-69% MVIC) for the anterior segment and very high activity (66-84% MVIC) for the posterior segment (Figures 2.3 and 2.4) (Table 2.6).

***Standing hip abduction***

*Gluteus medius*

Standing hip abduction was measured on the stance leg in four studies (Bolgla & Uhl, 2005; Ganderton, Pizzari, Cook, et al., 2017; Sinsurin et al., 2015; Youdas et al., 2014) (Table 2.5). For two studies that could be pooled together high activity levels (43.12 95% CI (35.91, 51.79))% MVIC) were recorded for the middle GMed segment (Figure 2.7). Moderate to high activity (56% MVIC anterior, 30% MVIC middle and 41% MVIC posterior) was found in one study (Ganderton, Pizzari, Cook, et al., 2017) that evaluated GMed segmental activity levels for isometric stance hip abduction.

*Gluteus minimus*

Gluteus minimus segmental activity levels were also recorded for isometric stance hip abduction and high activity (55% MVIC anterior and 49% MVIC posterior) was found for both segments (Ganderton, Pizzari, Cook, et al., 2017) (Figures 2.3 and 2.4) (Table 2.6).

***Supine bridge***

*Gluteus medius*

The single-leg bridge was investigated in seven single electrode GMed middle studies (Boren et al., 2011; Ekstrom et al., 2007; Lehecka et al., 2017; Oliver et al., 2010; Philippon et al., 2011; Selkowitz et al., 2013; Youdas et al., 2015) (Table 2.5). For six studies that could be pooled together, high activity levels (41.27 (95% CI (33.98, 50.13))% MVIC were produced (Figure 2.12). The double leg bridge was evaluated in five studies (Ekstrom et al., 2007; Oliver et al., 2010; Philippon et al., 2011; Selkowitz et al., 2013; Youdas et al., 2015) for GMed middle and when pooled together generated low activity levels (18.80 (13.83, 25.66)% MVIC) (Figure 2.12).

*Gluteus minimus*

The single leg bridge was measured in one study (Moore, Semciw, et al., 2019) and generated low activity (14% MVIC) in the anterior GMin segment and high activity (46% MVIC) for the posterior GMin segment (Figures 2.3 and 2.4) (Table 2.6).

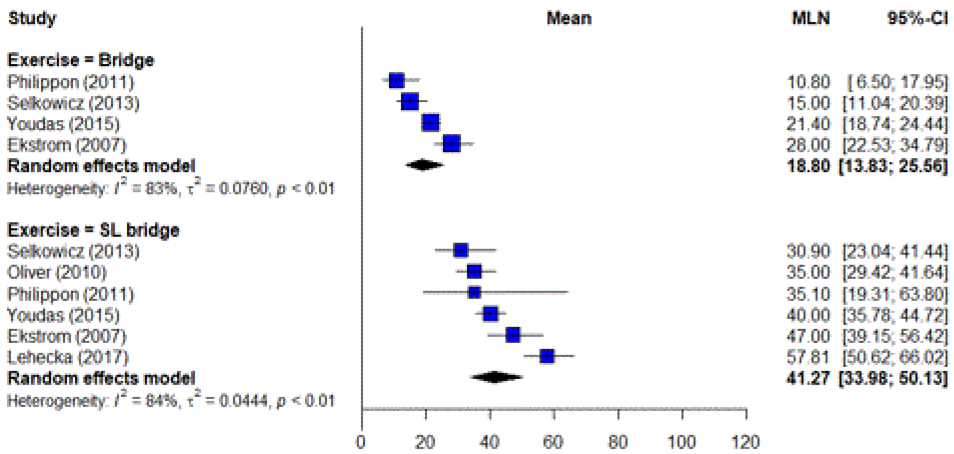


*Figure 2.12. Gluteus medius middle - bridge exercises*

## 2.5 Discussion

The aim of this systematic review was to determine whether commonly evaluated rehabilitation exercises generate at least high activity levels in GMed and GMin segments. The results indicate that different variations of the hip hitch/pelvic drop exercise are the best options to generate at least high activity in all segments of GMed. To target the anterior GMed segment, additional options could include isometric stand hip abduction and the dip test. For the middle GMed segment at least high activity was generated by the single leg bridge; side-lie hip abduction with hip internal rotation; lateral step-up; resisted side-step; and stand hip abduction on stance leg or swing leg with added resistance. Another exercise option for the posterior GMed segment is isometric stand hip abduction.

For the GMin different variations of the hip hitch/pelvic drop exercise and isometric stand hip abduction were the best options to generate at least high activity in both segments. Additional exercises to target the posterior GMin segment included the dip test; single leg bridge; single leg squat; and side-lie hip abduction.

Single leg weight-bearing exercises appeared to generate at least moderate activity in all three segments of GMed. This is despite the wide methodological variations between studies for similar exercises and the relatively small number of studies that evaluated the GMed segments for different exercises. This highlights the functional role of GMed as a multi-planar hip and pelvic stabiliser in weight-bearing activities. Based on the large physiological cross-sectional area and favourable coronal plane moment arm, (Dostal et al., 1986) GMed is well suited to maintaining pelvic and hip joint equilibrium during single-limb loading tasks.

The clam exercise appeared least favourable in terms of recruiting GMed muscle activity. With a relatively short anti-gravity lever arm to overcome, the clam recorded low activity in the anterior and middle segments, and moderate activity in the posterior segment. This perhaps reflects the biomechanical properties of GMed muscle segments, with the anterior segment having an internal rotation moment arm in the transverse plane, the middle segment a negligible rotation moment arm, and the posterior segment an external rotation moment arm. (Dostal et al., 1986) The clam may potentially be useful in early rehabilitation for motor control and recruitment but unlikely to elicit sufficient activity for strengthening. (Andersen et al., 2006) This is particularly the case for the anterior and middle segments.

Recruitment of posterior GMin with a wide variety of exercises appears more feasible than anterior GMin. There are a broader range of exercises available for strengthening the posterior GMin with single leg weight-bearing exercises, and side lie hip abduction potential options. In comparison, the anterior GMin functioning as an anterior hip capsule stabilizer, and prime hip abductor, (Flack et al., 2014) appears to be more difficult to target for strengthening compared to the posterior segment. For example, the single leg squat exercise is broadly useful for recruiting all segments of GMed as well as posterior GMin but may have less utility for anterior GMin (moderate level of activity). This might reflect the tendency of studies to include exercises with an external rotation bias. Since anterior GMin is highly active with internal rotation, (A. I. Semciw et al., 2014) and has a favourable moment arm for internal rotation, (Dostal et al., 1986) further research examining internal rotation-based exercises for anterior GMin highlight further options for recruiting this muscle segment. The clam exercise may not have great utility for GMin muscle strengthening. Both studies in this review showed similar results for the two GMin segments during the clam exercise with low activity generated (Ganderton, Pizzari, Cook, et al., 2017; Moore, Semciw, et al., 2019).

In the clinic, individual assessment is important to ensure that the most appropriate exercise strategy is prescribed to meet the client's functional requirements. Post-surgery or in the acute phases of an injury, some clients may be unable to perform weight-bearing exercises early in the rehabilitation process. Prescribing a suitable non-weight-bearing exercise such as side lie hip abduction may overcome this barrier while still delivering a strengthening stimulus for the muscle segment being targeted. Exercises that did not generate high levels of activity (Andersen et al., 2006) for a specific segment may still be beneficial in a progressive rehabilitation program as hypertrophy may not be the goal in the initial stages particularly if the client is deconditioned or in pain. Further to this, since most included studies contained healthy young participants performing rehabilitation exercises, the results from these studies may not be relevant to the elderly client or for the well-conditioned athlete. In both cases it is likely that the recommended exercises will need modifications to meet the individuals' functional goals. For example, the elderly client may need decreased loading strategies and less demanding forms of an exercise. In contrast, for the well-conditioned athlete to stimulate hypertrophy, an exercise may need added loading through weights or elastic resistance to meet that goal (Andersen et al., 2006).

### 2.5.1 Strength and limitations

From a summary of the results we were able to determine whether commonly evaluated therapeutic exercises specifically target the individual GMed and GMin segments effectively in generating at least high activity levels (>40% MVIC) considered essential for potential strengthening (Andersen et al., 2006). Through application of a stringent methodological process, we were able to provide an objective evaluation of current evidence to date.

A limitation of this systematic review was that not all commonly evaluated therapeutic exercises included in this review have been evaluated for the different segments of GMed and GMin making it difficult to make recommendations for some exercises.

The recording of GMed muscle activity with surface electrodes has some drawbacks. Five included studies (Ganderton, Pizzari, Cook, et al., 2017; Heo et al., 2013; Ju & Yoo, 2016; O'Sullivan et al., 2012; O'Sullivan et al., 2010) investigated therapeutic exercises for the three individual GMed segments, with one study (Ganderton, Pizzari, Cook, et al., 2017) using fine-wire electrodes positioned as per previously validated guidelines (Semciw, Green, et al., 2013) to measure segmental activity levels. The use of surface electrodes to record activity in the posterior and anterior segments of GMed must be questioned due to the anatomical coverage by the tensor fascia lata and gluteus maximus muscles. (Semciw, Green, et al., 2013) In fact, even recording GMed activity from the exposed portion of the muscle is subject to crosstalk from the gluteus maximus. (A. I. Semciw et al., 2014) During exercises involving large ranges of movement, there may also be artefact associated with movement of the muscle relative to the recording electrodes (Rainoldi, Melchiorri, & Caruso, 2004).

Other limitations of this review may be due to excluding studies that did not contain commonly evaluated therapeutic exercises or utilising gym and / or custom-made equipment; and eliminating data for dynamic activities like jogging, hopping and walking.

The original search strategy may have missed studies due to publication bias and not contacting experts for unpublished papers. Papers not published in peer-reviewed journals such as conference abstracts and theses were also excluded possibly missing potential data. This review only evaluated EMG activation levels and not muscle onset timing patterns or the balance of synergists and antagonists for a therapeutic exercise as may be considered in the clinical setting. Data for pathological populations were not considered in this review which makes it difficult to generalize to such populations.

## 2.6 Conclusion

The purpose of this review was to analyse studies that have evaluated segmental activity levels for the GMed and GMin with commonly evaluated therapeutic exercises to improve clinician knowledge of appropriate exercise prescription for targeted strengthening. With at least high activity levels necessary for potential strength gains this review found for healthy individuals that despite wide methodological variations between studies, different variations of the hip hitch/pelvic drop exercise elicits activity in all GMed segments sufficiently. The dip test; and isometric stand hip abduction can also be used to strengthen the anterior GMed segment, while isometric stand hip abduction can be used for the posterior GMed segment. For the middle GMed segment the single leg bridge; side-lie hip abduction with hip internal rotation; lateral step-up; stand hip abduction on stance leg or swing leg with added resistance; and resisted side-step were the best options for strengthening. Isometric stand hip abduction and different variations of the hip hitch/pelvic drop exercise can be prescribed for strengthening both GMin segments while side-lie hip abduction, the dip test, single leg bridge and single leg squat can also be used for targeting the posterior GMin segment.

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**Supplementary file: Database search strategy**

1. glute*.mp.

2. Buttocks/ or buttock*.mp.

3. hip extensor.mp.

4. (gluteal or glute or gluteus).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

5. (hip extension or hip extensor or hip extender).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

6. (buttock or buttocks).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

7. hip rotator.mp.

8. (hip rotation or hip rotator).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

9. hip abductor.mp.

10. (hip abduction or hip abductor).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

11. 1 or 2 or 3 or 4 or 5 or 6 or 7 or 8 or 9 or 10

12. Electromyography/ or electromyograph*.mp.

13. (electromyograph or electromyographic or electromyography).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

14. Electromyography/ or EMG.mp.

15. EMG.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

16. Electrode*.mp. or Electrodes/

17. (Electrode or electrodes).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

18. Electromyography/ or muscle activity.mp.

19. peak amplitude.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

20. Electromyography/ or muscle function.mp.

21. muscle function.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

22. muscle intensity.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

23. muscle contraction.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

24. muscle strengthen*.mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

25. (muscle activity or muscle activation).mp. [mp=title, abstract, original title, name of substance word, subject heading word, keyword heading word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]

26. 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23 or 24 or 25

27. 11 and 26

28. limit 27 to human

# CHAPTER 3: GLUTEUS MINIMUS SEGMENTAL ACTIVITY DURING SIMPLE REHABILITATION EXERCISES

## Introduction

The GMin is a small fan-shaped muscle of the hip abductor muscle complex that lies immediately deep to the larger GMed (Beck et al., 2000; Neumann, 2010; Wilson, Capen, & Stubbs, 1976). The GMin contains a higher proportion of Type I muscle fibers compared to GMed and is thought to consist of two distinct subdivisions with separate innervations and fiber orientations that perform different roles at the hip joint during functional tasks (Al-Hayani, 2009; Beck et al., 2000; A. I. Semciw et al., 2014; Sparks, 2011). There has been minimal literature devoted to understanding the functional characteristics of this muscle.

Radiological studies of the hip abductor muscles in people with hip pathology (Bremer et al., 2011; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005; Woodley et al., 2008; Zacharias et al., 2016) and in ageing individuals (Chi et al., 2015) have provided an insight into the propensity for atrophy to occur first in the anterior GMin before the posterior segment is affected. Targeted therapeutic exercise could minimise or reverse such atrophy, however up until a recent study (Ganderton, Pizzari, Cook, et al., 2017) on healthy older women there had been no studies on therapeutic exercises for GMin to guide clinicians on appropriate prescription.

The aim of this study was to investigate GMin segmental activity in healthy young adults during six simple rehabilitation exercises using previously-validated fine-wire EMG guidelines (Semciw, Green, et al., 2013; Semciw, Pizzari, & Green, 2013).

The study in this chapter has been published as:

Moore, D., Semciw, A. I., McClelland, J., Wajswelner, H., & Pizzari, T. (2019). Rehabilitation exercises for the gluteus minimus muscle segments: an electromyography study. *Journal of Sport Rehabilitation, 28*(6), 544-551. doi:10.1123/jsr.2017-0.

### 3.1 Abstract

***Context***: The gluteus minimus (GMin) muscle consists of two uniquely oriented segments that have potential for independent function, and have different responses to pathology and ageing. For healthy, young adults it is unknown which rehabilitation exercises specifically target the individual segments.

***Objective:*** To quantify segmental GMin activity for six common lower limb rehabilitation exercises in healthy young adults, and determine if significant differences exist in segmental activity levels between the exercises.

***Method:*** Six common lower limb rehabilitation exercises were performed by ten healthy young adults with fine-wire electromyography (EMG) electrodes inserted into the anterior and posterior segments of the GMin muscle.

***Main Outcome Measures:*** EMG signals were recorded and median normalised exercise activity levels were reported and compared for each GMin segment across the six exercises.

***Results:*** High activity levels were generated in the anterior segment by the resisted hip abduction-extension exercise (51% maximum voluntary isometric contraction (MVIC)), while for the posterior segment high activity levels were produced by the single leg bridge (49% MVIC), the side lie hip abduction (43% MVIC), the resisted hip abduction-extension exercise (43% MVIC), and the single leg squat (40% MVIC). There were significant differences ($P < .05$) in the median EMG activity levels for the anterior GMin segment but not for the posterior GMin segment across some of the exercises with large effect sizes.

***Conclusions:*** Targeted rehabilitation exercises graded by exercise intensity can be prescribed specifically for the anterior and posterior GMin segments to aid in restoration of hip function following injury or ageing.

***Keywords***: hip; exercise therapy; gluteal muscles; EMG

## 3.2 Introduction

The gluteus minimus (GMin) muscle is considered to be an important hip stabiliser (Retchford et al., 2013) with its function derived from anatomical (Al-Hayani, 2009; Beck et al., 2000; Flack, Nicholson, & Woodley, 2012; Gottschalk et al., 1989); biomechanical (Correa, Crossley, Kim, & Pandy, 2010; Neumann, 2010); radiological (Dieterich, Petzke, Pickard, Davey, & Falla, 2015; Kumagai, Shiba, Higuchi, Nishimura, & Inoue, 1997; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005); and electromyographic (A. I. Semciw et al., 2014; Wilson et al., 1976) studies. Its close relationship to the hip joint capsule and higher proportion of type 1 muscle fibers (Beck et al., 2000; Sparks, 2011), suggest a major role in hip joint stability. GMin is also comprised of two uniquely oriented and structurally distinct segments (anterior and posterior) (Al-Hayani, 2009; Flack et al., 2014) that have potential for independent function (Semciw, Green, et al., 2013). Based on morphology (Al-Hayani, 2009; Beck et al., 2000; Gottschalk et al., 1989) and previous gait studies (A. I. Semciw et al., 2014), the proposed role of the anterior segment is to reduce potential stresses on the hip joint's anterior-superior structures (e.g. hip joint capsule) and assist the posterior segment's primary function as a femoral head stabiliser.

The segmental function of GMin is furthered evidenced by its response to pathology. Decreased whole muscle size of the GMin is known to occur before the larger overlaying gluteus medius in people with hip osteoarthritis (Grimaldi, Richardson, Stanton, et al., 2009; Zacharias et al., 2016) and lateral hip pain (Woodley et al., 2008) illustrating its importance in normal hip joint health. However, targeted atrophy of the anterior GMin has been identified in ageing (Chi et al., 2015) and following a total hip replacement (Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005). Importantly, targeted atrophy of anterior GMin has been associated with a greater risk of falls (Kiyoshige & Watanabe, 2015). With clinical presentation of segmental GMin dysfunction addressed previously (Semciw, 2014), rehabilitation of GMin must consider targeting both structurally and functionally unique segments across a range of clinical conditions.

Up until recently there had been no studies to guide clinicians on effective prescription of rehabilitation exercises for the GMin segments. This may account for the lack of efficacy demonstrated previously in targeted hip strengthening programs for people with lower limb osteoarthritis (Bennell et al., 2014; Bennell et al., 2010; Foroughi et al., 2011). The lack of research evaluating GMin function in exercise is likely due to the technical difficulty of accessing this muscle with intramuscular electromyography (EMG) (Semciw, Pizzari, & Green, 2013). Some rehabilitation exercises for the GMin segments have been recently investigated in healthy older women (Ganderton, Pizzari, Cook, et al., 2017) but not in a younger population. Using recently verified fine-wire EMG guidelines for GMin (Semciw, Green, et al., 2013), the purpose of this study was to quantify the muscle activity of GMin segments across six common lower limb rehabilitation exercises in healthy young adults. This will provide clinicians with evidence for targeted exercise prescription options to use in clinical or athletic populations.

## 3.3 Methods

### 3.3.1 Design and participants

In a sample of convenience, 10 healthy individuals (6 male, 4 female) with a mean (SD) age, height and weight of 23.8 (1.6) years, 177.5 (10) centimetres and 79.9 (18.5) kilograms respectively who performed at least two hours of deliberate, sweat-inducing activity per week (Tegner activity score ≥ 3(Tegner & Lysholm, 1985)) were recruited for this single session, descriptive laboratory study of cross-sectional design. Participants were excluded if they reported a current or previous history of lower limb or low back pain in the last six months. All participants provided informed consent with their rights protected. Institutional review board approval was granted by the University Human Ethics Committee in the spirit of the Helsinki Declaration.

### 3.3.2 Procedures

Once the dominant stance limb (6 x left leg) (Bullock-Saxton, Wong, & Hogan, 2001) was determined for all participants, two bipolar fine-wire intramuscular electrodes were prepared and inserted with the aid of real time ultrasound (RTUS) imaging (HDI 3000; Advanced Technology Laboratories, Washington, USA) as per previously verified guidelines (Semciw, Green, et al., 2013; Semciw, Pizzari, & Green, 2013). The electrodes for each GMin segment were then connected to a wireless Trigno 16-Channel EMG system (Delsys® Inc., Boston, USA). An accelerometer (Trigno, Delsys® Inc., Boston, USA) with three degrees of freedom was secured to the top of the iliac crest, distal lateral femur and distal, anteromedial tibia, for the purpose of delineating between exercise repetitions. This was supplemented with retro-reflective markers (Vicon®) that were attached to selected anatomical landmarks for the purpose of determining the beginning and the end of an exercise repetition.

To ensure the fine-wire electrodes were secured within the muscle belly, participants were instructed to perform five minutes of comfortable walking followed by some standing open-chain hip abduction movements and signals from each electrode were checked for clarity. A warm-up of 5-10 minutes of walking and jogging was then performed in readiness for the exercise trials. The six rehabilitation exercises (Table 3.1) were performed in a randomised

*Table 3.1. Description of the six rehabilitation exercises.*

| Exercise | Description | Metronome (bpm) |
|---|---|---|
| **Single leg bridge**  | Supine with testing knee flexed $90^0$, hip flexed $45^0$ and other leg straight. Raise hips off floor to achieve a neutral trunk, hip and knee alignment with thighs parallel pushing through testing leg for 1 beat, then lower back to the start position for 1 beat. Repeat for 6 repetitions. | **40** |
| **Single leg squat**  | Single leg stance on testing leg, hands across chest with non-testing leg raised forward off floor, squat down by flexing through hip, knee and ankle as far as can without lifting heel for 1 beat then straighten through hip, knee and ankle back to start position for 1 beat. Repeat for 6 repetitions. | **40** |
| **Side lie abduction** | Side lie with testing leg facing up and both legs straight and in line with | **50** |

| | | |
|---|---|---|
|  | trunk. On 1 beat raise top leg to approximately $30^0$, then lower back to start position for 1 beat. Repeat for 6 repetitions. | |
| **Side lie clam**  | Side lie with testing leg facing up with both hips flexed $45^0$ and knees flexed $90^0$. On 1 beat, keeping feet together raise top knee off bottom knee to approximately $30^0$, then lower back to start position for 1 beat. Repeat for 6 repetitions. | **40** |
| **Resisted hip abduction-extension**  | Stand shoulder-width apart, yellow elastic resistance looped just taut at ankles. On 1 beat stand on stance testing leg and take non-testing leg into a backwards diagonal position ($45^0$) of combined hip extension and abduction towards a set mark on the floor (30cm square), then return to start position for 1 beat. Repeat for 6 repetitions. | **60** |
| **Running man** | Stand shoulder-width apart. On 1 beat stand on stance testing leg and bend non-testing hip and knee to $90^0$, then extend non-testing hip and knee back | **90** |

| | |
|---|---|
|  | to start position for 1 beat. The upper limbs were allowed to move to replicate running. Repeat for 6 repetitions. |

Key: bpm - beats per minute

order. The exercises were selected to include open and closed chain tasks, reflective of those commonly prescribed by clinicians to target the lateral gluteal muscles and performed in the home environment requiring use of minimal equipment. A metronome was used with each exercise to ensure consistency across the participants for contraction speed, and to ensure equal time were spent in the concentric and eccentric phases of dynamic exercises. For each exercise the metronome speed was determined by pilot testing and reflected previous studies of hip joint exercises (Ayotte et al., 2007; Bolgla & Uhl, 2005). Three trials of six repetitions were performed for each exercise with 1-2 minutes rest allowed between trials and each exercise to minimise the effects of fatigue. Practice repetitions were performed prior to each exercise to facilitate familiarity. Each exercise trial was monitored for quality (range of movement and speed) with the trial repeated when this was unsatisfactory.

Following the exercise trials and a rest period of 3 minutes, participants were then requested to perform a series of maximum voluntary isometric contractions (MVIC) to normalise each participant's exercise data for each GMin segment. This protocol has previously been established in trials that investigate level gait (A. I. Semciw et al., 2014; Semciw, Pizzari, Murley, et al., 2013). Previous pilot testing revealed that any one of six different hip actions performed in a randomised order could generate a true maximum amplitude value for MVIC for any of the GMin segments since it has been recommended that multiple tests be performed in order to obtain the optimum maximum value for a muscle's MVIC and that a compromise needs to be made on the number of tests performed in order to minimise participant fatigue (Burden, 2010; Vera-Garcia, Moreside, & McGill, 2010). The RMS amplitude during an MVIC was calculated from the middle one second of each trial. The MVICs for this study were performed in side lying except for hip extension which was performed in prone, and included hip abduction, hip internal rotation, hip abduction in internal rotation, hip flexion, hip extension and the clam exercise (opening knees whilst keeping feet together in $45^0$ hip flexion and $90^0$ knee flexion). With verbal encouragement, each MVIC trial was performed against a secured Velcro strap three times for three seconds duration whereby participants were instructed to slowly increase muscle contraction against the resistance over one second and sustain a maximum effort for three seconds then slowly decrease muscle contraction over one second with three minutes rest between trials as detailed previously (A. I. Semciw et al., 2014). This was repeated three times for each hip action to obtain the overall maximum value that was considered the MVIC for each segment and each participant.

### 3.3.3 Statistical Analysis

Raw EMG signals were collected using a Trigno wireless 16-Channel EMG system (Delsys® Inc., Boston, USA; CMRR > 80 dB @ 60 Hz; gain of 1000; band pass filtered at 20-900 Hz) and sampled at 2000 Hz. The accelerometer data was collected at 148Hz. The raw EMG signals were processed as for previous gait studies (Semciw, Freeman, Kunstler, Mendis, & Pizzari, 2015; A. I. Semciw et al., 2014; Semciw, Pizzari, Murley, et al., 2013), high-pass filtered (Butterworth $4^{th}$ order, 50 Hz), rectified and further filtered (low-pass 4$^{th}$ order Butterworth filter, 6 Hz) to generate a linear envelope. Exercise activation levels were amplitude-normalised to percent (%) MVIC, and time-normalised to 100 points (% of exercise repetition).

Marker and accelerometer data were used to determine the start and completion of each individual exercise repetition. To minimise exercise familiarity effects as well as limiting fatigue, the middle three of six repetitions for each exercise trial (x3) were selected and processed for further analysis. For each repetition, average amplitude was calculated to reflect performance in clinical rehabilitation across both the concentric and eccentric phases, and to allow comparisons between dynamic and isometric exercises. The nine repetitions were summed and averaged to represent mean muscle activity for a given exercise and participant.

Delsys® EMGworks version 4.1.7 signal analysis software was used to process the EMG data and acquire the dependant variables across the whole exercise. For each muscle segment, values were obtained for average amplitude (% MVIC) across the whole exercise.

Data obtained from the six MVIC positions were used for amplitude normalisation of the exercise variables. The mean EMG amplitude during an MVIC was calculated from the middle one second of each MVIC trial. The highest amplitude value across all six positions was considered the MVIC for each segment and for each participant.

The temporal and amplitude exercise variables from each segment for each exercise were used for both qualitative and quantitative comparisons between exercises. To make meaningful comparisons between exercises, the normalised EMG activation levels were classified according to previously defined criteria into low (0-20% MVIC), moderate (21-40% MVIC), high (41-60% MVIC), and very high (> 60% MVIC) (DiGiovine, Jobe, Pink, & Perry, 1992; Escamilla et al., 2010).

Each muscle segment (anterior and posterior) was analysed separately. Because of the small sample size, a non-parametric analysis was performed using a Friedman test to determine differences between each of the exercises with average amplitude (*nEMG)* as the dependent variable and exercise as the independent variable. Chi-square ($\chi^2$) test statistic was performed with degrees of freedom and significance level determined. Where significant differences were detected ($P < 0.05$), a post-hoc analysis (Nemenyi test) was used to identify which exercises differed in activity levels (Demsar, 2006). An effect size (ES) was calculated by dividing the z-score of the Nemenyi test by the square root of the sample size. An ES threshold of 0.2, 0.5, 0.8 was considered small, medium and large respectively (Cohen, 1988). All statistical analyses were performed in the R statistical software package Version 3.4.1 (https://cran.r-project.org/).

## 3.4 Results

### 3.4.1 Participants

Exercise data from four participants were excluded for the GMin anterior segment and three participants excluded for the GMin posterior segment due to poor quality EMG signals in one or more exercises during the repeated measures analysis. Therefore, analysis included six participants for the anterior segment and seven participants for the posterior segment.

### 3.4.2 Gluteus minimus anterior median activity

The resisted hip abduction-extension exercise generated high median (interquartile range) activity (51 (26)% MVIC) for the GMin anterior segment (Figure 3.1). The side-lie abduction (38 (13)% MVIC), the running man exercise (29 (18)% MVIC) and the single leg squat (24 (12)% MVIC) generated moderate median activity levels, whilst the single leg bridge (13 (16)% MVIC) and the side-lie clam (2 (4)% MVIC) generated low median activity levels.

