Effect of motor control training on hip muscles in elite football players with and without low back pain

M. Dilani Mendis[1,2]
Julie A. Hides[1,3]

[1]Centre for Musculoskeletal Research, Mary Mackillop Institute for Health Research, Brisbane, Australia
[2]Physiotherapy Department, Mater Health Services, South Brisbane, QLD, 4101, Australia
[3]Mater/ACU Back Stability Research Clinic, Mater Health Services, South Brisbane, QLD 4101, Australia

Corresponding Author & Contact Details:
Dr Dilani Mendis
Postal address: Centre for Musculoskeletal Research, Australian Catholic University, Level 1 631 Stanley Street, Woolloongabba, QLD, 4102
E-mail: dilani.mendis@acu.edu.au
Telephone: +61 7 3623 7707
Fax: +61 7 3623 7650

Word Count excluding title page, abstract, references, figures and tables: 3095
Abstract word count: 245
Number of Tables: 1
Number of Figures: 2

Effect of motor control training on hip muscles in elite football players with and without low back pain

Abstract

Objectives: Previous research has shown that motor control training improved size and function of trunk muscles in elite football players with and without low back pain (LBP). Imbalances in hip muscles have been found in athletes with LBP and it is not known if motor control training can change these muscles. This study investigated if a motor control intervention program affected hip muscle size in elite football players with and without LBP.

Design: Panel-randomised intervention design

Methods: Forty-six players from one club in the Australian Football League (AFL) participated in a motor control training program delivered across the season as a stepped-wedge intervention design with 3 treatment arms: 15 weeks intervention, 8 weeks intervention and a wait-list control who received 7 weeks intervention toward the end of the playing season. Presence of LBP was assessed by interview and physical examination. Cross-sectional areas of iliacus, psoas, iliopsoas, sartorius, gluteus minimus, and gluteus medius muscles were measured from magnetic resonance images taken at 3 time points during the season.

Results: Iliopsoas, sartorius and gluteus medius muscle size increased for players who received intervention ($p < 0.05$). For players with current LBP, sartorius and gluteus medius muscle size increased for those who received motor control training ($p<0.05$).

Conclusions: Motor control training programs aimed at the lumbo-pelvic region also benefit the hip muscles. For players with current LBP, the intervention mitigated sartorius muscle atrophy and increased gluteus medius muscle size. These findings may help guide the management of LBP in elite football players.

Keywords: Magnetic Resonance Imaging, Ultrasound Imaging, Exercise, Intervention Study, Iliopsoas muscle, Gluteus medius muscle

Introduction

The problem of low back pain among football players has received increasing attention in recent literature. Studies have noted a high prevalence (57-64%) and recurrence (59%) rate of low back pain (LBP) in this population [1, 2]. Apart from LBP affecting how athletes move [3], which could have an adverse impact on performance, a 2 year prospective radiological investigation indicated that playing football is a significant risk factor for the onset of LBP and progression of intervertebral disc degeneration [4]. Considering the high prevalence rate and possible long-term consequences, it is important to explore modifiable factors for the prevention and management of LBP in football players.

The presence of LBP can affect the size and function of not only the trunk muscles but also the hip muscles in elite athletes. While previous research has found decreased size and altered function of the trunk muscles responsible for spinal protection in elite football players[5, 6] and cricketers with LBP [7, 8], a recent review has highlighted the need to consider the hip in relation to spinal function in the management of LBP [9]. Previous studies have found imbalances in the hip muscles and decreased hip extension strength in collegiate athletes with LBP [10, 11]. Together with hip abductor weakness [12, 13] and hip flexor weakness[14], it is apparent that LBP has an effect on hip muscle function. Only one study to date has examined the effect of LBP on hip muscle size in football players and found a decrease in piriformis muscle size in players with current LBP [15]. However, other hip muscles were not examined in this study. While the deep hip external rotator muscles are important for hip joint function and stability, so too are the other hip muscles [16]. Therefore, it is important to examine the effect of LBP on hip muscle size in elite football players.

Motor control training is an intervention program used to treat people with LBP. It targets the neuromuscular control of the lumbo-pelvic region by focussing on the recruitment and control of key muscles involved in protection of the spine and pelvis [17, 18]. Training neuromotor control of the lumbo-pelvic region has improved the size and function of the multifidus and transversus abdominis muscles in elite cricketers [7, 8] and football players [19] and has been associated with a reduction in LBP in these populations [19]. Recent research has also shown that motor control training increased the size of the piriformis muscle in elite football players with LBP [15]. However, it is unknown if a motor control training program affects other muscles in the lower limb kinetic chain, in particular, muscles of the hip region. Therefore, the aim of this study was to investigate the effect of a motor control training program on hip muscle size (by comparison with a control group) in elite Australian football players with and without LBP.

