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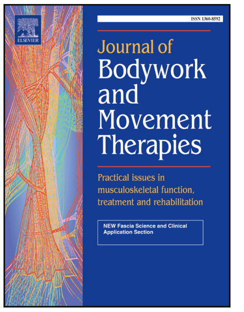

A dose response analysis of exercise prescription variables for lateral abdominal muscle thickness and activation: A systematic review

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ABSTRACT

Background: Various exercise programs are used to treat lateral abdominal muscle (LAM) impairments in people with low back pain. Factors comprising these programs include exercise type, session time, frequency, and program duration. However, specific clinical guidance about optimal exercise prescription is lacking.

Objectives: To perform a dose-response analysis on exercise prescription variables for LAM thickness and activation as measured by ultrasound imaging.

Design: Systematic review

Method: Databases were searched from their inception for studies examining the association between exercise interventions and LAM thickness/activation measured by ultrasound imaging in healthy individuals. Risk of bias was assessed using the Joanna Brigg's Institute critical appraisal tools. For each muscle, subgroup analyses were performed to determine the dose response of exercise prescription variables for LAM thickness and activation. Where there was insufficient data for subgroup analyses, data was narratively synthesised.

Results: Fourteen studies comprising 395 participants were included. Statistical and narrative synthesis revealed specific local abdominal exercises, programs from four weeks duration, three sessions per week and sessions of ≥30 minutes were associated with greatest improvements to LAM thickness. Only the variables exercise type, program duration and session frequency showed a significant between groups difference for the subgroup analysis. The main limitation was inability to perform subgroup analyses for all variables across all muscles measured at rest and during contraction, due to non-reporting of data.

Conclusion: This review provides preliminary guidance to practitioners on how the LAM respond to different exercise dosages. Future research should trial these findings.

Keywords: ultrasound imaging, abdomen, low back pain

TEXT

INTRODUCTION

Lower back pain (LBP) affects a considerable proportion of the global population, (GBD 2021 Low Back Pain Collaborators 2023) with devastating impacts to a patient's quality of life (Dutmer et al. 2019) and the broader economy (Yelin et al. 2016). With the burden of LBP expected to continue rising, (GBD 2021 Low Back Pain Collaborators 2023) pragmatic research on pathophysiology, prevention and treatment of LBP is essential. In some individuals with LBP, lateral abdominal muscles (LAM; inclusive of transversus abdominis [TrA], internal [IO] and external oblique [EO]) have shown altered thickness at rest and during activation, as evidenced by ultrasound imaging (USI) compared to asymptomatic controls (Noormohammadpour et al. 2019; Ota & Kaneoka 2011; Rahmani et al. 2018; Van Dieen et al. 2019). Exercise is prescribed regularly for LBP associated LAM impairment, with significant improvements reported in LAM thickness (Park & Yu 2013) and activation (Selkow et al. 2017), pain (Akbari et al. 2008) and disability rates (Park & Yu 2013). Thus, exercise is considered an effective tool in multidisciplinary LBP management (Oliveira et al. 2018).

Motor control exercise is the main form of exercise prescribed for patients with LAM impairments. However, the literature shows large variations in the exercise dosage variables, such as, session frequency and program duration (Saragiotto et al. 2016). A recent review examined the dose-response relationship of stabilisation exercises (inclusive of motor control exercises) in patients with chronic non-specific LBP. Exercising for 20-30 mins, 3-5 times per week was found to have the greatest effect on pain and disability based on low to moderate quality evidence (Mueller & Niederer 2020). However, to the best of our knowledge, research has yet to examine how the LAM respond to different exercise dosages and types. This may have clinical implications, considering improvements in LAM thickness and activation from exercise interventions show an association with improved pain and disability (Ferreira et al. 2004; Lariviere et al. 2019).

The presence and nature of LAM changes is variable in patients with persistent LBP (Lariviere et al. 2019; Van Dieen et al. 2019). Therefore, it is difficult to accurately compare the effect of exercise prescriptions across LBP studies when samples may or may not have LAM changes. To justify which exercise prescriptions are associated with greater LAM recruitment, it is necessary to remove this heterogeneity by examining exercise in healthy individuals. This may assist in identifying exercise prescription methods which are appropriate for inclusion in future research to address LAM impairment in LBP.

Previous studies in healthy individuals demonstrated considerable variation in exercise protocols. For example, programs have ranged from two to eight weeks, containing 60-240 minutes per week and the type of exercise has included specific core stabilisation exercise, Pilates or strength training (Critchley et al. 2011; Lee et al. 2018; Niewiadomy et al. 2021b). This heterogeneity creates difficulty in determining the effect of individual exercise variables in interventions. Thus, it remains unclear to clinicians how the LAM may respond to different exercise dosages and activation and whether there is an optimal prescription which may benefit individuals with LAM impairment.

The purpose of this review was to perform a dose-response analysis on exercise (considering the variables of session frequency, session duration, exercise type and program duration) for LAM thickness and activation as measured by USI in healthy asymptomatic individuals.

MATERIALS AND METHODS

PRISMA reporting guidelines were adhered to and this review was registered with PROSPERO (ID CRD42021249183).

Data sources and searches

A list of search terms under the categories of exercise, thickness/ contraction/ activation and the lateral abdominal muscles was developed (search strategy in Appendix A with adaptations to suit requirements of each database). Search terms within categories were combined using the 'OR' Boolean operator, whilst categories were combined using the 'AND' Boolean operator. Studies were limited to English language. Web of Science, SportDiscus, ProQuest Dissertations and Theses Global, PEDro, Medline, Emcare, Embase and the Cochrane Library databases as well as the International Clinical Trials Registry Platform, Australia and New Zealand Clinical Trial Registry and Clinicaltrials.gov were searched from their beginning on the 26th of April 2021. Search alerts were monitored for further papers from the search until submission.

Study selection

All citations were imported into Covidence© software (Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia) for screening. Duplicate citations were removed and title and abstracts and full texts were screened by two reviewers independently using specific inclusion and exclusion criteria (Table 1).

Table 1 here

The reference lists and citations of included full-text articles were examined for additional studies. Selection disagreements were settled via consensus or a third reviewer. The authors of eligible studies were contacted for clarification when LAM measurements, exercise specifics and statistical results data was not reported or unclear.

Data extraction and critical appraisal

Data was extracted twice by the same reviewer for retained full texts to minimise the risk of transcription error. Data was extracted using a custom data extraction tool developed by the authors (see Supplementary data 1).

Articles were then appraised separately by the two reviewers using the study design specific critical appraisal tool from the Joanna Briggs Institute (JBI) (Joannna Briggs Institute 2020a, b) that is, case series, quasi-experimental, randomised controlled trials and cohort study tools. Questions are scored as 'yes', 'no', 'unclear' or 'not applicable'. A modification made was for questions asking about whether outcomes were measured in a reliable way. This was broken into two separate items, one being whether reliability data was presented for the method and the second being whether the method was considered reproducible. Article quality did not affect inclusion or exclusion of retained full texts. Disagreements on study classification or appraisal scores were settled via consensus or a third reviewer. No pre-appraisal consensus on interpretation of the JBI tools was required.

Data analysis and synthesis

All analyses were conducted using Comprehensive Meta-analysis Software© (Biostat Inc, Englewood, USA). The required data was mean and standard deviation of LAM thickness (mm) pre and post intervention, the pre-post correlation and sample size. If studies did not report the pre/post correlation, the reported exact p-value or t-test output was used.

For an exercise prescription variable, such as program duration, all like studies were grouped (e.g. all with a program duration of 4 weeks). The standardised difference in means (SMD) was then calculated for each study, the pooled groups and across all studies using a random effects model. To compare within and between groups (e.g. 3 weeks vs 4 weeks program duration), *p* values were used to assess significance. Significance was set at *p* value (<0.05). To assess heterogeneity I^2 and Cochran's Q were used. This was conducted for TrA at rest, IO at rest, and TrA during contraction (data not available for EO or IO during contraction).

Due to non-reporting of all data points (e.g. exact *p* value), meta-analyses could not be performed for all exercise prescription variables across TrA and IO. In such instances, narrative synthesis was conducted. Studies with the same characteristic were again grouped and the pre-study muscle thickness was pooled for each group. Muscle thickness confidence intervals for each group were then narratively compared. Groups whose intervals overlapped were considered homogenous at baseline. The post-study muscle thickness was pooled for each group. Confidence intervals were compared and if they overlapped post-intervention, the authors considered there to be no difference between groups. If confidence intervals did not overlap, the group with a greater average muscle thickness was deemed to be superior. Where confidence intervals did not overlap at baseline, no further analysis was undertaken.

RESULTS

Study selection

A total of 8,104 articles were found, 4,195 of which were unique. One hundred and forty-two articles were full text screened with 30 retained. The authors of 18 of these studies were contacted for data clarification, but only one responded with data eligible for inclusion. One article was found through examining citations and reference lists, leaving a total of 14 articles (Cho 2013, 2015; Critchley et al. 2011; Gage 2009; Giacomini et al. 2016; Gong 2015, 2018; Kohiruimaki et al. 2019; Lee et al. 2018; Lee et al. 2015; Niewiadomy et al. 2021a; Niewiadomy et al. 2021b; Yang et al. 2015) (Figure 1).

Figure 1 here

Study Characteristics

Studies were published between 2009 and 2021 ($N_{participants} = 395$). Thirteen studies examined TrA and IO, and 10 examined EO. Eleven studies were randomised controlled trials (RCTs), one was a cohort study, one was a quasi-experimental study, and one was a case series.

Sample characteristics

Sample characteristics can be found in Supplementary data 1.

Risk of bias within studies

Figure 2 shows the quality appraisal results. Reporting quality was considered highest for the cohort study and lowest for the quasi-experimental study. Reporting quality was good for the RCTs (11 studies). The items that most RCTs failed to report on included whether true randomisation was used for assigning participants (two studies reported), blinding of participant allocation (one study reported) and outcome assessors (five studies reported), and describing participants follow up (6 studies reported). Blinding of participants to treatment assignment and blinding of those delivering treatment was not considered possible due to the nature of the intervention. Of the six studies that reported reliability data, all demonstrated between good and excellent intra and/or inter-rater reliability (ICC 0.88-0.99). Results for each study can be found in Appendix B.

Figure 2 here

There was insufficient data for meta-regressions or to perform subgroup analyses for all muscles at rest and during contraction. Results of subgroup analyses can be found in Table 2 (forest plots in Supplementary data 2).

