REVIEW PAPER

Physiotherapy Quarterly (ISSN 2544-4395)
2021, 29(2), 79–88

Trunk and hip muscles activation patterns in subjects with and without chronic low back pain: a systematic review

DOI: https://doi.org/10.5114/pq.2020.100280

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Abstract

The purpose of this study was to determine normal and abnormal patterns of activation of gluteus maximus (GM), hamstring (HAM), contralateral erector spinae (CES), and ipsilateral erector spinae (IES) muscles during a prone hip extension test in healthy or asymptomatic subjects and those with non-specific chronic low back pain through a systematic review. Studies were recognized by searching electronic databases (Embase, MEDLINE/PubMed, Cochrane Library, PEDro [Physiotherapy Evidence Database], and CINAHL) and scanning articles reference lists from the beginning until July 2018. Limits involved studies in the English language and performed among humans. Of 2112 citations and reference lists scanned, 15 articles were determined to be relevant to this review. From these studies, 4 investigated 157 subjects (88 asymptomatic and 69 with low back pain), and 11 investigated 257 healthy subjects. The results of the moderate and weak quality studies indicate that the HAM and ES muscles are activated early and almost simultaneously, but GM is consistently delayed in relation to leg movement and the other 3 muscles in healthy individuals. In low back pain subjects, CES are delayed and GM is significantly delayed in individuals who showed abnormal lumbar motions when compared with healthy ones.
Key words: activation patterns, low back pain, systematic review

Introduction

Chronic low back pain (CLBP) is the most common and exorbitant medical issue [1]. Reasons for CLBP give an impression of being intricate and multifactorial [2]. The primary causes of mechanical LBP were physical impairments, including postural abnormalities [3, 4], disturbance of motor control [5], and muscles imbalance [6].

Functional movement is never isolated because it is produced by several muscles acting as prime movers, synergists, or stabilizers that coordinate to produce an activation pattern [7]. In addition, functional strength does not require maximal activation; muscle onset and timing are more important [7]. The pattern of activation includes the timing (i.e., which muscle is activated first, second, third, etc.) and amount of muscle activity [8]. Adequate muscle activation patterns are recognized as important for the effective functioning of the lumbar spine when the synergic muscles are activated in a suitable temporal order [9].

Increased or decreased muscle activity and delayed muscular activation can change the normal movement pattern [10, 11]. It has been noted that patients with chronic or recurrent LBP have altered patterns of extensor muscles [8, 12, 13] and postural dysfunction [14, 15].

There are relatively few clinical tests that are used in practice to assess a patient's motor control. The prone hip extension (PHE) test is one of the most common tests used in LBP; it includes having a patient lying prone and lifting each leg alternatively while clinicians should look for the 'normal' activation sequence starting with ipsilateral gluteus maximus (GM), followed by ipsilateral hamstring (HAM) and contralateral erector spinae (CES), up to ipsilateral erector spinae (IES) muscles [10]. Recent evidence suggests that the 'normal' order of muscle activation is incorrect and being debated; it has been demonstrated that there is not a consistent order of muscle recruitment during PHE in healthy individuals [13, 16–18].

The lack of a clear understanding of activation patterns used in asymptomatic subjects and those with CLBP could be a possible reason for the less successful outcomes of long-term complaints in patients with CLBP. Up to the authors' knowledge, 1 review of literature investigated the activation patterns during a PHE test but there was no quality assessment of the included studies and the author could not reach a comprehensive conclusion regarding the pattern [19].

To address changes in the lumbopelvic muscle activation patterns in LBP subjects as a part of a rehabilitation program, the nature of these changes needs to be studied. Therefore, the objective of this study was to systematically review the observational studies that investigated the onset times and pattern of activation of GM, HAM, and ES by surface electromyography during a PHE test in healthy or asymptomatic subjects and those with non-specific CLBP.

Subjects and methods

This review followed the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [20].

The research considered all studies that investigated the activation pattern of GM, HAM (semitendinosus [ST] or biceps femoris [BF]), or ES muscles in healthy or asymptomatic and CLBP (male and female) subjects during a PHE test. Observational studies, studies on PHE with different positions, pa-

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Received: 16.02.2020
Accepted: 28.05.2020

Citation: Kamel E, Abdelmajeed S, El Khozamy H, Hassan K. Trunk and hip muscles activation patterns in subjects with and without chronic low back pain: a systematic review. Physiother Quart. 2021;29(2):79–88; doi: https://doi.org/10.5114/pq.2020.100280.

pers in the English language, and published papers were included. This review excluded studies that involved subjects with LBP due to fracture, tumour, neurological dysfunction, or sports injury; studies that used surface electromyography measurements in acute LBP; studies that applied PHE as a rehabilitation exercise; and conference proceedings.

Primary outcomes of interest were back and hip GM, HAM, ES muscles onset times measured by surface electromyography during a PHE test and the patterns of muscle activation. Secondary outcomes included back pain (severity, frequency, duration, and number of previous attacks).

Information sources and search strategy

The electronic search was conducted for the following databases: Embase, MEDLINE/PubMed, Cochrane Library, PEDro [Physiotherapy Evidence Database], and CINAHL, from inception until July 2018. The search strategy used search terms adapted to each database by a combination of Medical Subject Headings (MeSH) terms.

The search strategy for MEDLINE/PubMed, these terms were used:

(1): Activation Patterns OR Recruitment Pattern OR Movement Patterns OR Firing Order OR Electromyographic Activity,

(2): (1) AND Chronic Low Back Pain OR Non-Specific Low Backache OR Mechanical Back Pain,

(3): Prone Hip Extension Test OR Position,

(4): (1) AND Prone Hip Extension,

(5): (3) AND (Chronic Low Back Pain OR Non-Specific Low Back Pain OR Mechanical Back Pain),

(6): AND ("1976/01/01"[PDat]: "2018/07/31"[PDat]),

(7): Clinical Trial,

(8): Observational Study,

(9): Randomized Controlled Trial,

(10): Review,

(11): Systematic Review,

(12): English Abstract,

(13): Human Studies.