Methods

All players from the squad of a professional Australian Football League (AFL) club were eligible to participate in this study. This study was approved by the Medical Research Ethics Committee at The University of Queensland. Forty-six elite football players, representing the entire squad, participated in this study. Prior to participation, all players gave written informed consent and their rights were protected.

Details of the intervention protocol have been previously published [15, 19]. In brief, the intervention trial was delivered during the football playing season as a single blinded, stepped-wedge design in three blocks, each of 7-8 weeks duration. The main aim of the study was to compare the effects of motor control training intervention to a control group. As it was a requirement of the club that all players received the intervention during the playing season, a panel design was used which enabled one group to serve as a wait-list control for two-thirds of the season. Participants were randomly allocated into one of three groups, using a computer-generated list of numbers by a person independent to the study. Group 1 (n=17) received 15 weeks intervention in blocks 1 & 2, Group 2 (n = 15) received 8 weeks intervention in block 2 and Group 3 (n=14) was a wait-list control for Groups 1 and 2 during blocks 1 & 2. Group 3 then received 7 weeks intervention during the follow-up period for Groups 1 and 2 (block 3), thereby meeting the club’s requirements that all players receive intervention. No participants were excluded or lost to follow-up from the trial. A Pilates exercise program (combination of a floor and reformer program done twice a week for 30 minutes duration) was performed as part of the club's weekly training schedule from the start of the pre-season training period. Players did not do the Pilates exercise program when they were receiving the motor control training.

The motor control training program was delivered at the football club, in two 30 minute one-on-one sessions per week, by three qualified physiotherapists with expertise in motor control training and ultrasound imaging. The physiotherapists were trained in the specific intervention protocol used in this study. The motor control training program initially involved the performance of voluntary contractions of the trunk muscles (multifidus and transversus abdominis muscles) and a focus on diaphragmatic breathing, with feedback from ultrasound imaging. Training commenced in non-weightbearing positions such as supine and prone lying, and progressed to functional and sports specific positions (examples included sitting, one- or two-legged squats, hip movements in standing, single leg hop and kicking). Players were taught to focus on maintenance of their spinal curves, alignment of their lower limbs in functional positions and dissociation of hip movements from trunk movements. Resistance was added with the use of Thera-Band exercise bands (The Hygenic Corporation, Akron, OH).

An experienced musculoskeletal physiotherapist assessed all players at baseline prior to delivery of the intervention protocol. LBP was defined as pain localized between T12 and the gluteal fold and severe enough to interfere with playing games or training. Players with no experience of LBP and no positive findings on physical examination were allocated to the "no LBP" group. Players who reported a history of LBP but did not report any current LBP pain or have positive findings on examination were also included in the "no LBP" group. Players with current LBP who reported pain in the previous week and had one or more positive findings on physical assessment were included in the "current LBP" group. Positive findings included limited range of motion or reports of pain provocation on manual tests of lumbar intervertebral joint movement.

Magnetic resonance imaging (MRI) was used to assess size of the individual hip muscles. MRI assessments were performed in a hospital setting at baseline (start of block 1, Time 1), after 15 weeks of intervention (end of block 2, Time 2) and at the end of the intervention trial (end of block 3, Time 3) [15, 19]. Prior to imaging, a registered medical practitioner screened all players for contraindications to MRI. Height and weight of each player was measured and information regarding their age and dominant kicking leg was collected. Participants were positioned in supine lying on the imaging table with their hips and knees supported in a neutral position. Transverse MR images through the pelvis were taken from the top of the iliac crest to the hip joint using a 1.5T Siemens Magnetom Sonata MR system (Erlangen, Germany). A true fast imaging with steady state precession (FISP) sequence was used (repetition time: 4.3ms; echo time: 2.1 ms; number of averages: 1; flip angle: 45°; acquisition matrix: 384 x 512) to obtain 18 slices with a slice thickness of 7mm and an inter-slice distance of 10.5mm. Images were saved in a de-identified format for offline analysis.