Type of intervention

There was considerable heterogeneity regarding the types of exercises used. For subgroup analyses, there was only sufficient data to compare Pilates with the supine bridge using the abdominal drawing in maneuver for TrA thickness measured at rest and Pilates with the supine bridge using the abdominal drawing in maneuver and resistance training (inclusive of Critchley 2011 'strength training' and Kohiruimaki 2019 'suspended push-ups') for IO thickness measured at rest. There was a significant difference between groups for these analyses. The supine bridge using the abdominal drawing in maneuver showed significant differences between the pre and post measures for IO and TrA at rest. For TrA at rest, Yang 2015's standard difference in means was larger than results for the other studies. A subsequent sensitively analysis with Yang 2015 removed did not alter the findings.

Narrative comparison of pooled effect sizes (see Supplementary data 3) yielded similar results.

Minutes per week

Subgroup analyses revealed no significant difference between groups of greater than 100 minutes per week of exercise (>100m) and lesser than 100 minutes per week of exercise (<100m), for any muscle measured at rest or during contraction. Results were, TrA measured at rest (Q(df =1) = 1.634, p = 0.201), TrA during contraction (Q(df =1) = 3.64, p = 0.056), and IO measured at rest (Q(df =1) = 0.172, p = 0.678)]. However, there was a significant difference in pre to post thickness data for IO at rest with >100m (p = 0.039). For TrA measured during contraction, both >100m (p = 0.003) and <100m (p = <0.001) showed a significant difference in pre to post thickness data.

When the pooled effect sizes for the pre and post intervention thickness were narratively compared (Supplementary data 3), >100m resulted in greater effect sizes for the IO thickness. In contrast, <100m resulted in greater effect sizes for TrA at rest.

Program duration

Subgroup analyses, found between group significant differences for the variable program duration [TrA at rest (Q(df =4) = 93134618, p = <0.001), IO at rest (Q(df =4) = 19.19, p = 0.001)]. Five-week programs showed a significant difference in pre to post thickness data for TrA and IO measured at rest (p = <0.001). Also, a significant difference in pre to post thickness data for IO at rest existed in four-week (p = 0.013) and six-week (p = <0.001) programs. For TrA at rest, Yang 2015's standard difference in means was larger than results for the other studies. A subsequent sensitively analysis with Yang 2015 removed resulted in no significant difference between the groups of different program durations (Q(df = 4) = 7.286, p = 0.122). However, programs of 5-weeks duration continued to demonstrate a significant difference when comparing the pre and post thickness data (p = 0.02). There was no significant difference for TrA during contraction between groups of different program durations (Q(df =2) = 5.335, p = 0.069). Both pre to post thickness data was significantly different for five (p = 0.003) and six week (p = <0.001) programs.

Narrative comparison of pooled effect sizes for the pre and post intervention thickness (see Supplementary data 3), indicated that interventions from 4-weeks resulted in greater LAM thickness changes.

Number of sessions per week

Subgroup analyses for TrA at rest (Q(df =2) = 98287247, p = <0.001) and during contraction (Q(df =1) = 4.474, p = 0.034) and IO at rest (Q(df =2) = 8.532, p = 0.014) found a significant difference between groups for the variable number of sessions per week. For those muscles, three sessions per week revealed a significant difference in pre to post thickness data (p = <0.001). However, Yang 2015 displayed considerably larger SMD compared to the other studies for TrA at rest. A later sensitivity analysis removing Yang 2015 from the data set found there was no longer a significant difference between groups for TrA at rest (Q(df =2) = 5.83, p = 0.054). However, there was a significant difference when just examining the pre and post measures for programs of 3 sessions per week (p = 0.029). TrA measured during contraction also demonstrated a significant difference between the pre and post effect sizes for studies that conducted their exercise sessions four (p = 0.003) times per week.

Narrative comparison of pooled effect sizes (see Supplementary data 3), revealed 3 sessions per week demonstrated the greatest change between the pre and post thickness measures.

Session duration

Subgroup analyses revealed no significant difference between groups when examining the variable session duration [TrA measured at rest (Q(df =3) = 3.691, p = 0.297), IO measured at rest (Q(df =3) = 7.676, p = 0.053]. When examining at the pre and post thickness measures, only IO thickness measured at rest showed a significant difference for the protocols that had sessions of 30 mins duration (p = 0.003).

When narratively comparing the pooled effect sizes (see Supplementary data 3), greater changes between the pre and post thickness measures occurred for interventions that had 60-minute sessions.

DISCUSSION

This systematic review of 14 articles of good methodological quality identified that the current body of scientific research did not indicate an optimal exercise prescription for LAM thickness improvement. However, the review did identify evidence to allow broad yet cautious recommendations for exercise prescription.

Type of intervention

The subgroup analyses and narrative examination of pre and post effect sizes indicated that the supine bridge with an abdominal drawing in manoeuvre was superior to Pilates and resistance training for improving LAM thickness. While Critchley et al 2011 utilised the abdominal drawing in manoeuvre (ADIM) prior to commencing each Pilates exercise, the exercises were mainly whole-body focussed. Giacomini et al 2015 did not report using the ADIM in their Pilates intervention. This suggests that greater effectiveness for improving LAM thickness occurs via manoeuvres which focus on LAM recruitment compared more generalised exercises. Previous research in LBP populations has reported that both specific LAM core stabilisation exercises and generalised exercise/ generalised abdominal exercise prescriptions significantly improve LAM thickness.(Akbari et al. 2008; Hlaing et al. 2021) However, between group analyses in both studies found that the specific core stabilising prescription groups showed significantly greater improvements to LAM thickness. Both studies standardised program and session duration and frequency. Improvement to LAM thickness has also been demonstrated in LBP populations when Pilates,(Batibay et al. 2020) and aerobic exercises were combined with the abdominal drawing in manoeuvre (Gong 2016). This literature from LBP populations and the finding from this systematic review in healthy populations is therefore consistent, indicating that various types of exercise are associated with improved LAM thickness, but that superior results will be achieved from specific LAM activation exercises.

Program duration

This review found that programs from four weeks duration are associated with greater improvements to LAM thickness. This finding is consistent with research regarding resistance training adaptations which suggests that adaptations are predominantly neural activation rather than muscle hypertrophy in the initial weeks of a new program (Kenney et al. 2015). The longest intervention analysed in this review was eight weeks. Resistance training literature indicates that from eight weeks, muscle hypertrophy becomes a greater contributor to changes in strength (Kenney et al. 2015). Potentially greater improvements to LAM thickness could be obtained from programs with a minimum of 8-10 weeks in duration. From this review's search, it was observed most interventions in healthy and LBP samples did not exceed this duration. Future research should trial longer programs and examine LAM thickness at various stages of the program to determine the influence of longer durations on LAM thickness.

Number of sessions and minutes per week

This review found that programs using three sessions per week are associated with greater improvements to LAM thickness compared with programs using two or four sessions per week. The American College of Sports Medicine (ACSM) recommends the general population perform aerobic exercise ≥ five days per week and resistance training 2-3 days per week with a minimum of 48 hours rest between training the same muscles (Thompson et al. 2010). As the interventions examined in this study were generally closer to the resistance training category, these recommendations align well with our findings. Potentially three sessions per week were more effective than two due to a higher training volume. However, this logic would imply that four sessions per week would result in greater LAM thickness than three sessions. Perhaps four sessions per week was not as effective, as, this did not allow sufficient time resting between sessions as is recommended. A meta-analysis examining the effects of training frequency on muscle hypertrophy found higher frequencies were preferrable, but when considering overall training volume, the training frequency did not significantly influence muscle hypertrophy (measured through various modalities including USI) (Schoenfeld et al. 2019b). This suggests that considering the training volume (i.e. sets and repetitions or total number of minutes per week) is more important than session frequency. This review found that >100 mins per week and <100 mins per week are more effective for improving the thickness of the obliques and TrA respectively. This finding for the obliques is consistent with research suggesting that increased training volumes results in greater muscle hypertrophy (Schoenfeld et al. 2019a). However, the result for TrA appears to contradict this notion. This may be related to the ease with which one can contract the obliques compared to TrA. It has been demonstrated that the ability to achieve correct TrA contraction can be quite challenging in people with and without LBP (Richardson et al. 1999). To therefore achieve optimal muscle contraction, it is recommended to perform fewer repetitions with correct technique than to perform more repetitions with incorrect technique (Richardson et al. 1999). Therefore, the authors of this review hypothesise that for improvements in TrA thickness, the focus of interventions should be quality rather than quantity.

<u>Session duration</u>

This review's findings are inconclusive and may suggest that interventions from 30 minutes in duration may be preferred for improving LAM thickness. The inconclusive nature of our findings correspond with the ACSM guidelines, with their synthesis of the literature indicating that the most effective session duration for resistance training has not been identified (Thompson et al. 2010). Potentially the session duration is irrelevant and instead the quality and number of repetitions, sets and resting time which contributes to the session duration are the more important variables. Indeed, considerable research has been conducted into these variables in relation to the intensity of the exercise (Thompson et al. 2010). Whilst the repetitions and sets of exercise were generally well reported in the included studies, intensity was rarely reported. Future studies should consider reporting the intensity of the prescribed exercises to enable better comparisons.

A final factor to consider is that there may not be one perfect exercise prescription. A common theme amongst publications is the suggestion that exercise prescription should be individualized (Richardson et al. 1999) and prescriptions made through a combination of guidance from research and clinical expertise (McGill 1998). To explore this further, an area for future research is to gain clinician perspectives on optimal exercise prescriptions for the LAM (Richardson et al. 1999).

Limitations

This review was not without limitations. Firstly, subgroup analyses were unable to be performed for all muscles during rest and contraction for all variables. Therefore, a clear set of guidelines regarding exercise prescription for the LAM were unable to be produced. While data was not available to analyse responsiveness of IO and EO during contraction, the validity of interpreting IO and EO thickness changes as muscle activity during ADIM is questionable (ShahAli et al. 2019). Secondly the article was not limited to RCTs only. This would have strengthened the ability to evaluate a possible causation between exercise and LAM thickness. However, due to the few studies meeting the inclusion criteria and the good quality of included studies, the authors decided to include all study designs. As such, only association between exercise characteristics and LAM thickness was examined. Thirdly, some of the articles included were published by journals previously deemed to be ‘predatory’. These were included due to meeting eligibility criteria. While article quality remained reasonable, this may affect the credibility of results. In this article, where SMD appeared to be considerably larger compared to other studies, sensitivity analyses were conducted by removing such studies. Finally, only articles in English were included due to not having access to language translation and only studies with healthy human participants were included. Therefore, the results cannot be generalised to LBP populations. Nevertheless, the review was necessary to provide new evidence on the response of the LAM to various exercise prescriptions in healthy individuals so to provide normative evidence which can be applied in future research for comparison with LBP. There is thus a need to examine such findings in patients with LBP who have LAM impairments. Future research of this nature has potential to determine the clinical utility of specific exercise prescriptions.

