

The efficacy of a supervised and a home-based core strengthening programme in adults with poor core stability: a three-arm randomised controlled trial

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ABSTRACT

Background Poor core stability is linked to a range of musculoskeletal pathologies and core-strengthening programmes are widely used as treatment. Treatment outcomes, however, are highly variable, which may be related to the method of delivery of core strengthening programmes. We investigated the effect of identical 8 week core strengthening programmes delivered as either supervised or home-based on measures of core stability.

Methods Participants with poor core stability were randomised into three groups: supervised (n=26), home-based (n=26) or control (n=26). Primary outcomes were the Sahrman test and the Star Excursion Balance Test (SEBT) for dynamic core stability and three endurance tests (side-bridge, flexor and Sorensen) for static core stability. The exercise programme was devised and supervised by an exercise physiologist.

Results Analysis of covariance on the change from baseline over the 8 weeks showed that the supervised group performed significantly better on all core stability measures than both the home-based and control group. The home-based group produced significant improvements compared to the control group in all static core stability tests, but not in most of the dynamic core stability tests (Sahrman test and two out of three directions of the SEBT).

Conclusions Our results support the use of a supervised core-strengthening programme over a home-based programme to maximise improvements in core stability, especially in its dynamic aspects. Based on our findings in healthy individuals with low core stability, further research is recommended on potential therapeutic benefits of supervised core-strengthening programmes for pathologies associated with low core stability.

Trial registration number ACTRN12613000233729.

INTRODUCTION

Core stability refers to the ability of core musculature to stabilise the spine.¹ It is required to increase stiffness of the trunk and hip in preparation for, and in response to, spinal loading, to prevent instability of the vertebral column and to facilitate return to equilibrium following perturbation.² Poor core stability is linked to development of a range of musculoskeletal pathologies of the spine and lower extremities, including low back pain³ and over-use injuries of the hip, knee, ankle and foot.⁴⁻⁶

Core strengthening programmes aim to improve core stability by developing strength, endurance and neuromuscular control of core muscles.⁷ Such programmes are currently recommended as a primary treatment for chronic low back pain.⁸

Despite widespread use, treatment outcomes are highly variable and the efficacy of this exercise approach for treatment of pathology remains unclear.^{9 10}

A possible source of the heterogeneity of therapeutic outcomes following core-strengthening programmes is the method of programme delivery, with both supervised and home-based programmes in common use. Home-based exercise programmes of any type offer several benefits over supervised programmes including greater flexibility for patients and reduced associated healthcare system costs. However, home-based programmes rely on the participants' motivation and ability to correctly perform the exercises independently, and self-reported compliance is similar to, or lower than, supervised programmes.¹¹

To date there has been little investigation of the effect of home-based versus supervised exercise programmes for core stability. Bronfort *et al*¹² found better results with a supervised core-strengthening programme. However, as different exercises were used for the home-based and supervised group, it was not possible to determine if this was due to the delivery method or the specific exercises used. Poorer outcomes for home-based core strengthening programmes may be related to the difficulty participants have effectively performing exercises without external feedback. Specific instructions, as are given under supervision, induced improved activation of deep core stabilising muscles during trunk flexion activities.¹³ It is unknown, however, to what extent the absence of such instruction affects the efficacy of a home-based programme. Thus, we determined the effect of identical core-strengthening programmes delivered as either a (1) supervised or (2) home-based programme compared to (3) no intervention on measures of core stability.

METHODS

This was a three-arm, stratified (gender, age) with balanced randomisation, single-blind, controlled, parallel-group study conducted on the University of Newcastle Central Coast Campus. This project was approved by the institutional Human Research Ethics Committee and was registered with the Australian and New Zealand Clinical Trials Registry (available at <http://www.ANZCTR.org.au/ACTRN12613000233729.aspx>). Participants were recruited on a volunteer basis from staff and students via flyer advertising.

Inclusion criteria were 18 years of age or over with a Sahrman test score of level 1 or lower



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indicating poor core stability. Exclusion criteria included current pregnancy, current acute specific low back pain, current acute lower limb injury or any musculoskeletal, neurological, systemic or local pathology affecting balance, neuromuscular control or altering muscle response to exercise and current or previous participation in any form of core-strengthening programme.

Randomisation

Participants were randomised into the intervention or control groups with a software randomisation function by a researcher independent of the trial. Randomisations were stratified for age and gender.