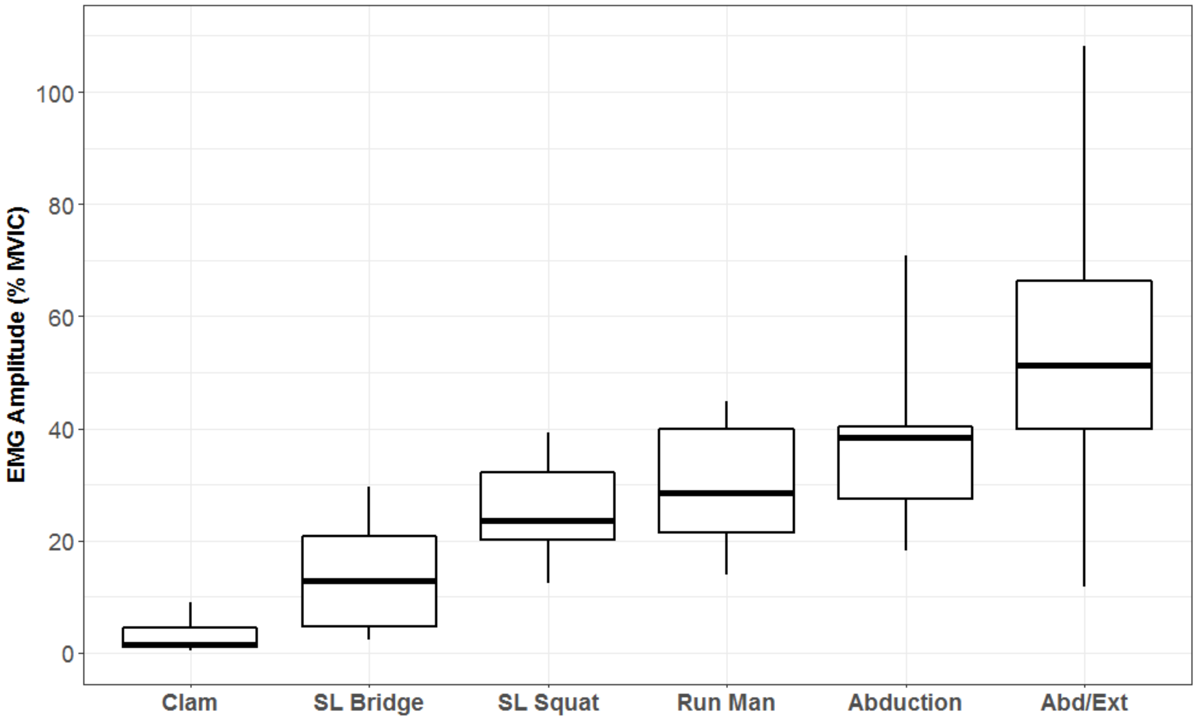


*Figure 3.1.* *Box plots illustrating median, interquartile range, and range of GMin anterior activity levels across the six exercises.*

There were significant within participant effects across all exercises for the median activity of the GMin anterior segment $\chi^2(5) = 22.762$, $P = 0.000$.

Post-hoc analysis of the GMin anterior median activity showed that the side lie clam had significantly lower activity levels ($P < 0.05$) than side-lie abduction and the resisted hip abduction-extension exercise (ES > 0.8) (Table 3.2). The resisted hip abduction-extension exercise also had significantly higher levels of median activity compared to the single leg bridge (ES > 0.8).

*Table 3.2. Post-hoc pairwise comparisons between exercises with ES for GMin anterior median activity.*

| | SLS | Ab | Clam | Abd/Ext | Running man |
|---|---|---|---|---|---|
| **Br** | 0.80 (0.730) | 1.51 (0.092) | 0.45 (0.972) | **1.78 (0.025)** | 1.16 (0.339) |
| **SLS** | | 0.71 (0.82) | 1.25 (0.257) | 0.98 (0.534) | 0.36 (0.989) |
| **Ab** | | | **1.96 (0.009)** | 0.27 (0.997) | 0.36 (0.990) |
| **Clam** | | | | **2.23 (0.002)** | 1.60 (0.061) |
| **Abd/Ext** | | | | | 0.62 (0.889) |
| Values are reported as ES with level of significance in brackets with significant differences ($P < 0.05$) highlighted in bold type. | | | | | |

### 3.4.3 Gluteus minimus posterior median activity

High median (interquartile) activity levels were recorded in the single leg bridge (49 (34)% MVIC), side lie abduction (43 (18)% MVIC), the resisted hip abduction-extension exercise (43 (23)% MVIC), and the single leg squat (40 (39)% MVIC). The running man exercise generated moderate median activity (37 (32)% MVIC). The side lie clam (6 (9)% MVIC) generated low median activity (Figure 3.2).

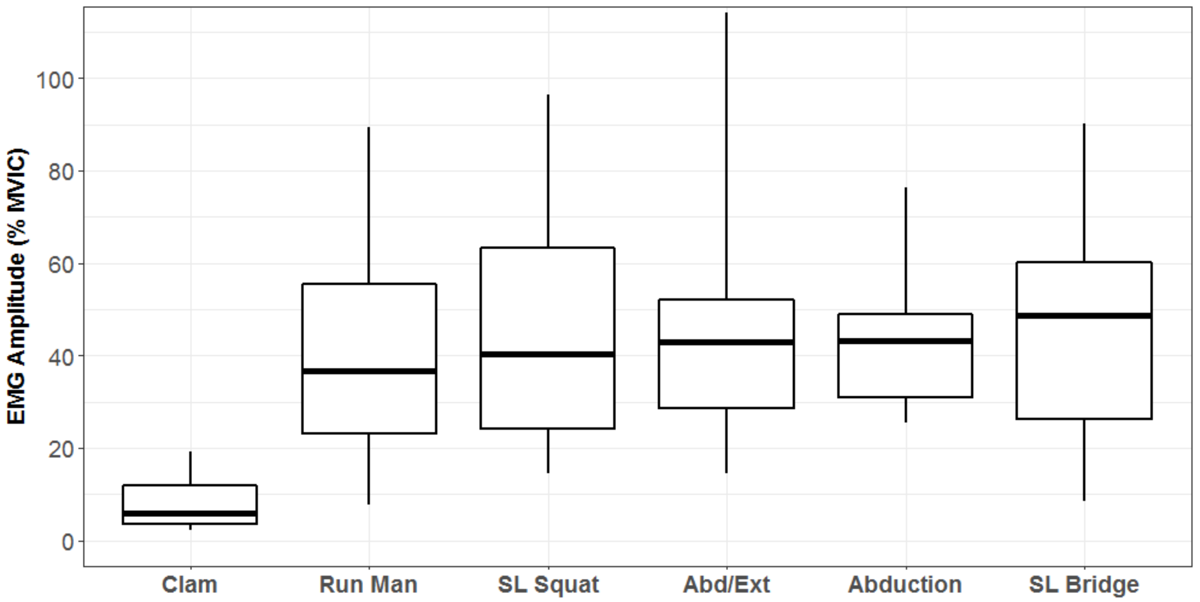


*Figure 3.2. Box plots illustrating median, interquartile range, and range of GMin posterior activity levels across the six exercises.*

There were no significant within participant effects across all the exercises for the median activity of the GMin posterior segment $\chi^2(5) = 9.694$, $P = 0.084$ (Table 3.3).

*Table 3.3. Post-hoc pairwise comparisons between exercises with ES for GMin posterior median activity.*

| | **SLS** | **Ab** | **Clam** | **Abd/Ext** | **Running man** |
|---|---|---|---|---|---|
| **Br** | 0.15 (0.999) | 0.23 (0.998) | 1.15 (0.265) | 0.23 (0.998) | 0.15 (0.999) |
| **SLS** | | 0.08 (1.00) | 1.30 (0.146) | 0.08 (1.00) | 0.31 (0.993) |
| **Ab** | | | 1.37 (0.104) | 0.00 (0.590) | 0.38 (0.980) |
| **Clam** | | | | 1.37 (0.104) | 0.99 (0.429) |
| **Abd/Ext** | | | | | 0.38 (0.980) |
| Values are reported as ES with level of significance in brackets with significant differences ($P < 0.05$) highlighted in bold type. | | | | | |

### 3.5 Discussion

This is the first study to investigate specific rehabilitation exercises targeted to the anterior and posterior segments of the GMin muscle in a healthy young population using minimal equipment. The results indicate that each segment can be preferentially targeted with rehabilitation exercises. High activity levels were generated in the anterior GMin segment during the resisted hip abduction-extension exercise, and the posterior GMin segment from the single leg bridge, side-lie abduction, the resisted hip abduction-extension exercise and single leg squat. Low activity levels were generated in both segments of the GMin for the side lie clam and in the anterior segment for the single leg bridge.

The resisted hip abduction-extension exercise was shown to generate high activity levels for both segments of GMin. The resisted motion of the non-testing leg is likely to recruit the large hip extensors and abductors such as the gluteus maximus potentially inducing a posterior pelvic tilt. With a moment arm favouring hip flexion (or anterior pelvic tilt) in the anatomical position (Dostal et al., 1986), it is possible that the anterior GMin acts synergistically with other anterior hip muscles to counterbalance the posterior pelvic tilt and to provide stability to the anterior hip joint. Posterior GMin is also highly active in this exercise, perhaps reflecting its contribution to femoral head stability in single limb support (Gottschalk et al., 1989; A. I. Semciw et al., 2014). The effectiveness of this exercise is likely to change with different levels of resistance by altering the elasticity, length or position of the band along the moving limb (Cambridge et al., 2012). Nevertheless, the exercise as conducted in this study appears to be a simple effective method of generating high activity levels across both segments of GMin and could be considered in rehabilitation programs for conditions where this muscle is weak or atrophied (Kiyoshige & Watanabe, 2015; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005; Woodley et al., 2008; Zacharias et al., 2016).

Other weight-bearing options for posterior GMin exercises include the running man, single leg squat and single leg bridge. All these exercises elicited moderate to high activity levels for this muscle segment and compares favourably with a previous study (Ganderton, Pizzari, Cook, et al., 2017) on an older female population that found high activity levels for single leg stance weight bearing exercises. In the anatomical position, biomechanical studies suggest that posterior GMin has a favourable moment arm for hip abduction, extension and external rotation(Dostal et al., 1986). It is likely that the running man exercise requires hip abduction and extension to maintain femoropelvic alignment and stability of the stance limb particularly when the contralateral (swing) limb is in the hip flexed position. The single leg squat is also likely to require activity from muscles with a favourable abduction moment arm to provide pelvic and hip stability. Potential for posterior GMin to contribute to hip extension increases with a greater degree of hip flexion(Beck et al., 2000), further supporting its role throughout the single leg squat. The single leg bridge requires activity from muscles with a favourable hip extension moment arm, particularly when initiating the movement from a resting position. In addition, having the contralateral limb raised during the single leg bridge creates an external rotation hip moment in the transverse plane requiring activity from hip internal rotators to counterbalance this moment. In a hip flexed position all segments of GMin become internal rotators of the hip joint (Beck et al., 2000) further supporting posterior GMin's contribution to a single leg bridge.

Activity of anterior GMin during common weight bearing exercises appears harder to elicit than the posterior segment in this study. In a previous study with healthy older women (Ganderton, Pizzari, Cook, et al., 2017), different variations of a hip hitch exercise and standing isometric abduction generated high activity levels for the anterior GMin confirming a favourable abduction moment arm for this segment. Besides the resisted abduction-extension exercise, activity of this segment can be considered as low (single leg bridge) to moderate (single leg squat and running man). The low level of activity during a single leg bridge was particularly surprising with previous studies establishing the anterior GMin has one of the largest internal rotation moment arms of all the hip muscles (Dostal et al., 1986); the potential to contribute to internal rotation is maintained when the hip is flexed through $0^0$ to $90^0$ (Beck et al., 2000); and EMG activity during resisted internal rotation in higher than all other directions(A. I. Semciw et al., 2014). Given the potential for a single leg bridge to generate a hip external rotation moment it was originally thought that this could be a great functional weight-bearing exercise to strengthen anterior GMin through the sagittal plane. Encouraging anterior GMin activity through sagittal range is considered functionally important, particularly as anterior GMin activity during gait peaks in mid to late stance as the hip extends through the gait cycle (A. I. Semciw et al., 2014). Nevertheless, prescribing a single leg bridge for targeted anterior GMin rehabilitation as performed in this study would not be recommended as very little to negligible activity is elicited. Further research could investigate the potential for greater anterior GMin activity during the single leg bridge by encouraging active hip internal rotation of the weight bearing limb against elastic resistance secured to the outside of the knee.

The side-lie abduction exercise is a non-weight bearing option for generating moderate to high activity levels in GMin. The activity generated during this exercise confirms that GMin has a key role in hip abduction (Al-Hayani, 2009; Beck et al., 2000; Kumagai et al., 1997) and supports studies that identify a favourable abduction moment arm in the coronal plane (Dostal et al., 1986). This exercise is therefore a feasible open chain option for anterior and posterior GMin rehabilitation.

The side-lie clam on the other hand, does not appear to be a realistic open chain option for targeting muscle hypertrophy of GMin as it was performed in the current study. This exercise produced negligible or low activity for both segments. Previous MVIC testing of the clam position found that low activity levels were generated for the anterior segment even when maximal isometric resistance was applied (A. I. Semciw et al., 2014). However, moderate levels of activity were generated in the posterior segment during maximum contraction (A. I. Semciw et al., 2014). Further to this the side lie clam was found to have low activity levels for both GMin segments in an older female population (Ganderton, Pizzari, Cook, et al., 2017). The clam exercise may therefore not be particularly useful for hypertrophy or motor control of anterior GMin, however could potentially be considered for targeting posterior GMin for motor activation as performed in this study, and potentially progressive resistance rehabilitation with additional loading applied through elastic resistance or weights.

This study has provided the clinician with confidence in optimising exercise prescription with a range of rehabilitation exercises provided in weight bearing and open chain positions to effectively target the anterior and posterior GMin segments. These common rehabilitation exercises were graded by exercise intensity and can be performed in various clinical settings with minimal use of equipment. For the anterior GMin, where at least 40% MVIC is considered sufficient to induce hypertrophy in the untrained individual (Andersen et al., 2006), we could prescribe the resisted hip abduction-extension exercise for targeted strengthening while for the posterior GMin we could prescribe all exercises except the running man exercise and the clam in its existing form.

Because each exercise had a relatively large interquartile range around the median EMG amplitude, it is important that individual clinical assessment is performed to determine the most appropriate exercise for the client's functional requirements as some clients depending on their initial strength levels may benefit from this study's exercises more than others. Clients that are better conditioned will need higher levels of stimulus (Kraemer et al., 2002) to obtain a strengthening effect than the untrained individual. This may require for those better conditioned clients to be prescribed the existing exercises with increased loading demands by adding weights or elastic resistance since it is assumed that modifying the level of resistance for an exercise will change the muscle activity level generated. For others who may be deconditioned or recovering from injury, the exercises described in this study may be too difficult to perform initially and may need to be modified to reduce the loading demands by decreasing the weight bearing of the testing leg, decreasing the lever arm, or selecting an exercise with lower activity levels.

Where strengthening is not the primary goal, the exercises that did not elicit at least 40% MVIC for each of the GMin segments may still be of benefit in a progressive rehabilitation program. With decreased neuro-muscular control at the hip associated with some common lower-limb injuries (Beckman & Buchanan, 1995; Brindle, Mattacola, & McCrory, 2003; Cowan et al., 2009), regaining motor control may be an appropriate goal for the client hence a lower intensity exercise in the low or moderate activity levels targeted to the specific segment could be prescribed depending on the individual's functional requirements (Gottschalk et al., 1989; Retchford et al., 2013).

There were some limitations with this study that need to be taken into consideration. Caution needs to be taken in generalising the results of this study for other populations such as the pathological, the elderly and elite sportspeople where future research would be of benefit in determining the most effective exercises for specific pathological populations such as hip osteoarthritis and gluteal tendinopathy. A larger number of participants would have increased the sensitivity of statistical analysis and increased the likelihood of detecting a difference in GMin posterior ($P$ = 0.084). The small sample size in this study is consistent with other fine-wire EMG studies of the hip musculature (Giphart, Stull, Laprade, Wahoff, & Philippon, 2012; Hodges, McLean, & Hodder, 2014; Philippon et al., 2011) and reflects the invasiveness and cost of the procedure and the lengthy pre-test preparation required.

Selecting exercises that incorporated hip internal rotation that may have preferentially activated the anterior segment more effectively as has been hypothesized from morphological studies(Al-Hayani, 2009; Beck et al., 2000; Flack et al., 2012) could have been beneficial for the anterior GMin segment's results. Another limitation of this study was unlike the other five exercises, the resisted hip abduction-extension used elastic resistance. This exercise is typically prescribed clinically with resistance, so for pragmatic reasons, we retained the use of resistance with this exercise. Elastic resistance wasn't quantified in absolute or relative terms and without the resistance would probably have generated lower activity levels for both GMin segments. Exercise selection for this study was based on rehabilitation exercises that were commonly prescribed in the clinic and could be performed relatively easily in the home environment with minimal use of equipment. This study's protocol was based on minimising the effects of cumulative fatigue on the hip muscles such that all participants could effectively perform the required repetitions and trials for each exercise in a randomised order as well as undergoing MVIC testing in a single testing session. Furthermore, the optimal dose and intensity can be easily manipulated to match the functional demands and requirements of the individuals since determining the optimal repetitions, sets, contraction speed, and frequency of the exercises for effective strengthening protocols was beyond the scope of the current study.

### 3.6 Conclusion

This study has provided the clinician with confidence in prescribing specific rehabilitation exercises graded by exercise intensity that can optimally target the anterior and posterior segments of the GMin for strengthening in open chain and weight bearing positions. With the GMin thought to provide an important role in optimal hip health and function in activities of daily living and athletic pursuits, these exercises when appropriately prescribed could benefit the individual from the effects of pathology and ageing. Further research would be beneficial to examine the most effective exercises for pathological populations such as hip OA and gluteal tendinopathy.

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# CHAPTER 4: GLUTEUS MEDIUS SEGMENTAL ACTIVITY DURING SIMPLE REHABILITATION EXERCISES

## Introduction

Many studies have evaluated and recommended therapeutic exercises to strengthen GMed and five previous reviews have synthesized these studies to provide overarching recommendations (Ebert et al., 2017; French, Dunleavy, et al., 2013; Hamstra-Wright & Huxel Bliven, 2012; Macadam et al., 2015; Reiman et al., 2012). Chapter 2 reported that a major shortcoming of these reviews was the lack of consideration for the GMed being composed of three functionally distinct segments (anterior, middle and posterior) with most EMG measures taken at middle GMed hence the uncertainty on the effectiveness of these exercises for the anterior and posterior GMed segments.

The aim of this study was to evaluate GMed segmental activity for six simple rehabilitation exercises using previously validated guidelines (Semciw, Green, et al., 2013; Semciw, Pizzari, & Green, 2013) for fine wire EMG. This will enable clinicians to be more confident in exercise prescription for targeting individual GMed segments.

The study in this chapter has been published as:

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## 4.1 Abstract

***Context****:* Many different rehabilitation exercises have been recommended in the literature to target the gluteus medius (GMed) muscle based mainly on single electrode, surface electromyography (EMG) measures. With the GMed consisting of three structurally and functionally independent segments there is uncertainty on whether these exercises will target the individual segments effectively.

***Objective:*** To measure individual GMed segmental activity during six common, lower-limb rehabilitation exercises in healthy young adults, and determine if there are significant differences between the exercises for each segment.

***Method:*** With fine-wire EMG electrodes inserted into the anterior, middle and posterior segments of the GMed muscle, ten healthy young adults performed six common, lower-limb rehabilitation exercises.

***Main Outcome Measures:*** Recorded EMG activity was normalised, then reported and compared for median activity for each of the GMed segments across the six exercises.

***Results:*** For the anterior GMed segment, high activity was recorded for the single leg squat (48% maximum voluntary isometric contraction (MVIC)), the single leg bridge (44% MVIC) and the resisted hip abduction-extension exercise (41% MVIC). No exercises recorded high activity for the middle GMed segment, but for the posterior GMed segment very high activity was recorded by the resisted hip abduction-extension exercise (69% MVIC), and high activity was generated by the single leg squat (48% MVIC) and side-lie hip abduction (43% MVIC). For each of the GMed segments, there were significant differences ($P < .05$) in the median EMG activity levels between some of the exercises and the side-lie clam with large effect sizes favouring these exercises over the side-lie clam.

***Conclusions:*** Open-chain hip abduction and single-limb support exercises appear to be effective options for recruiting the individual GMed segments with selection dependent on individual requirements. The side-lie clam however doesn't appear to be effective at recruiting the GMed segments particularly the anterior and middle segments.

***Keywords**:* hip; exercise therapy; gluteal muscles; EMG

## 4.2 Introduction

Gluteus medius (GMed) activity levels have been evaluated across a range of therapeutic exercises (Ebert et al., 2017). In most cases, single leg weight-bearing exercises show greater activity levels than non-weight bearing exercises when measured with a single surface electrode over the middle GMed region (Ebert et al., 2017). The GMed however, is structurally and functionally composed of three unique segments (Flack et al., 2014); and a large proportion of the anterior and posterior segments are deep to the superficially located tensor fascia lata and gluteus maximus respectively (A. I. Semciw et al., 2014). The aim of the study was to determine activity levels using fine-wire electromyography (EMG) for the anterior, middle and posterior GMed segments during six common rehabilitation exercises. This may assist clinicians with prescribing targeted rehabilitation programs to prevent, manage or treat segmental GMed dysfunction that is evident in pathology (Ganderton, Pizzari, Cook, et al., 2017; Zacharias et al., 2016).

## 4.3 Methods

### 4.3.1 Participants and design

This study was conducted on the same participants as described in a previous publication on gluteus minimus muscle activity (Moore, Semciw, et al., 2019). Ten healthy, active university students (6 male, 4 female) with a mean (standard deviation) age, height and weight of 23.8 (1.6) years, 177.5 (10) cm and 79.9 (18.5) kg respectively were recruited for this single session cross-sectional study. Institutional review board approval was granted in the spirit of the Helsinki Declaration (University Human Ethics Committee approval (UHEC 13-005)).

### 4.3.2 Instrumentation and electrode insertions

Fine-wire EMG electrodes were inserted into anterior, middle and posterior segments of GMed as described previously (Semciw, Green, et al., 2013; Semciw, Pizzari, & Green, 2013). The electrodes for each GMed segment were connected to a wireless EMG system (Delsys® Inc., Boston, USA). An accelerometer (Trigno, Delsys® Inc., Boston, USA) was secured to the top of the iliac crest, distal lateral femur and distal, anteromedial tibia along with retro-reflective markers (Vicon®) attached to selective anatomical landmarks for the purposes of delineating between exercise repetitions.

### 4.3.3 Experimental protocol

The experimental protocol has been described in detail previously (Moore, Semciw, et al., 2019). Each participant undertook at least five minutes of warm-up before performing six rehabilitation exercises in a randomised order paced to a metronome. Three trials of six repetitions were performed for the single leg squat (40 bpm), single leg bridge (40 bpm), side lie hip abduction (50 bpm), side lie clam (40 bpm), the running man exercise (90 bpm) and the resisted hip abduction-extension exercise (60 bpm) with two minutes rest between the trials and exercises. A series of maximum voluntary isometric contractions (MVICs) (across six hip actions) were performed for data normalisation.

### 4.3.4 Statistical analysis

The R statistical software package (Version 3.4.1 (https://cran.r-project.org/)) was used for analysis. The EMG data processing has been described in detail previously (Moore, Semciw, et al., 2019). Muscle activity was described qualitatively for each exercise using the following criteria; low (0-20% MVIC), moderate (21-40% MVIC), high (41-60% MVIC), and very high (>60% MVIC). To determine if normalised (% MVIC) muscle activity for each segment differed across exercises, a non-parametric Friedmans test was used along with a Nemenyi post-hoc tests ($P < 0.05$). An effect size was calculated by dividing the Chi-square ($\chi^2$) test with the square root of the sample size.

## 4.4 Results

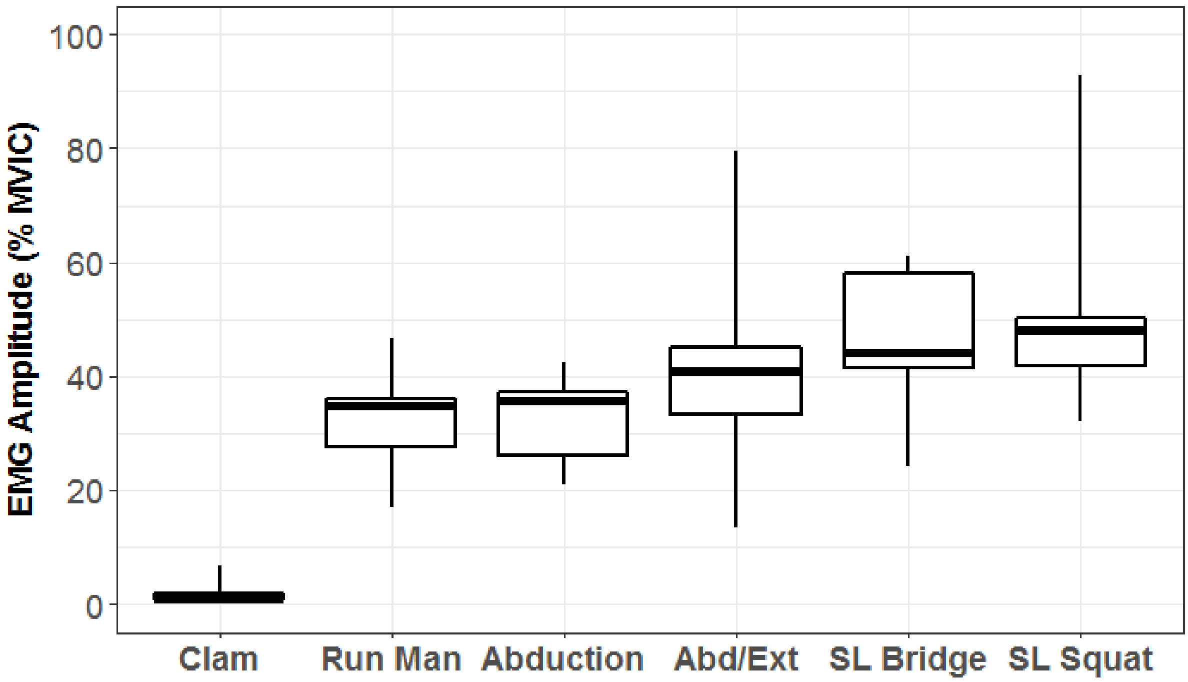
### 4.4.1 Participants

Three participants' data were excluded for each GMed segment due to artefact.

### 4.4.2 Gluteus medius anterior median activity

High median (interquartile range) activity was recorded for the single leg squat (48 (11)% MVIC), the single leg bridge (44 (9)% MVIC) and the resisted hip abduction-extension exercise (41 (8)% MVIC) (Figure 4.1A). Moderate activity was generated by the side-lie hip

**A.**




**B.**

| | Clam | Run Man | Abd | Abd / Ext | SL Bridge | SL Squat |
|---|---|---|---|---|---|---|
| Clam | | 2.63 (0.429) | 2.83 (0.342) | **4.44 (0.021)** | **5.25 (0.003)** | **6.06 (0.000)** |
| Run Man | | | 0.20 (1.000) | 1.82 (0.793) | 2.63 (0.429) | 3.43 (0.146) |
| Abd | | | | 1.62 (0.863) | 2.42 (0.522) | 3.23 (0.200) |
| Abd / Ext | | | | | 0.81 (0.993) | 1.62 (0.863) |
| SL Bridge | | | | | | 0.81 (0.993) |
| Values are reported as ES with level of significance in brackets with significant differences (*P* < .05) highlighted in bold type. | | | | | | |

*Figure 4.1. (A) Box plots illustrating median, interquartile range and range of GMed anterior activity levels across the six exercises. (B) Post-hoc pairwise comparisons between exercises with ES for GMed anterior median activity.*

abduction (36 (17)% MVIC) and the running man exercise (35 (12)% MVIC). Low activity (0-20% MVIC) was recorded during side-lie clam (1 (1)% MVIC).