All papers were imported to Mendeley Desktop (version 1.17.11) and screened for duplicates. In accordance with the predetermined eligibility criteria, 2 reviewers (EK, KA) independently screened the title and abstract of each paper. Discrepancies between the reviewers were resolved by discussion. Full-text papers that met the inclusion criteria were retrieved by the same reviewers. The reference lists of the included papers were hand-searched.

Data extraction was performed independently by 2 reviewers (HK, EK) with a predesigned data collection form. The following data items were extracted: authors, journal and year, study design, sample sizes, participants' characteristics (age, sex, body mass index, weight, and height), muscles investigated, electrode position, onset time calculations, outcomes, and results. The researchers were contacted in order to obtain data where required.

A modified Effective Public Health Practice Project (EPHPP) quality assessment tool was used to evaluate the quality of the included papers [21]. EPHPP was designed specifically for observational studies and consists of 8 items: selection bias, study design and randomization process in participants selection or assessment, control of confounders, blinding of participants and outcome assessors, data collection methods, sample size, withdrawal and dropouts, and the analysis of outcome variables. On the basis of the adjusted EPHPP, each item was rated strong, moderate, or weak. Then, each paper was given a global rating. The global rating of a study was dependent on the number of weak items, whereas strong meant no weak items, moderate meant 1 or 2 weak items but not including confounders, and weak meant 3 or more weak items. Two independent reviewers (KA, EK) assessed the methodological quality of the included studies and, if there was any disagreement, a third reviewer was consulted.

Data synthesis

Descriptive data synthesis was based on the extracted data and the quality assessment of the included studies. Different activation patterns were identified in the included studies in healthy or asymptomatic and LBP subjects.

Ethical approval

The conducted research is not related to either human or animal use.

Results

Study selection

The comprehensive search identified 2871 citations, with 2112 citations evaluated after removal of duplicates. The full text of 27 articles were retrieved and evaluated for eligibility, 11 studies fulfilled the inclusion criteria. Four additional papers were identified by hand searching of the included papers reference lists. A total of 15 studies met the selection criteria (Figure 1).

Study characteristics

Studies in healthy participants

Eleven cross-sectional studies out of the 15 studies examined the pattern of trunk and hip muscles in healthy participants. In these 11 studies, 257 healthy subjects were investigated; the sample sizes varied between 14 [13] to 40 [22] subjects. The range of age was 20–36 years. In 7 studies, both genders were included [13, 16, 18, 22–25], while in 4 studies, only male subjects participated [17, 26–28]. The characteristics of the included studies are presented in Table 1.

Studies comparing asymptomatic with LBP subjects

Four cross-sectional studies out of the 15 determined studies aimed to compare the activation pattern of the IES, CES, GM, and HAM (BF or ST) muscles during PHE between asymptomatic and CLBP subjects [29–32]. In these studies, 157 subjects were investigated (88 asymptomatic and 69 LBP) aged 20–43 years. In 3 studies, both genders were included [29–31], and female gender only participated in the remaining one [32]. The characteristics of the included studies are presented in Table 2.

Methodological quality

In accordance with the criteria used to assess the methodological quality of the studies, 3 studies out of the 15 were of moderate quality [26, 27, 31], and 12 were of weak quality [13, 16–18, 22–25, 28–30, 32]; no studies were of strong quality. The results of the quality assessment are presented in Table 3.