Interventions

This trial used two interventions and a control. The first intervention was a supervised core-strengthening programme which was performed over 8 weeks, with participants required to attend two classes per week.^{1 14–20} Details of the programme and rationale for included exercises are provided in online supplementary file 1. This programme was conducted by an exercise physiologist not involved in recruitment or testing who provided instruction, demonstration and individual feedback on correct execution of exercises. Compliance at these sessions was monitored via an attendance record completed by the exercise physiologist.

The second intervention was a home-based core-strengthening programme. Participants in the home-based programme received an initial instructional class in which they were taught the principles of deep abdominal muscle activation and the progression of all exercises used in the programme. They were also provided with written and diagrammatic instructions to follow for two sessions per week for 8 weeks. All exercise sessions in the home-based programme were identical to those in the supervised programme. All instructional sessions were provided by the same exercise physiologist who ran the supervised group classes. Compliance was assessed using a self-reported compliance questionnaire.

The third group served as controls and participated in baseline and follow-up testing only. All groups were instructed not to change their physical activity levels outside the prescribed programmes.

Procedures

Potential participants were initially screened using the Sahrman test. Participants achieving a score of level one or less were then eligible to enter the trial. The baseline testing consisted of the Sahrman test to evaluate dynamic lumbopelvic stability,^{21 22} three tests of static trunk muscle endurance requiring sustained isometric contraction, (the side bridge endurance test,¹⁴ the flexor endurance test¹⁸ and the Sorensen test²³) and the Star Excursion Balance Test (SEBT)^{24–26} to assess dynamic postural stability in three directions (anterior, posterolateral and posteromedial).²⁷ Details of and rationale for these tests are provided in online supplementary file 2.

The participants were then randomised to one of the three groups. The trial began once 13 participants had been recruited for the supervised core-strengthening group to allow for adequate class size. Within 1 week of completion of the 8 week intervention all participants performed the same tests as at baseline. All assessments were performed by the same researcher, who was blinded to participant group allocation.

Test-retest reliability of all core stability tests was assessed on a separate group of 15 participants who met the main study inclusion criteria. Following baseline testing these participants

returned 7–10 days later and repeated all core stability assessments. The testing was completed by the same researcher who performed baseline and follow-up testing.

A sample size of 26 per group was calculated based on a minimally important change of 7% for the SEBT assuming a SD of 10%, a power of 90%, an α of 0.05 and allowing for 10% attrition rate.²⁸

Outcomes

Primary outcomes were change in dynamic lumbopelvic stability measured with the Sahrman test, change in independent measures of static core stability assessed with the side bridge endurance test, the flexor endurance test and the Sorensen test and, change in dynamic postural stability measured with the SEBT. Secondary outcomes were compliance with the intervention and adverse events.

Statistical analysis

Statistical analysis was conducted on a blinded, intention-to-treat basis using SPSS software (V21.0 SPSS Chicago, Illinois, USA). For the primary outcomes, data were analysed with analysis of covariance (ANCOVA) using a linear regression approach to investigate change from baseline following the 8 week intervention for each variable. The baseline measure was the only covariate used in each analysis. Cohen's *d* was used to calculate effect sizes. An effect size of greater than or equal to 0.8 was considered to represent a large clinical effect, 0.5 a moderate effect and 0.2 a small effect.²⁹ Correlations were performed between all measures of core stability and self-reported and recorded compliance for the home-based and supervised group, respectively.

For the reliability component intraclass correlation coefficients (ICC) with 95% CI were calculated to determine level of agreement between test and retest for all measurements. All ICC values for test-retest reliability were interpreted according to criteria recommended by Fleiss.³⁰ Paired *t* tests were performed to determine whether statistically significant differences existed between sessions.

RESULTS

Seventy-eight participants were recruited between June and September 2012. Participant characteristics are included in table 1. Figure 1 demonstrates participants' progression through the trial. Participants in the supervised core strengthening programme attended approximately 76% (12.1) of the 16 scheduled classes for their programme. Those in the home-based programme self-reported a higher mean compliance rate with an average of 85% (13.6) of the 16 sessions completed. The trial

Table 1 Participant characteristics

Group	Sample size	Gender	Age (years)	BMI (kg/m ²)
Supervised program	26	15 males 11 females	26.31 (4.12)	25.29 (1.53)
Home-based program	26	14 males 12 females	25.22 (3.51)	23.24 (1.98)
Control	26	15 males 11 females	27.01 (3.90)	26.12 (2.01)
Reliability	15	10 males 5 females	24.68 (3.62)	24.25 (2.55)

Data are counts or mean (SD).