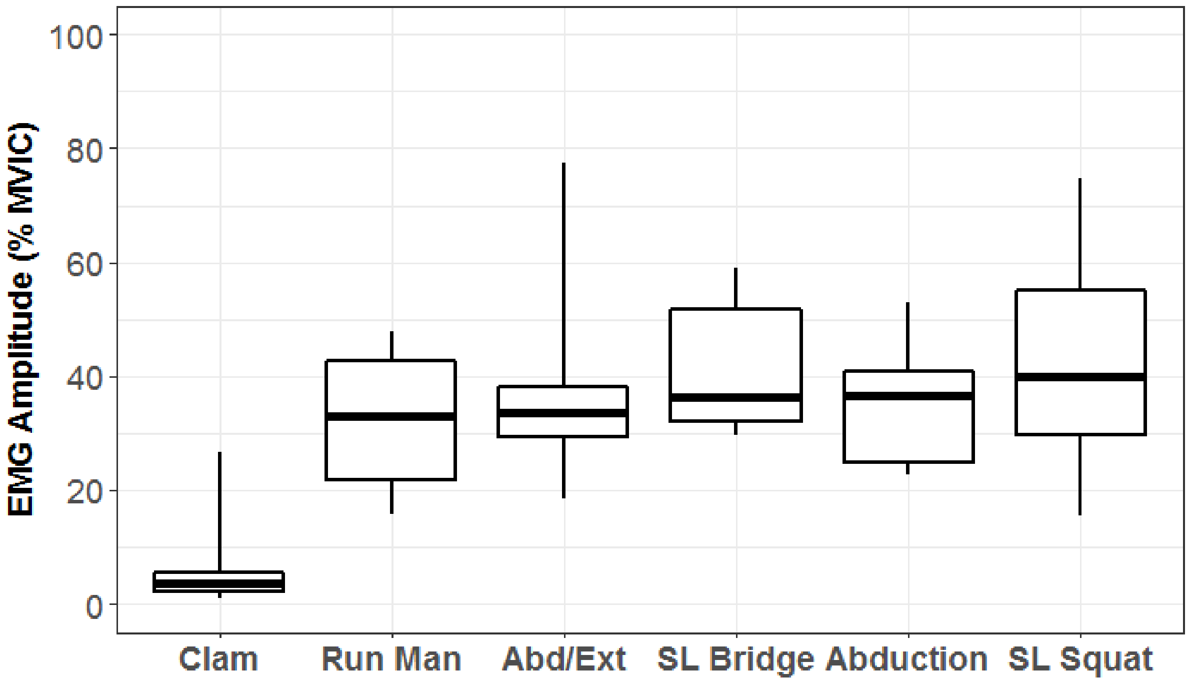
There were significant within participant effects across all the exercises for GMed anterior median activity ($\chi^2(5) = 23.98$, $P \leq 0.001$).

The side-lie clam had significantly lower activity levels than the single leg bridge, the single leg squat and the resisted hip abduction-extension exercise with large effect sizes generated (Figure 4.1B).

### 4.4.3 Gluteus medius middle median activity

Moderate median (interquartile range) activity was generated by the single leg squat (40 (9)% MVIC), the side-lie hip abduction (37 (16)% MVIC), the single leg bridge (36 (21)% MVIC), the resisted hip abduction-extension exercise (33 (26)% MVIC) and the running man exercise (33 (20)% MVIC) (Figure 4.2A). Low activity was recorded by the side-lie clam (4 (3)% MVIC).

**A.**




**B.**

| | Clam | Run Man | Abd / Ext | SL Bridge | Abd | SL Squat |
|---|---|---|---|---|---|---|
| Clam | | 1.22 (0.200) | 1.30 (0.146) | **1.99 (0.003)** | **1.53 (0.049)** | **1.99 (0.003)** |
| Run Man | | | 0.08 (1.000) | 0.76 (0.710) | 0.31 (0.993) | 0.76 (0.710) |
| Abd / Ext | | | | 0.69 (0.793) | 0.23 (0.998) | 0.69 (0.793) |
| SL Bridge | | | | | 0.46 (0.956) | 0.00 (1.000) |
| Abd | | | | | | 0.46 (0.956) |
| Values are reported as ES with level of significance in brackets with significant differences (*P* < .05) highlighted in bold type. | | | | | | |

*Figure 4.2. (A) Box plots illustrating median, interquartile range and range of GMed middle activity levels across the six exercises. (B) Post-hoc pairwise comparisons between exercises with ES for GMed middle median activity.*

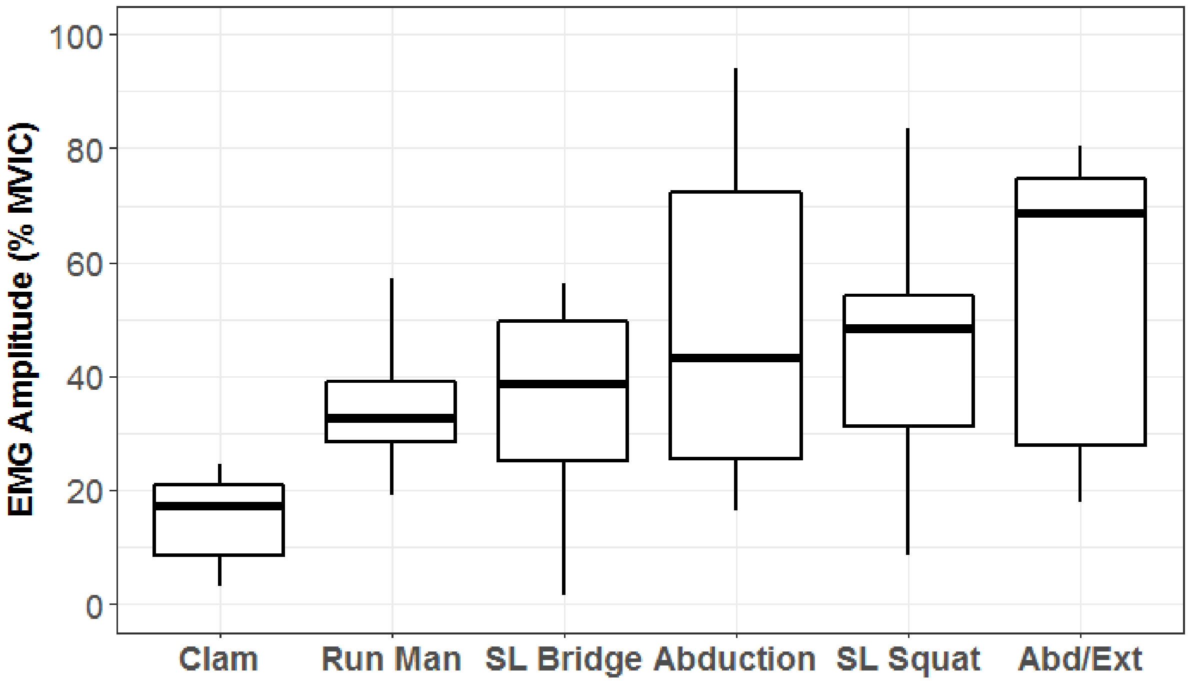
There were significant within participant effects across all the exercises for GMed middle median activity ($\chi^2(5) = 18.76$, $P \leq 0.002$).

The side-lie clam had significantly lower activity levels than the single leg bridge, the single leg squat and side-lie hip abduction with large effect sizes generated (Figure 4.2B).

### 4.4.4 Gluteus medius posterior median activity

Very high median (interquartile range) activity was recorded by the resisted hip abduction-extension exercise (69 (47)% MVIC) (Figure 4.3A). High activity was generated by the single leg squat (48 (24)% MVIC) and side-lie hip abduction (43 (23)% MVIC). Moderate activity was elicited by the single leg bridge (39 (11)% MVIC) and the running man exercise (33 (47)% MVIC). Low activity was recorded by the side-lie clam (17 (12)% MVIC).

**A.**




**B.**

| | Clam | Run Man | SL Bridge | Abd | SL Squat | Abd / Ext |
|---|---|---|---|---|---|---|
| Clam | | 3.23 (0.200) | 2.22 (0.618) | **4.65 (0.013)** | 3.43 (0.146) | **4.04 (0.049)** |
| Run Man | | | 1.01 (0.980) | 1.41 (0.918) | 0.20 (1.000) | 0.81 (0.993) |
| SL Bridge | | | | 2.42 (0.522) | 1.21 (0.956) | 1.82 (0.793) |
| Abd | | | | | 1.21 (0.956) | 0.61 (0.998) |
| SL Squat | | | | | | 0.61 (0.998) |
| Values are reported as ES with level of significance in brackets with significant differences (*P* < .05) highlighted in bold type. | | | | | | |

*Figure 4.3. (A) Box plots illustrating median, interquartile range and range of GMed posterior activity levels across the six exercises. (B) Post-hoc pairwise comparisons between exercises with ES for GMed posterior median activity.*

There were significant within participant effects across all the exercises for GMed posterior median activity ($\chi^2(5) = 13.61$, $P \leq 0.018$).

The side-lie clam had significantly lower activity levels than the side-lie hip abduction and the resisted hip extension-abduction exercise with large effect sizes generated (Figure 4.3B).

### 4.5 Discussion

This study investigated activity levels of anterior, middle and posterior segments of the GMed during common rehabilitation exercises in healthy young adults. The results indicate that simple rehabilitation exercises with minimal equipment can be prescribed to optimally target the individual GMed segments for strengthening (> 40% MVIC) (Andersen et al., 2006). The single leg squat generated relatively high activity levels in all three GMed segments. The resisted hip abduction-extension exercise generated high to very high activity in the anterior and posterior segments. The single leg bridge generated high activity in the anterior segment whilst the side lie hip abduction recorded high activity in the posterior segment. The side lie clam in contrast generated low activity in each of the GMed segments.

The single leg squat challenges all three GMed segments to maintain pelvic equilibrium while controlling hip adduction and internal rotation as the body's centre of mass is lowered towards the ground (Neumann, 2010). This exercise should be considered a valuable functional exercise for strengthening all three GMed segments due to the high activity recorded in each. This result compares well with a previous review (Ebert et al., 2017) that found high to very high GMed activity levels were recorded for this exercise.

The running man exercise and the resisted hip abduction-extension exercise are performed in single limb standing, requiring sizeable hip abduction torques from all three segments to maintain pelvic equilibrium (Neumann, 2010). This is reflected by the moderate to very high activity levels recorded across the GMed segments and would be potentially effective for targeted segmental strengthening where at least high activity was generated. The results of this study compare favourably with a recent study on healthy older women that investigated three different stance-leg, hip-hitch exercises with high to very high activity levels generated for all three GMed segments (Ganderton, Pizzari, Cook, et al., 2017).

The single leg bridge is a popular rehabilitation exercise that has been reported to generate high GMed activity (Ebert et al., 2017). With a substantial external torque created from the unsupported leg, moderate to high activity levels in all three GMed segments were required presumably to contribute to a hip extension and internal rotation torque for maintaining a neutral pelvic position throughout the exercise (Neumann, 2010).

Both the side-lie abduction and the side-lie clam are commonly prescribed rehabilitation exercises that have been previously reported to generate moderate to very high GMed activity (Ebert et al., 2017). The side-lie abduction provides the clinician with a reasonably effective open chain exercise for targeting the individual segments with moderate to high activity levels generated in each of the segments.

In contrast, the side-lie clam demonstrated in this study to be an ineffective exercise for targeting all three segments, with a smaller anti-gravity lever arm to overcome. Morphologically, the anterior and middle segments do not have favourable moment arms in the transverse plane for external rotation compared to the posterior segment (Neumann, 2010), and the results from this study compare well with a recent study (Ganderton, Pizzari, Cook, et al., 2017) on healthy older women performing the side-lie clam that also showed low activity levels in all three segments.

Based on the results of this study, open chain hip abduction and single limb support exercises appear to be effective options for strengthening all GMed segments to potentially counteract dysfunction with selection based on the individual's functional requirements. The side-lie clam in comparison doesn't appear to be particularly effective at GMed recruitment, especially the anterior and middle segments.

### 4.5.1 Limitations

The sample size in this study was limited due to the invasive nature of the procedure. Despite this, significant differences in activation levels were still observed, and the use of effect sizes has provided an estimate of the magnitude of difference between exercises. For pragmatic reasons, the rehabilitation exercises included in this study are commonly prescribed in the clinic with the assumption as for any exercise that adding external load will have an effect on recorded exercise intensity level.  Caution also needs to be applied when generalising these results to clinical populations such as those with hip osteoarthritis and lateral hip pain.

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**Supplementary table: Maximum voluntary isometric contractions of the hip**

| Hip action | Position | Resistance |
|---|---|---|
| Abduction | Side lie pillow between knees (hip and knee anatomical position) | Belt secured around participants knee and the plinth |
| Abduction in Internal rotation | Side lie pillow between knees (hip maximum hip internal rotation and knee anatomical position) | Belt secured around participants knee and the plinth |
| Flexion | Side lie pillow between knees (hip anatomical position and knee flexion $90^0$) | Applied by investigator on anterior aspect of participants distal femur |
| Extension | Prone (hip anatomical position and knee flexion $90^0$) | Belt secured around the participants foot and the plinth |
| Internal Rotation | Side lie (hip anatomical position and knee flexion $90^0$) | Applied by investigator at lateral border of participants foot |
| Clam | Side lie pillow between knees (hip flexion $45^0$ and knee flexion $45^0$) | Belt secured around participants knee and the plinth |

# CHAPTER 5: ENHANCING GLUTEUS MEDIUS AND GLUTEUS MINIMUS SEGMENTAL ACTIVITY WITH HIP ROTATION DURING THERAPEUTIC EXERCISES

## Introduction

Performing activities of daily living such as stair climbing and running requires optimal functioning of the multiplanar hip and pelvic stabilisers such as the GMed and GMin (Neumann, 2010; Ward et al., 2010). With hip pathology, movement quality dysfunction is observed during functional activities with an associated alteration in trunk posture, and increased pelvic drop and femoral adduction (Allison, Bennell, et al., 2016; Allison, Vicenzino, Bennell, et al., 2016; Allison, Wrigley, et al., 2016). Structural changes are also evident as a result of pathology (Bremer et al., 2011; Muller, Tohtz, Dewey, et al., 2010; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005; Woodley et al., 2008; Zacharias et al., 2016), ageing (Chi et al., 2015) and immobility (Miokovic et al., 2011). These structural changes occur for not only the entire GMed and GMin muscles in advanced disease states, but there appears to be a staged order of atrophy with disease and the ageing process, with the anterior and subsequently posterior GMin segments being affected before the anterior and subsequently middle/posterior GMed segments.

Rehabilitation as a result should then be focused on addressing the underlying structural and functional impairments with emphasis on the triplanar action of the GMed and GMin with targeted interventions. Chapters 3 and 4 (Moore, Pizzari, McClelland, & Semciw, 2019; Moore, Semciw, et al., 2019), and Ganderton, Pizzari, Cook, et al. (2017) have investigated segmental GMed and GMin activity levels with various exercises based on early GMed exercise research that focused predominantly on external rotation as an important action. Considering the limited evaluation of internal rotation exercises for

GMed and GMin in the literature (Ebert et al., 2017; French, Dunleavy, et al., 2013; Hamstra-Wright & Huxel Bliven, 2012; Macadam et al., 2015; Reiman et al., 2012), and it becoming clearer that segmental deficits appear in anterior GMin and GMed sooner, there is a need to evaluate whether adding hip internal rotation to therapeutic exercises could enhance activity levels for the anterior segments.

The addition of hip rotation to therapeutic exercise has been investigated previously for hip abduction (Lee et al., 2013; Lee et al., 2014; Morimoto et al., 2018; Philippon et al., 2011; Sidorkewicz et al., 2014). With methodological differences between the studies, generally adding hip internal rotation to hip abduction elicited higher activity levels in middle GMed compared to hip abduction with neutral rotation and hip abduction with external rotation. Since these studies evaluated hip abduction with a single surface electrode at the middle GMed segment, it is difficult to know how effective adding hip rotation is to the underlying GMin segments or to the anterior and posterior GMed segments.

The split squat with rearlimb resisted hip internal rotation has been proposed to selectively increase anterior hip muscle activity in a functional position of hip extension (Semciw et al., 2018). Despite the suggested benefit of this exercise for people with hip pathology, the muscle activity of GMed and GMin segments during the split squat has not been examined.

The aim of this study was to investigate if the addition of hip rotation to side lie hip abduction and the split squat exercise altered muscle activity of GMed and GMin segments.

The study in this chapter has been published as:

Moore, D., Semciw, A. I., Wisbey-Roth, T., & Pizzari, T. (2020). Adding hip rotation to therapeutic exercises can enhance gluteus medius and gluteus minimus segmental activity levels - An electromyography study. *Physical Therapy in Sport*, 43, 157-165. doi:10.1016/j.ptsp.2020.02.017.

A corrigendum for this study has been published as:

Moore, D., Semciw, A.I., Wisbey-Roth, T., Pizzari, T. (2020). Corrigendum to Adding hip rotation to therapeutic exercises can enhance gluteus medius and gluteus minimus segmental activity levels – An electromyography study. *Physical Therapy in Sport*, 43, 157-165. doi:10.1016/j.ptsp.2020.07.008.

## 5.1 Abstract

***Objectives:*** Quantify and compare gluteus medius (GMed) and gluteus minimus (GMin) segmental electromyography (EMG) activity levels for two therapeutic exercises with added hip internal and external rotation.

***Design:*** Cross-sectional

***Participants:*** Ten healthy young adults

***Main outcome measures:*** Normalised, fine-wire EMG signal amplitudes were quantified for each GMed (anterior, middle and posterior) and GMin (anterior and posterior) segment during side-lie hip abduction and split-squat exercises with added internal and external rotation. A non-parametric analysis was then performed to compare differences in median activity levels.

***Results:*** Side-lie hip abduction with internal rotation generated high activity levels in all GMed and GMin segments except posterior GMed. Side-lie hip abduction generated high activity levels in both GMin segments. There were significant differences ($P <.05$) in median activity levels across the hip abduction exercises for all GMed segments with large effect sizes.

For the split-squat exercises, low activity levels were recorded in all GMed and GMin segments. There were significant differences ($P < .05$) in median activity levels across the split-squat exercises for the anterior and posterior GMed and GMin segments with large effect sizes.

***Conclusions:*** Adding hip rotation to therapeutic exercises can enhance segmental GMed and GMin activity levels for targeted rehabilitation following injury.

***Keywords:*** hip, electromyography, exercise, gluteal muscles

## 5.2 Introduction

The gluteus medius (GMed) and gluteus minimus (GMin) are important muscles for providing multiplanar hip and pelvic stability during activities of daily living including walking, running and climbing stairs (Neumann, Soderberg, & Cook, 1988; Soderberg & Dostal, 1978). Dysfunction in these muscles has been associated with a contralateral pelvic drop and increased femoral adduction in functional activities (Allison, Salomoni, et al., 2018; Allison, Vicenzino, Bennell, et al., 2016; Allison, Wrigley, et al., 2016).

The GMed and GMin consist of structurally and functionally unique segments.(Flack et al., 2014; A. I. Semciw et al., 2014; Semciw, Pizzari, Murley, et al., 2013) This is particularly evident in people with end stage hip osteoarthritis (Kivle et al., 2018), following total hip replacement (Muller, Tohtz, Dewey, et al., 2010; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005) and in ageing (Chi et al., 2015; Takano et al., 2018) with segmental atrophy identified. It is important then to consider the tri-planar action of each segment when planning targeted rehabilitation exercises for these muscles to counteract these structural and functional impairments. Previous studies (Ganderton, Pizzari, Cook, et al., 2017; Moore, Pizzari, et al., 2019; Moore, Semciw, et al., 2019) have evaluated activity levels of individual segments of the GMed and GMin during therapeutic exercises. These studies found that single leg stance exercises and side lie hip abduction were able to generate moderate (20-40% maximum voluntary isometric contraction (MVIC)) to very high (>60% MVIC) activity in all segments of GMed and GMin. It is thought that adding hip rotation to therapeutic exercises may enhance segmental muscle activity particularly in the anterior and posterior segments as they have sizeable moment arms in the transverse plane (Dostal et al., 1986), and EMG studies (A. I. Semciw et al., 2014; Semciw, Pizzari, Murley, et al., 2013) demonstrate high activity levels in the anterior segments during maximum resisted hip internal rotation.

The use of hip rotation to augment GMed muscle activity during therapeutic exercise has been investigated with the side-lie hip abduction (Lee et al., 2013; Lee et al., 2014; Morimoto et al., 2018; Philippon et al., 2011; Sidorkewicz et al., 2014). The addition of hip internal rotation to side-lie hip abduction typically generated greater activity than hip abduction with a neutral or externally rotated hip. However, a single surface electrode positioned over middle GMed was used in all cases which may potentially be contaminated by cross talk from other muscles (A. I. Semciw et al., 2014) and may not provide information on individual muscle segments (Semciw, Pizzari, Murley, et al., 2013). There is a need to further investigate this exercise.

Another exercise that may be enhanced with the addition of hip rotation is the split squat. The split squat has been utilised in the clinical setting to target anterior hip muscle activation by promoting hip extension on the rear leg in a functional position. Gait studies (A. I. Semciw et al., 2014; Semciw, Pizzari, Murley, et al., 2013) have shown that the anterior GMin and GMed have increased EMG activity in the late mid-stance phase to potentially minimise the anterior hip joint forces associated with an extending hip joint (Lewis, Sahrmann, & Moran, 2007). With the knowledge that people with hip-related pathology have targeted structural (Bremer et al., 2011; Kivle et al., 2018; Muller, Tohtz, Dewey, et al., 2010; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005; Zacharias et al., 2016) and functional (Allison, Salomoni, et al., 2018; Ganderton, Pizzari, Harle, et al., 2017; Zacharias et al., 2019) impairments predominantly of the anterior GMin and GMed, and as result routinely walk with a reduced step length (Allison, Wrigley, et al., 2016; Beaulieu, Lamontagne, & Beaule, 2010) it is important to investigate the effectiveness of the split squat exercise with added rotation for augmenting segmental GMed and GMin activity.

The aim of this study was to evaluate GMed and GMin segmental activity levels during lower limb exercises that incorporate elements of hip rotation.

## 5.3 Methods

### 5.3.1 Participants

Ten (6 male, 4 female) healthy, active young adults (mean (SD), 23.8 (1.6) years, 177.5 (10) cm and 79.9 (18.5) kg) volunteered for this single session, cross-sectional study. Participants were eligible to take part if they had no current or previous history (six months) of lower limb or low back injuries; were active with at least 2 hours of sweat inducing activity per week; and satisfied a Tegner activity score ≥ 3 (Tegner & Lysholm, 1985). Informed consent was obtained from all participants and ethical approval was received from the University human ethics committee (UHEC 13-005). These participants have participated in previous studies (Moore, Pizzari, et al., 2019; Moore, Semciw, et al., 2019).

### 5.3.2 Instrumentation and electrode insertions

Fine-wire EMG wireless electrodes were inserted into standardised positions for the anterior, middle and posterior GMed segments, and the anterior and posterior GMin segments of the dominant stance limb using real-time ultrasound guidance (HDMI technologies) (Semciw, Green, et al., 2013; Semciw, Pizzari, & Green, 2013). Once inserted these electrodes were connected to a wireless Trigno 16-Channel EMG system (Delsys® Inc., Boston, USA). For the purpose of delineating the start and finish of exercise repetitions, an accelerometer (Trigno Delsys Inc., Boston, USA) was secured to the distal lateral femur and distal anteromedial tibia of the moving limb to determine exercise repetitions in dynamic tasks.

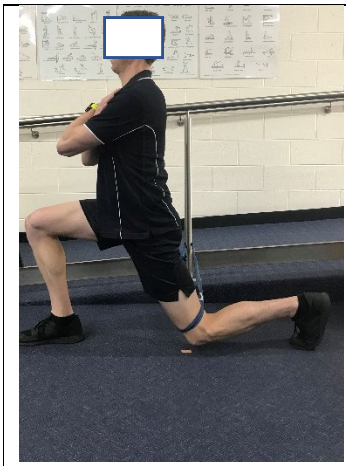
### 5.3.3 Procedure

Once the electrodes were secured and good quality baseline EMG signals were established, participants performed up to 10 mins of walking and jogging for a warmup followed by five exercises performed in a randomised order: side-lie hip abduction neutral rotation (AbN); side-lie hip abduction with hip internal rotation (AbIR); side-lie hip abduction with hip external rotation (AbER); split squat with elastic resisted rearlimb hip internal rotation (SSIR); and split squat with elastic resisted rearlimb hip external rotation (SSER) (Table 5.1).

*Table 5.1. Therapeutic exercises*

| Exercise | Description |
|---|---|
| Side lie hip abduction neutral rotation (AbN)<br> | Side lie with testing leg facing up with both legs straight and in line with trunk. On 1 beat raise top leg to approximately $30^0$, then lower back to start position for 1 beat (50 bpm).<br>Repeat for 6 repetitions. |
| Side lie hip abduction with hip internal rotation (AbIR)<br> | Side lie with testing leg facing up with heel pointing towards the ceiling in maximum hip internal rotation. Both legs straight and in line with trunk. On 1 beat raise top leg to approximately $30^0$, then lower back to start position for 1 beat (50 bpm) keeping heel pointing towards ceiling throughout.<br>Repeat for 6 repetitions. |
| Side lie hip abduction with hip external rotation (AbER)<br> | Side lie with testing leg facing up with toes pointing towards the ceiling in maximum hip external rotation. Both legs straight and in line with trunk. On 1 beat raise top leg to approximately $30^0$, then lower back to start position for 1 beat (50 bpm) keeping toes pointing towards ceiling throughout. |

| | |
|---|---|
| | Repeat for 6 repetitions. |
| Split squat with elastic resisted rearlimb hip internal rotation (SSIR)<br><br> | Position testing knee over ground mark, arms crossed, step out a comfortable distance forward with non-testing leg into a split-squat position keeping a vertical trunk position such as to maintain even weight distribution between legs until achieve approximately $90^0$ hip and knee flexion for non-testing leg such that the knee doesn't go beyond the toes. Elastic band looped taut positioned slightly above medial femoral condyle level of rear testing leg and providing a lateral force. For testing leg, participant instructed to rotate middle of anterior knee towards first toe against resistance. Hold position for 10 seconds and repeat 3 times. |
| Split squat with elastic resisted rearlimb hip external rotation (SSER) | Position testing knee over floor marking, arms crossed, step out a comfortable distance forward with non-testing leg into a split-squat position keeping a vertical trunk position such as to maintain even weight distribution between legs |

| | |
|---|---|
|   | until achieve approximately $90^0$ hip and knee flexion for non-testing leg such that the knee doesn't go beyond the toes. Elastic band looped taut positioned slightly above lateral femoral condyle level of rear testing leg and providing a medial force. For testing leg, participant instructed to rotate middle of anterior knee towards fifth toe against resistance. Hold position for 10 seconds and repeat 3 times. |

Familiarisation repetitions were performed for each exercise followed by three trials of six repetitions paced to a metronome (50 bpm) for the three hip abduction exercises, and three trials of 10 second isometric holds against elastic resistance for the two split squat exercises. Rest periods of two minutes were allowed between exercises and the trials to minimise fatigue. Exercise data were normalised to maximum voluntary isometric contractions recorded during six different hip actions (side lie hip abduction; side lie hip abduction with internal rotation; side lie hip clam (hip flexion $45^0$ and knee flexion $90^0$); side lie hip flexion; side lie hip internal rotation; and prone hip extension) to determine an overall maximum value for each GMed and GMin segment for each participant (Moore, Pizzari, et al., 2019; Moore, Semciw, et al., 2019).

### 5.3.4 Data synthesis

The Trigno wireless 16-Channel EMG system (CMRR > 80 dB @ 60 Hz; gain of 1000; band pass filtered at 20-900 Hz) collected and sampled raw EMG signals at 2000Hz. The raw EMG signals were imported into Delsys® EMGworks version 4.1.7 signal analysis software then high-pass filtered (Butterworth 4$^{th}$ order, 50Hz), rectified and low-pass filtered (Butterworth 4$^{th}$ order, 6Hz) to generate a linear envelope (Moore, Pizzari, et al., 2019; Moore, Semciw, et al., 2019). The accelerometer data were collected at 148Hz.

Once the repetitions were delineated from the accelerometer data for the hip abduction exercises, the middle three repetitions of each trial were used for further analysis and summed and averaged over the three trials to obtain an average amplitude across the whole exercise for each participants' individual muscle segments. For the split squat exercises the average amplitude was determined from the middle five seconds of the isometric hold and summed and averaged over the three trials to calculate the average amplitude for individual muscle segments.