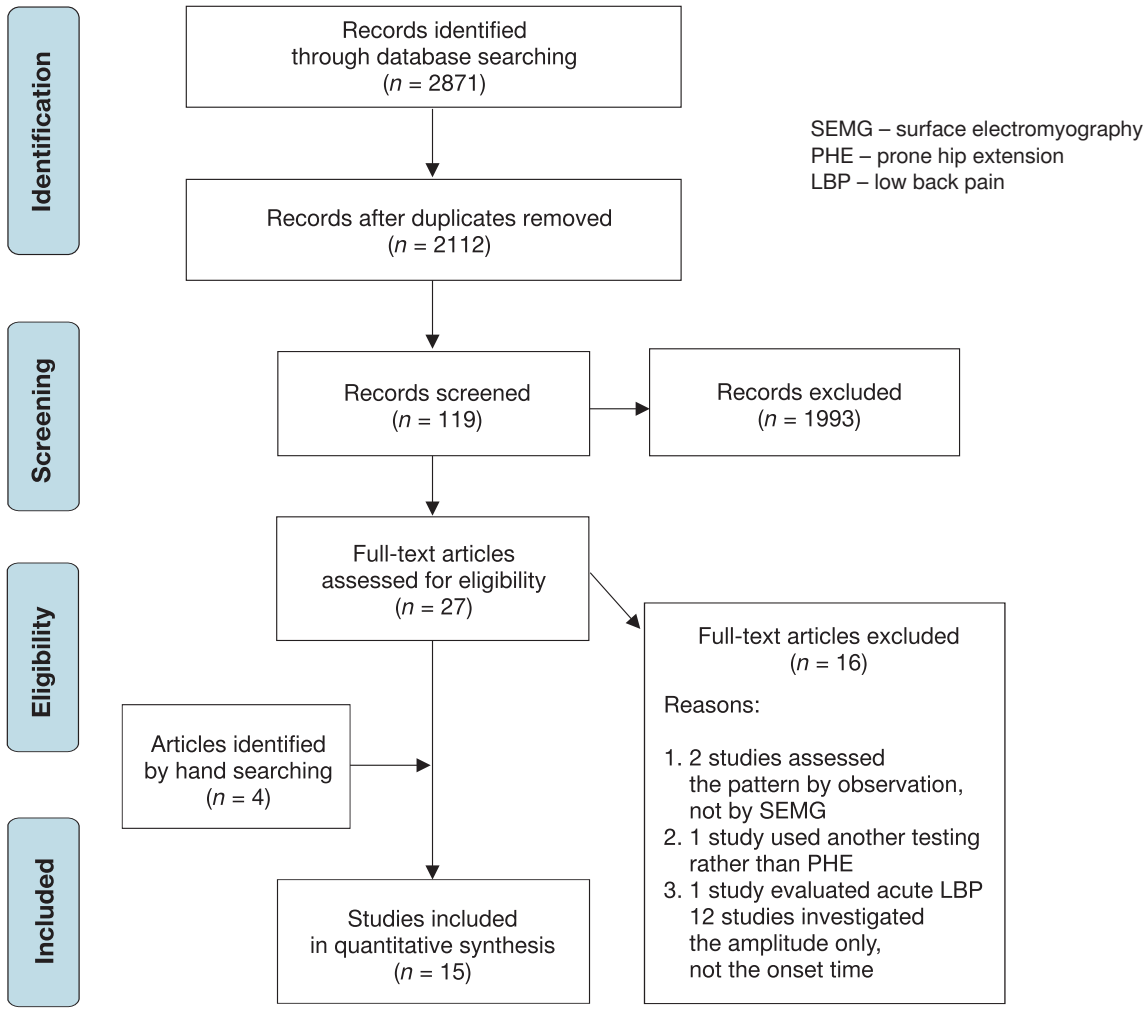

Figure 1. PRISMA flow diagram of the selection process

Synthesis of results

The results were organized into 2 categories: (a) activation patterns in healthy subjects, (b) differences in activation patterns between asymptomatic and LBP subjects.

Activation patterns in healthy subjects

Two of the studies in healthy subjects were of moderate rating quality [26, 27]. Activation patterns during PHE in subjects who demonstrated specific 'abnormal' lumbar spine motion patterns (positive group) and those who did not (negative group) were investigated and the authors found that patterns used by both groups were variable [26]. There were 6 activation orders most prevalent in the positive and negative groups; these accounted for the majority of each group's total repetitions (Table 1).

The HAM, CES, and IES activated almost simultaneously in a seemingly random order, followed by GM after a delay. GM was consistently delayed relative to the other 3 muscles in the 2 groups, with the magnitude of the delay being significantly greater in the positive group compared with the negative group [26].

The effect of 3 levels of pelvis compression (0 N, 50 N, 100 N) on the muscle firing pattern during the PHE test was investigated. There was a consistent and significant delay ($\alpha = 0.05$) in the GM muscle onset in relation with the ST muscle [27]. No significant differences were observed in the onset time of the ES muscles and ST: they activated almost simultaneously, whereas in 13 out of 20 subjects, IES contracted before ST, and the activation of CES prior to ST was seen in 15 out of 20 subjects. The compression force across the pelvis appeared to reduce the onset delay of GM, but it had no such effect on ES in asymptomatic subjects [27].

Another 9 studies among healthy subjects were of weak rating quality. The first study revealed a variability in the relative onset times among the 4 muscles (GM, HAM, IES, CES) both within and between subjects; 65 different muscle firing orders were observed [16]. However, in the second study, mean onset times of the muscles in the entire sample was calculated to determine an 'average' group activation order of IES–CES–ST–GM [17]. Electrical activities in the ST muscle appeared almost simultaneously with the activation of ES muscles [17].

The third study indicated that GM was significantly delayed ($p < 0.05$) compared with all other muscles [13]. The remaining muscles activation times were not statistically significantly different from each other [13]. In the fourth study, the consistency of activation orders within subjects (activation orders used for each set of 5 repetitions) and between subjects (activation orders used in the entire sample of 300 repetitions) was poor [23]. The results showed 6 different activation patterns used for 81.3% of the time (95% CI); GM activated last, with no clear activation order evident for HAM, IES, and CES [23] (Table 1).

The activation patterns in the fifth study were similar for hip extension associated with knee flexion, knee extension,

Table 1. Data extracted from studies that investigated activation patterns in healthy subjects