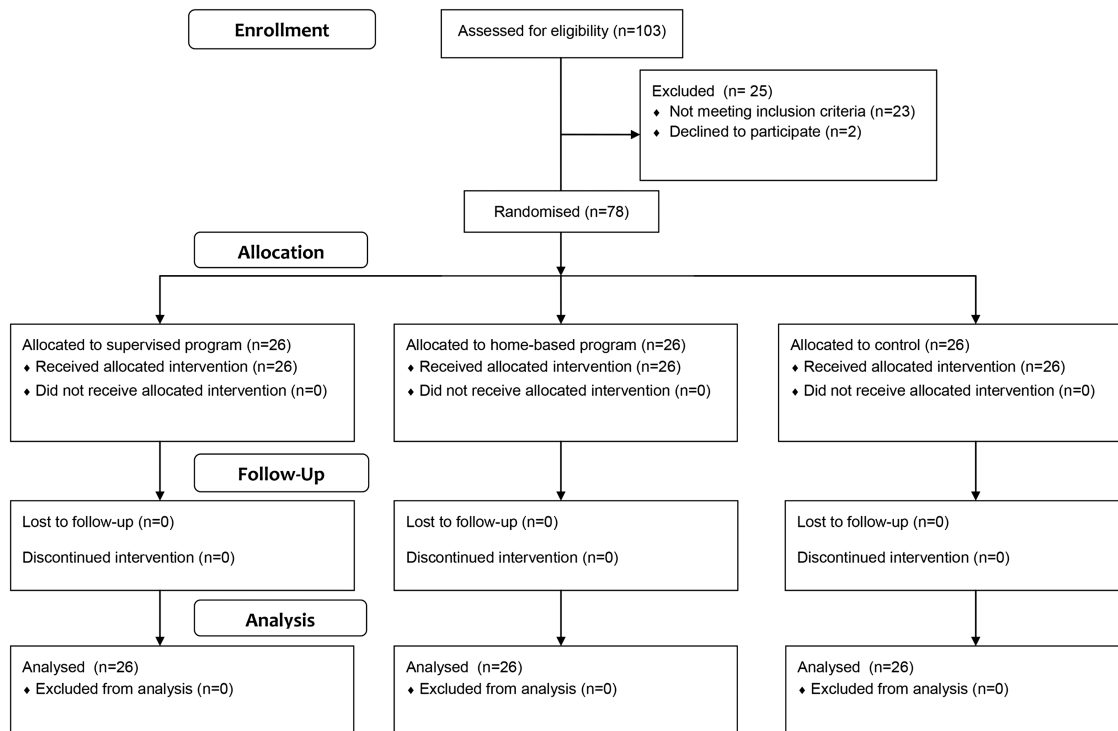


Figure 1 CONSORT flow diagram of participants' progression through the trial.

was ended once 26 participants had completed each intervention. The characteristics of the reliability group are also shown in [table 1](#).

Measures of core stability

Participants in the supervised core-strengthening programme demonstrated more statistically significant improvements in mean scores on all measures of core stability than those in the home-based programme and the control group and effect sizes were generally moderate to large ([tables 2 and 3](#)) and significant for the Sahrman and Sorenson tests. The home-based programme produced significant improvements compared to the control group in most tests, except for the Sahrman test and the SEBT posterolateral and posteromedial directions which had small to moderate effect sizes ([tables 2 and 3](#)).

Correlations

Correlations between compliance and outcomes of tests of core stability were strongest for the supervised group ([table 4](#)).

Significant positive correlations were demonstrated between the number of sessions attended in the supervised group and all core stability outcomes, except for the side bridge. In the home-based programme only outcomes for the flexor endurance test were positively correlated with self-reported compliance ([table 4](#)).

Reliability

Test-retest reliability for functional tests of core stability was excellent with ICCs ranging from 0.80 to 0.91 ([table 5](#)). Paired samples t tests demonstrated no significant differences between test and retest measures.

Adverse events

There were no reported adverse events associated with this research.