The normalised EMG activation levels were then classified according to previously defined criteria (DiGiovine et al., 1992; Escamilla et al., 2010) into low (0-20% MVIC), moderate (21-40% MVIC), high (41-60% MVIC), and very high (> 60% MVIC) to make meaningful comparisons between exercises.

### 5.3.5 Statistical Analysis

All statistical analysis was performed in SPSS version 24 software (IBM Corp., Armonk, USA). Each muscle segment was analysed separately. Due to the small sample size and non-normal data distribution a non-parametric analysis was performed. For the split squat exercises, a Wilcoxon signed rank test was used to describe the difference in activity levels between the addition of internal or external rotation. For the hip abduction exercises, a non-parametric Friedman's test was performed to determine differences in activity levels between the three hip abduction tasks. Where significant differences were detected ($P < 0.05$), a post-hoc Wilcoxon signed rank test was used to determine which pair of exercises differed in activity levels. To determine the magnitude of any difference, an effect size was calculated by dividing the z-score of the Wilcoxon signed rank test by the square root of the sample size. An effect size threshold of 0.2, 0.5 and 0.8 was considered small, medium and large respectively (Cohen, 1988).

## 5.4 Results

### 5.4.1 Participants

Due to movement artefact, data from 9 participants were included for analysis of the hip abduction exercises.

### 5.4.2 Hip abduction exercises

***Gluteus medius anterior median activity***

High median (interquartile range) activity (46.07 (19.57)% MVIC) was recorded for AbIR while moderate activity (35.74 (12.5)% MVIC) was recorded for AbN. Low activity (15.40 (6.66)% MVIC) was recorded for AbER (Figure 5.1A).

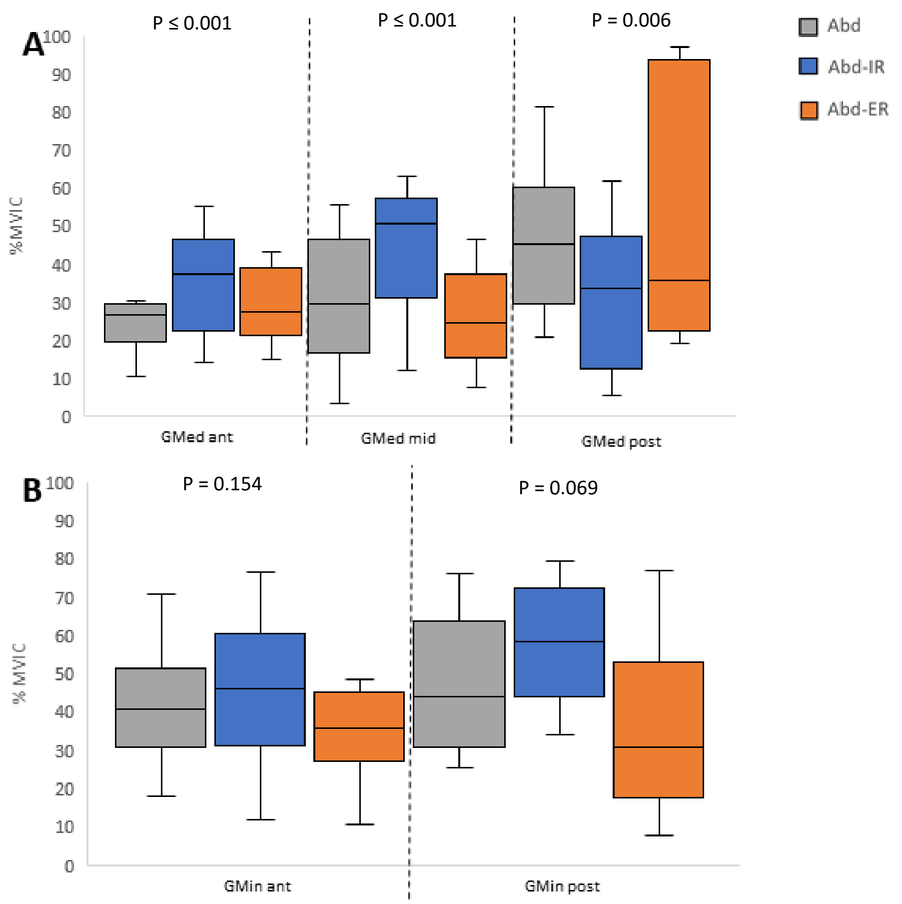



*Figure 5.1. Hip abduction exercises for GMed (A) and GMin (B)*

There was a significant difference in median activity across the hip abduction exercises for GMed anterior ($\chi^2$ (2) = 18.00, $P \leq 0.001$).

AbIR and AbN had significantly higher activity levels compared to AbER with large effect sizes generated for each combination (0.89, 0.89). AbIR also had significantly higher activity levels than AbN with a large effect size generated (0.89) (Appendix, Table 1).

***Gluteus medius middle median activity***

High median (interquartile range) activity was generated by AbIR (50.81 (19.98)% MVIC) and moderate activity was recorded for AbN (36.52 (23.81)% MVIC). AbER generated low activity (19.08 (14.42)% MVIC) (Figure 5.1A).

There was a significant difference in median activity across the hip abduction exercises for GMed middle ($\chi^2$ (2) = 16.22, $P \leq 0.001$).

AbIR and AbN had significantly higher activity levels compared to AbER with large effect sizes generated for each combination (0.89, 0.89). AbIR also had significantly higher activity levels than AbN with a large effect size generated (0.85) (Appendix, Table 2).

***Gluteus medius posterior median activity***

Moderate median (interquartile range) activity was recorded for AbIR (38.66 (30.96)% MVIC), AbN (37.97 (47.34)% MVIC) and AbER (25.71 (26.58)% MVIC) (Figure 5.1A).

There was a significant difference in median activity across the hip abduction exercises for GMed posterior ($\chi^2$ (2) = 9.56, $P = 0.006$).

AbIR had significantly higher activity levels than AbER with a large effect size generated (0.89) (Appendix, Table 3).

***Gluteus minimus anterior median activity***

High median (interquartile range) activity was recorded for AbIR (45.97 (29.46)% MVIC) and AbN (40.64 (20.74)% MVIC). Moderate activity was generated by AbER (35.70 (18.04)% MVIC) (Figure 5.1B).

There was no significant difference in median activity across the hip abduction exercises ($\chi^2$ (2) = 4.22, $P$ = 0.154) (Appendix, Table 4).

***Gluteus minimus posterior median activity***

High median (interquartile range) activity was generated by both AbIR (58.46 (28.42)% MVIC) and AbN (43.84 (33.06)% MVIC). Moderate activity was recorded for AbER (30.82 (35.26)% MVIC) (Figure 5.1B).

There was no significant difference in median activity across the hip abduction exercises ($\chi^2$ (2) = 5.556, $P$ = 0.069) (Appendix, Table 5).

5.4.3 Split squat exercises

***Gluteus medius anterior median activity***

Low activity was also recorded for SSIR (15.26 (19.74)% MVIC) and SSER (2.09 (3.38)% MVIC) (Figure 5.2A).

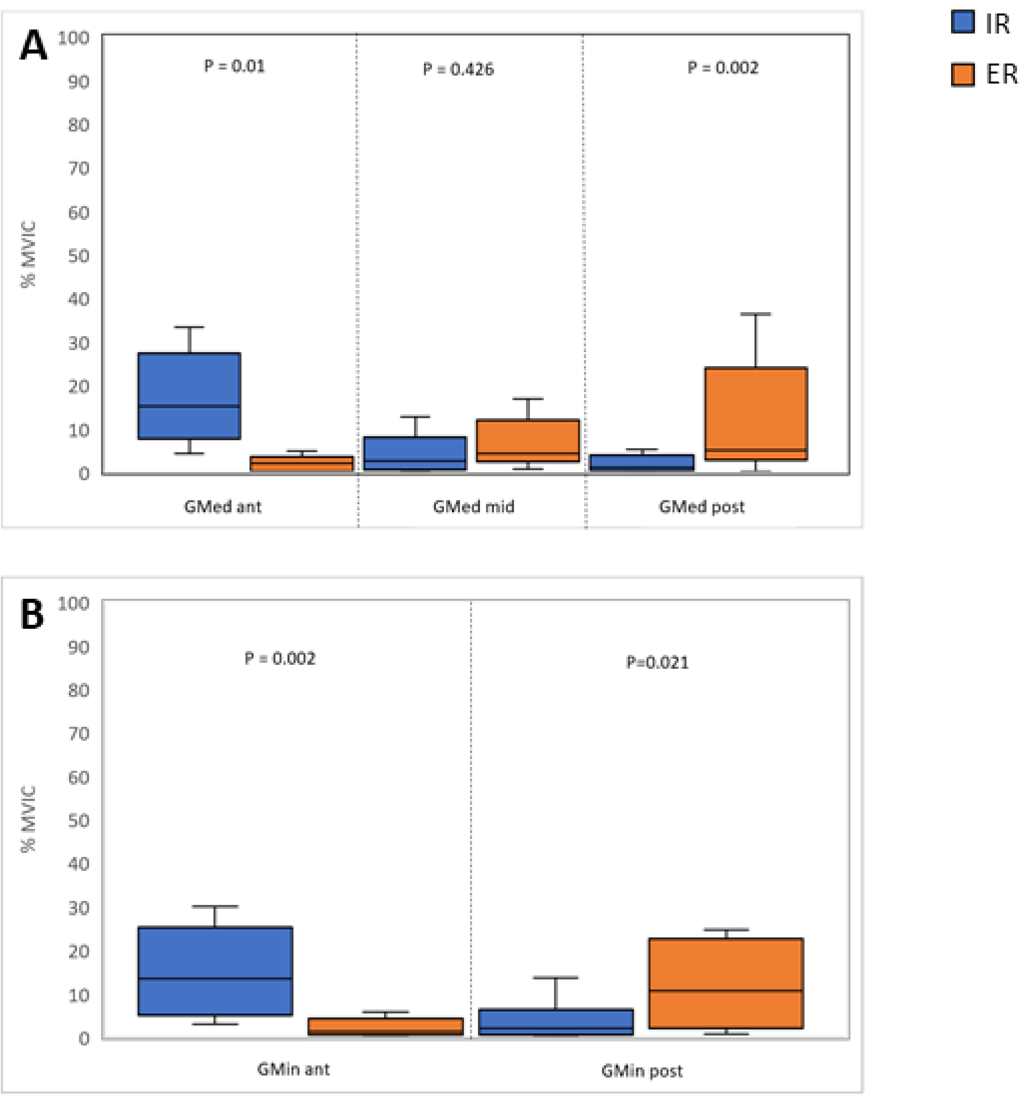



*Figure 5.2. Split squat exercises for GMed (A) and GMin (B)*

SSIR had significantly higher GMed anterior median activity levels (z = 2.497, $P = 0.01$) than SSER with a large effect size generated (0.79) (Appendix, Table 6).

***Gluteus medius middle median activity***

Low activity was also recorded for both SSIR (2.61 (7.55)% MVIC) and SSER (4.41 (9.57)% MVIC) (Figure 5.2A).

There was no significant difference in median activity between the split squat exercises (z = 0.889, $P$ = 0.426) (Appendix, Table 7).

***Gluteus medius posterior median activity***

Both the SSIR (1.10 (3.60)% MVIC) and SSER (5.08 (21.02)% MVIC) generated low activity levels (Figure 5.2A).

SSER had significantly higher GMed posterior median activity levels (z = 2.803, $P$ = 0.002) than SSIR with a large effect size generated (0.89) (Appendix, Table 8).

***Gluteus minimus anterior median activity***

Low activity was recorded for both SSIR (13.61 (20.24)% MVIC) and SSER (1.41 (3.70) % MVIC) (Figure 5.2B).

The SSIR had significantly higher GMin anterior median activity levels (z = 2.803, $P$ = 0.002) than the SSER with a large effect size generated (0.89) (Appendix, Table 9).

***Gluteus minimus posterior median activity***

Low activity was generated by both SSER (10.67 (20.54)% MVIC) and SSIR (2.08 (5.80)% MVIC) (Figure 5.2B).

The SSER had significantly higher GMin posterior median activity levels ($z = 2.497$, $P = 0.021$) than SSIR with a large effect size generated (0.79) (Appendix, Table 10).

## 5.5 Discussion

This study evaluated GMed and GMin segmental activity levels in healthy young adults performing side-lie hip abduction and split squat with added hip internal and external hip rotation. The results indicate that the addition of hip internal rotation to side-lie hip abduction generated significantly greater activity levels for the anterior and middle GMed. High activity levels were recorded in all GMed and GMin segments except GMed posterior where moderate activity was elicited. For the split squat exercises low activity was generated in all GMed and GMin segments, however augmenting with resisted hip internal rotation generated significantly greater activity levels for the anterior GMed and GMin segments while supplementing with resisted hip external rotation recorded significantly higher activity levels for the posterior GMed and GMin segments.

Side-lie hip abduction is a commonly prescribed therapeutic exercise for GMed and GMin muscle rehabilitation and strengthening (French, Cusack, et al., 2013). Adding internal rotation (i.e. leading with the heel) to side-lie hip abduction will achieve significantly greater activity levels for anterior and middle GMed and equivalent activity levels for posterior GMed. It may also have the advantage of minimising common compensation strategies such as rotating the trunk backwards and flexing the hip. The anterior GMed segment has a relatively moderate sized internal rotation moment arm in the transverse plane (Dostal et al., 1986), hence it was expected that AbIR would generate greater activity than the other variations of the hip abduction exercise. The middle GMed has a negligible transverse plane moment arm (Dostal et al., 1986) but still generated significantly greater activity with AbIR which was consistent with most single surface electrode studies measuring this segment (Lee et al., 2013; Lee et al., 2014; Morimoto et al., 2018; Philippon et al., 2011; Sidorkewicz et al., 2014). One explanation could be “leading with the heel” minimised potential compensation strategies as described above or that it provides a less optimal length-tension relationship for force-generating capacity for the middle GMed segment (Ward et al., 2010). For the posterior GMed segment, AbIR generated significantly greater activity than AbER even though this segment has a relatively moderate sized external rotation moment arm (Dostal et al., 1986). The reason could again be as a result of a less optimal length-tension relationship for force-generating capacity for the posterior GMed segment (Ward et al., 2010).

For the GMin high activity levels were generated in both segments for AbIR but this was not significant compared to the other variations of the hip abduction exercise. With the anterior GMin having a reasonably sized internal rotation moment arm (Dostal et al., 1986), AbIR may minimise potential compensation strategies as well as providing a less optimal length-tension relationship for force generating capacity. The posterior GMin has a moderately sized external rotation lever arm (Dostal et al., 1986), hence the results could be possibly explained by AbIR providing a less optimal length-tension relationship for that segment (Ward et al., 2010).

The split squat with rear limb resisted isometric hip internal and external rotation are exercises that are used clinically for hip muscle rehabilitation with the resisted hip internal rotation variation used potentially to target anterior hip stability and encourage terminal hip extension. In the split squat position with the base of support relatively evenly distributed between the two legs, functional demands placed on the GMed and GMin segments were not likely to be high which was demonstrated by our results where low activity levels were generated for all GMed and GMin segments. Only one study (Boudreau et al., 2009) has previously examined middle GMed activation levels on the trailing leg during the split squat using a single surface electrode and found there was no difference in GMed activity levels when compared to the dominant lead leg with low activity levels generated. With high activity levels considered important for strengthening (Andersen et al., 2006), prescription of the split squat with a rotation bias may be a potentially effective strategy in the early stages of rehabilitation for facilitating specific segmental activation and control in a functional position (i.e. terminal hip extension). This could be beneficial for increasing the confidence in regaining normal function particularly in those with hip pathology or the elderly where they may mobilise habitually with shorter strides (Beaulieu et al., 2010; Lewis et al., 2007).

### 5.5.1 Limitations

One limitation of this study in hindsight was the failure to measure activity for individual GMed and GMin segments during the split squat in neutral without the added rotation component. With this study showing low activity levels generated in all segments of GMed and GMin for both variations of the split squat, the neutral position would not be expected to be much different for activity levels. Another limitation was the low number of participants but this is common in fine-wire EMG studies due to financial and time constraints. Having EMG measurements for the neighbouring tensor fascia lata and gluteus maximus may have been beneficial for the clinician to determine their contribution as synergists during these exercises. Although the split squat exercises were closely supervised for technique and weight distribution between limbs no objective monitoring was undertaken and this is consistent with previous studies (Boudreau et al., 2009; Distefano et al., 2009; Dwyer et al., 2010; Ekstrom et al., 2007; Krause et al., 2018; Lin et al., 2016) that have evaluated this type of exercise for GMed activity. Although the added elastic resistance was not quantified for the split squat exercises, standardisation was achieved to some extent through using the same size loop and uniform participant positioning against the resistance. These results also need to be interpreted with caution when applying to pathological populations.

## 5.6 Conclusion

The results of this study have demonstrated that depending on which GMed or GMin segment is being targeted utilising the transverse plane through the addition of hip rotation to lower limb therapeutic exercises in a weight-bearing or non-weightbearing position can be effective at enhancing activity levels in individual GMed and GMin segments. If side lie hip abduction is part of the targeted exercise program, leading with the heel (i.e. hip internal rotation) will augment anterior and middle GMed activity without detrimentally affecting activity of the posterior GMed or both segments of GMin. For a closed chain exercise, the split squat with added rear limb resisted hip internal rotation is more effective than the split squat with added rear limb resisted hip external rotation for enhancing anterior GMed and GMin segmental activation while the split squat with added rear limb resisted hip external rotation is more effective than the split squat with added rear limb resisted hip internal rotation for augmenting posterior GMed and GMin segmental activation.

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**Supplementary tables**: Median activity, effect size and significance level for GMed and GMin segments

Table 1. Median (interquartile range) activity, effect size and significance level for GMed anterior for abduction exercises.

| | Abd | Abd-IR |
|---|---|---|
| Abd (35.75 (12.50) % MVIC) | | |
| Abd-IR (46.06 (19.57) % MVIC) | **0.89 (0.004)** | |
| Abd-ER (15.40 (6.66) % MVIC) | **-0.89 (0.004)** | **-0.89 (0.004)** |

Table 2. Median (interquartile range) activity, effect size and significance level for GMed middle for abduction exercises.

| | Abd | Abd-IR |
|---|---|---|
| Abd (35.52 (23.81) % MVIC) | | |
| Abd-IR (50.81 (19.98) % MVIC) | **0.85 (0.008)** | |
| Abd-ER (19.08 (14.42) % MVIC) | **-0.89 (0.004)** | **-0.89 (0.004)** |

Table 3. Median (interquartile range) activity, effect size and significance level for GMed posterior for abduction exercises.

| | Abd | Abd-IR |
|---|---|---|
| Abd (37.97 (47.34) % MVIC). | | |
| Abd-IR (38.66 (30.96) % MVIC). | 0.34 (0.359) | |
| Abd-ER (25.71 (26.58) % MVIC). | -0.65 (0.055) | **-0.89 (0.004)** |

Table 4. Median (interquartile range) activity, effect sizes and significance levels for GMin anterior for abduction exercises.

| | Abd | Abd-IR |
|---|---|---|
| Abd (40.64 (20.74) % MVIC) | | |
| Abd-IR (45.97 (29.46) % MVIC) | -0.18 (0.652) | |
| Abd-ER (35.70 (18.04) % MVIC) | -0.41 (0.25) | -0.38 (0.301) |

Table 5. Median (interquartile range) activity, effect sizes and significance levels for GMin posterior for abduction exercises.

| | Abd | Abd-IR |
|---|---|---|
| Abd (43.84 (33.06) % MVIC). | | |
| Abd-IR (58.46 (28.42) % MVIC). | -0.61 (0.074) | |
| Abd-ER (30.82 (35.26) % MVIC). | -0.53 (0.129) | -0.61 (0.074) |

Table 6. Median (interquartile range) activity, effect size and significance level for GMed anterior for split squat exercises.

| | Split squat + IR |
|---|---|
| Split squat + IR (15.26 (19.74) % MVIC) | |
| Split squat + ER (2.09 (3.38) % MVIC) | **-0.79 (0.01)** |

Table 7. Median (interquartile range) activity, effect size and significance level for GMed middle for split squat exercises.

| | Split squat + IR |
|---|---|
| Split squat + IR (2.61 (7.55) % MVIC) | |
| Split squat + ER (4.41 (9.57) % MVIC) | -0.3 (0.426) |

Table 8. Median (interquartile range) activity, effect size and significance level for GMed posterior for split squat exercises.

| | Split squat + IR |
|---|---|
| Split squat + IR (1.10 (3.60) % MVIC). | |
| Split squat + ER (5.08 (21.02) % MVIC). | **0.89 (0.002)** |

Table 9. Median (interquartile range) activity, effect size and significance level for GMin anterior for split squat exercises.

| | Split squat + IR |
|---|---|
| Split squat + IR (13.61 (20.24) % MVIC) | |
| Split squat + ER (1.41 (3.70) % MVIC) | **-0.89 (0.002)** |

Table 10. Median (interquartile range) activity, effect size and significance level for GMin posterior for split squat exercises.

| | Split squat + IR |
|---|---|
| Split squat + IR (2.08 (5.08) % MVIC). | |
| Split squat + ER (10.67 (20.54) % MVIC). | **0.79 (0.01)** |

**Corrigendum to 'Adding hip rotation to therapeutic exercises can enhance gluteus medius and gluteus minimus segmental activity levels – An electromyography study'**

The authors regret that the published Figure 5.1. Hip abduction exercises for GMed (A) and GMin (B) has been generated with incorrect medians and interquartile ranges. The data and analysis within the manuscript are still correct. The new Figure 1 with correct medians and interquartile ranges is displayed below.

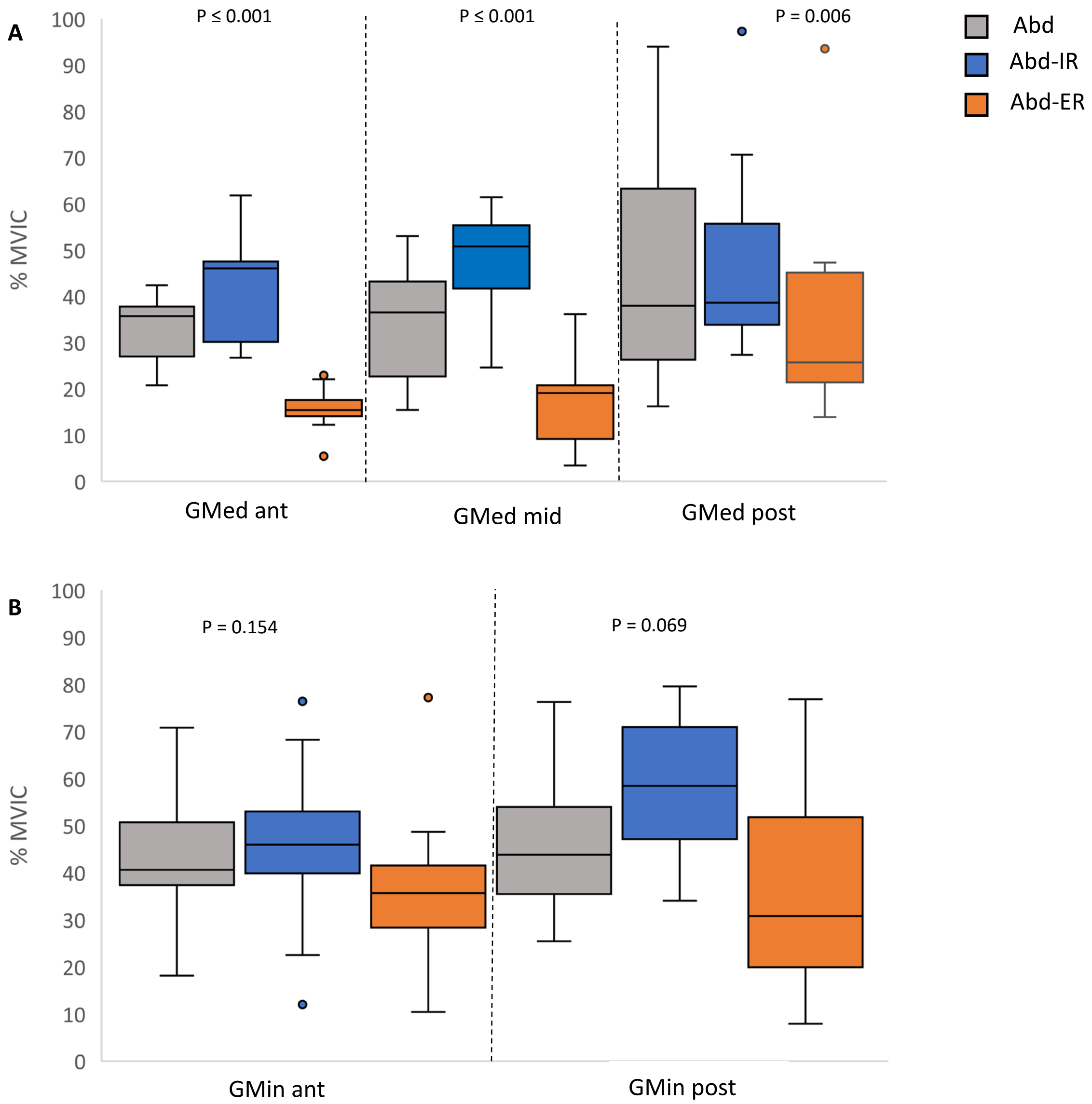


*Figure 5.1. Hip abduction exercises for GMed (A) and GMin (B).*

The authors would like to apologise for any inconvenience caused.

# CHAPTER 6: GRAND DISCUSSION

The overall aim of this thesis was to investigate which of a chosen selection of therapeutic exercises were most effective for increasing segmental GMed and GMin activity levels in healthy young adults. This was accomplished by first undertaking a systematic review to determine the current evidence on the topic (Chapter 2), then designing and performing a single group cross-sectional study to answer the research question followed by a series of original research papers (Chapters 3, 4 and 5). This chapter summarises the findings of the studies within the thesis, discusses clinical implications, and determines future directions based on this research.

This project: (1) demonstrated that individual GMed and GMin segments can be preferentially activated and targeted with simple therapeutic exercises in weight bearing and non-weight bearing positions; (2) established that GMed and GMin segmental activity levels can be enhanced by adding transverse plane rotation to simple therapeutic exercises in weight bearing and non-weight bearing positions; (3) published the first results on a chosen selection of therapeutic exercises that were most effective for increasing activity levels in GMed and GMin segments for healthy young adults using standardised intra-muscular electrode positions.

The systematic review in Chapter 2 identified a range of exercises that could target individual GMed and GMin segments effectively for strengthening. The middle GMed segment had the largest range of options since it had been studied the most. Chapter 2 highlighted that there has been a large increase in research into GMed exercises over the last few years and only two studies (including Chapter 3) evaluating GMin. This is likely due to the ease of measuring GMed with surface EMG electrodes compared to the more technically difficult and invasive application of fine-wire electrodes. Many previous studies have assumed that the findings of muscle activity in one segment of a muscle (middle GMed) represent activation across the entire muscle. It might have also been presumed that the deeper GMin muscle functions similarly to the overlying GMed (Muller, Tohtz, Winkler, et al., 2010). Using much of the current evidence to devise exercise programs to strengthen the GMed and GMin is problematic given the known segmental independence within and between these muscles.

With knowledge that the anterior GMin (and anterior GMed to a lesser extent) sustains earlier structural and functional impairments with hip pathology (Allison, Salomoni, et al., 2018; Ganderton, Pizzari, Harle, et al., 2017; Kawasaki et al., 2017; Kivle et al., 2018; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005; Woodley et al., 2008; Zacharias et al., 2019) and ageing (Chi et al., 2015; Takano et al., 2018) compared to other segments, emphasises a need to evaluate segmental muscle activation during exercise. From a clinical perspective, this may serve to enhance the impact of targeted exercise interventions to address these impairments.