Authors, year	Subject characteristics	Methods	Electrode position	Onset calculation	Statistics	Outcomes
Pierce and Lee, 1990 [16]	20 healthy right-handed males and females aged 21–35 years	Prone on a table. Right hip 30° flexion, knee extended. Active PHE from 30° flexion to neutral in 1 s. 3 sets of 10 repetitions	Bilateral LES, right GM, right BF	The first consistent increase in EMG activity which was readily discerned because electrical silence characterized the baseline period for all muscles	Means and *SD*s of the onset times of each muscle. Friedman two-way analysis of ranks. An α level of 0.05	Muscle firing order was extremely variable. 65 activation orders observed in 523 trials. The only consistent event was the activation of BF before the onset of hip extension
Vogt and Banzer, 1997 [17]	15 healthy right-handed males aged 23–27 years (mean: 25.3); height: 1.79 m (*SD*: 0.06); weight: 73.43 kg (*SD*: 8.08)	PHE test started from 0° of hip extension to hip extension maximum. Subject maintained neutral hip rotation, full knee extension, and neutral ankle flexion. 12 repetitions with 1-min rest	Bilateral LES, left and right lower RA, right GM, right TFL, right ST	Onset time calculated when the momentary rectified EMG exceeded 10% of the maximum rectified peak amplitude of the EMG (maximum peak = 100%) for each muscle	Descriptive and inferential statistical analyses were computed. MANOVA (PcO.01). Scheffé test was used for post-hoc analysis	A consistent pattern in all subjects initiated by IES-CES-ST-GM
Lehman et al., 2004 [13]	10 males; average height: 175.2 cm (*SD*: 6.5); average weight: 75.9 kg (*SD*: 6.5); average age: 27.1 years (*SD*: 1.28) 4 females; average height: 164.5 cm (*SD*: 2.9); average weight: 56.2 kg (*SD*: 8.9), average age: 25 years (*SD*: 1)	PHE repeated 5 times from 0° of right hip extension to 6 inches off the table. Leg held 3 s, then lowered to the table	Left LD, right GM, bilateral LES, right HAM	A muscle was considered 'on' when the level of muscle was greater than 10% of the peak muscle activity during PHE	Group average and *SD* of muscle onset times for each muscle were calculated. Kruskal-Wallis test (non-parametric ANOVA) with a post-hoc Dunn test	A large variability in muscle activation order between subjects, with no consistent firing pattern. In 13/14 subjects, GM was the last muscle active during PHE
Bruno and Bagust, 2006 [23]	20 males; age: 26.2 years (*SD*: 2.22); height: 179.7 cm (*SD*: 7.80); weight: 76.9 kg (*SD*: 12.37) 10 females; age: 24.3 years (*SD*: 2.54); height: 165.3 cm (*SD*: 6.06); weight: 62.6 kg (*SD*: 10.51)	PHE from 0° hip extension to 20–30° right hip extension while maintaining neutral hip rotation, full knee extension, and neutral ankle position. 2 sets of 5 repetitions of PHE	Right GM, bilateral LES, right HAM	The onset time of each muscle was calculated relative to the onset time of the leg movement as determined by the heel/toe strike transducer	95% CI. Mode, median, and mean of the activation orders were calculated	The 6 most prevalent activation orders were: (1) HAM–IES–CES–GM, (2) CES–IES–HAM–GM, (3) IES–CES–HAM–GM, (4) IES–HAM–CES–GM, (5) HAM–CES–IES–GM, (6) CES–HAM–IES–GM
Bruno et al., 2008 [26]	27 subjects (10 positive, 17 negative); age: 25.5 years (*SD*: 3.4); height: 171.9 cm (*SD*: 9.7); weight: 69.9 kg (*SD*: 15.7)	PHE from 0° to 20–30° hip extension while maintaining neutral hip rotation, full knee extension, and neutral ankle position. 4 repetitions of PHE for right and left sides	Bilateral GM, bilateral LES, bilateral HAM	The mean onset time of each muscle relative to the onset of leg movement, as well as to the other muscles (with 95% CIs) was calculated for each group	Activation order frequency (the frequency with which each of the 24 possible activation o rders was used was calculated with 95% CIs) for each group	The 6 most prevalent activation orders in both groups that were used in 80.8% of the negative group's repetitions and 96.2% of the positive group's repetitions: (1) HAM–IES–CES–GM, (2) CES–IES–HAM–GM, (3) IES–CES–HAM–GM, (4) IES–HAM–CES–GM, (5) HAM–CES–IES–GM, (6) CES–HAM–IES–GM
Sakamoto et al., 2009 [24]	31 subjects (16 males, 15 females); age: 20–36 years (24.5 ± 3.47); weight: 46–90 kg (66.89 ± 11.89); height: 1.50–1.84 m (1.70 ± 0.09); BMI: 22.09 ± 2.22 and 23.75 ± 3.49 kg/m^2	PHE in 4 positions: with knee extension, knee flexion, lateral hip rotation–knee extension, lateral hip rotation–knee flexion. 3 trials for each modality with a 2-min rest between trials	Bilateral GM, bilateral LES, bilateral ST	When the value exceeded 2 *SD*s from the mean value observed at baseline for a 50-ms period	Descriptive statistics and tests for normality and homogeneity. Repeated measure ANOVAs followed by planned contrasts with a significance level of $\alpha < 0.05$	The muscle firing order was ST–CES–IES–GM for the following modalities of exercises: knee extension, lateral hip rotation–knee extension, and lateral hip rotation–knee flexion. GM was the last activated in 82% of cases