CONCLUSION

This review has found that exercise programs of ≥ 4 weeks duration, those involving three sessions per week, each session being of ≥30 minutes duration and those containing specific local abdominal exercises may be associated with improvements to LAM thickness in healthy participants. Such findings may provide preliminary guidance to physiotherapists who are aiming to prescribe exercises for the LAM. Further research should examine these findings and gain clinician perspectives into the optimal exercise prescriptions for the LAM.

Clinical relevance

- Exercise programs of ≥ 4 weeks duration, those involving three sessions per week, each session being of ≥30 minutes duration and those containing specific local abdominal exercises may be associated with improvements to lateral abdominal muscle thickness in healthy participants
- Such findings may provide preliminary guidance to physiotherapists who are aiming to prescribe exercises for the lateral abdominal muscles

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REFERENCES

Akbari A, Khorashadizadeh S, Abdi G 2008 The effect of motor control exercise versus general exercise on lumbar local stabilising muscles thickness: randomised controlled trial of patients with chronic low back pain. Journal of Back and Musculoskeletal Rehabilitation 21, 105-112.
Batibay S, Kulcu DG, Kaleoglu O, Mesci N 2020 Effect of Pilates mat exercise and home exercise programs on pain, functional level, and core muscle thickness in women with chronic low back pain. Journal of Orthopaedic Science. 26, 979-985.
Cho M 2013 The effects of modified wall squat exercises on average adults' deep abdominal muscle thickness and lumbar stability. Journal of Physical Therapy Science 25, 689-692.
Cho M 2015 The effects of bridge exercise with the abdominal drawing-in maneuver on an unstable surface on the abdominal muscle thickness of healthy adults. Journal of Physical Therapy Science 27, 255-257.
Critchley DJ, Pierson Z, Battersby G 2011 Effect of pilates mat exercises and conventional exercise programmes on transversus abdominis and obliquus internus abdominis activity: pilot randomised trial. Manual Therapy 16, 183 - 189.
Dutmer A, Schiphorst Preuper H, Soer R, Brouwer SB, U, Dijkstra P, Coppes M, Stegeman P, Buskens E, van Asselt A, Wollf A, Reneman M 2019 Personal and societal impact of low back pain: The Groningen Spine Cohort. Spine (Phila Pa 1976) 44, E1443-E1451.
Ferreira PH, Ferreira ML, Hodges PW 2004 Changes in recruitment of the abdominal muscles in people with low back pain: Ultrasound measurement of muscle activity. Spine 29, 2560-2566.
Gage MJ 2009 The effects of abdominal training on postural control, lower extremity kinematics, kinetics, and muscle activation. Brigham Young University, Ann Arbor, p. 237.
GBD 2021 Low Back Pain Collaborators 2023 Global, regional, and national burden of low back pain, 1990-2020, its attributable risk factors, and projections to 2050: a systematic analysis of the Global Burden of Disease Study 2021. Lancet Rheumatology May 22, e316-e329.
Giacomini MB, da Silva AM, Weber LM, Monteiro MB 2016 The Pilates Method increases respiratory muscle strength and performance as well as abdominal muscle thickness. Journal of Bodywork & Movement Therapies 20, 258-264.
Gong W 2015 The effects of dynamic exercise utilizing PNF patterns on abdominal muscle thickness in healthy adults. Journal of Physical Therapy Science 27, 1933-1936.
Gong W 2016 The effects of running in place in a limited area with abdominal drawing-in maneuvers on abdominal muscle thickness in chronic low back pain patients. Journal of Back & Musculoskeletal Rehabilitation 29, 757-762.
Gong W 2018 The effects of the continuous bridge exercise on the thickness of abdominal muscles in normal adults. Journal of Physical Therapy Science 30, 921-925.
Hlaing S, Puntumetakul R, Khine E, Boucaut R 2021 Effects of core stabilization exercise and strengthening exercise on proprioception, balance, muscle thickness and pain related outcomes in patients with subacute nonspecific low back pain: a randomized controlled trial. BMC Musculoskeletal Disorders 22.
Joannna Briggs Institute 2020a JBI CRITICAL APPRAISAL CHECKLIST FOR QUASI-EXPERIMENTAL STUDIES.
Joannna Briggs Institute 2020b JBI CRITICAL APPRAISAL CHECKLIST FOR RANDOMIZED CONTROLLED TRIALS.
Kenney W, Wilmore J, Costil D 2015 Physiology of Sport and Exercise, 6 ed. Human Kinetics, United States of America.
Kohiruimaki R, Maeo S, Kanehisa H 2019 Suspended Push-up Training Augments Size of not only Upper Limb but also Abdominal Muscles. International Journal of Sports Medicine 40, 789-795.

Lariviere C, Henry S, Gagnon D, Preuss R, Dumas J 2019 Ultrasound measures of the abdominal wall in patients with low back pain before and after an 8-week lumbar stabilization exercise program, and their association with clinical outcomes. Physical Medicine and Rehabilitation 11, 710-721.
Lee DH, Hong SK, Lee YS, Kim CH, Hwang JM, Lee Z, Kim JM, Park D 2018 Is abdominal hollowing exercise using real-time ultrasound imaging feedback helpful for selective strengthening of the transversus abdominis muscle?: a prospective, randomized, parallel-group, comparative study. Medicine 97, e11369.
Lee JS, Kim TH, Kim DY, Shim JH, Lim JY 2015 Effects of selective exercise for the deep abdominal muscles and lumbar stabilization exercise on the thickness of the transversus abdominis and postural maintenance. Journal of Physical Therapy Science 27, 367-370.
McGill S 1998 Low back exercises: evidence for improving exercise regimens. Physical Therapy 78, 754-765.
Mueller J, Niederer D 2020 Dose-response-relationship of stabilisation exercises in patients with chronic non-specific low back pain: a systematic review with meta-regression. Sci Rep 10.
Niewiadomy P, Szuscik-Niewiadomy K, Kuszewski M, Kurpas A, Kochan M 2021a The influence of rotational movement exercise on the abdominal muscle thickness and trunk mobility - randomised control trial. Journal of Bodywork & Movement Therapies 27, 464-471.
Niewiadomy P, Szuscik-Niewiadomy K, Kuszewski MT, Kochan M, Pawlukiewicz M, Rychlik M, Piatkowska K 2021b Assessment of the influence of global and local exercises on core stabilization mechanisms: randomized controlled trial. Journal of Sports Medicine & Physical Fitness 61, 44-52.
Noormohammadpour P, Mirzaei S, Moghadam N, Mansournia M, Kordi R 2019 Comparision of lateral abdominal muscle thickness in young male soccer players with and without low back pain. International Journal of Sports Physical Therapy 14, 273-281.
Oliveira C, Maher C, Pinto R, Traeger A, Lin C, Chenot J, van Tulder M, Koes B 2018 Clinical practice guidelines for the management of non-specific low back pain in primary care: an updated overview. European Spine Journal 27, 2791-2803.
Ota M, Kaneoka K 2011 Differences in abdominal muscle thicknesses between chronic low back pain patients and healthy subjects. Journal of Physical Therapy Science 23, 855-858.
Park S, Yu S 2013 The effects of abdominal draw-in maneuver and core exercise on abdominal muscle thickness and oswestry disability index in subjects with chronic low back pain. Journal of Exercise Rehabilitation 9, 286-291.
Rahmani N, Mohseni-Bandpei M, Salavati M, Vameghi R, Abdollahi I 2018 Comparative study of abdominal muscle thickness on ultrasonography in healthy adolescents and patients with low back pain. Journal of Ultrasound in Medicine 37, 905-912.
Richardson C, Jull G, Hodges P, Hides J 1999 Therapeutic Exercise for Spinal Segmental Stabilisation in Low Back Pain: Scientific Basis and Clinical Approach. Churchill Livingstone, Edinburgh.
Saragiotto B, Maher C, Yamato T, Costa L, Menezes Costa L, Ostelo R, Macedo LG 2016 Motor control exercise for chronic non-specific low-back pain. Cochrane Database of Systematic Reviews Jan 8.
Schoenfeld BJ, Contreras B, Krieger J, Grgic J, Delcastillo K, Belliard R, Alto A 2019a Resistance training volume enhances muscle hypertrophy but not strength in trained men. Medicine & Science in Sports & Exercise 51, 94-103.
Schoenfeld BJ, Grgic J, Krieger J 2019b How many times per week should a muscle be trained to maximize muscle hypertrophy? A systematic review and meta-analysis of studies examining the effects of resistance training frequency. Journal of Sports Sciences 37, 1286-1295.

Selkow N, Eck M, Rivas S 2017 Transversus abdominis activation and timing improves following core stability training: a randomised trial. International Journal of Sports Physical Therapy 12, 1048-1056.
ShahAli S, Shanbehzadeh S, ShahAli S, Takamjani I 2019 Application of ultrasonography in the assessment of abdominal and lumbar trunk muscle activity in participants with and without low back pain: a systematic review. Journal of manipulative and physiological therapeutics 42, 541-550.
Thompson W, Gordon N, Pescatello L 2010 ACSM's Guidelines for Exercise Testing and Prescription, 8 ed. Lippincott Williams & Wilkins, Philadelphia, Pennsylvania.
Van Dieen J, Reeves NP, Kawchuk G, Van Dillen L, Hodges P 2019 Motor Control Changes in Low Back Pain: Divergence in Presentations and Mechanisms. Journal of Orthopaedic and Sports Physical Therapy 49, 370-379.
Yang HS, Lee YS, Jin SA 2015 Effect of evidence-based trunk stability exercises on the thickness of the trunk muscles. Journal of Physical Therapy Science 27, 473-475.
Yelin E, Weinstein S, King T 2016 The burden of musculoskeletal diseases in the United States. Seminars in Arthritis and Rheumatism 46, 259-260.