Cross-sectional areas (CSA) of the iliacus, psoas, iliopsoas, sartorius, gluteus minimus and gluteus medius muscles were measured. Other hip muscles, such as the hip extensors and hip adductors, could not be measured as the imaging sequence did not extend to capture these muscles. CSAs were obtained by manually tracing muscle outlines using Image J software (version 1.4, National Institutes of Health, Bethesda, USA, http://rsb.info.nih.gov/ij/) (Figure 1). For each muscle, the CSA was taken from consecutive slices at particular anatomical landmarks to enable consistent measurement between time points. Both sides of the body were measured. Average CSAs of the iliacus and psoas muscles were taken from consecutive slices starting at the iliac crest until the point where these two muscles fused. Average CSAs of the iliopsoas and sartorius muscles were measured from consecutive slices spanning the femoral head of the hip joint [20]. The average muscle CSA of gluteus minimus was measured from three consecutive slices starting at the apex of the sacrum while gluteus medius muscle CSA was measured from three consecutive slices starting at the base of the sacrum. Measurements were performed blinded to subject identification, time point and group allocation. Intra-rater reliability of CSA measurement for each muscle was high ($ICC_{1,1}$ ranging from 0.97 to 0.99; 95% CI 0.81-0.99; SEM 0.3cm^2), based on a sample of 10 subjects from the current study.

IBM SPSS Statistics (version 22, IBM Corp, Armonk, NY) was used for statistical analysis with a significance level set at 0.05. Gluteus medius CSA measurements were not possible at one time point due to truncated images for 2 participants. SPSS was used to estimate four data points using the series mean function (0.2% of total data set). Preliminary analyses were conducted to investigate differences in age, height, weight and distribution of players with and without LBP between the Intervention and Wait-list Control groups at baseline. Linear mixed models[21] were used to examine the effect of intervention on individual hip muscle size in players with and without LBP. Fixed factors of 'Time', 'Group' (Intervention (Group 1 and 2 combined) or Wait-list Control (Group 3)), and 'LBP' (no LBP or current LBP) and up to a 3-way interaction between these factors were fitted for each muscle with an autoregressive first order covariance structure. Intervention Groups 1 and 2 were combined for the analysis as previous research indicated no additional benefit of a prolonged intervention for trunk and hip muscles [15, 19]. All cases (n=46) were assessed.

Results

The mean age, height and weight for the 46 players were 22.8 (SD 3.5) years, 187.9 (SD 6.0) cm and 88.3 (SD 6.6) kg. The mean age, height and weight of players in each group were as follows: 22.6 (3.3) years, 188.1 (5.4) cm, 88.3 (7.1) kg in the Intervention group and 23.1 (3.9) years, 187.4 (7.5) cm, 88.2 (5.6) kg in the Wait-list Control group. At baseline, there were no significant differences for age, height and weight between groups (all $p > 0.63$). Thirty-three players did not have LBP (23 in Intervention group, 10 in Wait-list Control group) and 13 players had current LBP (9 in Intervention group, 4 in Wait-list Control group). Fisher's exact test indicated no significant difference in the distribution of players with or without LBP across the 2 groups at baseline ($p = 0.62$).

There was a significant interaction effect of 'Time' and 'Group' for the iliopsoas ($F = 3.65$, $p = 0.03$), sartorius ($F = 4.22$, $p = 0.02$), and gluteus medius ($F = 4.13$, $p = 0.02$) muscles. From Time 1 to Time 2, post hoc comparisons indicated a significant increase in iliopsoas, sartorius and gluteus medius muscle size for the Intervention group (all $p < 0.05$) with no significant change in size for the Wait-list Control group (all $p > 0.05$) (Figure 2 c, d, e). No significant interaction effects were found for the iliacus ($F = 0.27$, $p =0.76$), psoas ($F = 0.64$, $p = 0.53$) and gluteus minimus ($F = 0.77$, $p = 0.47$) muscles (Figure 2 a, b, f). In the follow-up period for the Intervention group (Time 2 to Time 3), the increase in iliopsoas, sartorius and gluteus medius muscle size was maintained (all $p < 0.01$) (Figure 2 c, d, e).

A significant interaction effect between 'Time', 'Group' and 'LBP' was found for the sartorius ($F = 2.50$, $p = 0.03$) and gluteus medius ($F = 2.85$, $p = 0.02$) muscles only. For players with current LBP in the Intervention group, sartorius and gluteus medius muscle size significantly increased for those who received motor control training (all $p < 0.05$, Table 1). For players with current LBP in the Wait-list Control group, the sartorius muscle significantly decreased in size from Time 1 to Time 2 ($p < 0.05$, Table 1) while no significant change in size occurred for the gluteus medius muscle ($p > 0.05$). In the follow-up period for the Intervention group (Time 2 to Time 3), the increase in sartorius and gluteus medius muscle size was maintained for players with current LBP (all $p < 0.01$).