Takasaki et al., 2009 [27]	20 males; age: 22.0 years (*SD*: 1.3); height: 172.6 cm (*SD*: 5.40); weight: 64.3 kg (*SD*: 5.2)	Condition A: right PHE until the lower edge of the patella was raised more than 15 cm from the starting position while maintaining knee extension. Condition B: PHE without compressive force. A set of 5 trials with a 2-min rest between sets	Right GM, bilateral LES, right ST	When the value exceeded 2 *SD*s from the mean value observed at baseline for a 50-ms period	One-way ANOVA. $p < 0.05$	In condition A, compressive force across the pelvis significantly reduced the delay of GM but did not affect CES or IES to HAM. The pattern in condition B was CES–IES–ST–GM
Rabel et al., 2011 [25]	23 subjects (12 males, 11 females); age ± *SD*: 27.2 ± 4.5 years; height: 171.4 ± 9.1 cm; weight: 74.3 ± 20.4 kg; BMI: 25.0 ± 4.9 kg/m^2	Dominant leg used for testing. During PHE, subjects were positioned on their abdomen, hips in neutral position, knees extended, ankles off the edge of the mat. Subject performed maximal hip extension. 3 trials with a 1-min rest between trials	Bilateral MF, bilateral LES, right ST and BF, right GM	A muscle was activated when the signal exceeded the trigger level of 3 *SD*s beyond the baseline level	Mean muscle onset times calculated and averaged across the group. A 1-sample *t*-test (2-tailed) for the differences in latencies. $p < 0.05$	GM was the only muscle activated significantly later than CES, the first muscle to fire ($p < 0.05$). The pattern was CES–ST–IES–GM
Tateuchi et al., 2012 [18]	16 subjects (10 males, 6 females); age (mean ± *SD*): 24.3 ± 5.2 years; weight: 59.0 ± 8.0 kg; height: 165.7 ± 7.9 cm	Right PHE with hip hanging over the edge of the table, which was tilted down to 30 flexions, to 10 extensions, with the knee extended. PHE for 5 repetitions	Right GM, bilateral LES, right ST, bilateral LMF, right RF, right TFL	The relative difference of the onset time between each muscle and the prime mover (ST) was calculated. A positive value indicates that the ST muscle was getting activated earlier	Spearman's rank correlation coefficients. Wilcoxon signed-rank test with Holm's correction for multiple comparisons. $p < 0.05$ for significance	No consistent recruitment pattern observed among the trunk muscles and ST. No significant correlation between the onset timing of the activity of each muscle and the onset timing of the pelvic motion
Kim et al., 2014 [22]	LHLA group: 20 subjects (9 males, 11 females); age: 22.7 ± 3.8 years; height: 165.7 ± 9.1 cm; weight: 60.4 ± 8.3 kg; LL angle: 36.2 ± 2.1°; PT angle: 16.9 ± 1.3° LNLA group: 20 subjects (9 males, 11 females); age: 23.2 ± 3.2 years; height: 164.5 ± 10.1 cm; weight: 62.4 ± 6.9 kg; LL angle: 60.6 ± 4.6°; PT angle: 7.1 ± 1.9°	PHE when hip extension reached 10°. A horizontal bar and electronic metronome was used. ADIM performed by both the LHLA and LNLA groups and monitored with a pressure biofeedback unit	GM, BF, bilateral LES	The time at which muscle activity deviated by at least 2 *SD*s from the mean muscle activity	Shapiro-Wilk tests. Independent *t*-test. $p < 0.05$ to indicate statistical significance	The muscle contraction onset sequence, regardless of ADIM application, was HAM–LES–GM in the LNLA group. Muscle contraction onset sequence changed from LES–HAM–GM to GM–HAM–LES by the application of ADIM in the LHLA group
Suehiro et al., 2015 [28]	21 males; age: 20.2 ± 0.4 years; weight: 64.3 ± 10.5 kg; height: 171.1 ± 5.0 cm	PHE with the hip joint in 3 positions: (1) neutral, (2) abduction, (3) abduction external rotation. 90° of right knee flexion. In neutral position, the right hip joint had 0° abduction and 0° external rotation. n abduction position, the joint had 15° abduction and 0° external rotation. In abduction external rotation position, the joint had 15° abduction and 20° external rotation. 3 times for each position and a 2-min rest between measurements	Right GM, bilateral LES, right ST, bilateral LMF	When the value exceeded 2 *SD*s from the mean value observed at baseline. The relative onset difference between each muscle and the HAMs was calculated; a negative value indicated that the target muscle fired before the HAM and vice versa	Repeated measures analysis of variance and multiple comparisons (Bonferroni test). The level of significance set at $p < 0.05$	GM onset relative to HAM was significantly earlier in abduction and abduction external rotation positions compared with neutral position. Bilateral LMF and left LES onset relative to HAM was significantly earlier in abduction external rotation position compared with neutral and abduction positions. Pattern in neutral position was ST–CES–IES–GM

ADIM – abdominal drawing-in manoeuvre, BF – biceps femoris, BMI – body mass index, CES – contralateral erector spinae, CI – confidence interval, EMG – electromyography, GM – gluteus maximus, HAM – hamstring, IES – ipsilateral erector spinae, LD – latissimus dorsi, LES – lumbar erector spinae, LHLA – lumbar hyper-lordotic angle, LL – lumbar lordosis, LMF – lumbar multifidus, LNLA – lumbar normal lordotic angle, MF – multifidus, PHE – prone hip extension, PT – pelvic tilt, RA – rectus abdominus, RF – rectus femoris, ST – semitendinosus, TFL – tensor fasciae latae

Table 2. Data extracted from studies that investigated activation patterns in asymptomatic and low back pain subjects