TABLES

Table 1: Inclusion/Exclusion criteria

	Inclusion	Exclusion
Population	Healthy adults	Adults with LBP or other comorbidities Children Pregnancy or < 6 months postpartum Athletes Obesity
Intervention	Exercise intervention lasting longer than one session. Must state what exercises were prescribed, frequency of sessions over the week and duration of intervention.	No exercise intervention Exercise intervention duration of one session. Insufficient description of intervention
Outcome	Measurement of resting and/or contracting (using abdominal drawing in manoeuvre to allow for consistency) LAM thickness using USI before and after the intervention.	Not measure LAM thickness before and after intervention using USI
Other	English language Available in full text Any date	Languages other than English No full text available

Note: LAM, lateral abdominal muscles; USI, ultrasound imaging.

Table 2: Meta analysis results

Exercise Prescription Variable		Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Exercise Type	Pilates	Critchley 2011	TrA at rest	Pilates	1	0	0	0	0				
	Pilates	Giacomini 2016	TrA at rest	Pilates	1	0.001	0.001	0.001	0				
	Overall Pilates		TrA at rest		2	0	0	0.001	0.14	11411.578	1	<0.001	99.929
	Supine bridge ADIM	Cho 2013	TrA at rest	Bridge with ADIM	1	1	1	1	0				
	Supine bridge ADIM	Lee 2018 a	TrA at rest	Supine bridge with ADIM	1	0.939	0.195	1.683	0.01				
	Supine bridge ADIM	Yang 2015	TrA at rest	Supine bridge with ADIM	1	10000	9999.8	10000	0				
	Supine bridge ADIM	Cho 2015	TrA at rest	Supine bridge with ADIM	1	1	1	1	0				
	Overall supine bridge ADIM		TrA at rest		4	2534.017	2532.6	2535.4	0	999800008	3	<0.001	100

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Overall Pilates vs Supine bridge ADIM		TrA at rest			0.001	0	0.001	0				
Without Yang 2015 below												
Pilates		TrA at rest		2	0	0	0.001	0.14	11411.578	1	<0.001	99.929
Supine bridge ADIM		TrA at rest		3	1	1	1	0	0.026	2	0.987	0
Overall Pilates vs Supine bridge ADIM		TrA at rest			0.999	0.999	0.999	0				
Pilates	Critchley 2011	IO at rest	Pilates	1	0.034	-0.398	0.466	0.88				
Pilates	Giacomini 2016	IO at rest	Pilates	1	0.909	0.364	1.454	0				
Overall Pilates		IO at rest		2	0.455	-0.401	1.312	0.3	6.076	1	0.014	83.542
Supine bridge ADIM	Cho 2013	IO at rest	Bridge with ADIM	1	1	0.42	1.58	0				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Supine bridge ADIM	Cho 2015	IO at rest	Supine bridge with ADIM	1	0.564	0.054	1.074	0.03				
Supine bridge ADIM	Lee 2018 a	IO at rest	Supine bridge with ADIM	1	0.427	-0.221	1.074	0.2				
Supine bridge ADIM	Yang 2015	IO at rest	Supine bridge with ADIM	1	1	0.29	1.71	0.01				
Overall supine bridge ADIM		IO at rest		4	0.728	0.429	1.027	0	2.637	3	0.451	0
Resistance training	Critchley 2011	IO at rest	Strength	1	-0.052	-0.511	0.406	0.82				
Resistance training	Kohiruimaki 2019	IO at rest	Suspended push ups	1	0.378	-0.339	1.096	0.3				
Overall resistance training		IO at rest		2	0.073	-0.314	0.459	0.71	0.984	1	0.321	0
Overall - Pilates vs Supine Bridge ADIM vs Resistance training		IO at rest			0.481	0.253	0.709	0				
20	Lee 2018	TrA at rest	Abdominal Hollowing	1	0.419	-0.228	1.065	0.2				

Exercise Prescription Variable		Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Session duration (mins)	20	Lee 2018	TrA at rest	Abdominal Hollowing with biofeedback	1	0.161	-0.462	0.785	0.61				
	Overall 20		TrA at rest		2	0.286	-0.163	0.734	0.21	0.315	1	0.574	0
	30	Cho 2013	TrA at rest	Bridge with ADIM	1	1	1	1	0				
	30	Lee 2015	TrA at rest	ADIM	1	0	0	0	0				
	30	Cho 2013	TrA at rest	Wall Squat	1	0	0	0	0				
	30	Lee 2015	TrA at rest	Lumbar stabilisation exercises	1	0	0	0	0				
	Overall 30		TrA at rest		4	0.25	-0.188	0.688	0.26	409010407	3	<0.001	100
	45	Niewiadomy 2021 a	TrA at rest	Rotational movement exercise	1	0.261	-0.054	0.576	0.11				
	45	Critchley 2011	TrA at rest	Pilates	1	0	0	0	0				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
45	Critchley 2011	TrA at rest	Strength	1	0	0	0	0.2				
Overall 45		TrA at rest		3	0	0	0	0.42	101.076	2	<0.001	98.021
60	Niewiadomy 2021	TrA at rest	Global muscle training	1	0.067	0.067	0.067	0				
60	Niewiadomy 2021	TrA at rest	Local Muscle training	1	0	0	0	0				
60	Giacomini 2016	TrA at rest	Pilates	1	0.001	0.001	0.001	0				
Overall 60		TrA at rest		3	0.023	-0.025	0.07	0.35	50125416	2	<0.001	100
Overall 20 vs 30 vs 45 vs 60 mins		TrA at rest			0	0	0	0.42				
20	Lee 2018	IO at rest	Abdominal Hollowing	1	0.06	-0.56	0.681	0.85				
20	Lee 2018	IO at rest	Abdominal Hollowing with biofeedback	1	-0.111	-0.733	0.51	0.73				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Overall 20		IO at rest		2	-0.025	-0.464	0.414	0.91	0.147	1	0.702	0
30	Cho 2013	IO at rest	Bridge with ADIM	1	1	0.42	1.58	0				
30	Cho 2013	IO at rest	Wall Squat	1	2	1.18	2.82	0				
Overall 30		IO at rest		2	1.456	0.48	2.432	0	3.81	1	0.051	73.75
45	Critchley 2011	IO at rest	Pilates	1	0.034	-0.398	0.466	0.88				
45	Critchley 2011	IO at rest	Strength	1	-0.052	-0.511	0.406	0.82				
45	Niewiadomy 2021 a	IO at rest	Rotational movement exercise	1	0.38	0.059	0.701	0.02				
Overall 45		IO at rest		3	0.161	-0.116	0.438	0.25	2.92	2	0.232	31.497
60	Giacomini 2016	IO at rest	Pilates	1	0.909	0.364	1.454	0				
60	Niewiadomy 2021	IO at rest	Global muscle training	1	0.073	-0.217	0.363	0.62				
60	Niewiadomy 2021	IO at rest	Local Muscle training	1	0.115	-0.196	0.426	0.47				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Overall 60		IO at rest		3	0.302	-0.107	0.71	0.15	7.523	2	0.023	73.415
Overall 20 vs 30 vs 45 vs 60 mins		IO at rest			0.21	0.011	0.409	0.04				
2	Critchley 2011	TrA at rest	Pilates	1	0	0	0	0				
2	Critchley 2011	TrA at rest	Strength	1	0	0	0	0.2				
2	Giacomini 2016	TrA at rest	Pilates	1	0.001	0.001	0.001	0				
Overall 2		TrA at rest		3	0	0	0.001	0.2	2390.184	2	<0.001	99.916
Sessions per week												
3	Cho 2013	TrA at rest	Bridge with ADIM	1	1	1	1	0				
3	Lee 2018	TrA at rest	Abdominal Hollowing	1	0.419	-0.228	1.065	0.2				
3	Lee 2018	TrA at rest	Abdominal Hollowing with biofeedback	1	0.161	-0.462	0.785	0.61				
3	Lee 2018 a	TrA at rest	Supine bridge	1	0.12	-0.502	0.742	0.71				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
3	Lee 2018 a	TrA at rest	Supine bridge with ADIM	1	0.939	0.195	1.683	0.01				
3	Yang 2015	TrA at rest	Supine bridge with ADIM	1	10000	9999.8	10000	0				
3	Yang 2015	TrA at rest	Supine bridge with ADIM and R leg lift	1	10000	9999.8	10000	0				
3	Cho 2013	TrA at rest	Wall Squat	1	0	0	0	0				
3	Yang 2015	TrA at rest	Quadruped arm and leg lift with ADIM	1	1	1	1	0				
3	Yang 2015	TrA at rest	Side bridge with ADIM	1	20000	20000	20000	0				
3	Cho 2015	TrA at rest	Supine bridge with ADIM	1	1	1	1	0				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
3	Cho 2015	TrA at rest	Supine bridge with ADIM unstable	1	0	0	0	0				
3	Gage 2009	TrA at rest	Abdominal resistance exercises	1	0	0	0	0				
Overall 3		TrA at rest		13	3108.373	3107.8	3109	0	386931350	12	<0.001	100
4	Lee 2015	TrA at rest	ADIM	1	0	0	0	0				
4	Niewiadomy 2021	TrA at rest	Global muscle training	1	0.067	0.067	0.067	0				
4	Niewiadomy 2021	TrA at rest	Local Muscle training	1	0	0	0	0				
4	Niewiadomy 2021 a	TrA at rest	Rotational movement exercise	1	0.261	-0.054	0.576	0.11				
4	Lee 2015	TrA at rest	Lumbar stabilisation exercises	1	0	0	0	0				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Overall 4		TrA at rest		5	0.02	-0.017	0.058	0.29	55734880	4	<0.001	100
Overall 2 vs 3 vs 4 sessions per week		TrA at rest			0.002	0.001	0.002	0				
Without Yang 2015 below		TrA at rest										
2		TrA at rest		3	0	0	0.001	0.2	2390.184	2	<0.001	99.916
3		TrA at rest		9	0.398	0.04	0.756	0.03	714221801	8	<0.001	100
4		TrA at rest		5	0.02	-0.017	0.058	0.29	55734880	4	<0.001	100
Overall 2 vs 3 vs 4 sessions per week without Yang 2015		TrA at rest			0	0	0.001	0.2				
2	Critchley 2011	IO at rest	Pilates	1	0.034	-0.398	0.466	0.88				
2	Critchley 2011	IO at rest	Strength	1	-0.052	-0.511	0.406	0.82				
2	Giacomini 2016	IO at rest	Pilates	1	0.909	0.364	1.454	0				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Overall 2		IO at rest		3	0.277	-0.281	0.834	0.33	8.206	2	0.017	75.628
3	Cho 2013	IO at rest	Bridge with ADIM	1	1	0.42	1.58	0				
3	Cho 2013	IO at rest	Wall Squat	1	2	1.18	2.82	0				
3	Cho 2015	IO at rest	Supine bridge with ADIM	1	0.564	0.054	1.074	0.03				
3	Cho 2015	IO at rest	Supine bridge with ADIM unstable	1	2	1.18	2.82	0				
3	Gage 2009	IO at rest	Abdominal resistance exercises	1	0.15	-0.262	0.562	0.48				
3	Kohiruimaki 2019	IO at rest	Suspended push ups	1	0.378	-0.339	1.096	0.3				
3	Lee 2018	IO at rest	Abdominal Hollowing	1	0.06	-0.56	0.681	0.85				
3	Lee 2018	IO at rest	Abdominal Hollowing with biofeedback	1	-0.111	-0.733	0.51	0.73				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
3	Lee 2018 a	IO at rest	Supine bridge	1	0.37	-0.271	1.011	0.26				
3	Lee 2018 a	IO at rest	Supine bridge with ADIM	1	0.427	-0.221	1.074	0.2				
3	Yang 2015	IO at rest	Supine bridge with ADIM	1	1	0.29	1.71	0.01				
3	Yang 2015	IO at rest	Supine bridge with ADIM and R leg lift	1	1	0.29	1.71	0.01				
3	Yang 2015	IO at rest	Quadruped arm and leg lift with ADIM	1	1.872	0.91	2.834	0				
3	Yang 2015	IO at rest	Side bridge with ADIM	1	0.5	-1.15	1.115	0.11				
Overall 3		IO at rest		14	0.741	0.414	1.069	0	47.111	13	<0.001	72.405
4	Niewiadomy 2021	IO at rest	Global muscle training	1	0.073	-0.217	0.363	0.62				
4	Niewiadomy 2021	IO at rest	Local Muscle training	1	0.115	-0.196	0.426	0.47				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
4	Niewiadomy 2021 a	IO at rest	Rotational movement exercise	1	0.38	0.059	0.701	0.02				
Overall 4		IO at rest		3	0.181	-0.004	0.366	0.06	2.184	2	0.335	8.446
Overall 2 vs 3 vs 4 sessions per week		IO at rest			0.313	0.159	0.468	0				
Without Cho 2013, 2015 and Yang 2015 below		IO at rest										
2		IO at rest		3	0.277	-0.281	0.834	0.33	8.206	2	0.017	75.628
3		IO at rest		6	0.191	-0.046	0.428	0.11	2.189	5	0.822	0
4		IO at rest		3	0.181	-0.004	0.366	0.06	2.184	2	0.335	8.446
Overall		IO at rest			0.191	0.05	0.332	0.01				
3	Gage 2009	TrA Contract	Abdominal resistance exercises	1	0.514	0.048	0.98	0.03				
3	Gong 2018	TrA Contract	Prone and side bridging	1	0.924	0.257	1.591	0.01				
3	Gong 2015	TrA Contract	Proprioceptive neuomuscular facilitation	1	0.734	0.105	1.363	0.02				