DISCUSSION

We found that a supervised core-strengthening programme results in significantly greater improvements in static and

Table 2 Adjusted means for follow-up core stability testing

	Sahrman (level)	Side-bridge endurance (s)	Flexor endurance (s)	Sorenson (s)	SEBT Anterior (cm)	SEBT posterolateral (cm)	SEBT posteromedial (cm)
Supervised group							
Mean	2.63	27.84	53.60	26.51	87.69	79.21	83.01
95% CI	2.09 to 2.92	23.38 to 31.11	47.12 to 60.23	21.74 to 31.29	84.08 to 91.22	75.68 to 82.61	78.79 to 87.34
Home-based group							
Mean	1.14	20.62	41.09	21.27	84.25	73.71	77.02
95% CI	0.66 to 1.41	16.83 to 23.49	33.52 to 45.65	16.49 to 26.13	80.31 to 87.80	70.19 to 76.10	72.82 to 82.26
Control group							
Mean	0.90	13.91	27.28	15.44	80.36	72.02	74.43
95% CI	0.51 to 1.14	10.59 to 17.30	20.68 to 33.91	10.63 to 20.17	76.88 to 84.01	68.64 to 75.02	70.08 to 78.06

SEBT, Star Excursion Balance Test.

Table 3 Effect sizes (Cohen's *d*) in mean (95% CI) and *p* values for difference in adjusted means between groups at follow-up

Core stability test	Supervised vs control		Supervised vs home-based		Home-based vs control	
	Effect size	<i>p</i> Value	Effect size	<i>p</i> Value	Effect size	<i>p</i> Value
Sahrmann	2.06 (1.86 to 2.26)	0.0001	1.45 (0.84 to 2.06)	0.0001	0.27 (−0.27 to 0.81)	0.09
Side-bridge endurance	1.75 (−0.42 to 3.90)	0.0001	0.83 (−1.53 to 3.19)	0.0001	0.81 (−1.43 to 3.07)	0.001
Flexor endurance	2.35 (−0.70 to 5.39)	0.0001	1.19 (−1.66 to 4.03)	0.0001	1.45 (−1.12 to 4.03)	0.01
Sorensen	1.46 (0.61 to 3.53)	0.001	0.67 (−1.43 to 2.78)	0.03	0.81 (−1.15 to 2.78)	0.02
SEBT anterior	0.73 (−1.97 to 3.42)	0.001	0.32 (−2.39 to 3.02)	0.01	0.40 (−2.26 to 3.06)	0.02
SEBT posterolateral	1.03 (−0.82 to 2.87)	0.0001	0.54 (−1.21 to 2.29)	0.04	0.24 (−1.49 to 1.96)	0.07
SEBT posteromedial	1.08 (−1.10 to 3.25)	0.0001	0.71 (−1.61 to 3.01)	0.001	0.36 (−1.98 to 2.61)	0.08

SEBT, Star Excursion Balance Test.

dynamic core stability measures than an identical home-based programme. The home-based programme's effect was restricted to greater static core muscle endurance compared to the control group and may have been influenced by the similarity between some of the less complex exercises and the specific tests used, for example side-bridge endurance. This finding may have therapeutic relevance as greater isometric core muscle endurance in the three static tests selected for the current study is associated with better spine stability during most activities.¹⁴

Supervised intervention provides superior outcome

In general, supervised exercise interventions are more effective than home-based interventions.^{11 31–33} Bronfort *et al*¹² also showed greater improvement in trunk muscle endurance in people undertaking supervised classes compared to those doing a different exercise programme at home. Based on the outcomes of the current trial, it is likely that the difference in method of programme delivery used by Bronfort *et al*¹² may largely explain the superior outcomes in the supervised group, independent of the different types of exercises being used. Our use of the same exercise programme for both the home-based and supervised groups in the present study clearly demonstrates that the delivery method of the programme has a significant influence on the outcomes of core-strengthening programmes.

For the dynamic measures of core stability the supervised programme again produced significantly better results than the home-based programme. Furthermore the home-based programme failed to produce any significant improvement in the Sahrmann test and the posterolateral and posteromedial directions of the SEBT compared to the control condition. Although there was a significant improvement in the anterior direction of the SEBT by those in the home-based programme compared to the control group, the improvement in the supervised group was significantly greater.