Authors, year	Subject characteristics	Methods	Electrode position	Onset calculation	Statistics	Outcomes
Bruno and Bagust, 2007 [29]	Non-LBP: 31 subjects; mean age: 27.5 years (*SD*: 6.9); mean height: 172.8 cm (*SD*: 9.7); mean weight: 70.2 kg (*SD*: 11.6) LBP: 20 subjects; mean age: 35.7 years (*SD*: 8.4); mean height: 168.4 cm (*SD*: 7.3); mean weight: 71.6 kg (*SD*: 12.6)	Subjects were instructed to perform right PHE of 20–30° while maintaining neutral hip rotation, full knee extension, and neutral ankle position. 2 sets of 5 repetitions of PHE. For the non-LBP sample, only the right leg was tested. For the LBP sample, both legs were tested	Bilateral LES, right GM, right HAM	The mean onset times of each muscle relative to the onset of leg movement, as well as to the other muscles (with 95% CIs) were calculated for each group	Mode, median, and mean of the activation orders were calculated with 95% CI. Kruskal-Wallis test and post-hoc Dunn's test were used for all *p* calculations	The most common pattern in non-LBP sample was HAM–CES–IES–GM. The most common pattern in LBP sample was HAM–IES–CES–GM. The 6 most prevalent activation orders were: (1) HAM–IES–CES–GM, (2) CES–IES–HAM–GM, (3) IES–CES–HAM–GM, (4) IES–HAM–CES–GM, (5) HAM–CES–IES–GM, (6) CES–HAM–IES–GM
Guimarães et al., 2010 [30]	Asymptomatic: 27 subjects; mean age: 24.85 ± 3.60 years; weight: 67.36 ± 12.55 kg; height: 1.70 ± 0.09 m; BMI: 23.13 ± 3.09 kg/m^2 LBP: 19 subjects; mean age: 28.79 ± 5.67 years; weight: 66.92 ± 16.76 kg; height: 1.68 ± 0.09 m; BMI: 23.48 ± 3.84 kg/m^2	After electrode and passive markers placement, the subjects were instructed to perform active PHE at their natural speed. 3 trials, 2-min rest between trials	Bilateral GM, bilateral LES, bilateral ST	When the values respectively exceeded and dropped below 2 *SD*s from the mean values observed at baseline for a 50-ms period	Descriptive statistics and tests for normality. Student's *t*-tests or Mann-Whitney *U* tests. Repeated measure ANOVAs with a significance level of $\alpha < 0.05$	For the asymptomatic group, the pattern was ST–IES–CES–GM. For the LBP group, the pattern was ST–CES–IES–GM
Suehiro et al., 2015 [31]	Asymptomatic: 20 subjects (14 males, 6 females); mean age: 24.5 ± 5.8 years; mean height: 165.7 ± 7.0 cm; mean weight: 56.9 ± 6.8 kg; mean BMI: 20.7 ± 1.9 kg/m^2 LBP: 20 subjects (13 males, 7 females); mean age: 24.2 ± 4.9 years; mean height: 168.3 ± 8.8 cm; mean weight: 59.9 ± 14.2 kg; mean BMI: 20.8 ± 2.9 kg/m^2, NRS: 3.5 ± 1.3; ODI: 16.9 ± 7.6%	PHE from 0° to 10° while keeping the knee extended. Individuals with unilateral CLBP performed the movement using the leg of the painful side, those with bilateral CLBP used the leg of the more painful side, and controls used the non-dominant leg to avoid comparison with superior members. 3 trials with rest periods of 1 min between them	Bilateral LES, bilateral LMF, ST, GM	The onset of muscle activity was defined as the time when the EMG signal exceeded the threshold (2 *SD*s from the mean value observed at baseline) for a period of 50 ms	Independent samples *t*-tests and chi-squared test. One-way analysis of variance with repeated measures. Post-hoc analyses were performed with the Bonferroni method for $p < 0.05$	The pattern in the control group was IMF–ST–CMF–CES–IES–GM. The pattern in the LBP group was ST–IMF–CMF–CES–IES–GM
Kahlaee et al., 2017 [32]	10 healthy women; mean age: 29.8 (± 5.67) years; height: 161.2 (± 7.36) cm; weight: 58.4 (± 5.44) kg; physical activity: 4093 (± 964.7) MET · min^{-1} · week^{-1} 10 women with non-specific CLBP: mean age: 33.6 (± 7.27) years; height: 163.1 (± 8.25) cm; weight: 59.5 (± 10.34) kg; physical activity: 4280.5 (± 860.4 MET · min^{-1} · week^{-1})	The leg that the participant used for kicking a ball was considered dominant and was chosen for investigation. The subjects were instructed to perform 3 manoeuvres: PHE alone, PHE with AH, and PHE with AB. 3 trials for each manoeuvre with a 1-min rest between trials and a 2-min rest between manoeuvres	GM, BF, bilateral LES	The onset of the EMG activity was identified by using a mathematical algorithm that calculated the data point at which the EMG signal deviated by more than 3 *SD*s above the mean baseline activity level (averaged over 500 data points before the movement)	Shapiro-Wilk test. Intraclass correlation coefficient values (model 3.3) with a 95% CI and the standard error of measurement. ANOVA tests. 3-way mixed model ANOVA. Post-hoc analyses (Bonferroni correction). Effect sizes (Cohen's *d*). Statistical significance set at $p < 0.05$	In the CLBP group, the pattern was IES–CES–BF–GM. In the asymptomatic group, the pattern was CES–GM–IES–BF

AB – abdominal bracing, AH – abdominal hollowing, BF – biceps femoris, BMI – body mass index, CES – contralateral erector spinae, CI – confidence interval, CLBP – chronic low back pain, CMF – contralateral multifidus, EMG – electromyography, GM – gluteus maximus, HAM – hamstring, IES – ipsilateral erector spinae, IMF – ipsilateral multifidus, LBP – low back pain, LES – lumbar erector spinae, LMF – lumbar multifidus, MET – metabolic equivalent, NRS – numerical rating scale, ODI – Oswestry Disability Index, PHE – prone hip extension, ST – semitendinosus

Table 3. Results of quality assessment

Authors, year	(1) Selection bias	(2) Study design	(3) Confounders	(4) Blinding	(5) Data collection methods	(6) Sample size	(7) Withdrawals and drop-outs	(8) Analyses	Global rating
Pierce and Lee, 1990 [16]	2	2	3	3	1	2	1	2	Weak
Vogt and Banzer, 1997 [17]	3	2	3	3	1	3	1	3	Weak
Lehman et al., 2004 [13]	2	2	3	3	3	3	1	3	Weak
Bruno and Bagust, 2006 [23]	2	2	3	3	3	2	1	2	Weak
Bruno and Bagust, 2007 [29]	2	2	3	3	3	2	1	1	Weak
Bruno et al., 2008 [26]	2	2	2	3	3	2	1	1	Moderate
Sakamoto et al., 2009 [24]	3	2	3	3	3	2	1	2	Weak
Takasaki et al., 2009 [27]	2	2	2	3	2	2	1	3	Moderate
Guimarães et al., 2010 [30]	3	2	1	3	3	2	1	1	Weak
Rabel et al., 2011 [25]	2	2	3	3	2	2	1	2	Weak
Tateuchi et al., 2012 [18]	3	2	3	2	3	3	1	2	Weak
Kim and Kim, 2014 [22]	3	2	2	3	3	2	1	2	Weak
Suehiro et al., 2015 [28]	3	2	1	3	3	2	1	3	Weak
Suehiro et al., 2015 [31]	2	2	1	3	3	1	1	2	Moderate
Kahlaee et al., 2017 [32]	3	2	1	3	1	3	1	1	Weak