Discussion

A main finding of this study was that the motor control training program was commensurate with an increase in iliopsoas, sartorius and gluteus medius muscle size. This effect may be explained by the functional role of these hip muscles and the types of exercises used in the motor control training program. Hip flexor muscles such as the iliopsoas and sartorius muscles play an important role in functional tasks that involve hip flexion such as walking or kicking [22, 23]. In addition to hip abduction, the gluteus medius muscle is an important stabilizer of the hip and pelvis in single leg stance [24]. The types of exercises employed in the motor control program involved facilitation of voluntary control of the lumbopelvic muscles, initially in non-weightbearing positions and then progressing to functional weightbearing positions such as single leg stance or squats and in dynamic tasks such as single leg hopping and kicking [19]. In the program, there was a focus on good postural alignment, adopting a diaphragmatic breathing pattern, dissociation of trunk movement from hip movement and optimal trunk, pelvic and lower limb alignment when load was added in functional sports specific positions. The functional weightbearing positions used for training would have required the use of hip muscles, such as the iliopsoas, sartorius, and gluteus medius muscles, that are responsible for the control of alignment and joint stability in the hip and pelvic region as well as normal hip function [23-25]. This may explain the observed increase in size of these specific hip muscles in the Intervention group. This finding is similar to previous research, which also found that motor control training increased the size of the piriformis muscle[15], a hip external rotator that is important in the control of pelvic stability and lower limb alignment in weightbearing positions [26].

Motor control training did not result in a change in iliacus, psoas and gluteus minimus muscle size. The iliacus and psoas muscles are proposed to contribute to stability of the lumbar spine, pelvis and hip joint[27]. Similar to the rotator cuff muscles of the shoulder, the iliacus and psoas muscles are proposed to contribute to stability of the femoral head in the acetabulum through the muscle belly and tendon of the iliopsoas muscle as it crosses the anterior hip joint [25]. In the current study, an increase in size of the iliopsoas muscle at the hip joint was found but no change in size of the iliacus and psoas muscles with intervention. This finding may indicate that the motor control training targeted the functional role of this muscle complex at the hip joint rather than across the lumbar spine and pelvis. In addition to hip abduction, the gluteus minimus muscle is a deep hip muscle proposed to primarily control the femoral head in the acetabulum[24]. Considering the weightbearing positions used in the motor control training program, it is surprising that this muscle did not respond to the intervention. Perhaps specific exercises targeted to its functional role are required for an increase in gluteus minimus muscle size.

The motor control training program has previously been used to treat patients and elite athletes with LBP and has resulted in improved size and function of the trunk muscles [7, 8, 19] and increased size of the piriformis muscle [15]. Similarly, in the current study, the motor control training program was found to be associated with an increase in size of the sartorius and gluteus medius muscles for football players with current LBP. A decrease in the size of the sartorius muscle was also found in players with current LBP who did not receive the intervention during the season. This finding of decreased hip flexor (sartorius) muscle size is similar to previous research which has found piriformis muscle atrophy in football players with LBP [15]. This suggests that, despite the high levels of activity that these elite football players undertake, the presence of LBP may inhibit specific hip muscles, resulting in muscle atrophy. As the motor control training program improved hip muscle size in players with LBP, this suggests that the effects of LBP on hip muscle size can be mitigated by use of this intervention.

The motor control training program could be incorporated into rehabilitation or training programs for football players with and without low back pain to target muscles of the trunk and hip simultaneously. Considering the physically demanding sports specific skills involved in playing football, optimal function of the lumbo-pelvic region would be important for these athletes. The motor control training approach has also been shown to be beneficial in injury prevention with increased availability for games demonstrated for those players who received motor control training [19, 28]. This beneficial effect on availability for games was thought to be due to improved trunk control. However, considering the effect of motor control training on hip muscle size, the increased availability for playing games, may also be due to the effect of the intervention on other muscles of the lower limb kinetic chain.

A limitation of the current study is its small sample size, which involved one professional football club. Another limitation is that all hip muscles could not be measured in the current study. Future research could investigate the effect of motor control training on a larger sample of athletes and investigate other hip muscles such as the adductor and extensor muscles.