The Sahrmann test assesses spinal stability with and without movement of the lumbopelvic complex,¹⁶ whereas the SEBT measures dynamic stability with poorer performance associated with mechanical or sensorimotor deficits.³⁴ Our findings suggest that a home-based unsupervised core-strengthening programme may be less effective for neuromuscular retraining and produces less improvement in core stability during dynamic tasks than a supervised programme. Previous research demonstrated improved activation of deep core stabilising muscles during trunk flexion activities in association with verbal and tactile cues.¹³ Instruction on stabilisation also altered the motor control strategy of trunk musculature and produced increased lumbar spine control during upper and lower body movements.³⁵ Although participants in the home-based group in our trial received initial verbal instruction, demonstration and written instruction on performance of all exercises, our results suggest this was not sufficient to achieve significant change in neuromuscular control strategies to improve dynamic core stability. This may be related to a lack of understanding of the progression of exercises demonstrated in the initial instruction session potentially resulting in reduced compliance or participants performing more demanding tasks incorrectly.

Compliance

Self-reported compliance in the home-based programme was higher than recorded attendance for the supervised group. However, correlations between compliance and pre-test and post-test change in core stability measures demonstrated stronger associations in the supervised group. This may have been due to more effective training in the supervised programme, but may also have been influenced by over-reporting of compliance in the home-based group. Although increased attendance at the supervised classes was associated with improved performance across all tests, the strongest relationships occurred with the

Table 4 Correlations between compliance and measurement outcomes at follow-up testing for the supervised and home-based groups

Core stability test	Supervised group (<i>r</i>)	Home-based group (<i>r</i>)
Sahrmann	0.63**	−0.13
Side-bridge endurance	0.33	0.23
Flexor endurance	0.57**	0.49*
Sorensen	0.54*	0.26
SEBT anterior	0.44*	0.20
SEBT posterolateral	0.59**	0.18
SEBT posteromedial	0.61**	0.24

*Significant at *p*=0.05; **Significant at *p*=0.01.
SEBT, Star Excursion Balance Test.

Table 5 Test–retest reliability

Measurement	Test mean	Retest mean	ICC	95% CI for ICC	Paired <i>t</i> test <i>p</i> value
Sahrmann (level)	0.50	0.57	0.87	0.74 to 0.96	0.19
Side-bridge endurance (s)	13.93	15.33	0.82	0.62 to 0.93	0.85
Flexor endurance (s)	33.54	30.72	0.91	0.75 to 0.97	0.17
Sorensen (s)	17.22	16.69	0.80	0.60 to 0.92	0.61
SEBT anterior (cm)	79.06	78.43	0.83	0.72 to 0.94	0.71
SEBT posterolateral (cm)	70.73	71.67	0.86	0.71 to 0.96	0.31
SEBT Posteromedial (cm)	74.08	75.24	0.85	0.79 to 0.98	0.42

n=15.

ICC, intraclass correlation coefficient; SEBT, Star Excursion Balance Test.

Sahrmann test, the posteromedial and posterolateral SEBT. These results suggest increased adherence to supervised training programmes may produce better outcomes for more demanding dynamic tasks that not only require increases in core muscle strength, but also high levels of neuromuscular control. The strong association between the compliance and both the flexor endurance and the Sorensen tests suggests maintaining the training programme as close to two sessions per week as possible can produce better trunk flexor and extensor endurance.

In the home-based programme the strength of association between self-reported compliance and change in measured outcomes was generally low. This may have been due to a smaller effect on outcome measures of the exercise programme conducted in a non-supervised environment or due to over-reporting of compliance. The significant positive correlation for flexor endurance with the number of sessions performed, in conjunction with the significant improvement seen for this outcome postintervention, suggests participants may have performed exercises targeting the anterior abdominal muscles more frequently or with better technique. High reported compliance with the intervention and small changes in measured outcomes may also have confounded other potential associations.

Outcome measure reliability

Test–retest reliability was performed for all outcome measures in this trial. This was not our primary aim and the assessments used have been demonstrated previously to have adequate reliability.^{3 21 35–38} However, the subjective nature of the end point of several of the tests, where the researcher was required to specify the time point at which a participant ‘failed’ based on observation, meant establishing reliability of assessments specifically for this trial was warranted. The ICCs ranging from 0.80 to 0.91 indicated excellent test–retest reliability and were consistent with existing literature.^{3 21 35–38} No change in values between test sessions is a further indicator of good test–retest reliability. This indicates that improvements in outcome measures for the home-based and supervised training programmes represent true changes as a result of the intervention.