1 – strong, 2 – moderate, 3 – weak

and lateral rotation and knee flexion, starting with ST, followed by ES, and then GM ($p < 0.0001$) [24]. The sixth study examined the difference in intermuscular timing between the firing of the first muscle and all remaining muscles during the PHE test. It was found that GM was the only muscle activated significantly later than CES (the first muscle to fire). Also, there were no significant differences in the latency between the CES, IES, and HAM muscles during PHE ($p = 0.004$) [25].

Relations between balance of hip and trunk muscle temporal patterns, pelvic motion, and low back muscle activity during PHE were examined in the seventh study [18]. The results implied that there was no consistent recruitment pattern among trunk muscles and ST. The mean onset time of all hip and trunk muscles except GM was earlier than the onset of leg movement. The onset timing of GM was delayed significantly relative to the onset timing of contralateral multifidus (CMF) ($p = 0.027$), ipsilateral multifidus (IMF) ($p = 0.008$), CES ($p = 0.038$), IES ($p = 0.035$), and ST ($p = 0.009$). The delay of the hip and trunk muscles relative to ST firing was significantly associated with an increase of the anterior pelvic tilt during hip extension [18].

The authors of the eighth study investigated the effect of the abdominal drawing-in manoeuvre (ADIM) on muscle onset time in HAM, GM, and ES during PHE in subjects with hyper-lordotic angle but without LBP [22]. The subjects were divided into 2 groups: with lumbar hyper-lordotic angle (LHLA) and with lumbar normal lordotic angle (LNLA). No significant differences were observed between the groups in the differential values of HAM or ES onset time with or without ADIM application ($p > 0.05$). Only GM in the LHLA group presented a significant difference during ADIM ($p < 0.01$) [22].

The results revealed that the muscle contraction onset sequence, regardless of ADIM, was HAM–ES–GM in the LNLA group. However, the muscle contraction onset sequence changed from ES–HAM–GM to GM–HAM–ES with the application of ADIM in the LHLA group [22].

Finally, the ninth study investigated the effect of 3 hip positions – neutral, abduction, and abduction with external rotation – on muscle onset time during PHE with knee flexion [28]. GM was the last muscle to activate in the neutral position. However, GM onset relative to HAM was significantly earlier with hip abduction and with hip abduction with external rotation compared with that with hip in neutral position. Bilateral multifidus (MF) and CES onset relative to HAM was significantly earlier in the abduction with external rotation position than in the neutral and abduction positions. The sequence of muscle contraction was HAM–CES–IES–GM in the neutral position, IES–GM–HAM–CES in the abduction position, and CES–IES–GM–HAM in the abduction with external rotation position [28].

Differences in activation patterns between asymptomatic and LBP subjects

One of the 4 studies in LBP subjects was of moderate rating quality [31]. It revealed that the onset of GM was delayed significantly relative to the onset of IMF ($p < 0.001$), CMF ($p < 0.001$), IES ($p < 0.01$), and CES ($p < 0.001$) in both the control and CLBP group. There were no significant differences in the onset times of GM ($p = 0.32$) or IES ($p = 0.11$) between the groups. However, the onset times of bilateral MF ($p < 0.001$) and CES ($p = 0.001$) were delayed in the CLBP group compared with the control group [31].

The second study demonstrated that the onset of GM was significantly delayed in both the symptomatic (95% CI; $p < 0.001$) and the asymptomatic leg (95% CI; $p < 0.001$) in the LBP group compared with the non-LBP group [29]. CES onset was also significantly delayed in the symptomatic leg in the LBP group (95% CI; $p < 0.05$), but no significant differ-

ence was found with the asymptomatic leg. There was a high degree of variability in the activation patterns. Six activation orders were the most prevalent in both samples, with none showing a strong predominance [29] (Table 2).

The most common muscle to become active first was HAM in all the 3 groups. The most common muscle to become active second was CES in the non-LBP sample and IES in both legs in the LBP sample. The most common muscle to become active third was IES in the non-LBP sample and CES in both legs in the LBP sample. The most common muscle to become active fourth was GM in all 3 groups [29].

The authors of the third study suggested that the patterns in the asymptomatic group were initiated by ST, followed by IES, CES, and finished by GM. The patterns in the LBP group were initiated by ST, followed by CES, IES, and finally GM [30]. ANOVAs demonstrated significant differences in latencies for GM in relation to other muscles in both groups (non-LBP: $F > 41.78$; LBP: $F > 23.64$; $p < 0.001$). No significant differences were found between groups regarding latencies for any investigated muscle [30].

Finally, the effect of abdominal hollowing (AH) and abdominal bracing (AB) manoeuvres on the activity pattern of lumbopelvic muscles during PHE in participants with or without non-specific CLBP was investigated [32]. There were no significant differences in muscle activation onset times between patients and asymptomatic participants in any of the manoeuvres (PHE, PHE + AH, PHE + AB), except for CES in PHE ($p = 0.03$), which was delayed in the CLBP group compared with the asymptomatic group [32].

Discussion

Concerning the patterns in healthy individuals, there was moderate evidence [26, 27] and weak evidence [13, 17, 24, 25] that the HAM and ES muscles were almost simultaneously activated before the onset of the leg movement during PHE, while they exhibited inconsistent and variable patterns in the remaining studies [16, 18, 22, 23, 28]. GM was significantly delayed and constituted the last muscle to activate during PHE in all studies which examined healthy participants.