Conclusion

The motor control training program was associated with an increase in iliopsoas, sartorius and gluteus medius muscle size in elite Australian football players. Due to the functional components of the training program that encourage optimal trunk, pelvic and lower limb alignment when load is added in functional weight bearing positions, motor control training programs may benefit more muscles in the kinetic chain than trunk muscles alone. For players with current LBP, the motor control training program mitigated sartorius muscle atrophy and improved gluteus medius muscle size. These findings may help in the management of LBP in elite football players.

Practical implications

- Motor control training resulted in an increase in iliopsoas, sartorius and gluteus medius muscle size
- Presence of LBP in football players was associated with specific hip muscle atrophy
- For football players with LBP, assessment and treatment of hip muscles may be indicated.
- Use of the motor control training program could be incorporated into rehabilitation or training programs for football players with or without LBP to improve hip muscle size.

Acknowledgements

The authors thank Prof Warren Stanton for consultation on statistical advice and research design, the players who participated in the study and the UQ Centre for Advanced Imaging. This study was funded by a sports medicine research grant from the Brisbane Lions Football Club.

References

1. van Hilst J, Hilgersom NF, Kuilman MC, et al. Low back pain in young elite field hockey players, football players and speed skaters: Prevalence and risk factors. *J Back Musculoskelet Rehabil* 2015; 28(1):67-73.

2. Tunas P, Nilstad A, Myklebust G. Low back pain in female elite football and handball players compared with an active control group. *Knee Surg Sports Traumatol Arthrosc* 2015; 23(9):2540-2547.

3. Muller R, Ertelt T, Blickhan R. Low back pain affects trunk as well as lower limb movements during walking and running. *Journal of biomechanics* 2015; 48(6):1009-1014.

4. Nagashima M, Abe H, Amaya K, et al. Risk factors for lumbar disc degeneration in high school American football players: a prospective 2-year follow-up study. *Am J Sports Med* 2013; 41(9):2059-2064.

5. Hides JA, Boughen CL, Stanton WR, et al. A magnetic resonance imaging investigation of the transversus abdominis muscle during drawing-in of the abdominal wall in elite Australian Football League players with and without low back pain. *Journal of Orthopaedic and Sports Physical Therapy* 2010; 40(1):4-10.

6. Hides J, Hughes B, Stanton W. Magnetic resonance imaging assessment of regional abdominal muscle function in elite AFL players with and without low back pain. *Man Ther* 2011; 16(3):279-284.

7. Hides JA, Stanton WR, McMahon S, et al. Effect of stabilization training on multifidus muscle cross-sectional area among young elite cricketers with low back pain. *Journal of Orthopaedic and Sports Physical Therapy* 2008; 38(3):101-108.

8. Hides JA, Stanton WR, Wilson SJ, et al. Retraining motor control of abdominal muscles among elite cricketers with low back pain. *Scandinavian Journal of Medicine and Science in Sports* 2010; 20(6):834-842.

9. McGregor AH, Hukins DWL. Lower limb involvement in spinal function and low back pain. *Journal of back and musculoskeletal rehabilitation* 2009; 22(4):219-222.

10. Nadler SF, Malanga GA, DePrince M, et al. The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female collegiate athletes. *Clin J Sport Med* 2000; 10(2):89-97.

11. Nadler SF, Malanga GA, Feinberg JH, et al. Relationship between hip muscle imbalance and occurrence of low back pain in collegiate athletes: a prospective study. *Am J Phys Med Rehabil* 2001; 80(8):572-577.

12. Cooper NA, Scavo KM, Strickland KJ, et al. Prevalence of gluteus medius weakness in people with chronic low back pain compared to healthy controls. *Eur Spine J* 2015.

13. Kendall KD, Schmidt C, Ferber R. The relationship between hip-abductor strength and the magnitude of pelvic drop in patients with low back pain. *J Sport Rehabil* 2010; 19(4):422-435.

14. Lemaire A, Ripamonti M, Ritz M, et al. Relationships between hip muscles and trunk flexor and extensor muscles in chronic low back pain patients: a preliminary study. *Computer methods in biomechanics and biomedical engineering* 2013; 16 Suppl 1:161-163.

15. Leung FT, Mendis MD, Stanton WR, et al. The relationship between the piriformis muscle, low back pain, lower limb injuries and motor control training among elite football players. *J Sci Med Sport* 2015; 18(4):407-411.