With the GMed thought to function as a stabiliser of the pelvis and as a controller of the hip adduction and internal rotation moment in single leg stance activities like jogging (Al-Hayani, 2009; Gottschalk et al., 1989), there has been a trend in the literature (as evidenced in Chapter 2) to evaluate exercises that have a neutral or external rotation bias for improving hip control and strength. Little consideration has been given to exercises that incorporate hip internal rotation to enhance the anterior GMin and GMed segments. This is highlighted in Chapter 3 where only one of the selected exercises that were based on early GMed exercise research, generated high activity levels for the anterior GMin segment. The one exercise, the resisted hip abduction-extension exercise, generates an internal rotation moment around the stance leg. This emphasizes the importance morphologically of the moderate-sized internal rotation moment arm for increasing activity levels of the anterior segments (Dostal et al., 1986) with Chapter 5 reinforcing that therapeutic exercise activity levels can be enhanced by adding hip internal rotation. The addition of exercises with an internal rotation bias could be a missing element from current hip rehabilitation and general strength programs, and might be a factor in the limited efficacy of rehabilitation for conditions such as hip osteoarthritis (OA) (Bennell et al., 2014; Fransen et al., 2014). From the results of this thesis, and considering the lack of evidence for hip rehabilitation in hip OA, the GHOst (Gluteal exercise for Hip Osteoarthritis) trial has been proposed (Semciw et al., 2018). This randomised controlled trial will compare targeted gluteal exercise versus sham exercise for improving self-reported physical function for people with mild to moderate hip OA by incorporating progressive high intensity strength training, gait re-training and motor control strategies specifically targeted to GMin.

Based on the results from this thesis showing limited exercise options available for achieving high activity levels for the anterior GMin, it is recommended that the clinician also considers including external load through weights or elastic resistance against internal rotation to therapeutic exercises to facilitate increased activity levels.

The posterior GMin segment, in contrast, was shown in Chapters 2 and 3 to have a broader range of exercise choices for targeted strengthening. As a result, we may not have to be as reliant on its moderate sized external rotation moment arm (Dostal et al., 1986) to facilitate increased activity levels since single limb weight-bearing exercises and side lie hip abduction generate adequate activity levels for potential strengthening (Andersen et al., 2006).

Although GMed appears to be less affected by hip pathology (Allison, Salomoni, et al., 2018; Bremer et al., 2011; Ganderton, Pizzari, Harle, et al., 2017; Kivle et al., 2018; Muller, Tohtz, Dewey, et al., 2010; Muller, Tohtz, Winkler, et al., 2010; Pfirrmann et al., 2005; Zacharias et al., 2019) and ageing (Chi et al., 2015; Takano et al., 2018) compared to the GMin, it is still an important consideration in rehabilitation. For targeting all GMed segments with at least high activity it was identified from Chapter 2 that different variations of the hip hitch/ pelvic drop exercise were the best options. The results from Chapters 2 and 4 highlighted that single-limb weight bearing exercises and side lie hip abduction were effective options for generating at least moderate to very high activity in all segments of GMed and supported previous research (Al-Hayani, 2009; Flack et al., 2014; Semciw, Pizzari, Murley, et al., 2013) that the GMed is comprised of functionally independent segments.

## 6.1 Clinical implications

The exercises studied for this thesis are generalisable to healthy young adults without pathology but could be potentially effective for a range of hip-related conditions across the lifespan. It may be useful to combat age-related sarcopenia (Lexell, Taylor, & Sjostrom, 1988), particularly for the anterior GMin and GMed segments, by incorporating some of these targeted exercises into fitness programs for older adults. The inclusion of some targeted anterior GMin exercises into falls-prevention programs for the elderly may theoretically be beneficial (Kiyoshige & Watanabe, 2015). Prescription of these exercises could also assist clients recovering from relative periods of immobility such as following an operation or illness, and from a sedentary lifestyle (Miokovic et al., 2011).

For these therapeutic exercises to be effective, they do need to be optimized to the individuals' functional requirements and to universally accepted exercise prescription principles for enhancing muscle fitness (Garber et al., 2011). Highly trained athletes may find the physical demands of the therapeutic exercises to be relatively easy and require additional loading through weights or elastic resistance to elicit a strengthening stimulus (Kraemer et al., 2002). For an individual who is deconditioned or in pain, performing these therapeutic exercises could be too difficult to achieve and they may require modifications or selection of a lower activity exercise to commence with. From the findings of this thesis, therapeutic exercises that recorded low or moderate activity for a specific segment can still be of value in a graduated rehabilitation program especially in the early stages where motor activation and endurance may be the goal, particularly for the GMin segments that contain a higher proportion of Type 1 muscle fibres (Sparks, 2011).

### 6.2 Strengths of the research

A strength of this thesis is the utilisation of a range of simple therapeutic exercises requiring minimal equipment that can be readily prescribed by health practitioners in a variety of settings to specifically target weak or dysfunctional GMed and / or GMin muscle segments.

The findings of this thesis are strengthened by a homogeneous study population of healthy young active adults; validated procedures for the application of fine-wire electrodes into the GMin and GMed segments (Semciw, Green, et al., 2013; Semciw, Pizzari, & Green, 2013); a consistent protocol for warm-up, exercise familiarisation and testing procedures; randomisation of the exercise sequence and order of MVIC testing; and standardised collection and processing techniques for the EMG data. Using validated guidelines for insertion of fine-wire electrodes into individual GMed and GMin segments has overcome many limitations of previous EMG studies investigating therapeutic exercises for the GMed and GMin as well as providing new areas for research into the function of GMin.

### 6.3 Limitations of the research

With the findings of this thesis based on healthy active young adults, there is uncertainty about the generalisability of the results to populations with hip pathology. There is also uncertainty about the optimal sets and repetitions for each of the exercises as this was beyond the scope of this thesis. The selected repetitions, exercise speed and number of trials was determined from pilot testing to balance the effects of fatigue with repeatability of data within a single session. As has been discussed previously, another limitation was the low participant numbers (n=10). This may have potentially affected the statistical power of the results. Participant numbers were however similar to previous fine-wire EMG studies for the hip musculature (Giphart et al., 2012; Hodges et al., 2014; Philippon et al., 2011). During testing for a small number of participants, poor quality EMG signal were recorded due to movement artefact or electrode dislodgement for some of the GMed and GMin segments impacting the amount of exercise data collected and analysed. This limitation is not uncommon in fine-wire EMG research (Chapman, Vicenzino, Blanch, Knox, & Hodges, 2010; Giphart et al., 2012). Fine-wire EMG is also more technically difficult to apply compared to surface EMG and assumes that the recording of activity of a small sample of muscle fibres is representative of the entire segment (Soderberg & Knutson, 2000).

Selection into the study could have been more rigorous by excluding participants with increased relative femoral anteversion (> $42^0$) since this been shown to have a significant effect on GMed activity levels (Nyland, Kuzemchek, Parks, & Caborn, 2004) and has been previously used in EMG studies evaluating GMed activity during therapeutic exercises (Lee et al., 2014; McBeth et al., 2012; Monteiro et al., 2017). Although trunk position and exercise technique was closely monitored during testing, objectively measuring trunk alignment during standing exercises may have been beneficial as this could have affected hip abductor activity levels to maintain a level pelvic position (Neumann, 1998). It may have also been beneficial from a clinician's perspective to have evaluated the relative contribution (EMG activity) from neighbouring synergist muscles such as TFL and gluteus maximus during the therapeutic exercises given the association between abnormal hip kinematics and various lower limb musculoskeletal conditions (Allison, Bennell, et al., 2016; Azevedo et al., 2009; Cowan et al., 2009; Franettovich et al., 2010; Morrissey et al., 2012), and atrophy of the gluteus maximus relative to the TFL with degenerative hip pathology (Grimaldi, Richardson, Durbridge, et al., 2009).

## 6.4 Future research directions

This thesis has established a good foundation to explore the effectiveness of these exercises on clinical populations such as hip OA (Semciw et al., 2018). Targeted gluteal exercise programs could potentially be evaluated for their effect on pain, function, changes in whole muscle and segmental size, and quality of life for a range of hip conditions, falls prevention, and ageing. To provide a broader range exercises for clinicians, further exercises could be explored in healthy populations particularly for the anterior segments by using isometric banded internal rotation during a single leg squat (Figure 6.1) and single leg bridge (Figure 6.2), and band resistance for prone hip internal rotation (Figure 6.3).

*Figure 6.25. Single leg squat with isometric banded internal rotation*

*Figure 6.26. Single leg bridge with isometric banded internal rotation*

*Figure 6.27. Band resisted hip internal rotation*

## 6.5 Conclusions

The thesis has addressed the aim of identifying simple therapeutic exercises for generating high activity in individual GMed and GMin segments in healthy young adults. The findings have provided further insights and a greater understanding for clinicians on developing targeted exercise programs to address segmental gluteal dysfunction. Further work is required to identify more exercises to elicit activity in the anterior GMin and GMed segments and to determine the effect of these exercises on populations with hip pathology and ageing populations.

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## Appendix A: Ethics approval for chapters 3,4 and 5.

LA TROBE UNIVERSITY

RESEARCH SERVICES

**MEMORANDUM**

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| | |
|---|---|
| **To:** | **Mr. Adam Semciw, Department of Physiotherapy, FHS**<br>**Ms. Rachel Neate, Department of Physiotherapy, FHS** |
| **From:** | **Acting Secretary, La Trobe University Human Ethics Committee** |
| **Subject:** | **Review of Human Ethics Committee Application No. 13-005** |
| **Title:** | **What role do the deep hip stabilizers have in running?** |
| **Date:** | **12 April 2013** |

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Thank you for your recent correspondence in relation to the research project referred to above. The project has been assessed as complying with the *National Statement on Ethical Conduct in Human Research*. I am pleased to advise that your project has been granted ethics approval and you may commence the study.

**The project has been approved from the date of this letter until 31 January 2014.**

*Please note that your application has been reviewed by a sub-committee of the University Human Ethics Committee (UHEC) to facilitate a decision about the study before the next Committee meeting. This decision will require ratification by the full UHEC at its next meeting and the UHEC reserves the right to alter conditions of approval or withdraw approval. You will be notified if the approval status of your project changes. The UHEC is a fully constituted Ethics Committee in accordance with the National Statement on Ethical Conduct in Research Involving Humans-March 2007 under Section 5.1.29.*

The following standard conditions apply to your project:

- **Limit of Approval.** Approval is limited strictly to the research proposal as submitted in your application while taking into account any additional conditions advised by the UHEC.

- **Variation to Project.** Any subsequent variations or modifications you wish to make to your project must be formally notified to the UHEC for approval in advance of these modifications being introduced into the project. This can be done using the appropriate form: *Ethics - Application for Modification to Project* which is available on the Research Services website at *http://www.latrobe.edu.au/research-services/ethics/HEC_human.htm*. If the UHEC considers that the proposed changes are significant, you may be required to submit a new application form for approval of the revised project.

- **Adverse Events.** If any unforeseen or adverse events occur, including adverse effects on participants, during the course of the project which may affect the ethical acceptability of the project, the Chief Investigator must immediately notify the UHEC Secretary on telephone (03) 9479 1443. Any complaints about the project received by the researchers must also be referred immediately to the UHEC Secretary.

- **Withdrawal of Project.** If you decide to discontinue your research before its planned completion, you must advise the UHEC and clarify the circumstances.

- **Annual Progress Reports.** If your project continues for more than 12 months, you are required to submit an *Ethics - Progress/Final Report Form* annually, **on or just prior to 12 February**. The form is available on the Research Services website (see above address). Failure to submit a Progress Report will mean approval for this project will lapse. An audit may be conducted by the UHEC at any time.

- **Final Report.** A Final Report (see above address) is required within six months of the completion of the project or by **31 July 2014.**

If you have any queries on the information above or require further clarification please contact me through Research Services on telephone (03) 9479-3589, or e-mail at: **humanethics@latrobe.edu.au**.

On behalf of the University Human Ethics Committee, best wishes with your research.

Ms. Lynda Boldt

Administrative Officer – Research
Acting Secretariat – University Human Ethics Committee
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LA TROBE UNIVERSITY

RESEARCH SERVICES

**MEMORANDUM**

| | |
|---|---|
| **To:** | **Mr. Adam Semciw, Department of Physiotherapy, FHS**<br>**Ms. Rachel Neate, Department of Physiotherapy, FHS** |
| **From:** | **Acting Secretary, La Trobe University Human Ethics Committee** |
| **Subject:** | **Review of Human Ethics Committee Application No. 13-005** |
| **Title:** | **What role do the deep hip stabilizers have in running?** |
| **Date:** | **14 May 2013** |

Thank you for submitting your modification request for ethics approval to the La Trobe University Human Ethics Committee (UHEC) for the project referred to above. The UHEC has reviewed and approved the following modifications which may commence now:

- **Change in procedures to:**
    - **Investigate two additional hip joint muscles (iliopsoas and quadratus femoris), as outlined in the request.**
    - **Collect kinematic data which involves the fixing of light-reflective markers to participants' skin with adhesive tape, as outlined in the request.**
- **Addition of Dr. Jodie McClelland as a co-investigator on the project.**

*Please note that your request has been reviewed by a sub-committee of the UHEC to facilitate a decision before the next Committee meeting. This decision will require ratification by the UHEC and it reserves the right to alter conditions of approval or withdraw approval at that time. However, you may commence prior to ratification and you will be notified if the approval status of your project changes.*

The following standard conditions apply to your project:

- **Limit of Approval.** Approval is limited strictly to the research proposal as submitted in your application while taking into account any additional conditions advised by the UHEC.
- **Variation to Project.** Any subsequent variations or modifications you wish to make to your project must be formally notified to the UHEC for approval in advance of these modifications being introduced into the project. This can be done using the appropriate form: *Ethics - Application for Modification to Project* which is available on the Research Services website at *http://www.latrobe.edu.au/research-services/ethics/HEC_human.htm*. If the UHEC considers that the proposed changes are significant, you may be required to submit a new application form for approval of the revised project.

- **Adverse Events.** If any unforeseen or adverse events occur, including adverse effects on participants, during the course of the project which may affect the ethical acceptability of the project, the Chief Investigator must immediately notify the UHEC Secretary on telephone (03) 9479 1443. Any complaints about the project received by the researchers must also be referred immediately to the UHEC Secretary.

- **Withdrawal of Project.** If you decide to discontinue your research before its planned completion, you must advise the UHEC and clarify the circumstances.

- **Monitoring.** All projects are subject to monitoring at any time by the UHEC.

- **Annual Progress Reports.** If your project continues for more than 12 months, you are required to submit an *Ethics - Progress/Final Report Form* annually, **on or just prior to 12 February**. The form is available on the Research Services website (see above address). Failure to submit a Progress Report will mean approval for this project will lapse.

- **Auditing**. An audit of the project may be conducted by members of the UHEC.

- **Final Report.** A Final Report (see above address) is required within six months of the completion of the project or by **31 July 2014.**

If you have any queries on the information above or require further clarification please contact me through Research Services on telephone (03) 9479-3589, or e-mail at: humanethics@latrobe.edu.au.

Ms. Lynda Boldt

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# Appendix B: Participant information and consent form

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## PARTICIPANT INFORMATION STATEMENT

| | |
|---|---|
| Project Title: | WHAT ROLE DO THE DEEP HIP STABILIZERS HAVE IN RUNNING? |
| Investigators | Mr Adam Semciw, Department of Physiotherapy, La Trobe University. A.semciw@latrobe.edu.au<br><br>Dr Tania Pizzari, Department of Physiotherapy, La Trobe University T.Pizzari@latrobe.edu.au<br><br>Miss Rachel Neate, Department of Physiotherapy, La Trobe University. Raneate@students.edu.au (Physiotherapy student) |

**What is this study about?**
This study aims to investigate the role of hip muscles in running. It also aims to determine the most accurate method of measuring hip muscle activity.

**What does participation in this study involve?**
To participate in this study, you will be asked to partake in one three hour testing session at La Trobe University, Bundoora. Prior to testing, you will be asked to fill out questionnaires which will aim to identify your current activity levels (approximately 5 minutes). You will be partially reimbursed $50 at the completion of the testing session (funding provided by the lower Extremity and Gait Studies program, La Trobe University).

The testing session will involve a technique called intramuscular electromyography (EMG). You will be asked to wear pants with a loose elasticised waist such as bike pants or shorts (a pair will be provided if needed). One of the investigators named above will mark and prepare eight sites just below your hip bone, where one surface electrode will be placed and seven intramuscular electrodes will be inserted. The intramuscular electrodes consist of extremely thin pieces of wire that enable information about muscle activity to be transferred from within your muscles, to a computer in order to be analysed. The electrodes will be inserted using a needle under the guidance of ultrasound. You might experience discomfort at this point; however this should only be minor and temporary. **You are offered the opportunity to withdraw your consent to participate if discomfort continues, or at any time if you wish, simply by informing the investigators**. In addition to collecting information about your muscles (EMG), we will also analyse the movements of the joints in your legs and your trunk. To do this, we will attach light reflective markers to your shoulders, hips, thighs, lower back, knees, ankles, heels and feet. These markers are sphere shaped and approximately 1cm in diameter (similar to a miniature table tennis ball) and they are fixed to your skin with surgical tape. Once electrodes have been inserted, you will be guided through a series of walking, running and exercise trials. You will finally be asked to push your leg against a resistance at maximal effort. You will be asked to complete these movements in view of 10 infra-red cameras that will detect the movement of the reflective markers attached to your body, and from this, a computer program can create an image of your moving body as you perform each activity. You will not be able to be identified from this image. This session will take up to 3.5 hours.

**If you decide not to participate, or you decide to withdraw your consent during the study, there will be no disadvantages, penalties or adverse consequences. This also applies to students of investigators involved in this study. You have the right to demand that data arising from your participation are not used in the research project provided that this right is exercised within four weeks of the completion of your participation in the project. Should you wish to withdraw your consent for your data to be used, you are asked to complete the "Withdrawal of Consent Form" or to notify the investigator by e-mail or telephone that you wish to withdraw your consent for your data to be used in this project.**

**What are the risks of the study?**
Intramuscular EMG procedures are considered safe with minimal risk. Possible risks include;

1) The insertion site may become infected. This risk is minimized through practice of a sterile technique by formally trained investigators.
2) The very small wire tip (2 mm in length) may break off the electrode during withdrawal. This is extremely rare and has never occurred in our laboratory. The wire is so small that there are no ill effects if the tip breaks off and is retained in the body.
3) You may feel unwell (sweating, dizziness or tunnel vision) during or immediately after intramuscular electrode insertion. This is usually brief and dealt with by having you seated or lying and in very rare events, may require testing to be cancelled. Mr Adam Semciw is trained in Senior first aid and will be present at every EMG testing session.

At the completion of your EMG testing session you may experience a mild, dull, bruise-like sensation around the electrode sites for up to two days. This is not abnormal and should not be a cause for alarm. If any mild discomfort does not subside after two days, or if you experience harsh or throbbing pain at any time you are advised to call Mr Adam Semciw on the number below, or seek medical assistance.

**What are the benefits of participating?**
Students who participate will gain exposure to a unique field or research. There are no other foreseen direct benefits. However, results from this study will help define optimum hip muscle activity during running, and potentially enable researchers and clinicians to develop targeted rehabilitation and preventative conditioning programs for running related injuries.

**What will happen to the results?**
Results from the questionnaires and EMG testing will be confidential and only accessible by the researchers named above. Results will be entered into a password protected computer using a number system so that no one other than the researchers will be able to identify you. Hard copies of questionnaires will be kept in a locked filing cabinet at La Trobe University. Records will be kept for 5 years following completion of the project and then destroyed.

The results of this project will appear in journal publications and conference presentations and the data may be used in future projects relating to the same testing procedures, but you will not be able to be identified in any of these reports. Results of the study will be available to you upon request.

**Who can I contact if I have any questions?**
Any questions regarding this project entitled "What role do the deep hip stabilizers have in running?" may be directed to Mr. Adam Semciw of the Department of Physiotherapy, La Trobe University on the telephone number (03) 9479 5851.

**If you have any concerns or complaints that the investigator has not been able to answer to your satisfaction, you may contact the Secretary, Human Ethics Committee, Research Services, La Trobe University, Victoria, 3086, (ph: 03 9479 1443, e-mail: humanethics@latrobe.edu.au). Please quote UHEC application reference number HEC 13-005.**

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## PARTICIPANT CONSENT FORM

WHAT ROLE DO THE DEEP HIP STABILIZERS HAVE IN RUNNING?

I, ......................................……………………………..., have read and understood the participant information statement and consent form, have had potential risks clearly explained to me, and any questions I have asked have been answered to my satisfaction. I understand that even though I agree to be involved in this project, I can withdraw from the study at any time, up to four weeks following the completion of my participation in the research. Further, in withdrawing from the study, I can request that no information from my involvement be used. I agree that research data collected during the project may be presented at conferences and published in journals and may be used in future projects relating to the same testing procedures, on condition that my name is not used.

I consent to having photographs and/ or videos taken during the testing session. I am willing for these images to be used solely for education and research purposes at physiotherapy schools at other universities in Australia and when presentations are made at conferences / workshops in National and International Settings – Tick box □

NAME OF PARTICIPANT (in block letters):

...............………………………………………..............................................................

Signature: ........................…………………………………….....................................

DATE: .............……..................

NAME OF INVESTIGATOR (in block letters):

ADAM SEMCIW

Signature: .........………………………………................……………………………

DATE: .............……...................





ABN 64 804 735 113
CRICOS Provider 00115M

**Appendix C: Testing protocol for cross-sectional study**

Preparation and set-up

- Participant information and consent form signed
- Participant stance leg dominance determined by three tests – stamp out an imaginary fire; step up onto a block; and kick a ball towards a target with the skill-dominant leg used for at least two of the three tasks. The contralateral leg was considered the stance-dominant leg (Bullock-Saxton et al., 2001).
- The stance dominant hip was then marked up for standardized locations for bipolar fine-wire intra-muscular electrode insertions into anterior GMed, middle GMed, posterior GMed, anterior GMin, and posterior GMin using a sterile technique and real-time ultrasound guidance (HDI 3000; Advanced Technology Laboratories, Washington, WA) (Semciw, Green, et al., 2013; Semciw, Pizzari, & Green, 2013).
- The electrodes for each GMed and GMin segment were then connected to a wireless Trigno 16-channel EMG system (Delsys® Inc, Boston, MA).
- Retro-reflective markers (Vicon®, Oxford, UK) were attached to selected anatomical landmarks.
- An accelerometer (Trigno; Delsys® Inc, Boston, MA) with 3 degrees of freedom was secured either to the top of the iliac crest, distal lateral-femur, or distal anteromedial tibia depending on the exercise being performed.

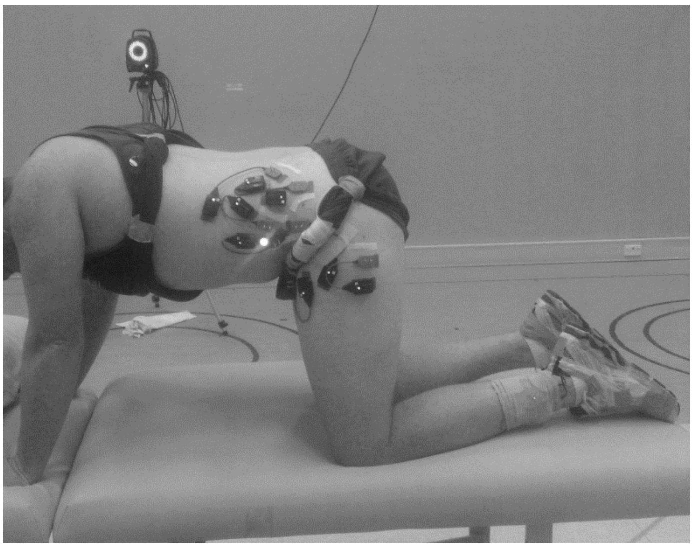


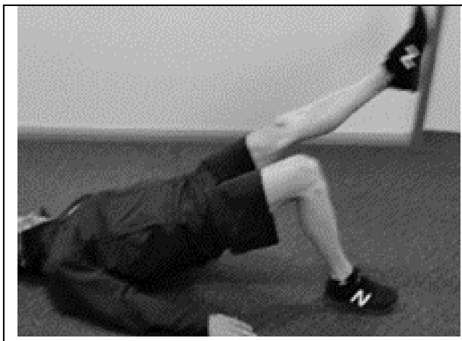
*Figure 1. GMed and GMin wireless electrode setup*

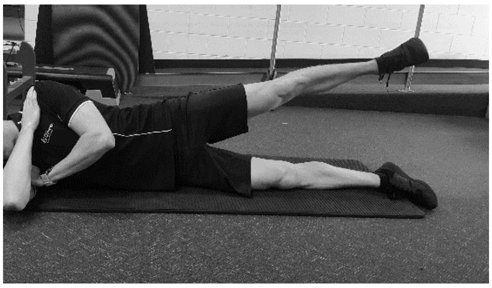
Testing

- Five minutes of walking and open chain hip abduction movements were performed to ensure clear signals were being obtained from each electrode.
- Five minutes of walking and running for warm-up
- Ten exercises were performed in a randomised order
- Practice repetitions were performed until satisfactory technique was achieved
- Three trials were performed for each exercise with up to 2 minutes rest allowed between trials and exercises

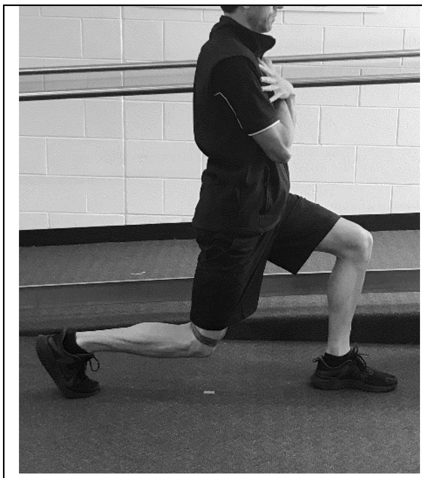
*Table 1. Exercise descriptions*

| Exercise | Description |
|---|---|
| Single leg bridge | Supine with testing knee flexed 90°, hip flexed 45°, and other leg straight. Raise hips off floor to achieve a neutral trunk, hip and knee alignment with thighs parallel pushing through |

| | |
|---|---|
|  | testing leg for I beat, then lower back to the start position for 1 beat (40bpm).<br><br>Repeat for 6 repetitions. |
| Single-leg squat<br> | Single-leg stance on testing leg, hands across chest with non-testing leg raised forward off floor, squat down by flexing through hip, knee and ankle as far as can without lifting heel for 1 beat then straighten through hip, knee, and ankle back to start position for 1 beat (40 bpm). Repeat for 6 repetitions. |
| Side-lie abduction<br> | Side lie with testing leg facing up and both legs straight and in line with trunk (neutral hip position). On 1 beat raise top leg to approximately 30°, then lower back to start position for 1 beat (50 bpm). Repeat for 6 repetitions. |
| Side-lie abduction with internal rotation<br> | Side lie with testing leg facing up with heel pointing towards the ceiling in maximum hip internal rotation. Both legs straight and in line with trunk (neutral hip position). On 1 beat raise top leg to approximately $30^0$, then lower back to start position for 1 beat (50 bpm) keeping heel pointing towards ceiling throughout.<br>Repeat for 6 repetitions. |

| | |
|---|---|
| Side-lie abduction with external rotation  | Side lie with testing leg facing up with heel pointing towards the ceiling in maximum hip external rotation. Both legs straight and in line with trunk (neutral hip position). On 1 beat raise top leg to approximately $30^0$, then lower back to start position for 1 beat (50 bpm) keeping toes pointing towards ceiling throughout.<br>Repeat for 6 repetitions. |
| Side-lie clam  | Side lie with testing leg facing up with both hips flexed 45° and knees flexed 90°. On 1 beat, keeping feet together raise top knee off bottom knee to approximately 30°, then lower back to start position for 1 beat (40 bpm).<br>Repeat for 6 repetitions. |
| Resisted hip abduction-extension  | Stand shoulder-width apart, yellow elastic resistance looped just taut at ankles. On 1 beat, stand on stance testing leg and take non-testing leg into a backward diagonal position (45°) of combined hip extension and abduction toward a set mark on the floor (30-cm square), then return to start position for 1 beat (60 bpm).<br>Repeat for 6 repetitions. |
| Running man | Stand shoulder-width apart. On I beat, stand on stance testing leg and bend non-testing hip and knee to 90°, then extend non-testing hip and knee back to start position for 1 beat (90 bpm). The upper limbs move to replicate running. Repeat for 6 repetitions. |

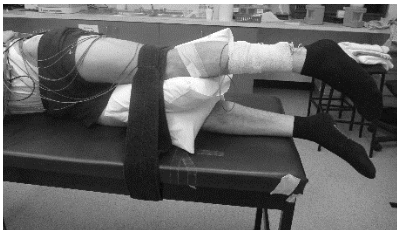
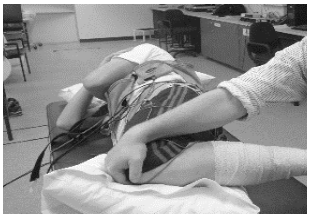
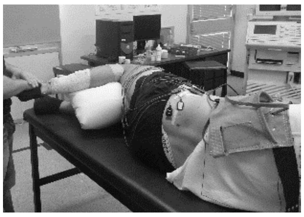
| | |
|---|---|
|  | |
| Split squat with elastic resisted rear limb hip internal rotation  | Position testing knee over ground mark, arms crossed, step out a comfortable distance forward with non-testing leg into a split-squat position keeping a vertical trunk position such as to maintain even weight distribution between legs until achieve approximately $90^0$ hip and knee flexion for non-testing leg such that knee doesn't go beyond the toes. Elastic band looped taut positioned slightly above medial femoral condyle level of rear testing leg and providing a lateral force. For testing leg, participant instructed to rotate middle of anterior knee towards first toe against resistance. Hold position for 10 seconds and repeat 3 times. |
| Split squat with elastic resisted rear limb hip external rotation | Position testing knee over floor marking, arms crossed, step out a comfortable distance forward with non-testing leg into a split-squat position keeping a vertical trunk position such as to maintain even weight distribution between legs until achieve approximately $90^0$ hip and knee flexion for non-testing leg such that knee doesn't go beyond the toes. Elastic band looped taut positioned |

| | |
|---|---|
|  | slightly above lateral femoral condyle level of rear testing leg and providing a medial force. For testing leg, participant instructed to rotate middle of anterior knee towards fifth toe against resistance. Hold position for 10 seconds and repeat 3 times. |

- Following 3 minutes rest, for normalisation purposes six different hip actions were performed as a maximum isometric voluntary contraction (MVIC) to determine a true maximum value for each segment for each participant.
- Three trials for 3 seconds for six different hip actions. With verbal encouragement, each MVIC trial was performed against a secured Velcro strap 3 times for 3-second duration, whereby participants were instructed to slowly increase muscle contraction against the resistance over 1 second and sustain a maximum effort for 3 seconds then slowly decrease muscle contraction over 1 second with 3-minute rest between trials.