Regarding the activation patterns in CLBP subjects, there was moderate evidence [31] and weak evidence [29, 32] that the onset of CES was significantly delayed when compared with non-LBP participants, while no significant differences were found for the other muscles (HAM, IES, GM). GM was significantly delayed relative to the other muscles in both CLBP and control group.

Only one study revealed that the onset of GM activity was delayed in individuals with LBP relative to the control group during PHE [29]. This inconsistency may originate from the difference in the proportion of individuals with LBP who presented abnormal lumbar spine motion during PHE between other studies and the report of this study [29]. In this regard, a subsequent report suggested that the delay in the onset of GM activity during PHE was associated with abnormal motion, such as rotation, lateral flexion, and extension, of the lumbar spine in individuals with or without LBP [22, 26].

The results of this systematic review support the conclusions drawn in previous studies [33, 34] that proximal musculature was activated first in order to create stability and a feedforward mechanism needed to move the limb. This finding suggests that healthy individuals can recruit the stabilizing musculature (ES) in anticipation of lower extremity movement associated with PHE to achieve lumbopelvic stability. The stabilization cascade occurred very rapidly, and the only muscle that was significantly delayed, possibly owing to its primary role in producing torque on the limb, was GM [25].

Therefore, the delayed activation of CES in CLBP subjects reduced the spinal control and pelvic stability at initiation of leg motion during PHE. Inability to stabilize the lumbopelvic region effectively during limb movement may contribute to continued trauma to spinal structures, resulting in sustained or repeated episodes of LBP [35]. In this regard, it was reported that delayed MF and CES activity increased anterior pelvic tilt in healthy individuals during PHE [18]. Moreover, a later onset of the MF and ES muscles activity was observed during rapid arm movements and reaching task in patients with LBP and segmental instability relative to control subjects [36]. These results with the PHE task refute prior literature reports that GM should fire early in the sequence [37]. It was found that it was normal for GM to fire last.

The results of this systematic review implied delayed GM activation relative to the other 3 muscles in healthy and LBP subjects but failed to reach agreement on the delay magnitude. This is due to methodological differences between the studies, such as PHE position, repetitions, number of muscles evaluated, gender of participants, control of movement speed, and onset calculation.

Although most of the studies in this review used PHE test starting from neutral to maximum hyperextension, in 2 studies the participants started the test with hip in 30° flexion to maximum extension [16, 28]. These papers suggested that those subjects with a limited end range of extension would be performing trunk hyperextension instead of hip extension during prone leg lifting. This would not provide valid information on the muscle firing order during active PHE.

Concerning the number of muscles evaluated, all studies investigated GM, ES, and HAM; however, some studies investigated other muscles in addition to the mentioned above. One study examined rectus abdominus (RA) and tensor fasciae latae (TFL) [17]. Another study investigated latissimus dorsi (LD) [13], while MF muscles were considered in 2 studies [18, 28]. It was suggested that if more muscles were evaluated, it would be difficult to find a consistent pattern of muscle activation [38].

Referring to the speed of movement, PHE was performed at a low speed in 3 of the included studies [16–18] and with a high speed in 1 study [31]; the remaining studies did not specify the speed of limb movement. The studies indicated that performing movement at a low speed reduced the frequency of response of trunk muscles and increased the variability [39, 40].

Another difference was the participants' gender. Some studies investigated both genders and found variable patterns [13, 16, 23]. Others investigated only males and reported consistency [17], although 1 study implied a pattern variability in male participants [26]. One study included only females to compare the pattern in healthy and CLBP subjects and no difference was found in the pattern except for CES, which was delayed in CLBP subjects [32]. Future electromyographic research should examine if differences in muscle firing patterns exist between males and females. It was observed that during certain movement tasks, electromyographic signal amplitude levels were consistently higher in the lumbar MF in women as compared with men [41].

As for the method of onset calculation, the studies included in this review used methods that varied from a researcher's visual assessment of the signal [16] to the application of the percentage of the maximum rectified peak amplitude [13, 17, 18] or a certain number of standard deviations above the baseline average [22–32]. It was suggested

that 2 standard deviations from the mean values observed at baseline for a 50-ms period was a reliable method and helped avoid type I (when using 1 standard deviation) and type II (3 standard deviations) methodological errors [42]. In contrast, the method of 3 standard deviations beyond the level at the beginning of the movement was considered reliable in previous reports [43, 44].

Clinical implications

As most studies in this review were of weak quality and at a risk of bias, there is no sufficient evidence regarding an ideal activation pattern in healthy individuals that could be used as a reference point in comparisons with abnormal activation patterns in LBP subjects. Large, high-quality studies are needed to identify faulty patterns and to evaluate the movement patterns during PHE to indicate changes, such as pelvic anteversion or lumbar spine rotation, which could generate excessive stress and pain in the spine.

Limitations of the review

The first limitation is that only studies that investigated muscle onset time were included but not studies that examined the amplitude of muscle contractions. The second limitation is that the searching process was limited to the English language.

Conclusions

Despite no strong evidence, HAM and ES muscles are activated simultaneously and early before the onset of the leg movement, and GM is significantly delayed in relation to the HAM and ES muscles and to the onset of the leg movement. The CES muscles are delayed in LBP subjects in comparison with healthy individuals. GM is significantly delayed in LBP subjects who present abnormal lumbar motions when compared with healthy people.

Acknowledgments

The authors express their deep thanks, respect, and appreciation to Dr. Amir A. Beltagi, lecturer in the Department of Biomechanics, Faculty of Physical Therapy, Cairo University, for his kind help in searching databases.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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