Exercise Prescription Variable		Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
	Overall 3		TrA Contract		3	0.672	0.345	0.998	0	1.025	2	0.599	0
	4	Lee 2015	TrA Contract	Lumbar stabilisation exercises	1	1.766	0.844	0.2689	0				
	4	Lee 2015	TrA Contract	ADIM	1	3.492	1.956	5.029	0				
	Overall 4		TrA Contract		2	2.516	0.839	4.193	0	3.565	1	0.059	71.947
	Overall 3 vs 4 sessions per week		TrA Contract			0.739	0.419	1.06	0				
	2 weeks	Lee 2018	TrA at rest	Abdominal Hollowing	1	0.419	-0.228	1.065	0.2				
	2 weeks	Lee 2018	TrA at rest	Abdominal Hollowing with biofeedback	1	0.161	-0.462	0.785	0.61				
	Overall 2 weeks		TrA at rest		2	0.286	-0.163	0.734	0.21	0.315	1	0.574	0
Program duration	4 weeks	Lee 2018 a	TrA at rest	Supine bridge	1	0.12	-0.502	0.742	0.71				
	4 weeks	Lee 2018 a	TrA at rest	Supine bridge with ADIM	1	0.939	0.195	1.683	0.01				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
4 weeks	Niewiadomy 2021	TrA at rest	Global muscle training	1	0.067	0.067	0.067	0				
4 weeks	Niewiadomy 2021	TrA at rest	Local Muscle training	1	0	0	0	0				
4 weeks	Niewiadomy 2021 a	TrA at rest	Rotational movement exercise	1	0.261	-0.054	0.576	0.11				
Overall 4 weeks		TrA at rest		5	0.05	-0.014	0.114	0.13	41869498	4	<0.001	100
5 weeks	Lee 2015	TrA at rest	ADIM	1	0	0	0	0				
5 weeks	Yang 2015	TrA at rest	Supine bridge with ADIM	1	10000	9999.8	10000	0				
5 weeks	Yang 2015	TrA at rest	Supine bridge with ADIM and R leg lift	1	10000	9999.8	10000	0				
5 weeks	Yang 2015	TrA at rest	Quadruped arm and leg lift with ADIM	1	1	1	1	0				
5 weeks	Yang 2015	TrA at rest	Side bridge with ADIM	1	20000	20000	20000	0				
5 weeks	Lee 2015	TrA at rest	Lumbar stabilisation exercises	1	0	0	0	0				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Overall 5 weeks		TrA at rest		6	6631.746	6630.4	6633.1	0	327256801	5	<0.001	100
6 weeks	Cho 2013	TrA at rest	Bridge with ADIM	1	1	1	1	0				
6 weeks	Cho 2013	TrA at rest	Wall Squat	1	0	0	0	0				
6 weeks	Cho 2015	TrA at rest	Supine bridge with ADIM	1	1	1	1	0				
6 weeks	Cho 2015	TrA at rest	Supine bridge with ADIM unstable	1	0	0	0	0				
Overall 6 weeks		TrA at rest		4	0.5	-0.058	1.058	0.08	599946309	3	<0.001	100
8 weeks	Critchley 2011	TrA at rest	Pilates	1	0	0	0	0				
8 weeks	Critchley 2011	TrA at rest	Strength	1	0	0	0	0.2				
8 weeks	Gage 2009	TrA at rest	Abdominal resistance exercises	1	0	0	0	0				
8 weeks	Giacomini 2016	TrA at rest	Pilates	1	0.001	0.001	0.001	0				
Overall 8 weeks		TrA at rest		4	0	0	0.001	0.17	2766.273	3	<0.001	99.892

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
Overall 2 vs 4 vs 5 vs 6 vs 8 weeks program duration		TrA at rest			0.001	0	0.001	0				
Without Yang 2015 below												
Overall 2 weeks		TrA at rest		2	0.286	-0.163	0.734	0.21	0.315	1	0.574	0
Overall 4 weeks		TrA at rest		5	0.05	-0.014	0.114	0.13	41869498	4	<0.001	100
Overall 5 weeks		TrA at rest		2	0	0	0	0.02	43.2	1	<0.001	97.685
Overall 6 weeks		TrA at rest		4	0.5	-0.058	1.058	0.08	599946309	3	<0.001	100
Overall 8 weeks		TrA at rest		4	0	0	0.001	0.17	2766.273	3	<0.001	99.892
Overall 2 vs 4 vs 5 vs 6 vs 8 weeks program duration without Yang 2015		TrA at rest			0	0	0	0.01				
2 weeks	Lee 2018	IO at rest	Abdominal Hollowing	1	0.06	-0.56	0.681	0.85				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
2 weeks	Lee 2018	IO at rest	Abdominal Hollowing with biofeedback	1	-0.111	-0.733	0.51	0.73				
Overall 2 weeks		IO at rest		2	-0.025	-0.464	0.414	0.91	0.147	1	0.702	0
4 weeks	Lee 2018 a	IO at rest	Supine bridge	1	0.37	-0.271	1.011	0.26				
4 weeks	Lee 2018 a	IO at rest	Supine bridge with ADIM	1	0.427	-0.221	1.074	0.2				
4 weeks	Niewiadomy 2021	IO at rest	Global muscle training	1	0.073	-0.217	0.363	0.62				
4 weeks	Niewiadomy 2021	IO at rest	Local Muscle training	1	0.115	-0.196	0.426	0.47				
4 weeks	Niewiadomy 2021 a	IO at rest	Rotational movement exercise	1	0.38	0.059	0.701	0.02				
Overall 4 weeks		IO at rest		5	0.209	0.044	0.374	0.01	2.964	4	0.564	0

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
5 weeks	Yang 2015	IO at rest	Supine bridge with ADIM	1	1	0.29	1.71	0.01				
5 weeks	Yang 2015	IO at rest	Supine bridge with ADIM and R leg lift	1	1	0.29	1.71	0.01				
5 weeks	Yang 2015	IO at rest	Quadruped arm and leg lift with ADIM	1	1.872	0.91	2.834	0				
5 weeks	Yang 2015	IO at rest	Side bridge with ADIM	1	0.5	-0.115	1.15	0.11				
Overall 5 weeks		IO at rest		4	1.009	0.506	1.512	0	5.625	3	0.131	46.663
6 weeks	Cho 2013	IO at rest	Bridge with ADIM	1	1	0.42	1.58	0				
6 weeks	Cho 2013	IO at rest	Wall Squat	1	2	1.18	2.82	0				
6 weeks	Cho 2015	IO at rest	Supine bridge with ADIM	1	0.564	0.054	1.074	0.03				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
6 weeks	Cho 2015	IO at rest	Supine bridge with ADIM unstable	1	2	1.18	2.82	0				
Overall 6 weeks		IO at rest		4	1.332	0.626	2.038	0	13.58	3	0.004	77.909
8 weeks	Critchley 2011	IO at rest	Pilates	1	0.034	-0.398	0.466	0.88				
8 weeks	Critchley 2011	IO at rest	Strength	1	-0.052	-0.511	0.406	0.82				
8 weeks	Gage 2009	IO at rest	Abdominal resistance exercises	1	0.15	-0.262	0.562	0.48				
8 weeks	Giacomini 2016	IO at rest	Pilates	1	0.909	0.364	1.454	0				
8 weeks	Kohiruimaki 2019	IO at rest	Suspended push ups	1	0.378	-0.339	1.096	0.3				
Overall 8 weeks		IO at rest		5	0.25	-0.074	0.573	0.13	8.503	4	0.075	52.959
Overall 2 vs 4 vs 5 vs 6 vs 8 weeks program duration		IO at rest			0.289	0.157	0.421	0				
5 weeks	Lee 2015	TrA Contract	Lumbar stabilisation exercises	1	1.766	0.844	2.689	0				