*Table 2. Maximum voluntary isometric contractions of the hip*

| Hip action | Position | Resistance |
|---|---|---|
| Abduction  | Side lie pillow between knees (hip and knee anatomical position) | Belt secured around participants knee and the plinth |

| | | |
|---|---|---|
| Abduction in Internal rotation  | Side lie pillow between knees (hip maximum hip internal rotation and knee anatomical position) | Belt secured around participants knee and the plinth |
| Flexion  | Side lie pillow between knees (hip anatomical position and knee flexion $90^0$) | Applied by investigator on anterior aspect of participants distal femur |
| Extension  | Prone (hip anatomical position and knee flexion $90^0$) | Belt secured around the participants foot and the plinth |
| Internal Rotation  | Side lie (hip anatomical position and knee flexion $90^0$) | Applied by investigator at lateral border of participants foot |
| Clam  | Side lie pillow between knees (hip flexion $45^0$ and knee flexion $45^0$) | Belt secured around participants knee and the plinth |

## Appendix D: Original systematic review

### What exercises produce the greatest muscle activation for the gluteus medius and minimus: a systematic review.

## 1.0 Abstract

In contemporary physiotherapy and rehabilitation settings there has been increased focus on prescribing therapeutic exercises to address gluteal dysfunction for common lower limb and lower back musculoskeletal pathologies. What is not known however, is what therapeutic exercises produce the greatest amount of muscle activation for the different segments of the gluteus minimus and medius muscles. It was therefore the aim of this systematic review, to investigate the current literature for healthy subjects on such a topic looking specifically at electromyographical (EMG) studies since EMG has long been accepted as the outcome of choice in determining levels of muscle activity for specific muscles.

Twenty-one studies that met the inclusion criteria were included into this review. There were no studies found that had investigated therapeutic exercises for the gluteus minimus muscle, hence this review focussed on exercises for the gluteus medius. The methodological quality of the included studies was generally good but there were some differences between the studies making it difficult to compare results. Some common trends did emerge across the studies when exercises were analysed in weight-bearing and non-weight bearing positions. Weight-bearing exercises generally produced higher activation levels than non-weight bearing ones. Only one study analysed therapeutic exercises for the three segments of the gluteus medius and found that that the weight-bearing wall press exercise was the number one ranking exercise for that study generating the highest levels of EMG activation for all three segments. The side-lie-plank / bridge; side-lie hip abduction; single-leg squat; and forward and lateral step-up-and-down exercises were generally the highest-ranking exercises for their respective studies for the

middle segment of the gluteus medius generating very-high EMG levels to produce strength adaptations.

Heterogeneity in factors including EMG settings, electrode type and placement, normalisation method, and exercise characteristics made it difficult to draw precise conclusions on the most effective exercises for the gluteus medius, although some general exercise trends did emerge from this review. No conclusions could be drawn on the most effective exercises for the gluteus minimus muscle or on pathological populations.

## 2.0 Introduction

With emerging knowledge of common musculoskeletal pathologies of the lower limb and lower back there has been an increased focus in contemporary physiotherapy and rehabilitation settings of prescribing therapeutic exercises to address gluteal muscle dysfunction (Boling, Bolgla, Mattacola, Uhl, & Hosey, 2006; Fredericson & Wolf, 2005; Sled, Khoja, Deluzio, Olney, & Culham, 2010; Tyler, Nicholas, Mullaney, & McHugh, 2006). Previous research has shown that there is an association of gluteal dysfunction with many common lower limb pathologies including; patello-femoral pain syndrome (Aminaka, Pietrosimone, Armstrong, Meszaros, & Gribble, 2011; Baldon et al., 2011; Bolgla, Malone, Umberger, & Uhl, 2011); ilio-tibial band friction syndrome (Fredericson et al., 2000); exercise-related leg pain (Franettovich, Chapman, Blanch, & Vicenzino, 2010) ; achilles tendinopathy (Azevedo, Lambert, Vaughan, O'Connor, & Schwellnus, 2009) ; lateral ankle sprains (Beckman & Buchanan, 1995) ; anterior cruciate ligament injuries (Hewett et al., 2005; McLean, Huang, & van den Bogert, 2005; Sigward, Ota, & Powers, 2008); femoro-acetabular impingement (Casartelli et al., 2011); hip osteoarthritis (Amaro, Amado, Duarte, & Appell, 2007; Grimaldi et al., 2009); and groin (Morrissey et al., 2012; O'Connor, 2004), and low back pain . By prescribing therapeutic exercises to address the gluteal dysfunction it is hypothesised to assist in restoration of normal activity and function.

The main function of the gluteus medius (GMed) in healthy adults is to provide coronal plane pelvic and hip stability during single leg stance controlling eccentric hip adduction and internal rotation in many activities such as running, jumping and stair climbing (Flack, Nicholson, & Woodley, 2012; Gottschalk, Kourosh, & Leveau, 1989). In an open-chain position GMed also functions as an abductor and rotator of the hip, and during gait the posterior portion of GMed provides support throughout mid-stance whilst the anterior portion contributes significantly towards the end of mid-stance (Anderson & Pandy, 2003). The gluteus minimus (GMin) assists GMed during gait with the posterior portion providing support throughout mid-stance and the anterior portion contributing towards the end of mid-stance (Anderson & Pandy, 2003). The GMin also provides stability to the head of the femur in its socket (Beck, Sledge, Gautier, Dora, & Ganz, 2000; Kumagai, Shiba, Higuchi, Nishimura, & Inoue, 1997; Oi et al., 2003).

Three distinct segments (anterior, middle and posterior) with separate innervations and different muscle fibre orientations have been identified for the GMed and correspondingly two different segments have been identified for the GMin (Beck et al., 2000; Flack et al., 2012; Gottschalk et al., 1989). Phasic activity of the different segments of the GMed and GMin have been identified in EMG studies of gait (Anderson & Pandy, 2003) suggesting a "muscles within muscles concept" whereby distinct segments of a muscle have different functional characteristics and potential for independent control (Wickham & Brown, 1998).

Electromyography (EMG) has long been established and has evolved over several decades of availability as the method of choice for measuring the physiological process of muscle activation in generating force and movement for a particular muscle. (Cram, Kasman, & Holtz, 1998; De Luca, 1997; Soderberg & Cook, 1984; Soderberg & Knutson, 2000). In a clinical setting where comparative analysis of an EMG signal is required and because the EMG signal amplitude can be highly variable and difficult to control for, factors such as electrode application and placement, perspiration and temperature, muscle fatigue, contraction velocity, muscle length and size, cross talk from nearby muscles, subcutaneous fat, and task execution etc., normalisation is usually applied (De Luca, 1997; Lehman & McGill, 1999). Normalisation is a universally advocated concept for measuring and comparing levels of muscle activation for different exercises between subjects or between-days within a subject by eliminating such factors and improving group homogeneity (Burden, 2010; De Luca, 1997; Soderberg & Cook, 1984; Soderberg & Knutson, 2000). This technique has also been previously shown to have good repeatability for the EMG amplitude and EMG profile with improved test-retest, within-day, and between-day reliability of un-normalised EMGs (Burden, 2010; Hug, 2011; Soderberg & Knutson, 2000).

The normalised EMG amplitude is usually expressed as a percentage of the maximum EMG amplitude for an individual muscle and provides an approximate estimate of the level of intensity for a particular exercise (Andersen et al., 2006). Strength adaptations have been shown in the literature where the intensity of an exercise has ranged between 40 to 95% of maximal intensity (Fry, 2004), however it has been generally agreed that intensities of at least 60% should be used for effective gains to occur in untrained individuals (Kraemer et al., 2002). With a dose-response relationship existing between exercise intensity and rate of muscle strength adaptations, it would be expected that higher levels of neuromuscular activation will yield greater strength gains (Campos et al., 2002; Kraemer et al., 2002).

When prescribing specifically GMed and GMin exercises, what is not known is which exercises produce the great amount of muscle activation (normalised EMG) for each particular segment of the muscle. A previous systematic review was published in 2010 (French, Dunleavy, & Cusack) on activation levels for GMed therapeutic exercises and contained 15 papers that compared similar exercises between studies for the middle gluteus medius segment in healthy and pathological subjects. With wide variations in methodology of the included studies, comparing similar exercises across the studies is difficult to perform especially when there are healthy and pathological subjects. This review differed to the previous review by containing 15 different papers, and focused on comparing and ranking therapeutic exercises within the studies for the different segments of the GMed and GMin for healthy subjects. At the time of writing this review, to the author's knowledge there had been no previously published systematic reviews for therapeutic exercises for the GMin.

The aim of this review therefore was to determine what exercises for the GMed and GMin were the most effective in terms of producing the highest normalised EMG levels for the different segments of the respective muscles.

## 3.0 Method

### 3.1 Search strategy

A systematic literature search was conducted of MEDLINE, CINAHL, EMBASE, AUSPORT, SPORTDiscus, PEDRO and the Cochrane Library from inception to 4$^{th}$ week March 2012. These databases were searched using free-text words, keywords mapped to subject headings, and filters were applied for human subjects where possible. Boolean operators were used to combine the key words listed (Table 1).

Table 1. *Search strategy key words*

| Concept 1 (Gluteus medius and gluteus minimus) | Concept 2 (Electromyography) |
|---|---|
| Glute* or gluteal or gluteus | Electromyography or electromyographic or electromyograph* |
| Buttock or buttocks | EMG |
| Hip rotator or hip rotation | Electrode or electrodes |
| Hip extensor or hip extender or hip extension | Muscle activity or muscle activation |
| | Peak amplitude |
| | Muscle function |
| | Muscle intensity |
| | Muscle contraction |
| | Muscle strengthen* |

Further relevant trials were identified through grey literature searching using citation tracking of Google Scholar, and reference scanning of already included full-text studies were undertaken to capture any trials not previously identified from the main search strategy.

### 3.2 Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were determined prior to administering the search strategy (Table 2).

Table 2. *Inclusion criteria*

| Concept | Inclusion |
|---|---|
| Study design | RCTs (quasi and randomised controlled trials); cross-sectional studies; case studies; single group pre- and post-test designs. |
| Participants | Humans (healthy) |
| Intervention | Therapeutic exercise |
| Outcome | Electromyography / EMG recording of gluteus medius and minimus (normalised) |
| Comparison | None specified |

Since the majority of the studies in this area of research were either cross-sectional or single group pre- and post-test design, it was decided that limiting the studies to only randomised controlled trials would restrict the ability to provide a comprehensive review of the literature. This type of study inclusion criteria has been applied previously in similar systematic reviews (Crow, Pizzari, & Buttifant, 2011; Smith et al., 2009). Clinical commentary or opinion articles were excluded from this review as were unpublished material such as theses, abstracts, and conference proceedings.

Studies comprising of only healthy participants were included in this review, as it was expected that studies including pathological participants would confound the data on determining the most effective gluteus medius and minimus exercises. A study with pathological participants was only included if there was a group of healthy controls that data could be extracted for.

EMG was selected as the outcome measure of interest since as discussed previously that when normalised it has been long established and universally advocated as the method of choice in measuring and comparing muscle activity between different exercises and individuals as a ratio or percentage of a reference voluntary contraction (Burden, 2010; De Luca, 1997; Soderberg & Cook, 1984; Soderberg & Knutson, 2000).

Studies containing at least one type of therapeutic strengthening exercises each for the gluteus medius and minimus were included in this review ranging from exercises using different types of commonly available rehabilitation equipment (for e.g. steps, thera-band resistance, and Airex mats) in weight-bearing (WB) and non-weight-bearing (NWB) positions since these were generally the forms of exercise prescribed in the typical rehabilitation setting and performed in the home environment. Studies assessing exercises using custom-made devices or commercial gym equipment were excluded from this review, as were dynamic exercise activities such as walking, hopping and running. A study with these forms of excluded exercise was only included if partial data extraction could obtain results for at least one therapeutic exercise.

From the initial search yield, articles were imported into Endnote version X5, duplicate papers were removed, and the abstract and title of the remaining papers were screened independently through application of the inclusion and exclusion criteria by two reviewers (DM and TP) for level of agreement. Full-text was then obtained for the remaining studies to determine appropriateness for inclusion into the review through consultation and consensus between the reviewers.

### 3.3 Quality assessment

Methodological quality of included studies in this review were assessed independently by two reviewers (DM, TP) using a previously validated checklist for randomised and non-randomised studies (Downs & Black, 1998). The Downs and Black checklist has been used previously in systematic reviews involving mixed study designs (Cusimano & Kwok, 2010; Hignett, 2003; Stuber & Smith, 2008) and has been shown to have good intra-rater ($r = 0.88$) and inter-rater ($r = 0.75$) reliability (Downs & Black, 1998). Due to all of the studies included in this review being cross-sectional it was decided by the two reviewers to modify the Downs and Black checklist to criteria relevant to the type of studies being assessed in this review. Katrak, Bialocerkowski, Massy-Westropp, Kumar, and Grimmer (2004) recommended that since there was no gold-standard critical appraisal tool for any type of study design, selection of a critical appraisal tool should be appropriate for its particular use. The 27 criteria of the original Downs and Black checklist covered topics such as reporting, internal and external validity, and power were narrowed down to 15 criteria (score out of 16) through mutual consensus between the reviewers. Questions 8, 9, 13 14, 17, 19, 21-26 were eliminated from the original checklist as they were considered irrelevant to the studies being examined. Discrepancies in quality assessment ratings between reviewers were resolved through discussion such that an agreement on a score could be achieved. Studies were not excluded from this review on the basis of quality providing they met the necessary inclusion and exclusion criteria.

### 3.4 Data extraction

The articles included in this review were read and the applicable data were extracted by one reviewer (DM) and verified by a second (TP) using a standardised form (York, 2001) that was modified for this review (Appendix A). Before data extraction commenced, the main study characteristics of relevance to this review were mutually agreed upon between the reviewers and included; participant characteristics; electrode placement; normalisation method; exercise characteristics; and the results and conclusions. Where studies had healthy and pathological participants performing therapeutic exercises, data were extracted for the healthy participants. Data were also partly extracted from studies involving participants performing therapeutic exercises as one part of the exercise protocol that also included hopping or other dynamic activities. Electromyographical technical data for collection, processing and analysis were also extracted from all the included studies as it was important to disseminate the data for comparison between studies since it has been shown previously that for example the choice of the low-pass filter during EMG signal processing considerably affects both the shape and the properties of the computer-averaged EMG profiles for the gluteus medius muscle (Kleissen, 1990). EMG measurement noise can also be affected by inappropriate skin preparation and poor selection of active electrodes influencing the EMG signal amplitude (Clancy, Morin, & Merletti, 2002).

**3.5 Data analysis**

A meta-analysis was not performed in this review due to the type of included study designs, and the heterogeneity between the studies with methodology including electrode placement; normalisation method; exercise characteristics; and EMG technical features making it difficult to pool data.

For simplicity in analysing the exercises for activation levels across the studies, exercise results were divided into non-weight-bearing and weight-bearing, and then further characterised into very-high (>60% MVC), high (41-60% MVC), moderate (21-40% MVC) or low (0-20% MVC) levels of activation as has been determined in previous EMG studies (DiGiovine, Jobe, Pink, & Perry, 1992; Escamilla et al., 2010).

Because of the specific methodological differences between the studies in exercise characteristics such as position; technique; active range of movement; speed of contraction; stabilisation methods; repetitions; rest periods etc. it was difficult to compare activation levels for a similar exercise hence the focus was on determining the most effective exercises within each of the studies.

## 4.0 Results

### 4.1 Flow of studies through the review

From 4223 articles identified from the initial search strategy, 1883 remained following removal of duplicates and 31 articles were obtained in full-text for further evaluation after application of the selection criteria (Figure 1). From reference scanning and citation tracking of the full-text articles one further article was obtained. After evaluation of the full-text, 11 studies were excluded and the remaining 21 were included in the review. Three studies were excluded because they did not normalise the EMG values for the gluteus medius or minimus muscles (Blanpied, 1999; Flanagan, Salem, Wang, Sanker, & Greendale, 2003; Stevens et al., 2007); and four studies did not normalise the EMG values (Earl, 2005; McCurdy et al., 2010; Schmitz, Riemann, & Thompson, 2002; Wilson, Capen, & Stubbs, 1976). Two studies were conference abstracts (Bolgla et al., 2009; Krause et al., 2009a); one study did not provide data for the individual exercises instead giving a mean percent MVC for the four included exercises (Oliver, Dwelly, Sarantis, Helmer, & Bonacci, 2010); and one study translated from French did not assess therapeutic exercise (Manueddu, Blanc, & Taillard, 1989).

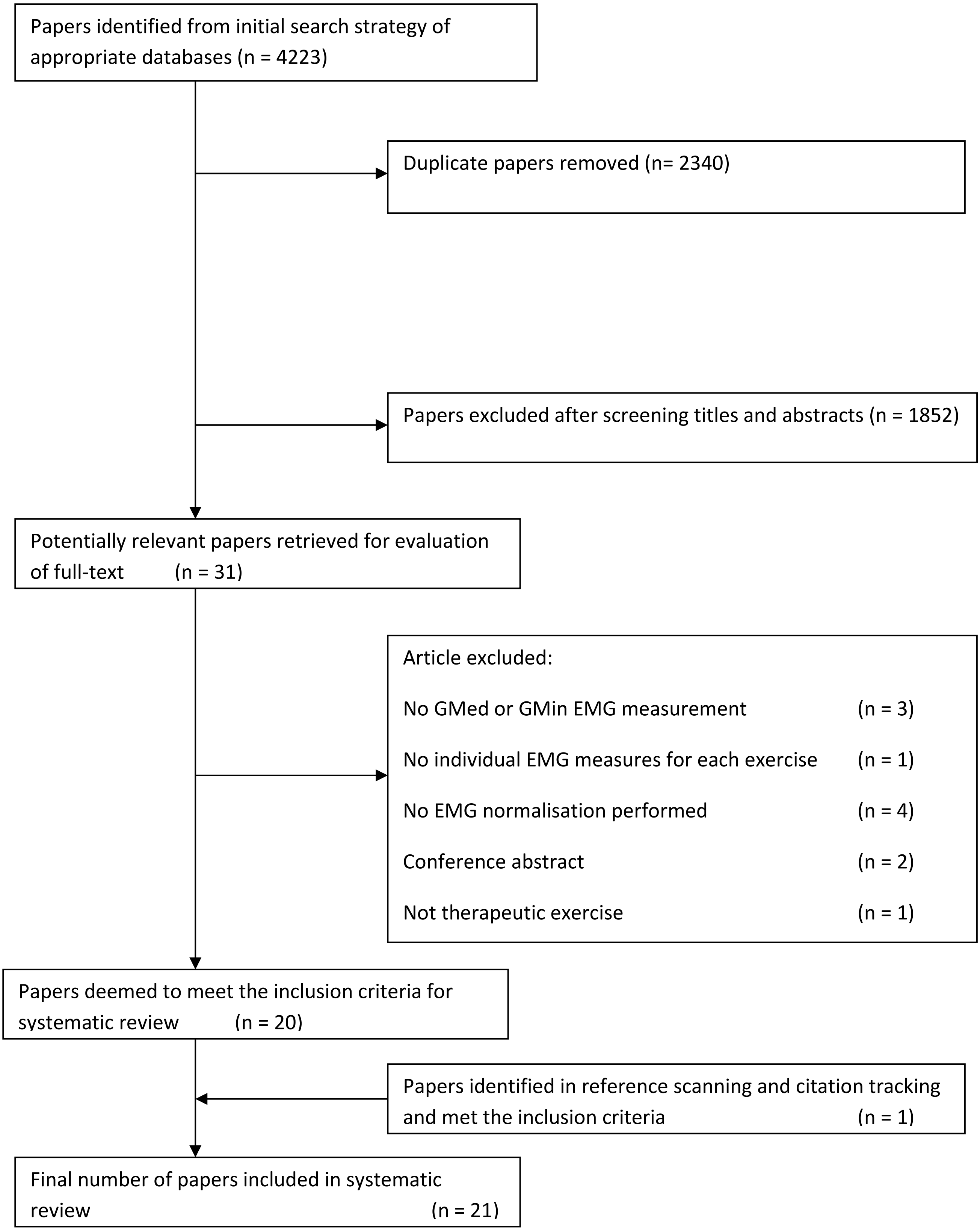



*Figure 1.* Flow of studies through the review

### 4.2 Methodological assessment results

Using a modified Downs and Black checklist specific for the type of studies included in this review, it was found that the quality of the studies' design ranged from scores of 7 to 13 out of a possible total score of 16 (Table 3). All included studies except Boren et al. (2011) achieved a reasonable quality score of at least 11. Boren et al. scored 7 and compared to all the other included studies failed to report on baseline characteristics of their experimental group such as age, weight, height and sex, and provided no estimates of the random variability (for e.g. standard deviations) for their results. There was also no reporting on use of statistical tests for analysis of the results. Generally, for the reporting section of the checklist, there was considerable variability on the specifics of participants' inclusion and exclusion criteria listed in individual studies. Some studies were quite vague only reporting that their subjects were healthy (Hertel, Sloss, & Earl, 2005; McGill & Karpowicz, 2009; Oliver & Dougherty, 2009; Philippon et al., 2011; Tateuchi et al., 2006) whilst all the others reported specific pathologies and injury histories that excluded potential participants. A few studies were even more specific with their inclusion criteria standardising for activity levels (Distefano, Blackburn, Marshall, & Padua, 2009; Felício, Dias, Silva, Oliveira, & Bevilaqua-Grossi, 2011; McBeth, Earl-Boehm, Cobb, & Huddleston, 2012; Oliver, Dwelly, et al., 2010) and body mass index (McBeth et al., 2012). All the studies except Mercer et al. (2009) provided little or no information on the source of their participants and how they were recruited as well as whether they were representative of the population that they were recruited from which could make it difficult with repeatability of the exercise results in the clinic. A significant methodological flaw of all the included studies was the lack of reporting on whether there was a blinded investigator analysing EMG levels to reduce experimenter bias on the results. Another area that was generally poorly executed in the methodology of the studies was performing

Table 3. *Methodological quality of the included studies using a modified Downs and Black checklist*

| | Ayotte et al., 2007 | Bolgla and Uhl, 2005 | Boren et al., 2011 | Boudreau et al., 2009 | Distefano et al., 2009 | Dwyer et al., 2010 | Ekstrom et al., 2007 | Felicio et al., 2011 | Hertel at al., 2005 | Krause et al., 2009 | Lubahn et al., 2011 | McBeth et al., 2012 | McGill and Karpowicz, | Mercer et al., 2009 | Oliver et al., 2010 | Oliver and Dougherty, | O' Sullivan et al., 2010 | Petrofsky et al., 2005 | Philippon et al., 2011 | Soderburg et al., 1987 | Tateuchi et al 2006 |
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| 1. *Is the hypothesis/aim/objective of the study clearly described?* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2. *Are the main outcomes to be measured clearly described in the Introduction or Methods section?* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3. *Are the characteristics of the patients included in the study clearly described?* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4. *Are the interventions of interest clearly described?* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5. *Are the distributions of principal confounders in each group of subjects to be compared clearly described?* | 2 | 2 | 0 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| 6. *Are the main findings of the study clearly described?* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7. *Does the study provide estimates of the random variability in the data for the main outcomes?* | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 10. *Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?* | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| 11. *Were the subjects asked to participate in the study representative of the entire population from which they were recruited?* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12. *Were those subjects who were prepared to participate, representative of the entire population from which they were recruited?* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15. *Was an attempt made to blind those measuring the main outcomes of the intervention?* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 16. *If any of the results of the study were based on "data dredging", was this made clear?* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 18. *Were the statistical tests used to assess the main outcomes appropriate?* | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 20. *Were the main outcome measures used accurate (valid and reliable)?* | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 27. *Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%?* | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total score (0-16) | 12 | 11 | 7 | 11 | 12 | 13 | 11 | 11 | 11 | 12 | 12 | 13 | 12 | 13 | 11 | 12 | 12 | 11 | 11 | 12 | 11 |

power calculations to determine sample size with only three studies (Dwyer, Boudreau, Mattacola, Uhl, & Lattermann, 2010; McBeth et al., 2012; Mercer et al., 2009) undertaking this.

### 4.3 Characteristics of the included studies

The 21 included studies for this review are summarised in Tables 4 and 5. All of the studies were cross-sectional in design with Hertel, Sloss and Earl (2005) and Soderburg et al. (1987) having comparison groups. Hertel et al. had three control groups equally divided into similar foot types whilst Soderburg et al. had a control group and a knee pathology group. Sample sizes of the included studies ranged from 6 to 44 participants. All but one (Felício et al., 2011) of the studies included a mixture of males and females in their third decade of life. All of the studies recruited from a university setting except for Mercer, Gross, Sharma and Weeks (2009) who included community dwelling participants aged in their eighth decade and Ayotte, Stetts, Keenan and Greenway (2007) who recruited from the Defence Force.