Limitations

Our findings support the use of a supervised programme over a home-based programme for improving static core muscle endurance and dynamic core stability. This study targeted participants with poor dynamic core stability, with trial inclusion requiring a Sahrmann test performance of level one or less. Participants with current pathology that may be attributable to poor core stability, such as low back pain, were excluded. Therefore, although it is evident from this trial that participants with poor dynamic core stability demonstrate an improved response to core training in a supervised environment, it is not known if this translates to exercise intervention for pathologies, such as low back pain, where the initial level of dynamic core stability may be more variable. Existing evidence has demonstrated altered function of deep core stabilising muscles, such as transversus abdominis, during activity in people with low back pain.³ This suggests that improving dynamic core stability is an essential component of rehabilitation for low back pain. The current trial findings indicate that a supervised core strengthening programme may be advisable, but further investigation on specific cohorts, including those with low back pain,³⁹ needs to be undertaken to determine if supervised programmes also provide the best results in those cohorts.

A further limitation of this study was the nature of the core strengthening programme delivered. The same programme was given to both the supervised and home-based groups to isolate

the effect of method of delivery on core muscle endurance and dynamic stability. However, due to the reliance on the participant to perform the exercises in an ongoing manner following initial instruction, a home-based programme may require a different approach. Home-based programmes may benefit from including specific exercises more congruent with being performed without instruction to maximise outcomes. Investigation of effectiveness of specific types of programmes delivered in a home-based environment needs to be undertaken to develop a more effective method for core strengthening to be undertaken without supervision. In addition the outcomes of supervised programmes may be influenced by the method of instruction. While it was not the purpose of this study to investigate the role of the instructor this is also an important area for further investigation.

CONCLUSION

The results of this study support the use of a supervised core-strengthening programme over a home-based programme to maximise improvement in static core muscle endurance and dynamic core stability in a healthy population with low core stability. Further research is recommended to assess if a supervised core-strengthening programme will also provide a greater therapeutic benefit than a similar home-based programme for pathologies associated with reduced core stability, such as low back pain.

What are the new findings

- ▶ Supervised core-strengthening programmes result in better static and dynamic core stability outcomes than home-based programmes.
- ▶ Home-based core strengthening programmes improve static core endurance, but not dynamic core stability.
- ▶ Training compliance in the supervised programme was positively correlated with most core stability outcomes.

How might it impact on clinical practice in the near future

- ▶ Supervised core strengthening-programmes may provide greater treatment benefits for musculoskeletal pathologies associated with poor core stability than home-based programmes.
- ▶ Home-based core-strengthening programmes may be prescribed to improve static core stability, but are not likely to improve dynamic core stability.
- ▶ Supervised core-strengthening programmes are needed to improve core stability for more demanding dynamic tasks.

Contributors VHC and XAKJdJ planned the randomised controlled trial. VHC, XAKJdJ and BMT conducted the trial. All authors contributed to the reporting of the trial.

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Competing interests None.

Ethics approval Human Research Ethics Committee of the University of Newcastle Australia (protocol # H-2012-0013).

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Supplementary file 1, The core strengthening program

Exercises	Characteristics	Justification
Cat/camel	Cycles of flexion and extension in quadruped position.	Cat/camel reduces spinal viscosity (14).
Abdominal muscle contractions in supine and quadruped. Side bridge	Activation of the deep core musculature in static positions.	The local system consists of mostly type I tonic muscles which are activated with low intensities and slow movements (15). These muscles therefore require exercises that involve little to no motion through the spine and pelvis (16). The side bridge and bird dog exercises produce muscle activation in the absence of external loading to train stabilisation and endurance to the musculature of the torso and hips (17).
Dead bug Bird dog	Maintenance of core control while performing controlled arm and leg movements.	
Hip abduction	Activation of the hip musculature while maintaining lumbar and pelvic control.	Hip abduction is an effective non-weight-bearing method for isolating function and strength training of the gluteus medius muscle (17).
Abdominal isometric contraction on a Swiss ball.	Maintenance of core control in an unstable environment.	Given that isolation exercises of the local musculature tend to be in non-functional positions, exercise training that shifts to additional functional positions and actions is required as a progression, which initiates training of the global system (16).
Lunges	Maintenance of lumbar control during hip movement.	
Directional lunges and oblique twists	Maintenance of lumbar control during multiplanar movements.	Exercises that produce dynamic concentric and eccentric movement of the spine emphasise the global system musculature while providing an environment for the local system to stabilise the spine in a variety of multiplanar movements (16).
Trunk twists on a Swiss ball	Maintenance of core control during movement in an unstable environment.	
Trunk twists with theraband on Swiss ball	Progress to movement under resistance in an unstable environment.	