Exercise Prescription Variable		Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
	5 weeks	Lee 2015	TrA Contract	ADIM	1	3.492	1.956	5.029	0				
	Overall 5 weeks		TrA contract		2	2.516	0.839	4.193	0	3.565	1	0.059	71.947
	6 weeks	Gong 2018	TrA Contract	Prone and side bridging	1	0.924	0.257	1.591	0.01				
	6 weeks	Gong 2015	TrA Contract	Proprioceptive neuomuscular facilitation	1	0.734	0.105	1.363	0.02				
	Overall 6 weeks		TrA Contract		2	0.823	0.366	1.281	0	0.164	1	0.686	0
	Overall 5 vs 6 weeks program duration		TrA Contract			0.739	0.419	1.06	0				
Minutes per week	<100	Cho 2013	TrA at rest	Bridge with ADIM	1	1	1	1	0				
	<100	Lee 2018	TrA at rest	Abdominal Hollowing	1	0.419	-0.228	1.065	0.2				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
<100	Lee 2018	TrA at rest	Abdominal Hollowing with biofeedback	1	0.161	-0.462	0.785	0.61				
<100	Cho 2013	TrA at rest	Wall Squat	1	0	0	0	0				
<100	Critchley 2011	TrA at rest	Pilates	1	0	0	0	0				
<100	Critchley 2011	TrA at rest	Strength	1	0	0	0	0.2				
Overall <100 mins per week		TrA at rest		6	0.259	-0.112	0.631	0.17	415204551	5	<0.001	100
>100	Lee 2015	TrA at rest	ADIM	1	0	0	0	0				
>100	Niewiadomy 2021	TrA at rest	Global muscle training	1	0.067	0.067	0.067	0				
>100	Niewiadomy 2021	TrA at rest	Local Muscle training	1	0	0	0	0				
>100	Niewiadomy 2021 a	TrA at rest	Rotational movement exercise	1	0.261	-0.054	0.576	0.11				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
>100	Giacomini 2016	TrA at rest	Pilates	1	0.001	0.001	0.001	0				
>100	Lee 2015	TrA at rest	Lumbar stabilisation exercises	1	0	0	0	0				
Overall >100 mins per week		TrA at rest		6	0.016	-0.015	0.048	0.32	60108230	5	<0.001	100
Overall <100 vs >100 mins per week		TrA at rest			0.018	-0.014	0.049	0.27				
<100	Cho 2013	IO at rest	Bridge with ADIM	1	1	0.42	1.58	0				
<100	Cho 2013	IO at rest	Wall Squat	1	2	1.18	2.82	0				
<100	Critchley 2011	IO at rest	Pilates	1	0.034	-0.398	0.466	0.88				
<100	Critchley 2011	IO at rest	Strength	1	-0.052	-0.511	0.406	0.82				
<100	Lee 2018	IO at rest	Abdominal Hollowing	1	0.06	-0.56	0.681	0.85				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
<100	Lee 2018	IO at rest	Abdominal Hollowing with biofeedback	1	-0.111	-0.733	0.51	0.73				
Overall <100 mins per week		IO at rest		6	0.439	-0.109	0.987	0.12	28.084	5	<0.001	82.196
>100	Giacomini 2016	IO at rest	Pilates	1	0.909	0.364	1.454	0				
>100	Niewiadomy 2021	IO at rest	Global muscle training	1	0.073	-0.217	0.363	0.62				
>100	Niewiadomy 2021	IO at rest	Local Muscle training	1	0.115	-0.196	0.426	0.47				
>100	Niewiadomy 2021 a	IO at rest	Rotational movement exercise	1	0.38	0.059	0.701	0.02				
Overall >100 mins per week		IO at rest		4	0.308	0.015	0.6	0.04	8.4	3	0.038	64.288
Overall <100 vs		IO at rest			0.337	0.079	0.595	0.01				

Exercise Prescription Variable	Study	Muscle	Group	N samples	Standard difference in means	Lower limit	Upper limit	P	Heterogeneity Q	df	p value	I2
>100 mins per week												
<100	Gong 2018	TrA Contract	Prone and side bridging	1	0.924	0.257	1.591	0.01				
<100	Gong 2015	TrA Contract	Proprioceptive neuomuscular facilitation	1	0.734	0.105	1.363	0.02				
Overall <100 mins per week		TrA contract		2	0.823	0.366	1.281	0	0.164	1	0.686	0
>100	Lee 2015	TrA contract	Lumbar stabilisation exercises	1	1.766	0.844	2.689	0				
>100	Lee 2015	TrA contract	ADIM	1	3.492	1.956	5.029	0				
Overall >100 mins per week		TrA contract		2	2.516	0.839	4.193	0	3.565	1	0.059	71.947
Overall <100 vs >100 mins per week		TrA contract			0.941	0.499	1.382	0				

CAPTIONS TO ILLUSTRATIONS

Figure 1: PRISMA diagram

Figure 2 Risk of bias across different study designs

Appendix A – Full Search strategy for each database

Logic Grid for MEDLINE and The Cochrane Library (note Cochrane uses near/n for adj)

Exercise	**Thickness or activation**	**Abdominal muscles**
MESH Exercise OR Physical conditioning, human OR Exercise therapy OR Exercise movement techniques OR Athletic performance	**MESH** Ultrasonography	**MESH** Abdominal muscles Abdominal oblique muscles
Keywords (exercis* or (physical adj1 activit*) or (muscle adj1 stretch*) or run* or walk* or (physical adj1 condition*) or (physical adj1 train*) or endurance or "high intensity interval training" or HIIT or plyometric* or resist* or pilates or danc* or "tai chi" or yoga or strength* or cardio* or fitness or (athletic adj1 train*) or (functional adj1 train*) or concentric or eccentric or isokinetic or isometric or weight or flexibility or balance or "motor control" or (abdominal adj3 man*) or ADIM or (abdominal adj1 hollow*)).tw,kf	**Keywords** (morphology or "cross section" or "cross sectional" or size or dimension* or thickness or hypertrop* or contract* or ultrasound or ultrasonography or sonography or DUSI or RUSI or activation).tw,kf.	**Keywords** (abdominis or (abdominal adj1 musc*) or "internal oblique" or "external oblique" or "obliquus externus" or "obliquus internus").tw,kf.

Logic Grid for Embase

Exercise	Morphology	Abdominal muscles
MESH Exercise OR Physical conditioning, human OR Exercise therapy OR Exercise movement techniques OR Athletic performance OR Muscle exercise **Keywords** (exercis* or (physical adj1 activit*) or (muscle adj1 stretch*) or run* or walk* or (physical adj1 condition*) or (physical adj1 train*) or endurance or "high intensity interval training" or HIIT or plyometric* or resist* or pilates or danc* or "tai chi" or yoga or strength* or cardio* or fitness or (athletic adj1 train*) or (functional adj1 train*) or concentric or eccentric or isokinetic or isometric or weight or flexibility or balance or "motor control" or (abdominal adj3 man*) or ADIM or (abdominal adj1 hollow*)).tw,kf	**MESH** Muscle thickness OR Muscle hypertrophy OR Echography **Keywords** (morphology or "cross section" or "cross sectional" or size or dimension* or thickness or hypertrop* or contraction ultrasound or ultrasonography or sonography or DUSI or RUSI or activation).tw,kf.	**MESH** Abdominal muscles OR Abdominal oblique muscles OR Abdominal wall musculature **Keywords** (abdominis or (abdominal adj1 musc*) or "internal oblique" or "external oblique" or "obliquus externus" or "obliquus internus").tw,kf.

Logic Grid for Web of science (nil MESH terms)

Exercise	Morphology	Abdominal muscles
(AB=(exercis* or (physical near/1 activit*) or (muscle near/1 stretch*) or run* or walk* or (physical near/1 condition*) or (physical near/1 train*) or endurance or "high intensity interval training" or HIIT or plyometric* or resist* or pilates or danc* or "tai chi" or yoga or strength* or cardio* or fitness or (athletic near/1 train*) or (functional near/1 train*) or concentric or eccentric or isokinetic or isometric or weight or flexibility or balance or "motor control" or (abdominal near/3 man*) or ADIM or (abdominal near/1 hollow*))	(AB=(morphology or "cross section" or "cross sectional" or size or dimension* or thickness or hypertrop* or contraction ultrasound or ultrasonography or sonography or DUSI or RUSI or activation)	(AB=(abdominis or (abdominal near/1 musc*) or "internal oblique" or "external oblique" or "obliquus externus" or "obliquus internus")

Logic Grid for Sportdiscus

Exercise	Morphology	Abdominal muscles
MESH terms DE "EXERCISE" OR DE "EXERCISE therapy" OR DE "ABDOMINAL exercises" **Keywords** exercis* or (physical n1 activit*) or (muscle n1 stretch*) or run* or walk* or (physical n1 condition*) or (physical n1 train*) or endurance or "high intensity interval training" or HIIT or plyometric* or resist* or pilates or danc* or "tai chi" or yoga or strength* or cardio* or fitness or (athletic n1 train*) or (functional n1 train*) or concentric or eccentric or isokinetic or isometric or weight or flexibility or balance or "motor control" or (abdominal n3	**MESH terms** (DE "MUSCULAR hypertrophy" OR DE "MORPHOLOGY" OR DE “ULTRASONIC imaging”) **Keywords** morphology or "cross section" or "cross sectional" or size or dimension* or thickness or hypertrop* or contraction ultrasound or ultrasonography or sonography or DUSI or RUSI or activation	**MESH terms** (DE "ABDOMINAL muscles") **Keywords** abdominis or (abdominal n1 musc*) or "internal oblique" or "external oblique" or "obliquus externus" or "obliquus internus"

man*) or ADIM or (abdominal n1 hollow*)		

Logic Grid for Emcare

Exercise	**Morphology**	**Abdominal muscles**
MESH Exercise OR Muscle exercise OR Kinesiotherapy OR Exercise movement techniques OR Athletic performance **Keywords** (exercis* or (physical adj1 activit*) or (muscle adj1 stretch*) or run* or walk* or (physical adj1 condition*) or (physical adj1 train*) or endurance or "high intensity interval training" or HIIT or plyometric* or resist* or pilates or danc* or "tai chi" or yoga or strength* or cardio* or fitness or (athletic adj1 train*) or (functional adj1 train*) or concentric or eccentric or isokinetic or isometric or weight or flexibility or balance or "motor control" or (abdominal adj3 man*) or ADIM or (abdominal adj1 hollow*)).ab,ti,kw	**MESH** Muscle thickness OR Muscle hypertrophy OR Echography **Keywords** (morphology or "cross section" or "cross sectional" or size or dimension* or thickness or hypertrop* or contraction ultrasound or ultrasonography or sonography or DUSI or RUSI or activation).ab,ti,kw.	**MESH** Abdominal muscles OR Oblique abdominal muscle OR Abdominal wall musculature **Keywords** (abdominis or (abdominal adj1 musc*) or "internal oblique" or "external oblique" or "obliquus externus" or "obliquus internus").ab,ti,kw.