16. Torry MR, Schenker ML, Martin HD, et al. Neuromuscular hip biomechanics and pathology in the athlete. *Clinics in Sports Medicine* 2006; 25(2):179-197.

17. Wilke HJ, Wolf S, Claes LE, et al. Stability increase of the lumbar spine with different muscle groups. A biomechanical in vitro study. *Spine* 1995; 20(2):192-198.

18. Richardson CA, Snijders CJ, Hides JA, et al. The relation between the transversus abdominis muscles, sacroiliac joint mechanics, and low back pain. *Spine* 2002; 27(4):399-405.

19. Hides JA, Stanton WR, Mendis MD, et al. Effect of motor control training on muscle size and football games missed from injury. *Medicine and Science in Sports and Exercise* 2012; 44(6):1141-1149.

20. Mendis MD, Hides JA, Wilson S, et al. Effect of prolonged bed rest on the anterior hip muscles. *Gait and Posture* 2009; 30:533-537.

21. Barton B, Peat J. *Medical Statistics: A Guide to SPSS, Data Analysis and Critical Appraisal,* 2nd ed, Oxford, UK, John Wiley & Sons Ltd; 2014.

22. Baczkowski K, Marks P, Silberstein M, et al. A new look into kicking a football: an investigation of muscle activity using MRI. *Australasian Radiology* 2006; 50(4):324-329.

23. Andersson E, Nilsson J, Thorstensson A. Intramuscular EMG from the hip flexor muscles during human locomotion. *Acta Physiologica Scandinavica* 1997; 161:361-370.

24. Gottschalk F, Kourosh S, Leveau B. The functional anatomy of tensor fasciae latae and gluteus medius and minimus. *Journal of Anatomy* 1989; 166:179-189.

25. Lewis CL, Sahrmann SA, Moran DW. Effect of position and alteration in synergist muscle force contribution on hip forces when performing hip strengthening exercises. *Clinical Biomechanics* 2009; 24:35-42.

26. Giphart JE, Stull JD, LaPrade RF, et al. Recruitment and activity of the pectineus and piriformis muscles during hip rehabilitation exercises: An electromyography study. *American Journal of Sports Medicine* 2012; 40(7):1654-1663.

27. Andersson E, Oddsson L, Grundstrom H, et al. The role of the psoas and iliacus muscles for stability and movement of the lumbar spine, pelvis and hip. *Scandinavian Journal of Medicine and Science in Sports* 1995; 5(1):10-16.

28. Hides JA, Stanton WR. Can motor control training lower the risk of injury for professional football players? *Medicine and Science in Sports and Exercise* 2014; 46(4):762-768.

Tables

Table 1. Effect of motor control training on hip muscle cross-sectional area (cm^2) in the intervention and wait-list control groups for players with and without low back pain[a]