Exercise	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Week 7		Week 8	
	sets	reps	sets	reps	sets	reps	sets	reps	sets	reps	sets	reps	sets	reps	sets	reps
Warm up																
Cat/camel	1	6	1	6	1	6	1	6	1	6	1	6	1	6	1	6
Activation of core musculature																
- Supine	2	15	2	15	2	15	2	15	2	15	2	15	2	15	2	15
- Quadruped	2	15	2	15	2	15	2	15	2	15	2	15	2	15	2	15
- Side bridge (on knees)	1 (10s holds)	6	1 (10s holds)	6 (10s holds)	1 (10s holds)	6	1 (10s holds)	6 (10s holds)	1 (10s holds)	6	1 (10s holds)	6 (10s holds)	1 (10s holds)	6	1 (10s holds)	6 (10s holds)
Dead bug																
Supine position	Supported position, extend 1 arm and flex opposite knee and hip to 90°	Supported position, extend both arms over head	Supported position, hands clasped, extend arms over head	Supported position, hands clasped, extend arms over head	Unsupported position, hands clasped, extend arms over head, extend 1 leg	Unsupported position, hands clasped, extend arms overhead, extend both legs	Unsupported position, hands clasped, extend arms overhead, extend both legs	Unsupported position, hands clasped, extend arms overhead, extend both legs	Unsupported position, extend opposite arm and opposite leg							
Supported position - knees bent and feet placed on floor																
Unsupported position - feet raised from floor with knees and hips bent at 90°																
Hold time	2s		2s		2s		2s		2s		2s		2s		2s	
Duration	30s		45s		60s		60s		75s		90s		90s		105s	
Side bridging																
On side, forearm on floor, elbow under shoulder	Raise hips 3cm off floor with knees bent at 90°	Raise hips 8 cm off floor (max bridging height) with knees bent at 90°	Raise hips 8 cm off floor (max height) with legs straight	Raise hips 8 cm off floor (max height) with legs straight	Raise hips 8 cm off floor (max height) with legs straight and extend 1 leg	Raise hips 8 cm off floor (max height) with legs straight and extend 1 leg, add 0.5kgs to legs	Raise hips 8 cm off floor (max height) with legs straight and extend 1 leg, add 0.5kgs to legs	Raise hips 8 cm off floor (max height) with legs straight and extend 1 leg, add 0.5kgs to legs	Raise hips 8 cm off floor (max height) after each side bridge hold, "roll" from one elbow to the other.							
Sets	3 each side		3 each side		3 each side		3 each side		3 each side		3 each side		3 each side		3 each side	
Duration	30s		45s		20s		30s		30s		20s		30s		60s	

Birdog exercises	Raise one leg at a time, repeat with other leg then, raising each arm at a time	Raise opposite arm and opposite leg	Raise opposite arm and opposite leg	Raise opposite arm and opposite leg, refrain from placing limbs back on ground between sets	Raise opposite arm and opposite leg, refrain from placing limbs back on ground between sets	Raise opposite arm and opposite leg, add 0.5kg leg weight	Raise opposite arm and opposite leg, add 0.5kg leg weight	Raise opposite arm and opposite leg, add 1kg leg weight
In quadruped position (four point kneeling)								
Sets	3 on each limb	3 on each side	3 on each side	3 on each side	3 on each side	3 on each side	3 on each side	3 on each side
Duration	20s	20s	30s	15s	20s	20s	30s	30s
Hip abduction	Raise and lower top leg.	Raise and lower top leg.	Raise and lower top leg.	Raise and lower top leg.	Raise and lower top leg.	Raise and lower top leg with 0.5kg leg weight	Raise and lower top leg with 0.5kg leg weight	Raise and lower top leg with 1kg leg weight
Lying on side, core muscles activated, legs extended.								
Sets	2 each side	3 each side	2 each side	3 each side	3 each side	2 each side	3 each side	3 each side
Reps	10	10	15	15	15	15	15	15
Stability ball exercises	Seated on stability ball while activating core musculature	Seated on stability ball while activating core musculature	Squat with stability ball 90° hip and knee flexion	Squat with stability ball 90° hip and knee flexion	Diagonal curls on stability ball	Diagonal curls on stability ball	Twists on stability ball holding a medicine ball	Twists on stability ball with theraband
Sets	3	3	3	3	3	3	3	3
Duration	30s	30s	Reps 15	Reps 15	Reps 10	Reps 15	Reps 10	Reps 10
Lunges/obliques	Lunges with 2kg weight in each hand	Lunges with 2kg weight in each hand	Lunges at 45°	Lunges at 45° with a 2kg weight in each hand	Lunges to sides	Lunges to sides with 2kg weights in each hand	Oblique pulley twist with theraband	Oblique pulley twist with theraband
Sets	3	3	3	3	3	3	3	3
Reps	10	10	15	10	15	10	10	15