PEDro – only able to search abdomin* oblique (OR is selected at bottom of search)

Proquest dissertations and theses global

(limited to abstracts only, no subject headings used).

Exercise	**Morphology**	**Abdominal muscles**
exercis* OR "physical activit*" OR "muscle stretch*" OR run* OR walk* OR "physical condition*" OR "physical train*" OR endurance OR "high intensity interval training" OR HIIT OR plyometric* OR resist* OR pilates OR danc* OR "tai chi" OR yoga OR strength* OR cardio* OR fitness OR "athletic train*" OR "functional train*" OR concentric OR eccentric OR isokinetic OR isometric OR weight OR flexibility OR balance OR "motor control" OR "abdominal man*" OR ADIM OR "abdominal hollow*"	morphology or "cross section" or "cross sectional" or size or dimension* or thickness or hypertrop* or contraction ultrasound or ultrasonography or sonography or DUSI or RUSI or activation	abdominis OR "abdominal musc*" OR "internal oblique" OR "external oblique" OR "obliquus externus" OR "obliquus internus"

Trial registries – searched for only those with results

- ICTRP
  - Abdom and exercise
- Clinical trials.gov
  - Exercise and muscle, adults
- ANZCTR
  - Intervention/exposure: Exercise
  - Recruitment status: completed
  - Condition category: physical medicine/rehabilitation
  - Condition code: physiotherapy
  - Age group: 18 years and over

Limited to English language for all databases

Appendix B: Quality Appraisal results for each included study

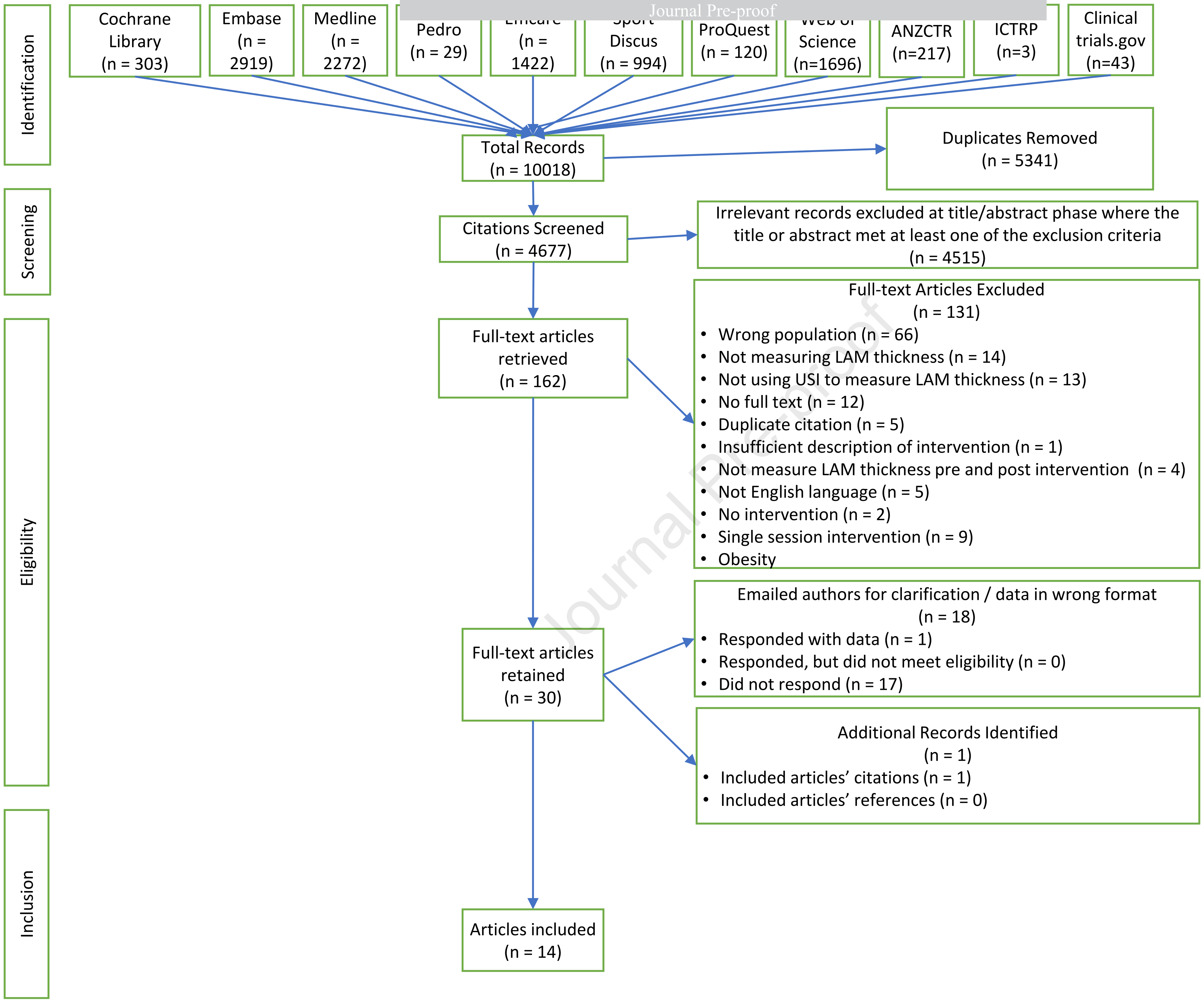
Randomised Controlled Trials

	Cho 2013	Cho 2015	Critchley 2011	Gong 2018	Gong 2015	Lee 2018	Lee 2018 a	Lee 2015	Niewiadomy 2021	Niewiadomy 2021 a	Yang 2015
1. Was true randomisation used for assignment of participants to treatment groups?	U	U	Y	U	U	U	Y	U	U	U	U
2. Was allocation to treatment groups concealed?	U	U	Y	U	U	U	U	U	U	U	U
3. Were treatment groups similar at baseline?	Y	Y	Y	Y	Y	U	Y	Y	Y	Y	Y
4. Were participants blind to treatment assignment?	N	N	N	N	N	N	N	N	N	N	N
5. Were those delivering treatment blind to treatment assignment?	N	N	N	N	N	N	N	N	N	N	N
6. Were outcomes assessors blind to treatment assignment?	U	U	Y	Y	Y	U	U	U	Y	Y	U
7. Were treatment groups treated identically other than the intervention of interest?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8. Was follow up complete and if not were differences between groups in terms of their follow up adequately described and analysed?	U	U	U	U	U	Y	Y	Y	Y	Y	Y
9. Were participants analysed in the groups to which they were analysed?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
10. Were outcomes measured in the same way for treatment groups?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
11. Were outcomes measured in a reliable way (was reliability data present for the method?)?	N	N	Y	N	N	Y	N	Y	Y	Y	N
12. Were outcomes measured in a reliable way (was the method reproducible?)?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
13. Was appropriate statistical analysis used?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
14. Was the trial design appropriate and any deviations from the standard RCT design	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Appendix B: Quality Appraisal results for each included study

accounted for in the conduct and analysis of the
trial?