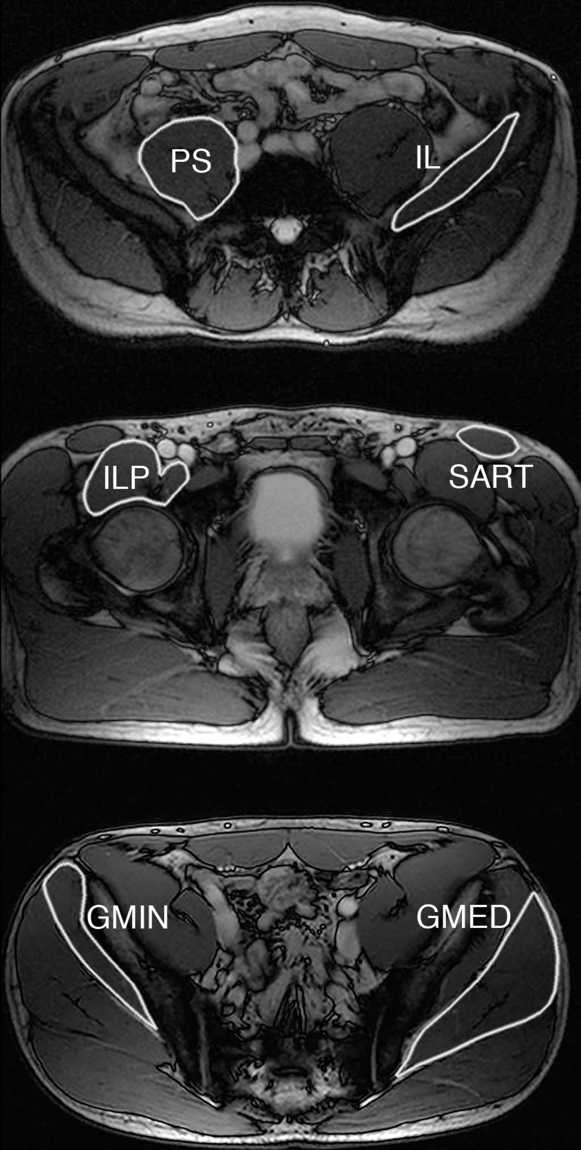
		Intervention		Wait-list Control	
Muscle	**Time**	**No LBP n=23**	**Current LBP n=9**	**No LBP n=10**	**Current LBP n=4**
Iliacus	Time 1	13.1 (0.5)	11.1 (0.8)	13.0 (0.8)	13.0 (1.2)
	Time 2	13.2 (0.5)	12.1 (0.8)	12.7 (0.8)	13.8 (1.2)
	Time 3	11.7 (0.5)	10.9 (0.8)	12.4 (0.8)	12.6 (1.2)
Psoas	Time 1	20.2 (0.6)	19.4 (0.9)	20.3 (0.8)	21.1 (1.3)
	Time 2	19.4 (0.5)	19.2 (0.9)	19.8 (0.8)	19.2 (1.3)
	Time 3	19.8 (0.6)	19.7 (0.9)	20.2 (0.8)	19.1 (1.3)
Iliopsoas	Time 1	13.7 (0.4)	13.9 (0.6)	15.2 (0.6)	14.9 (0.9)
	Time 2	14.2 (0.4)	14.9 (0.6)	15.1 (0.6)	13.2 (0.9)
	Time 3	15.2 (0.4)	16.1 (0.6)	16.4 (0.6)	15.9 (0.9)
Sartorius	Time 1	3.8 (0.2)	3.5 (0.3)	3.3 (0.3)	3.9 (0.4)
	Time 2	4.3 (0.2)†	4.2 (0.3)‡	3.8 (0.2)†	3.3 (0.4)*
	Time 3	4.3 (0.2)†	4.5 (0.3)‡	4.0 (0.2)†	3.6 (0.4)
Gluteus Medius	Time 1	37.3 (0.9)	35.8 (1.5)	37.2 (1.4)	40.9 (2.2)
	Time 2	38.5 (0.9)	40.5 (1.4)‡	39.4 (1.4)*	39.5 (2.2)
	Time 3	38.7 (0.9)	41.4 (1.5)‡	39.4 (1.4)	37.2 (2.2)
Gluteus Minimus	Time 1	14.6 (0.4)	14.3 (0.7)	15.3 (0.6)	14.3 (1.0)
	Time 2	15.4 (0.4)	15.6 (0.7)	16.6 (0.6)	14.6 (1.0)
	Time 3	16.8 (0.4)	16.9 (0.7)	16.7 (0.6)	15.5 (1.0)