Surface EMG measurements on the dominant middle portion of GMed were used in almost all studies. One study (O'Sullivan, Smith, & Sainsbury, 2010) recorded EMG measurements for the anterior, middle and posterior portions of the GMed. Six different electrode placement methods for the middle portion of GMed were described in this review with 13 studies (Ayotte et al., 2007; Bolgla & Uhl, 2005; Boudreau et al., 2009; Distefano et al., 2009; Dwyer et al., 2010; Felício et al., 2011; Hertel et al., 2005; Krause et al., 2009b; Lubahn et al., 2011; McBeth et al., 2012; O'Sullivan et al., 2010; Oliver, Dwelly, et al., 2010; Soderberg et al., 1987) positioning the electrode one-third to one-half the distance from the mid-iliac crest to the greater trochanter.  One study (Philippon et al., 2011)  used fine-wire EMG measurements

Table 4. *Summary of included studies*

| Study | Quality score (out of 16) | Design | Participants | EMG electrode type and placement | Normalisation method | Exercise characteristics | Results ( ranking and %MVIC) / Conclusions |
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| Ayotte et al. (2007) | 12 | Cross-sectional. | n =23 (16 males) healthy from Department of Defence. Mean age 31.2 ± 5.8 yrs. | Surface EMG for GMed (33% distance from iliac crest to greater trochanter) dominant leg. | MVIC av. of 3 reps using Biodex dynamometer over lateral femoral condyle in side-lie $0^0$ hip abd, neutral flex / ext. 1 min rest between reps. | • Exercises – 5 unilateral exercises randomised: (1) wall squat, (2) mini squat, (3) forward step-up, (4) lateral step-up, and (5) retro step-up.<br>• Repetitions – 3 of 1.5 secs concentric and 1.5 eccentric phases set to a metronome (40 b/min). Practice reps performed prior to testing protocol.<br>• Rest time of 5mins between MVIC testing and exercises, but not stated for between exercises. | • (1) wall squat 52 ± 22; (2) forward step-up 44 ± 17; (3) lateral step-up 38 ± 18; (4) retro step-up 37 ± 18; and (5) mini squat 36 ± 17.<br>• Both the wall squat and forward step-up elicit sufficient GMed EMG peak signal to strengthen the GMed. |
| **Bolgla and Uhl (2005)** | **11** | **Cross-sectional.** | **n = 16 (8 males) healthy from local university. Mean age 27 ± 5 yrs.** | **Surface EMG for GMed (1/3 distance between iliac crest and greater trochanter) over (R) GMed.** | **MVIC 3 reps 3-5 secs in side lie $25^0$ hip abd against resist. strap over lateral femoral condyle. 1 min rest between reps.** | • **Exercises – 6 randomised: (1) NWB side lie hip abd; (2) NWB stand hip abd; (3) NWB stand hip flex hip abd; (4) pelvic drop in stand; (5) WB (L) hip abd; and (6) WB with flex (L) hip abd.**<br>• **Repetitions – 15 set to a metronome (60 b/min) of 1 beat up, 1 beat down and 1 beat rest. 8-10 familiarisation reps 10mins before testing protocol.**<br>• **Rest time of 3 mins between exercises but not stated between MVIC testing and exercises.** | • **(1) pelvic drop 57 ± 32; (2) WB with flex (L) hip abd 46 ± 34; (3) WB (L) hip abd 42 ± 27; (4) NWB side lie hip abd 42 ± 23; (5) NWB stand hip abd 33 ± 23; (6) NWB stand flex hip abd 28 ± 21.**<br>• **The WB exercises and NWB side-lie abd resulted in greater muscle activation because of greater external torque applied to GMed.** |
| Boren et al. (2011) | 7 | Cross-sectional. | n = 26 healthy from university and surrounds. | Surface EMG for GMed (positioned per standard EMG protocol) dominant leg. | MVIC 3 reps of 5 secs in standard MMT protocol position against resist. strap on distal femur. 1 min rest between reps. | • Exercises – 22 randomized: (1) side plank abd DL down; (2) side plank abd DL up; (3) single limb squat; (4) clamshell position 1; (5) clamshell position 2; (6) clamshell position 3; (7) clamshell position 4; (8) front plank with hip ext; (9) side lie abd; (10) lateral step-up; (11) skater squat; (12) pelvic drop; (13) hip | • (1) side plank abd DL down 103.11; (2) side plank abd DL up 88.82; (3) single leg squat 82.26; (4) clamshell position 4 76.88; (5) front plank with hip ext 75.13; (6) clamshell position 3 67.63; (7) side lie abd 62.91; (8) clamshell position 2 62.45; (9) lateral step-up 59.87; (10) skater squat 59.84; (11) pelvic |

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| | | | | | | circumduction stable; (14) dynamic leg swing; (15) single limb deadlift; (16) single limb bridge stable; (17) forward step-up; (18) single limb bridge unstable; (19) quadruped hip ext DOM; (20) gluteal squeeze; (21) hip circumduction unstable; and (22) quadruped hip ext non DOM.<br>• Repetitions – 8 set to a metronome (60 b/min) of 1 beat up and 1 beat down including 3 practice reps.<br>• Rest time of 2mins between exercises. Rest time not stated between MVIC testing and exercises. | drop 58.43; (12) hip circumduction stable 57.39; (13) dynamic leg swing 57.30; (14) single limb deadlift 56.08; (15) single limb bridge stable 54.99; (16) forward step-up 54.62; (17) single limb bridge unstable 47.29; (18) clamshell position 1 47.23; (19) quadruped hip ext DOM 46.67; (20) gluteal squeeze 43.72; (21) hip circumduction unstable 37.88; and (22) quadruped hip ext non DOM 22.03.<br>• In order to maximally challenge gluteus medius, use a front plank with hip ext, single leg squat and a side plank on either extremity with hip abd. |
| **Boudreau et al. (2009)** | **11** | **Cross-sectional.** | **n = 44 (22 males) healthy. Mean age 23.3 ± 5.1yrs** | **Surface EMG for GMed (prox. 1/3 of distance between iliac crest and greater trochanter ant. to the GMax) bilaterally.** | **RVC 3 reps of 3 secs in stand pushing against a band around lower legs. 30 sec rest between reps.** | **• Exercises – 3 randomised: (1) single leg squat; (2) lunge; and (3) step-up and over.<br>• Repetitions – 3 for each exercise. 2 practice reps for each exercise before testing.<br>• Rest – 30 secs between trials and 2 mins between exercises.** | **• Dominant side: (1) single leg squat 30.1 ± 9.1; (2) lunge 17.7 ± 8.8; and (3) step-up and over 15.2 ± 6.9.<br>• Non-dominant side: (1) lunge 19.0 ± 11.7; (2) step-up and over 16.8 ± 10.4; and (3) single leg squat 12.0 ± 7.5.<br>• Activation of both the dominant and non-dominant GMed during all exercises were less than 20% MVC highlighting the importance of GMed as a pelvic stabilizer.** |
| Distefano et al. (2009) | 12 | Cross-sectional. | n = 21 (9 males) healthy. Mean age 22 ± 3 yrs. | Surface EMG for GMed (33% of distance between the greater trochanter and iliac crest) on dominant limb. | MVIC 3 reps of 5 secs in common MMT position of side lie $25^0$ abd. Rest not stated between reps. | • Exercises – 8 randomised: (1) hip clams hip flex 30 and $60^0$; (2) side-lie hip abd; (3) single-limb squat; (4) single-limb deadlift; (5) multiplanar lunges forward / sideways / transverse.<br>• Repetitions – 8 performed to a metronome (60 b/min) with 2 beats up and 2 beats down. Practice reps prior to testing.<br>• Rest – 2 mins rest between exercises. 5 mins rest between exercises and MVIC testing. | • (1) side-lie hip abd 81 ± 42; (2) single-limb squat 64 ± 24; (3) single-limb deadlift 58 ± 25; (4) transverse lunge 48 ± 21; (5) forward lunge 42 ± 21; (6) clam with $30^0$ hip flex 40 ± 38; (7) sideways lunge 39 ± 19; (8) clam with $60^0$ hip flex 38 ± 29.<br>• The best exercise for the GMed was side-lie hip abd. |

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| **Dwyer et al. (2010)** | **13** | **Cross-sectional with 1 between-subject factor (sex) and 1 within-subject factor (exercise).** | **n = 42 (21 males) healthy asymptomatic. Mean age women (23 ± 5.8) and men (23 ± 4.0) yrs.** | **Surface EMG for bilateral GMed (positioned as described by Cram et al. (1998)) on dominant limb.** | **MVIC 3 reps of 3 secs in stand with strap around both feet holding onto pole to stabilize. 30 sec rest between reps.** | • **Exercises – 3 randomised: (1) single-leg squat; (2) lunge; and (3) step-up-and-over.**<br>• **Repetitions – 3 for each exercise. Practice repetitions prior to testing.**<br>• **Rest – 30 secs between reps and 2 mins between exercises.** | • **Concentric and eccentric phases dominant side; (1) single-leg squat 31.2 ± 10.9, 25.3 ± 11.5 (M), 29.5 ± 7.5, 26.6 ± 6.8 (W); (2) step-up-and–over 15.5 ± 7.9, 14.4 ± 9.6 (M), 16.5 ± 5.7, 14.5 ± 4.6 (W); and (3) lunge 11.6 ± 8.3, 15.5 ± 9 (M), 11.4 ± 4.8, 17.8 ± 8.8 (W).**<br>• **Concentric and eccentric phases non-dominant side; (1) single-leg squat 11.6 ± 6.1, 10.6 ± 5.8 (M), 12.5 ± 9.3, 12.6 ± 9 (W); (2) lunge 17.2 ± 7.3, 14.8 ± 4.7 (M), 24.6 ± 18.1, 20.8 ± 15.9 (W); (3) step-up-and-over 14.8 ± 3.8, 13.3 ± 4.6 (M), 20.7 ± 14.6, 18.7 ± 14.3 (W).**<br>• **Based on moderate levels of activation observed, GMed appears to function as a joint stabilizer not as an active mover.** |
| Ekstrom et al. (2007) | 11 | Cross-sectional | n = 30 (19 males) healthy from university. Mean age 27± 8 yrs | Surface EMG for GMed (ant-sup. to Gmax and just inf. to the iliac crest) applied unilaterally. | MVIC 3 reps of 5 secs in side lie neutral hip rot, sl. ext, active end-range abd against resist. just above ankle. 30 sec rest between reps | • Exercises – 8 randomised: (1) side-lie hip abd; (2) bridge; (3) unilateral bridge with opposite kn. ext; (4) side bridge; (5) prone bridge; (6) quadruped arm and opposite lower extremity lift; (7) lateral step-up; and (8) stand lunge<br>• Repetitions – 3 for trunk stabilisation exercises held for 5 secs; lateral step-up and lunge held 5secs at max kn. flex; Practice reps prior to testing.<br>• Rest – 30 secs between reps; 1 min between exercises. | • (1) side bridge 74 ± 30; (2) unilateral bridge 47 ± 24; (3) lateral step-up 43 ± 18; (4) quadruped arm / lower extremity lift 42 ± 17; (5) active hip abd 39 ± 17; (6) lunge 29 ± 12; (7) bridge 28 ± 17; (8) prone bridge 27 ± 11.<br>• Side bridge, unilateral bridge, prone bridge, bridge, and quadruped arm / lower extremity lift exercises demonstrated co-activation of muscle groups and should be beneficial for stabilisation or endurance training. Active hip abd was effective in isolating function of the GMed. |
| **Felicio et al. (2011)** | **11** | **Cross-sectional** | **n = 15 healthy sedentary females with misalignment of lower limb. Mean age 22.26 ± 2.22 yrs.** | **Surface EMG bilaterally for GMed (positioned as described in Hermens, Freriks, Disselhorst-Klug, and Rau (2000)).** | **MVIC 3 reps of 6 secs in MMT position in $20^0$ abd, $10^0$ ext. against resist distal portion of leg.** | • **Exercises – 3 randomised isometric with 25% additional BW: (1) ball wall squat; (2) ball wall squat with add; and (3) ball wall squat with abd.**<br>• **Repetitions – 3 for each exercise held for 6 secs.**<br>• **Rest – 2mins between each repetition.** | • **Dominant side: (1) squat with add 59 ± 22; (2) squat with abd 47 ± 20; and (3) squat 33 ± 27.**<br>• **Non-dominant side: (1) squat with add 59 ± 27; (2) squat with abd 52 ± 24; and (3) squat 26 ± 13.**<br>• **No differences between squats with add and squat with abd in activation of GMed.** |

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| Hertel et al. (2005) | 11 | Cross-sectional with 3 foot-type control groups. | n= 30 (15 males) healthy recreationally active equally divided into 3 groups depending on foot-type (pes planus, pes cavus, pes rectus).<br>Mean age 21.1 ± 1.6 yrs. | Surface EMG for GMed (1/2 the distance between iliac crest and greater trochanter) on leg contralateral to dominant throwing arm. | MVIC 3 reps for a WB isometric task using a custom-made testing apparatus. Lift contralateral foot and max. push up and back into the wall with test leg. 90 sec between reps. | • Exercises – 2 randomised (1) SL squat; and (2) lateral step-down for 4 different orthotic conditions: no orthotic; $7^0$ med. rearfoot post.; $4^0$ lat. rearfoot post.; and neutral rearfoot post. ($7^0$ med. and $4^0$ lat. posts). A 60 b/min metronome used for lateral step down task of 2 secs down and 2 sec up.<br>• Repetitions – 3 for each task under the 4 different orthotic conditions.<br>• Rest – subjects given 5 mins to adjust to each new orthotic condition before testing. | • (1) SL squat approx. 82-85 ± 10-18 for all orthotic conditions; approx. 77 ± 5 for no orthotic; (2) lateral step down approx. 80-81 ± 8-10 for all orthotic conditions; approx. 74± 6 for no orthotic.<br>• Off-the-shelf orthotics regardless of rearfoot posting increased GMed activity during SL squat and lateral step-down exercises. |
| **Krause et al. (2009)** | **12** | **Cross-sectional** | **n = 20 (6 males) healthy.<br>Mean age 23.6 ± 1.7 yrs (f), 26.3 ± 2.5yrs (m).** | **Surface EMG for GMed (1/2 the distance between the greater trochanter and the iliac crest) over dominant kicking leg.** | **MVIC 3 reps in side lie sl. hip ext., knee ext. and hip abd. $30^0$, manual resist. applied just prox. to ankle. Adequate rest between reps.** | **• Exercises – 5 WB randomized: (1) DL stance; (2) SL stance; (3) SL squat; (4) SL stance on Airex cushion; (5) SL squat on Airex cushion.<br>• Repetitions – 3 for each exercise. Stance exercises held for 10 secs. Exercises practiced prior to testing procedure.<br>• Rest – adequate rest time provided between each set of exercises.** | **• (1) SL squat on Airex 58.5 ± 35.32; (2) SL squat 47.79 ± 22.61; (3) SL stance on Airex 25.17 ± 15.54; (4) SL stance 19.1 ± 12.38; (5) DL stance 4.9 ± 3.35.<br>• To increase the challenge to the GMed, dynamic SL exercises performed on unstable surfaces such as the Airex place greater demands than similar exercises performed on stable surfaces.** |
| Lubahn et al. (2011) | 12 | Cross-sectional | n = 18 healthy females.<br>Mean age 22.3 ± 2.3 yrs. | Surface EMG for GMed (positioned as described by Cram et al., (1998)) of the dominant leg. | MVIC 3 reps for 5 secs in side lie with neutral hip lower extremity in frontal plane during abd. against manual resist. | • Exercises – 6 randomised: (1) DL squat; (2) DL squat with lateral resistance band; (3) front step-up; (4) front step-up with cable resistance; (5) single-leg squat; (6) single-leg squat with cable resistance.<br>• Repetitions – 5 for each exercise set to a metronome (40 b/min) with 1 beat for initiation of rep. then beat 2 at midpoint then beat 3 for end of rep. Several practice reps before data collection.<br>• Rest - 10-15 secs between each rep. 45-60 secs rest between each exercise. | • (1) SL squat 65.6 ± 23.8; (2) SL squat with cable resistance 53.7 ± 27.6; (3) step-up 48.2 ± 20.4; (4) step-up with cable resistance 45.2 ± 21.7; (5) DL squat with lateral resistance band 23.7 ± 16.3; and (6) DL squat 20.8 ± 14.7.<br>• Overall, the SL squat was the most effective exercise for activating the GMed. Applied knee load does not appear to increase muscle activation during SL squat and front step-up. |

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| **McBeth et al. (2012)** | **13** | **Cross-sectional.** | **n = 20 (9 males) healthy runners from the community. Mean age 25.45 ± 5.8 yrs.** | **Surface EMG for GMed (1/3 distance between iliac crest and greater trochanter) on preferred kicking leg.** | **MVIC 3 reps of 5 secs in side lie MMT position against manual resist. at the ankle. 10 sec rest between reps.** | • **Exercises – 3 side-lie: (1) hip abd; (2) hip abd – ER; and (3) clam.**<br>• **Repetitions – 7 set to a metronome (60 b/min) of 1 beat up, 1 beat down, and 4 beat rest phase. 4 practice sets of 5 reps prior to testing protocol.**<br>• **Rest - 1 min between exercises. 2 mins between MVC testing and exercises.** | • **(1) side lie hip abd 79.1 ± 29.9; (2) side lie hip abd – ER 53.03 ± 28.4; and (3) side lie clam 32.6 ± 16.9.**<br>• **The abd exercise is preferred if targeted activation of GMed is the goal.** |
| McGill and Karpowicz (2009) | 12 | Single-group retest design. | n = 8 healthy males. Mean age 21.6 ± 4.1 yrs | Surface EMG applied bilaterally for GMed (thumb on ASIS and fingertips reaching around to muscle belly). | MVIC - manual resisted clam in side lie for 3-5secs. | • Exercises – (1) curl-up; (2) dead bug; (3) side-bridge; (4) birddog. The curl-up and dead bug were held for 5sec. | • (1) birddog with reach approx. 21 ±5; (2) birddog with brace approx. 20 ± 8; (3) birddog arm and leg approx. 17 ± 8; (4) birddog leg approx. 15 ± 6; (5) dead bug approx. 5-18 ±1-10; (6) birddog arm approx. 5 ± 3; and (7) curl-up approx. 4-6 ± 2-7.<br>• Birddog with arm and leg motion should be considered if wish to train control in hip and shoulder musculature. |
| **Mercer et al. (2009)** | **13** | **Cross-sectional.** | **n = 28 (7 males) community-dwelling older adults. Mean age 79.4 ± 8.0** | **Surface EMG for bilateral GMed (positioned 2-3 cm distal to midpoint of the iliac crest).** | **1 submax. rep for each side for 8secs in side lie with lower extremity level with lat. aspect of the trunk and hip joint in approx $0^0$ abd. with knee ext and hip in neutral against gravity.** | • **Exercises – 2 randomised; (1) forward step-up; (2) lateral step-up.**<br>• **Repetitions – 3 sets of 8 for each exercise set to a metronome (66 b/min) with 1 beat per foot movement. Participants were instructed to lead with the (R) leg during ascent and (L) leg during descent. Practice reps performed until comfortable with the exercise prior to testing.**<br>• **Rest – 2 mins between sets and 5 mins between exercises.** | • **(R) side: (1) lateral step-up ascent 157.7 ± 64.4; (2) forward step-up ascent 154.6 ± 65.4; (3) lateral step-up descent 123.3 ± 53.1; and (4) forward step-up descent 108 ± 43.8.**<br>• **(L) side: (1) lateral step-up ascent 147 ± 71.2; (2) lateral step-up descent 138.3 ± 77.5; (3) forward step-up ascent 131.4 ± 68.9; and (4) forward step-up descent 128.9 ± 82.3.**<br>• **Step-up exercises are effective in activating the GMed with lateral step-up exercises requiring greater GMed activation than forward step-up.** |

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| Oliver and Dougherty (2009) | 12 | Cross-sectional. | n = 8 female intercollegiate athletes. Mean age 20.8 ± 3.9 yrs. | Surface EMG for GMed (over muscle belly and parallel to fibres) on dominant side. | MVIC 3 max. reps for 5 secs in MMT position as described by Kendall et al.(1993). | • Exercises – 2; (1) razor curl; and (2) prone hamstring curl.<br>• Repetitions – 5 for each exercise. Several warm-up reps prior to data collection.<br>• Rest – none in-between sets. | • (1) razor curl approx. 28 ± 9; and (2) prone hamstring curl approx. 25 ± 9.<br>• No significant differences between muscle activations during the two exercises. |
| **Oliver et al. (2010)** | **11** | **Cross-sectional.** | **n = 30 healthy collegiate students. Mean age 23.4 ± 1.4yrs.** | **Surface EMG for bilateral GMed (positioned as described in Basmajian and De Luca (1985)).** | **MVIC 2 max reps for 5secs in MMT as described by Kendall et al. (1993).** | • **Exercises – 4 randomised; (1) superman; (2) flying squirrel; (3) abdominal bridge; and (4) single-leg abdominal bridge. Each exercise held for 10 secs.**<br>• **Repetitions – 3 for each exercise. Warm-up reps prior to data collection.** | • **(L) side: (1) (R) bridge approx. 35 ± 17; (2) flying squirrel approx. 32 ± 10; (3) superman approx. 32 ± 20; (4) abdominal bridge approx. 17 ± 11; and (5) (L) bridge approx. 10 ± 13.**<br>• **(R) side: (1) (L) bridge approx. 33 ± 16; (2) flying squirrel approx. 32 ± 10; (3) superman approx. 28 ± 13; (4) abdominal bridge approx. 17 ± 9; and (5) (R) bridge approx. 14 ± 14.**<br>• **The squirrel, superman and SL bridge exercises produced the greatest muscle activation of GMed.** |
| O'Sullivan et al. (2010) | 12 | Cross-sectional. | n = 15 (7 male) healthy from university. Mean age 22 ± 4 yrs. | Surface EMG for GMed (ant. electrode 50% of distance between ASIS and the greater trochanter; middle electrode 50% distance between greater trochanter and iliac crest; and post electrode 33% of distance between post. ilium and greater trochanter) on the (R) leg. | MVIC 3 max.reps for 5 secs against a Biodex dynamometer in 2 positions; (1) Abd - stand hip abd $30^0$ hip neutral flex /ext and IR / ER; and (2) ER / IR - prone hip neutral rotation $90^0$ kn. flex. to determine the highest EMG reading from all 3 hip movements of abd / IR / ER. The resist. pad 2cm sup. to sup. pole of patella for abd, and 2cm sup. to lat. malleolus for IR / | • Exercises - 3 unilateral WB exercises randomized; (1) wall squat; (2) pelvic drop; (3) wall press.<br>• Repetitions – 3 for each exercise with wall squat held for 5secs; pelvic drop 2 secs down and 2 secs up; and wall press held for 5 secs. 3 practice reps for each exercise performed before testing.<br>• Rest – 30 secs between reps and 1 min rest between exercises. | • Anterior: (1) wall press 27.64 ± 11.14; (2) pelvic drop 21.12 ± 6.80; and (3) wall squat 13.30 ± 7.50.<br>• Middle: (1) wall press 38.60 ± 13.22; (2) pelvic drop 28.45 ± 8.49; and (3) wall squat 24.60 ± 8.89.<br>• Posterior: (1) wall press 76.42 ± 38.31; (2) pelvic drop 38.17 ± 16.76; and (3) 34.82 ± 19.86.<br>• Posterior GMed displayed higher activation across all 3 exercises than both anterior and middle GMed. The wall press produced the highest % MVIC activation for all GMed subdivisions. |

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| | | | | | ER. 30 sec rest between reps. | | |
| **Petrofsky et al. (2005)** | **11** | **Cross-sectional.** | **n = 6 (4 male) healthy.<br>Mean age 25.3 ± 1.5 yrs.** | **Surface EMG for hip abd (over muscle belly).** | **MVIC 3 max. reps for 3 secs in a position to isolate each muscle against manual resistance. 1min rest between reps.** | **• Exercises – 2 series of exercises: (1) pilates exercises with no resist. band; and (2) pilates exercises with resist. band (placed ½-way between hip and knee) performing (a) $45^0$ squat, (b) $90^0$ squat, (c) (L) leg add, (d) (R) leg add, (e) (L) hip ext, and (f) (R) hip ext.** | **• Pilates no resist. band: (1) $90^0$ squat 28.4 ± 6.7; (2) $45^0$ squat 22.1± 9.3; (3) (L) hip add 16.0 ± 3.8; (4) (R) hip ext 13.2 ± 2.2; (5) (L) hip ext 13.0 ± 3.7; and (6) (R) hip add 3.8 ± 1.5.<br>• Pilates with resist. band: (1) (L) hip add 44.3 ± 2.1; (2) (R) hip ext 16.3 ± 3.2; (3) (L) hip ext 11.5 ± 3.8; (4) $45^0$ squat 11.2 ± 5.1; (5) $90^0$ squat 9.6 ± 3.7; and (6) (R) hip add 3.7 ± 1.4.** |
| Philippon et al. (2011) | 11 | Cross-sectional. | n =10 (5 male) healthy.<br>Mean age 28.7 ± 2.0 yrs. | Fine-wire EMG for GMed (1 inch distal to midpoint of iliac crest under US). | MVIC av. 3 max. reps for 3 secs in stand position with sl. hip ER and abd hip against manual resist. 3-5 sec rest between reps. | • Exercises – 13 randomised; (1) DL bridge; (2) resisted terminal knee ext; (3) resisted knee flex; (4) resisted hip ext; (5) traditional hip clam; (6) hip clam with neutral hip; (7) stool hip rotation; (8) prone heel squeeze; (9) side lie hip abd with hip IR; (10) side lie hip abd with hip ER; (11) side lie hip abd against wall; (12) SL bridge; (13) supine hip flex.<br>• Repetitions – 2 sets of 5 for each exercise performed to a metronome. | • Concentric and eccentric phases; (1) SL bridge 72.5 ± 18.4, 51.1 ± 3.8; (2) side lie hip abd – IR 65.8 ± 16.8, 44.1 ± 3.1; (3) side lie hip abd – wall 58.1 ± 12.9, 43.3 ± 2.6; (4) side lie hip abd – ER 55.4 ± 14.1, 39.4 ± 3.6 (5) prone heel squeeze 55.2 ± 15.2, 54.7 ± 4.7; (6) traditional hip clam 43.4 ± 13.0, 32.3 ± 3.4; (7) resist hip ext 39.6 ± 6.3, 39.1 ± 1.7; (8) hip clam – neutral 28.4 ± 8.6, 17.9 ± 1.5; (9) DL bridge 26.2 ± 7.7, 21.7 ± 1.7; (10) supine hip flex 23.8 ± 13.5, 17.9 ± 2.9; (11) stool hip rotations 22.9 ± 8.9, 21.7 ± 2.0; (12) resist knee ext 19.7 ± 4.9, 15.5 ± 1.3; and (13) resist knee flex 17.3 ± 4.3, 15.6 ± 1.2.<br>• Prone heel squeezes, side lie hip abd – IR and SL bridge were identified as high-level GMed rehabilitation exercises. |

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| **Soderburg et al. (1987)** | **12** | **Two-factor mixed design based on independent groups and measures.** | **n = 30 (14 healthy). Mean age 23.3 ± 1.4 yrs (healthy)** | **Surface EMG for GMed (1/3 of distance along a line from the midpoint of the iliac crest to the greater trochanter).** | **MVIC 3 max. reps for 3secs in 30$^0$ abd with knee ext position.** | • **Exercises – 2 randomised: (1) straight leg raise against max. manual resist.; (2) quadriceps setting.**<br>• **Repetitions – 3 reps of each exercise.**<br>• **Rest – 30 secs between reps.** | • **Healthy: (1) quadriceps setting approx. 45 ± 5; and (2) straight leg raise approx. 30 ± 5.**<br>• **Significantly greater activation of GMed during quads setting exercises than during straight leg raise exercises.** |
| Tateuchi et al. (2006) | 11 | Cross-sectional. | n = 10 healthy females. Mean age 24.3 ± 1.8 yrs. | Surface EMG bilaterally for GMed (position not stated). | MVIC hip abd in supine with hip in neutral position. | • Exercises – 4 randomised; (1) lateral step 10cm; (2) lateral step 20cm; (3) lateral step-up 10cm; (4) lateral step-up 20cm started by a random LED and performed as fast as a possible and hold the final position for 3secs.<br>• Repetitions – 3. Several practice reps before testing. | • Supporting leg: (1) lateral step 20cm 55.9 ± 11.2; (2) lateral step 10cm 49.7 ± 9.3; (3) lateral step-up 20cm 44.6 ± 10.3; and (4) lateral step-up 10cm 41.6 ± 8.4.<br>• Stepping leg: (1) ) lateral step 20cm 13.4 ± 12.8; (2) lateral step 10cm 12.7 ± 13.4; (3) lateral step-up 20cm 7.5 ± 4.5; and (4) lateral step-up 10cm 5.9 ± 3.8.<br>• Increase in GMed activity doesn't depend on the height of stepping but on the length of stepping in lateral step and step-up motions. |

Key: abd – abduction; add – adduction; ant – anterior; DL – double leg; ER – external rotation; ext – extension; flex – flexion; GMed – gluteus medius; inf – inferior; IR – internal rotation; lat – lateral; MMT – manual muscle test; MVIC – maximum voluntary isometric contraction; NWB – non-weight-bearing; post – posterior; reps – repetitions; SL – single leg; sup – superior; WB – weight-bearing.