Individual results for Kohiruimaki (case series study), Giacomini (quasi-experimental study) and Gage (cohort study) are presented in the manuscript.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Screening
Eligibility
Inclusion
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Embase (n = 2919)
Medline (n = 2272)
Pedro (n = 29)
(n = 1422)
Discus (n = 994)
ProQuest (n = 120)
Science (n=1696)
ANZCTR (n=217)
ICTRP (n=3)
Clinical trials.gov (n=43)
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Duplicates Removed (n = 5341)
Citations Screened (n = 4677)
Irrelevant records excluded at title/abstract phase where the title or abstract met at least one of the exclusion criteria (n = 4515)
Full-text articles retrieved (n = 162)
Full-text Articles Excluded (n = 131)
• Wrong population (n = 66)
• Not measuring LAM thickness (n = 14)
• Not using USI to measure LAM thickness (n = 13)
• No full text (n = 12)
• Duplicate citation (n = 5)
• Insufficient description of intervention (n = 1)
• Not measure LAM thickness pre and post intervention (n = 4)
• Not English language (n = 5)
• No intervention (n = 2)
• Single session intervention (n = 9)
• Obesity
Full-text articles retained (n = 30)
Emailed authors for clarification / data in wrong format (n = 18)
• Responded with data (n = 1)
• Responded, but did not meet eligibility (n = 0)
• Did not respond (n = 17)
Additional Records Identified (n = 1)
• Included articles' citations (n = 1)
• Included articles' references (n = 0)
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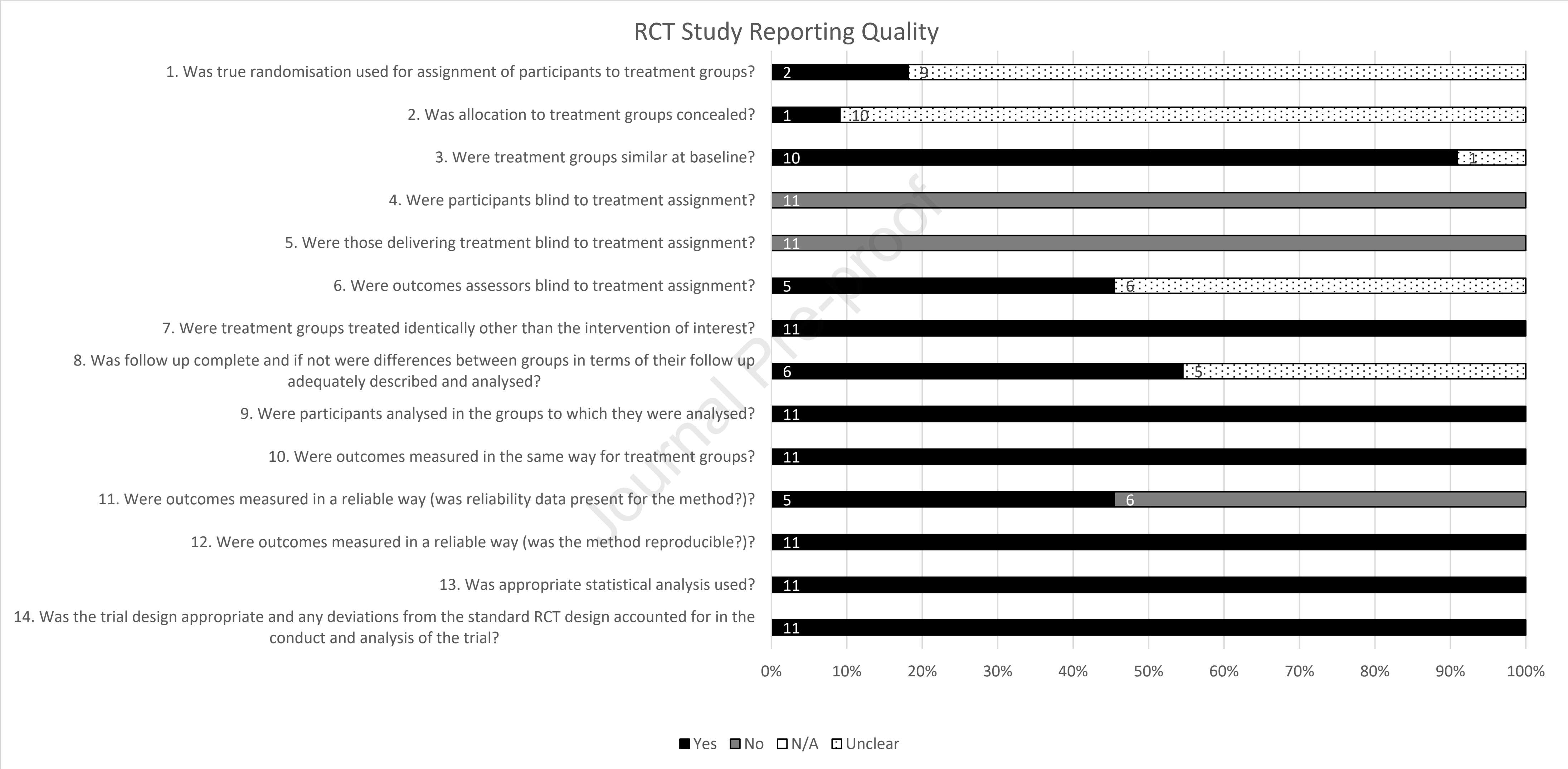
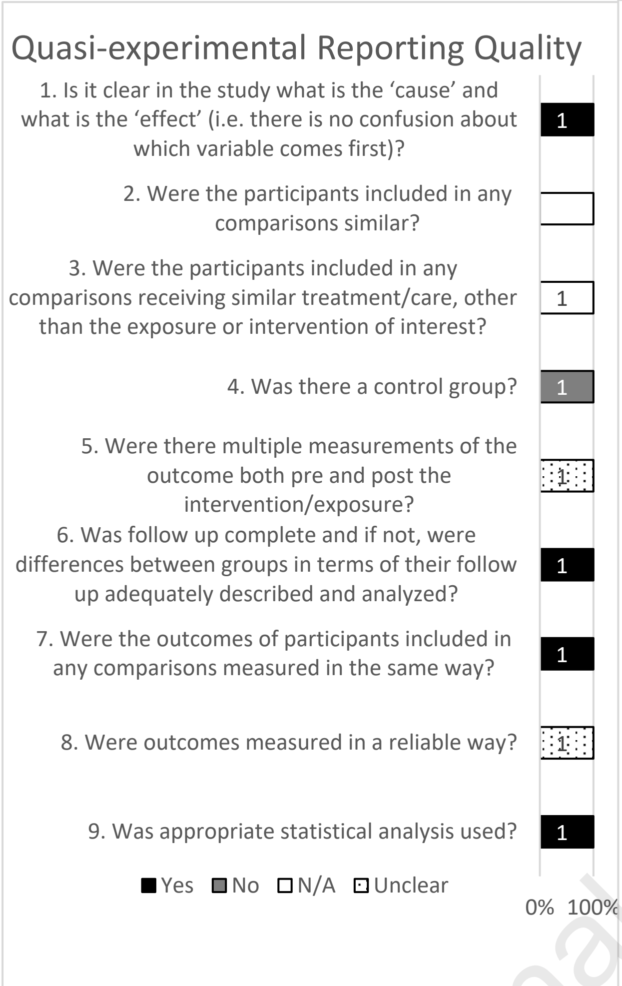


Figure 2 Risk of bias across different study designs



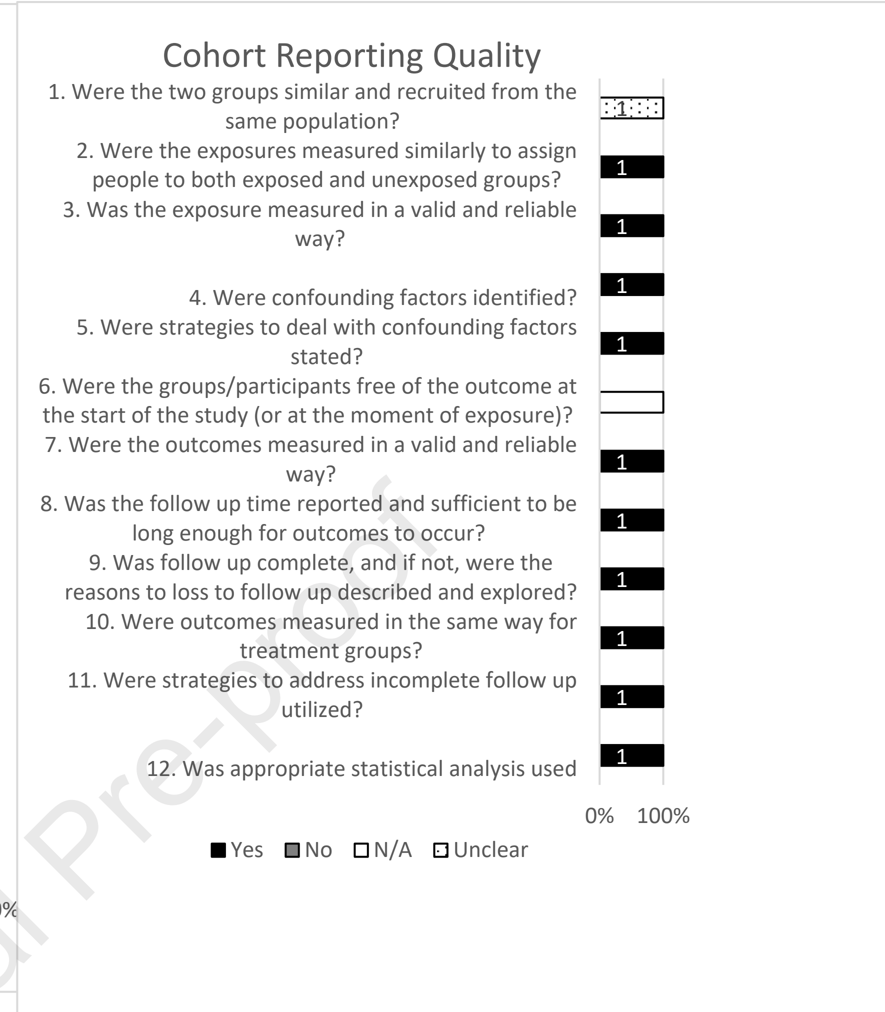
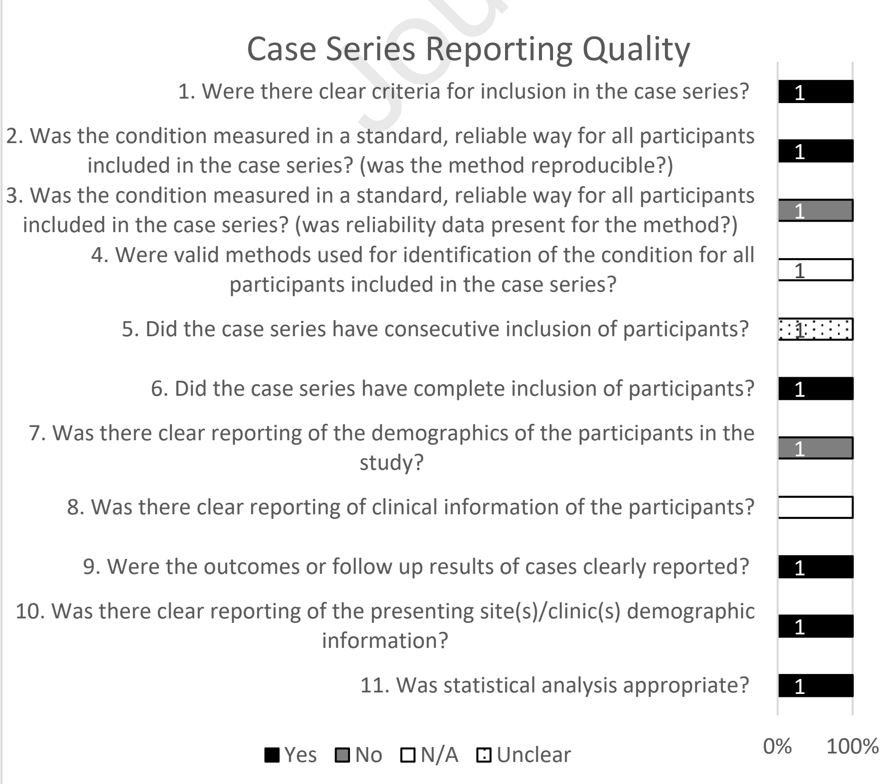


Figure 2 Risk of bias across different study designs



Conflict of Interest Statement

The authors have no conflicts of interest to disclose.