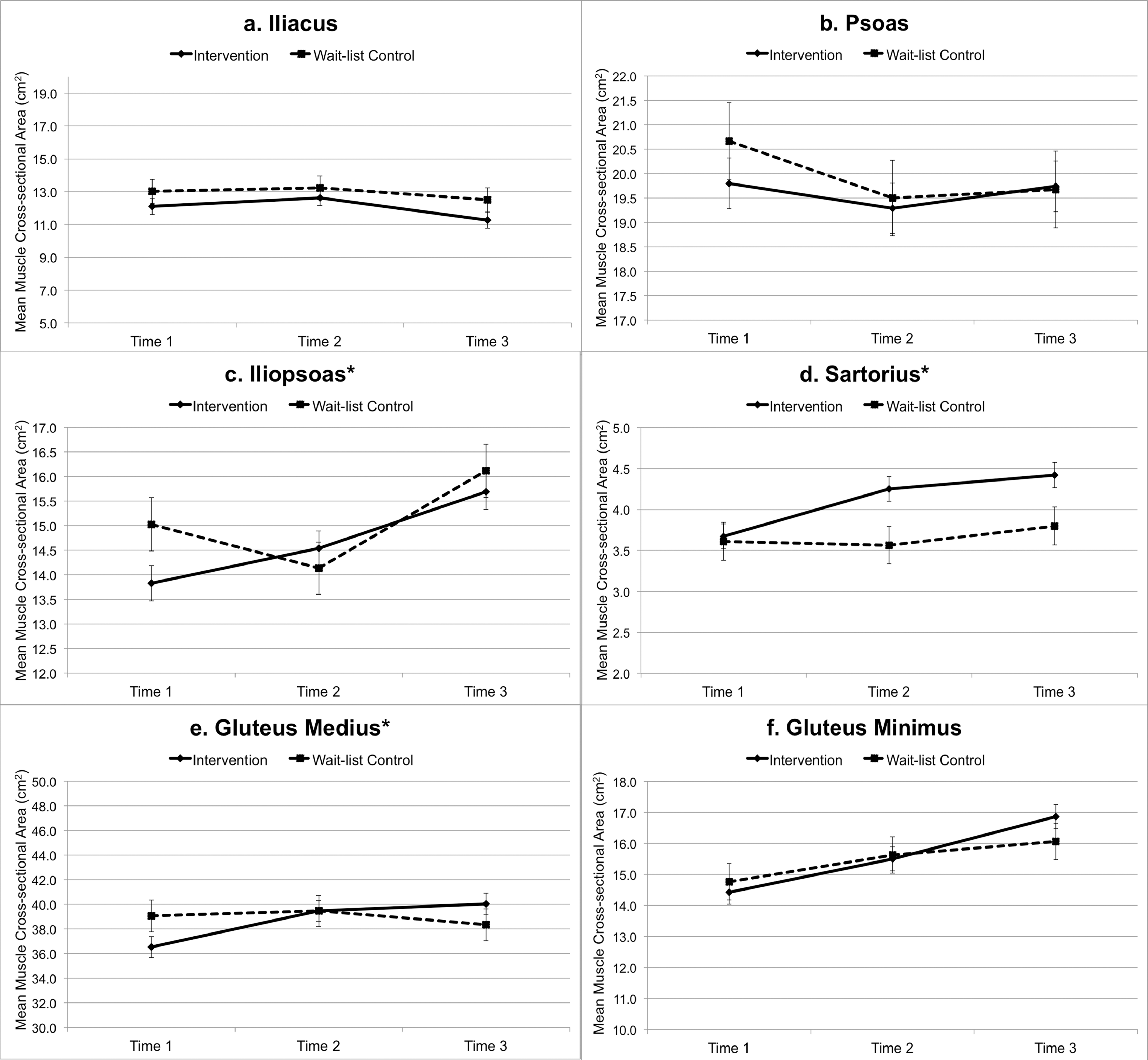
[a] Values are marginal means (SE). Intervention group (n = 32) had motor control intervention by Time 2 while the Wait-list Control group (n = 14) had no intervention. *$p < 0.05$; †$P < 0.01$; ‡$P < 0.001$ indicate significance of difference to Time 1.

Figure legends

Figure 1. Individual muscle boundaries were outlined on MRI slices to measure muscle cross-sectional area for the iliacus (IL), psoas (PS), iliopsoas (ILP), sartorius (SART), gluteus minimus (GMIN) and gluteus medius (GMED) muscles.

Figure 2. Mean hip muscle cross-sectional area in the intervention and wait-list control groups across time. * indicates significant Time x Group effect p<0.05


PS
IL
ILP
SART
GMIN
GMED


a. Iliacus
Intervention
Wait-list Control
Mean Muscle Cross-sectional Area (cm2)
19.0
17.0
15.0
13.0
11.0
9.0
7.0
5.0
Time 1
Time 2
Time 3
b. Psoas
Intervention
Wait-list Control
Mean Muscle Cross-sectional Area (cm2)
22.0
21.5
21.0
20.5
20.0
19.5
19.0
18.5
18.0
17.5
17.0
Time 1
Time 2
Time 3
c. Iliopsoas*
Intervention
Wait-list Control
Mean Muscle Cross-sectional Area (cm2)
17.0
16.5
16.0
15.5
15.0
14.5
14.0
13.5
13.0
12.5
12.0
Time 1
Time 2
Time 3
d. Sartorius*
Intervention
Wait-list Control
Mean Muscle Cross-sectional Area (cm2)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
Time 1
Time 2
Time 3
e. Gluteus Medius*
Intervention
Wait-list Control
Mean Muscle Cross-sectional Area (cm2)
50.0
48.0
46.0
44.0
42.0
40.0
38.0
36.0
34.0
32.0
30.0
Time 1
Time 2
Time 3
f. Gluteus Minimus
Intervention
Wait-list Control
Mean Muscle Cross-sectional Area (cm2)
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
Time 1
Time 2
Time 3