Table 5. *EMG technical aspects of included studies*

| Study | EMG unit type | Electrode size and skin preparation | Inter-electrode distance (mm) | Input impedance (Ω) | Common mode rejection ratio (dB) | Amplifier gain | Data filtering (Hz) | Sampling frequency (Hz) | Rectification (full or half wave) | Data processing (ms) |
|---|---|---|---|---|---|---|---|---|---|---|
| Ayotte et al. (2007) | NS | NS; Skin debrided and cleansed | 30 | NS | >110 @ 50-60 Hz | NS | Band pass 30 – 10000 | 20000 | Full-wave | NS |
| Bolgla and Uhl (2005) | 16 channel | 5mm diameter; skin prepared in standard manner | 20 | NS | 90 | 2000 | Band pass 20-500 | NS | NS | RMS 15 |
| Boren et al. (2011) | NS | NS; skin cleansed | NS | NS | NS | NS | NS | NS | NS | RMS 50 |

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| Boudreau et al (2009) | 16 lead | 5mm diameter; skin debrided and cleansed | 20 | NS | 90 | 2000 | Band pass 20-500 | 1339 | NS | RMS 20 |
| Distefano et al. (2009) | NS | NS; skin cleansed | 10 | NS | >80 @ 60Hz | 10000 | 20-450 | 1000 | NS | RMS 20 |
| Dwyer et al. (2010) | 16 lead | 5mm diameter; skin debrided and cleansed | 20 | 1 M | 90 | 2000 | Band pass 20-500 | 1339 | Full-wave | RMS 20 |
| Ekstrom et al. (2007) | 16 channel 12 bit A/D card | NS; skin debrided and cleansed | 20 | 10 M | >100 @ 60 Hz | 1000 | Band pass 10-500 | 1000 | Full-wave | RMS 20 |
| Felicio et al. (2011) | NS | 23x21x5mm; skin prepared | 10 | 10 G | 130 | 20 | Band pass 20-500 | 2000 | NS | RMS |
| Hertel et al. (2005) | NS | 10 mm contact area; skin debrided and cleansed | 20 | 2 M | 11 | 1000 | 10-500 | 1000 | NS | RMS 500 |
| Krause et al. (2008) | NS | NS; skin cleansed | 22 | >15 M @ 100 Hz | 87 @ 60 Hz | 35 | NS | 1000 | NS | RMS 55 |
| Lubahn et al. (2011) | NS | NS; skin debrided and cleansed | NS | NS | NS | 1000 | Band pass 6-30 | 960 | NS | NS |
| McBeth et al. (2012) | 16 channel | NS; skin debrided and cleansed | 26 | NS | NS | 1000 | Band pass 10-499 | 1000 | NS | RMS 20 |
| McGill and Karpowicz (2009) | 16 channel 12 bit A/D card | NS; skin cleansed | 25 | NS | NS | NS | Low pass 2.5 | 1024 | Full-wave | NS |
| Mercer et al. (2009) | 16 channel | 15mm diameter; skin cleansed | 20 | >1 M | >90 | NS | Band pass 10-1000 | 1000 | NS | RMS 30 |
| Oliver and Dougherty (2009) | NS | NS; skin cleansed and debrided | 25 | NS | 90 | 2000 | NS | NS | NS | NS |
| Oliver et al. (2010) | 8 channel | NS; skin cleansed and debrided | 25 | NS | NS | NS | Band pass 20-350 | 1000 | Full-wave | RMS 100 |
| O'Sullivan et al. (2010) | NS | 144 $mm^2$ size; skin cleansed and debrided | 18 | NS | >100 @ 60 Hz | 2000 | 5-500 | 1250 | Full-wave | RMS 150 |
| Petrofsky et al. (2005) | 12 bit A/D card | NS | 20 | NS | NS | 5000 | NS | 2000 | NS | RMS |

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| Philippon et al. (2011) | NS | .07mm fine-wire | NS | >10 M | >84 | NS | Low pass 10 | 1200 | NS | RMS 50 |
| Soderberg et al. (1987) | NS | 8mm diameter; skin cleansed | 20 | NS | NS | 35 | Low pass 8 | >100 | Full-wave | NS |
| Tateuchi et al. (2006) | NS | NS | 20 | NS | NS | NS | Band pass 10-500 | 1080 | Full-wave | RMS |

Key: A/D – analogue-digital conversion; NS – not stated; RMS – root mean square for the middle GMed and positioned the electrode using ultrasound guidance. No included studies took any EMG measurements of GMin activity.

The reporting of EMG technical parameters varied between the studies with only one study (Dwyer et al., 2010) documenting all EMG technical parameters that were considered important for collecting, processing and analysing a reliable EMG signal amplitude whilst minimising signal noise contamination.

EMG normalisation procedures for the gluteus medius varied amongst the included studies with positions such as side-lie (Ayotte et al., 2007; Bolgla & Uhl, 2005; Boren et al., 2011; Distefano et al., 2009; Ekstrom, Donatelli, & Carp, 2007; Felício et al., 2011; Krause et al., 2009b; Lubahn et al., 2011; McBeth et al., 2012; McGill & Karpowicz, 2009; Oliver & Dougherty, 2009; Oliver, Dwelly, et al., 2010; Soderberg et al., 1987), standing (Boudreau et al., 2009; Dwyer et al., 2010; Hertel et al., 2005; O'Sullivan et al., 2010; Philippon et al., 2011), prone (O'Sullivan et al., 2010), and supine (Tateuchi et al., 2006) used to determine a reference isometric voluntary contraction.

Therapeutic exercise characteristics were diverse amongst the 21 included studies and broadly contained dynamic weight-bearing and non-weight-bearing exercises. All included studies attempted to control to some extent variations in the EMG signal during performance of the exercises by; regulating the range of motion of the exercises by a goniometer or tape measure (Ayotte et al., 2007; Bolgla & Uhl, 2005; Boudreau et al., 2009; Ekstrom et al., 2007; Krause et al., 2009b; McBeth et al., 2012; O'Sullivan et al., 2010); identifying the concentric and eccentric phases of the exercises (Dwyer et al., 2010; Mercer et al., 2009; Philippon et al., 2011); standardising the speed of contraction through the use of a metronome (Ayotte et al., 2007; Bolgla & Uhl, 2005; Boren et al., 2011; Distefano et al., 2009; Hertel et al., 2005; McBeth et al., 2012; Mercer et al., 2009; Philippon et al., 2011); allowing for adequate rest between exercises and repetitions ;and limited repetitions to control for muscular fatigue.

The exercise results in all studies but one (Boren et al., 2011) were reported as percent reference voluntary contraction (% RVC) as a mean and standard. Although most studies had a mixture of male and female participants only one study (Dwyer et al., 2010) measured separate activation levels for the male and female participants for each of the exercises.

**3.3 Non-weight bearing (NWB) exercises**

*Very high – level activation (> 60% MVC)*

Side lie hip abduction was analysed in six studies (Bolgla & Uhl, 2005; Boren et al., 2011; Distefano et al., 2009; Ekstrom et al., 2007; McBeth et al., 2012; Philippon et al., 2011) producing high-to-very-high GMed activation levels (Table 6).

Variations of the side-lying plank exercise on the NWB and WB GMed were assessed in three studies (Boren et al., 2011; Ekstrom et al., 2007; McGill & Karpowicz, 2009) and found to be a top-ranking exercise producing very high GMed activation levels (Tables 6 and 7).

The front-plank with non-weight bearing hip extension was assessed by one study (Boren et al., 2011) and was found to generate substantial activity in the non-weight bearing side (Table 6). Another study (Ekstrom et al., 2007) in contrast also analysed this exercise as a WB exercise without hip extension and found it to generate relatively low levels of activity (Table 7).

Table 6. *Overall exercise ranking and NWB exercises mean %MVC*

| Level of activation | Exercises | Bolgla and Uhl (2005) 6 exs. | Boren et al. (2011) 22 exs. | Distefano et al. (2009) | Ekstrom et al. (2007) 8 exs. | McBeth et al. (2012) 3 exs. | McGill and Karpowicz (2009) 4 exs. | Oliver and Dougherty (2009) 2 exs. | Oliver et al. (2010) 4 exs. | Philippon et al. (2011) 13 exs. | Soderberg et al. (1987) 2 exs. |
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| **Very high (>60%)** | Side-lie hip abduction | 4$^{th}$ 42 | 7$^{th}$ 62.91 | 1$^{st}$ 81 | 5$^{th}$ 39 | 1$^{st}$ 79.1; 2$^{nd}$ 53.03 (ER) | | | | 2$^{nd}$ 65.8 (IR); 3$^{rd}$ 58.1 (ext.); 4$^{th}$ 55.4 (ER) | |
| | Side-lie plank / bridge | | 2$^{nd}$ 88.82 | | | | | | | | |
| | Prone plank / bridge | | 5$^{th}$ 75.13 (hip ext.) | | 7$^{th}$ 27 | | | | | | |
| **High (41-60%)** | Side-lie clam | | 4$^{th}$ 76.88 (hip ext.); 6$^{th}$ 67.63 (hip flex. $45^0$); 8$^{th}$ 62.45 (hip flex. $45^0$); 18$^{th}$ 47.23 () | 6$^{th}$ 40 (hip flex. $30^0$); 8$^{th}$ 38 (hip flex. $60^0$) | | 3$^{rd}$ 32.6 (hip flex. $45^0$) | | | | 6$^{th}$ 43.4 (hip flex. $45^0$); 8$^{th}$ 28.4 (hip neutral) | |

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| **Moderate (21-40%)** | Miscellaneous exercises | | | | | $1^{st}$ 28 (razor curl); $2^{nd}$ 25 (ham.curl) | | $5^{th}$ 55.2 (prone heel squeeze); $7^{th}$ 39.6 (resist. hip ext.); $10^{th}$ 23.8 (supine hip flex.); $11^{th}$ 22.9 (stool hip rot.); $12^{th}$ 19.7 (resist. knee ext.); $13^{th}$ 17.3 (resist. knee flex.) | $1^{st}$ 45 (quads setting); $2^{nd}$ 30 (SLR) |
| | Quadruped exs. | | $22^{nd}$ 22.03 (leg lift) | $4^{th}$ 42 (arm-leg lift) | $1^{st}$ 20 (arm lift); $2^{nd}$ 19 (ab. brace); $3^{rd}$ 17; $4^{th}$ 15 (leg lift) | | | | |
| | Stand NWB hip abduction | $5^{th}$ 33 (hip flex. $20^0$); $6^{th}$ (hip neutral) | | | | | | | |
| **Low (0-20%)** | Other core exercises | | | | $5^{th}$ 5-18 (deadbug); $7^{th}$ 4-6 (curl-up) | | $2^{nd}$ 32 (flying squirrel); $3^{rd}$ 28-32 (superman); $5^{th}$ 10-14 (SL bridge) | | |

Key: exs – exercises; IR – internal rotation; ER – external rotation; ext – extension; flex – flexion; SL – single-leg; resist – resisted; rot – rotation; ab – abdominal; SLR – straight leg raise; ham - hamstring

Table 7. *Overall study exercise ranking and WB exercises mean %MVC*

| **Level of activation** | **Exercise** | **Ayotte et al. (2007) 5 exs.** | **Bolgla and Uhl (2005) 6 exs.** | **Boren et al. (2011) 22 exs.** | **Boudreau et al. 2009) 3exs.** | **Distefano et al. (2009) 8 exs.** | **Dwyer et al. (2010) 3 exs.** | **Ekstrom et al. (2007) 8 exs.** | **Felecio et al. (2011) 3 exs.** | **Hertel et al. (2005) 2 exs.** | **Krause et al. (2008) 5 exs.** | **Lubahn et al. (2011) 6 exs.** | **Mercer et al. (2009) 2 exs.** | **Oliver et al. (2010) 4 exs.** | **O' Sullivan et al. (2010) 3 exs.** | **Petrofsky et al. (2005) 6 exs.** | **Philippon et al. (2011) 13 exs** | **Tateuchi et al. (2006) 4 exs.** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Very High (>60%)** | SL squat | 5th 36 (mini) | | 3rd 82.26; 10th 59.84 (skater) | 1st 30.1 (dom.) | 2nd 64 | 1st 31.2 (dom. M); 29.5 (dom. W) | | | 1st 82-85 (orthotics), 77 (no orthotics) | 1st 58.5 (Airex); 2nd 47.79 | 1st 65.6; 2nd 53.7 (med. resist) | | | | | | |
| | Lateral step-up | 3rd 38 | | | 9th 59.87 | | | | | 2nd 80-81 (orthotics), 74 (no orthotics) | | | 1st 157.7 (asc.); 3rd 123.3 (des.) | | | | | 3rd 44.6 (20cm); 4th 41.6 (10cm) |
| | Forward step-up | 2nd 44; 4th 37 (retro) | | 16th 54.62 | 3rd 15.2 (step-over, dom.) | | 2nd 15.5 (dom. M); 16.5 (dom. W) | 3rd 43 | | | | 3rd 48.2; 4th 45.2 (med. resist) | 2nd 154.6 (asc.); 4th 108 (des.) | | | | | |

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| | Side-lie plank / bridge | | | 1st 103.1 | | | 1st 74 | | | | | | | |
| **High (41-60%)** | Squat + frontal plane resist. | | | | | 1st 57 | | 1st 59 (add); 2nd 47-52 (abd); 3rd 26-33 | 5th 23.7 (lat. resist); 6th 20.8 | | | 1st 28.4 ($90^0$); 2nd 22.1 ($45^0$) | | |
| | Single-leg wall squat | 1st 52 | | | | | | | | | 3rd 13.3 (ant.), 24.6 (mid.), 34.82 (post.) | | | |
| | Single-leg supine bridge | | | 15th 54.99 (stable); 17th 47.29 (unstable) | | | 2nd 47; 8th 28 (DL) | | | 1st 33-35; 4th 17 (DL) | | | 1st 72.5; 9th 26.2 | |
| | Pelvic drop | | 1st 57 | 11th 58.43 | | | | | | | 2nd 21.12 (ant.), 28.45 (mid.), 38.17 (post.) | | | |
| **Moderate (21-40%)** | Single-leg stance exs. | | 2nd 46 (hip flex. $20^0$ abd.); 3rd 42 | 12th 57.39 (hip circ. stand); 13th 57.30 (leg swing) | 3rd (dead-lift) | | | | 3rd 25.17 (Airex); 4th 19.1; 5th 4.9 (DL) | | 1st 27.64 (ant.), 38.6 (mid.), 76.42 (post.) | 3rd 16 (hip add.); 5th 13 (hip ext.) | | 1st 55.9 (20cm); 2nd 49.7 (10cm) |

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| | (hip abd.) | | | | | | (wall press) |
| Quadruped exs. | | 19th 46.67 (leg lift) | | | | | |
| Lunge | | | 2nd 17.7 (dom.) | 4th 48 (trans.); 5th 42; 11th 39 (side) | 3rd 11.6 (dom. M); 11.4 (dom. W) | 6th 29 | |

Key: ant – anterior; mid – middle; post – posterior; abd – abduction; dom – dominant; flex – flexion; SL – single-leg; DL – double-leg; trans – transverse; ext – extension; asc ascend; des – descend; circ – circumduction; med – medial; lat – lateral; add – adduction; resist - resistance

*High-level activation (41-60%)*

The clam exercise was examined in four studies (Boren et al., 2011; Distefano et al., 2009; McBeth et al., 2012; Philippon et al., 2011). This exercise was found to generally have high activation levels depending on how the exercise was performed as there were wide variations in the exercise position across the studies as well as the rankings (Table 6).

*Moderate-level activation (21-40%)*

Standing hip abduction for the NWB leg was found to have moderate levels of activation and was assessed by only one study (Bolgla & Uhl, 2005) for two different positions (hip flexed $20^0$ and hip neutral) (Table 6).

Two studies (Ekstrom et al., 2007; McGill & Karpowicz, 2009) assessed various exercises in the quadruped position with wide-ranging levels of GMed activation generated depending on the exercise (Table 6).

*Low-level activation (0-20%)*

Abdominal exercises such as supine dead-bugs and curl-ups were assessed in one study (McGill & Karpowicz, 2009) and found to generate low levels of activation (Table 6).

### 3.4 Weight-bearing (WB) exercises

Eighteen out of the 21 studies included in this review assessed some form of weight-bearing exercise with different variations of squats; lunges; step-up and down; bridges, single-leg stance exercises; and pelvic drops being commonly analysed.

*Very high – level activation (> 60% MVC)*

Single leg squats produced generally high-to-very high levels of GMed activity for nearly all of the eight studies (Ayotte et al., 2007; Boren et al., 2011; Boudreau et al., 2009; Distefano et al., 2009; Dwyer et al., 2010; Hertel et al., 2005; Krause et al., 2009b; Lubahn et al., 2011) (Table 7). There were however some differences in how the exercise was performed between the studies including knee active range of movement, exercise surface, and addition of medio-lateral resistance.

Variations of step-up-and-down were a frequently examined exercise in the literature of nine included studies (Ayotte et al., 2007; Boren et al., 2011; Boudreau et al., 2009; Dwyer et al., 2010; Ekstrom et al., 2007; Hertel et al., 2005; Lubahn et al., 2011; Mercer et al., 2009; Tateuchi et al., 2006) producing high-to-very high levels of activation (Table 7). In most cases lateral step-up-and-down produced higher activity levels than forward step-up-and-down, however like the other exercises there was differences across the studies on how the exercise was performed in terms of step height; step distance; addition of medio-lateral resistance; and technique.

*High-level activation (41-60%)*

Single leg wall squats were found to produce moderate-to-high levels of activation in two studies (Ayotte et al., 2007; O'Sullivan et al., 2010) (Table 7).

The squat with frontal plane resistance into hip abduction or adduction produced moderate-to-high levels of GMed activation in the three studies (Felício et al., 2011; Lubahn et al., 2011; Petrofsky et al., 2005) that analysed the exercise (Table 7).

The lunge was a common weight-bearing exercise that was assessed in four studies (Boudreau et al., 2009; Distefano et al., 2009; Dwyer et al., 2010; Ekstrom et al., 2007) and was found to produce moderate-to-high levels of GMed activation (Table 7). There was some variation between the studies on how the exercise was performed with knee active range of movement and technique.

The WB supine single-leg bridge is frequently prescribed to strengthen the gluteus maximus and was examined for GMed activity in four studies (Boren et al., 2011; Ekstrom et al., 2007; Oliver, Stone, & Plummer, 2010; Philippon et al., 2011), and found to produce high levels of activation (Table 7).

*Moderate-level activation (21-40%)*

Other exercises measuring the WB stance leg including single-leg wall press, standing hip abduction, single leg stance, and standing hip circumduction were assessed in five studies

(Bolgla & Uhl, 2005; Boren et al., 2011; Krause et al., 2009b; O'Sullivan et al., 2010; Petrofsky et al., 2005) and were found to generate wide variability in activation levels from low to very high depending on the exercise and the study (Table 7).

The pelvic-drop exercise was examined in three studies (Bolgla & Uhl, 2005; Boren et al., 2011; O'Sullivan et al., 2010) and found to generally produce moderate-to-high levels of activation (Table 7).

*Low-level activation (0-20%)*

There was no WB exercise found in this review that consistently generated low levels of GMed activity across the studies.

## 5.0 Discussion

The aim of this systematic review was to determine from the current literature what were the most effective therapeutic exercises for producing the greatest amount of GMed and GMin activity for the different segments of the respective muscles in healthy subjects. Because there were no studies that had assessed GMin activity for different therapeutic exercises, this review focussed on therapeutic exercises for GMed.

One study (O'Sullivan et al, 2010) examined exercises for the three different segments of GMed using surface electrodes. There were concerns on whether the posterior GMed electrode placement was optimally positioned for recording of the posterior segment due to difficulties with accessibility using surface electrodes (Semciw, Green, Pizzari, & Briggs, 2013). All other included studies examined the relative activation levels of the middle GMed segment to different therapeutic exercises in weight-bearing or non-weight bearing positions utilising surface EMG electrodes except Philippon et al. (2009) who used an ultrasound-guided fine-wire electrode.

Due to all of the included studies being cross-sectional in design and the heterogeneity in factors such as; exercise characteristics; normalisation method; electrode type and placement; and EMG technical parameters, it was not possible to pool the results of studies together. Despite this, there were some general trends that did emerge such as weight-bearing exercises tended to generate more activity than non-weight-bearing exercises which highlighted GMed's functional role as a multi-planar weight-bearing hip and pelvic stabiliser. Side-lie hip abduction generated very-high levels of activation confirming that the GMed's role as a primary hip abductor. For the clinician it is important to know that individuals who can't perform weight-bearing GMed exercises due to post-surgical protocols or other reasons can still get similar benefits with a NWB exercise such as side-lie hip abduction. The posterior GMed segment despite questions over its electrode placement generated relatively higher levels of activity than the middle and anterior segments for all three exercises examined suggesting that this portion may provide a much larger role due to its orientation of its fibres as a hip and pelvic stabiliser confirming previous gait studies (Anderson & Pandy, 2003). It was unable to be determined due to the type of exercises selected for that study how much each of the segments contributes to hip rotation. The side-lie plank / bridge and the prone plank / bridge NWB hip extension exercises are not usually prescribed as GMed strengthening exercises, however based on their very high levels of activation could provide an added benefit of strengthening the GMed when prescribed as a core exercise in the management of for example low back pain.

With the exercises further categorised into activation levels; this can be further beneficial to the clinician in providing information on what exercises will provide strength adaptations for the GMed (i.e. >60%MVC) and how to progress GMed exercises from low intensity through to very high intensity activation. With the wide variation in results across the studies, it was difficult at times classifying exercises into a specific activation category. This was probably due to differences for example the way the exercise was performed in technique (i.e. speed and whether held at midpoint of range); AROM at the hip and knee; repetitions performed; and rest between repetitions and exercises. Variations in other methodological factors between the studies were also likely to explain the differences in the results for a particular exercise.

As previously discussed all of the included studies except Philippon et al. (2011) collected EMG data for the GMed through the use of surface electrodes. The recordings whilst useful for general information however can be inaccurate due to cross-talk from underlying or surrounding muscles such as tensor facia lata and GMin (Soderberg & Knutson, 2000), and during dynamic tasks involving large ranges of movement such as in the single-leg squat and lunge there can be artefact activity due to movement of the muscle relative to the recording electrodes (Rainoldi, Melchiorri, & Caruso, 2004). Fine-wire electrodes in contrast have the potential to be a more reliable recording method minimising cross talk through use of flexible fine-wire electrodes to avoid relative displacement during dynamic activities (Hodges & Gandevia, 2000) and through standardised positioning using ultrasound guidance for the different segments of the GMed and GMin (Semciw et al., 2013). Bogey et al. (2003) was also able to demonstrate that fine-wire electrodes were as reliable as surface electrodes in a test-retest study during gait analysis.

Proper electrode placement was crucial for obtaining reliable information from the surface EMG signal and reducing sources of variability (Farina, Merletti, Nazzaro, & Caruso, 2001). The six different positioning methods described in this review for placement of surface electrodes for GMed explained some of the variability in results across the studies and limited potential replication of these studies accurately with electrodes in some studies being placed over the muscle belly.

Only five studies (Bolgla & Uhl, 2005; Distefano et al., 2009; Ekstrom et al., 2007; Hertel et al., 2005; Mercer et al., 2009) in this review performed reliability measures of the EMG testing procedures producing high coefficients placing some doubt over the reliability of the results for the other 16 studies contained in this review.

Since all but one study were mixed gender, gender differences in GMed activation levels may have contributed to the variability of the results across the studies with only one study (Dwyer et al., 2010) assessing the results between genders. Despite no significant differences found in this study it is still an important factor to consider since women have been shown to have hip abductor strength deficits compared to men (Lephart, Ferris, Riemann, Myers, & Fu, 2002).

The MVIC was used for normalisation across all but one study (Mercer et al., 2009) and was the most reliable method as the reference standard for hip musculature due to the dynamic contraction being confounded by the EMG-force-velocity relationship (Bolgla & Uhl, 2007; Soderberg & Knutson, 2000). Only one study in this review performed test-retest reliability on their normalisation method with a high reliability coefficient (Bolgla & Uhl, 2005). Some of the variability in the results across the studies therefore may have been due to an un-reliable MVIC method since its dependent on many factors such as; the muscle activated, training level, task familiarisation, and motivation of the participant because the MVIC can be 20-40% less than the true maximum (Bolgla & Uhl, 2007; Soderberg & Knutson, 2000). Mercer et al. (2009) in contrast utilised a sub-maximal MVC as their normalisation method for their subjects since this has been found to be more reliable than the MVIC method for an elderly population (Klass, Baudry, & Duchateau, 2007; Kollmitzer, Ebenbichler, & Kopf, 1999). Muscle fatigue can also influence the EMG signal with changes in the amplitude and frequency (Soderberg & Cook, 1984) which could have had an effect on the results with some studies that didn't have adequate rest periods between exercises or too many repetitions.

Methodologically, most of the included studies in this review could have been improved by determining appropriate subject numbers through performing power calculations based on a pre-determined effect size. It would have been beneficial for the clinician for the included studies to also report on the source population and methods of recruitment such that the results could be widely applied with more certainty in different therapeutic environments. The lack of application of a blinded observer to analyse the EMG for the different exercises was a significant omission from all of the included studies with experimenter biases unintentionally on EMG studies having a potential impact on results through non-verbal cues such as facial expressions, tone of voice, and length of time explaining tasks etc. (Fridlund & Cacioppo, 1986).

*Strength and limitations*

This is the first known review to investigate therapeutic exercises for the different subdivisions of GMed and GMin and rank the exercises accordingly within the studies in terms of EMG activation levels. From a summary of the results we were able to determine generally across the studies with some caution the most effective therapeutic exercises for generating very high levels of EMG activity as well as exercises for low, moderate and high activity levels. Through application of a stringent methodological process, we were able to provide an objective evaluation of current evidence to date.

This systematic review did have some limitations such as excluding studies utilising gym-based or custom-made equipment; and eliminating data for dynamic activities like jogging and hopping. The original search strategy possibly missed studies due to publication bias and not contacting experts for unpublished papers. Papers not published in peer-reviewed journals such as conference abstracts and theses were also excluded possibly missing potential data. Variable quality evaluations of the included studies may have been produced if a different critical appraisal tool was utilised. Furthermore, there was potential for a different critical appraiser to interpret the instrument items in the modified Downs and Black (1998) in different ways as well (Katrak et al., 2004). With this review we were also only looking at EMG activation levels and not at muscle onset timing patterns or considering the balance of synergists and antagonists for a particular therapeutic exercise as would be normally considered in the clinical situation. Data for pathological populations were not considered in this review which furthermore makes it difficult to determine their response to this review's results.

## 6.0 Conclusion

For healthy individuals, the most effective exercises for the middle GMed in terms of EMG activation levels across the 21 included studies are the side-lie plank / bridge; side-lie hip abduction; single-leg squat; forward and lateral step-up-and-down for producing activation levels (>60% MVC) for strength adaptations. For the one study that examined the anterior, middle and posterior segments the single-leg wall press was the most effective exercise but only produced moderate (21-40%), high (41-60%), and very high (> 60%) activation levels for each of the segments respectively. There were no included studies that examined therapeutic exercises for the GMin. The results do however need to be interpreted with some caution due to the large methodological differences between the studies. Future research is required to examine the effectiveness of therapeutic exercises for the different segments of the GMed and GMin with the potentially more reliable fine-wire EMG into standardised locations.

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**Appendix A**

**Data extraction form**

**Reviewer**........ **Date of abstraction**.............

**Included**.......... **Excluded.**.............

**Author:**

**Title:**

**Source:**

**Study objective:**

**Study design:**

**Subject details:**

Inclusion criteria:

Exclusion criteria:

Recruitment procedures used:

Experimental group subject number: Experimental sex:

Experimental age (mean and SD range):

Control group subject number: Control sex:

Control age (mean and SD / range):

Group characteristics:

Experimental group:

Control group:

**Description of intervention:**

Electrode type (surface / fine wire): Electrode position:

Normalisation method position: Type of resistance:

Number of reps: Rest:

Exercises: Repetitions:

Number of reps: Rest:

**Outcome measures (EMG):**

Unit type: Electrode size / skin preparation:

Inter-electrode distance: Input impedance:

Common mode rejection ratio:
Amplifier gain:

Data filtering:
Sampling frequency:

Rectification (full or half wave):
Data processing:

EMG measures valid and reliable?

**Results (%MVC):**

Statistical techniques:

Statistical results (mean and SD):

**Conclusion:**