(1, 14-20)

Supplementary file 2, Details of the core stability tests

Given that the core musculature is a complex, integrated system that functions synergistically to stabilise the spine (1), a battery of tests was deemed most appropriate to assess core stability. As the trunk flexors, extensors and lateral musculature are responsible for spinal stability during most activities (14), endurance was measured for all three muscle groups using the side bridge endurance test, the flexor endurance test, and the Sorensen test. The Star Excursion Balance test was selected to assess dynamic postural control due to the importance of the core musculature in providing a stable base for distal movement (1). In addition, the Sahrman test was used to assess the ability of the deep core musculature to stabilise the spine during lumbopelvic motion (16). This battery of core stability tests aims to assess the important isometric endurance and dynamic control aspects of the core musculature.

The side bridge endurance test

This test was used to assess strength of quadratus lumborum and muscles of the anterolateral wall. The test was performed in accordance with McGill (14) with the lateral musculature tested with the subject lying in the full side bridge position. Feet are placed with the top foot in front of the lower foot for support with the legs extended. The participant supports themselves on their elbow and feet whilst lifting their hips from the floor to generate a straight body alignment from head to toe. The top arm is placed across the body with the hand resting on the supporting arm's shoulder. Failure arises when the subject loses the straight back posture and/or the hip touches the ground.



Figure S2.1 The side-bridge endurance test

The flexor endurance test

Endurance of the rectus abdominis and abdominal oblique muscles was evaluated through the abdominal fatigue test, which is an isometric contraction at an angle of 60° (18). The test is performed with the participant's hips and knees flexed at 90° with the feet fixed to the floor (18). The participant's hands are placed crossed the chest on opposite shoulders, while they lean against a wedge angled at

60°. The test begins when the supporting wedge is removed and terminated when the subject could no longer maintain the upper body at 60°, with the length of the hold being recorded in seconds (18).



Figure S2.2 The flexor endurance test

The Sorensen test

The Sorensen test has been validated as a simple and reproducible method for evaluating the isometric endurance of the trunk extensor muscles (23). During this test the participant lies on an examining table in the prone position with the upper edge of the iliac crests in line with the edge of the table. The lower body is fixed to the table by three straps, situated around the pelvis, knees, and ankles, respectively (23). With the arms folded across the chest, the participant is asked to isometrically sustain the upper body in a horizontal position (23). Failure occurs when the upper body drops from the horizontal position. The time during which the patient keeps the upper body straight and horizontal is recorded. In participants who experience no difficulty in holding the position, the test is stopped after 240 seconds (23).



Figure S2.3 The Sorensen test

The star excursion balance test

Dynamic postural control was measured via the Star Excursion Balance Test (SEBT), which requires the participant to preserve their balance on a single limb while manipulating the opposite limb in one of 8 unilateral directions (24). This test requires the participant to stand at the centre of a grid on the

floor with eight lines projecting at 45° increments from the centre (24). The stance leg operates in the closed kinetic chain with movement taking place at the ankle, knee and hip joints as the opposite leg reaches down the line in the specified direction and contacts the line with the most distal part of their foot without using it for support (24). In accordance with Hertel and colleagues (27) only the anterior, posterolateral and posteromedial directions were measured to avoid capturing redundant information. Excursion distances are then normalised to leg length to provide a percentage of excursion distance in relation to leg length (25). Participants performed four practice trials before the actual testing to prevent learning effect influencing outcomes (26). Improvement in SEBT performance has been observed following core stability training indicating that this test is sensitive to change, which supports the use of the SEBT to assess the effectiveness of a core stability program (24).



Figure S2.4 The anterior direction of the star excursion balance test

The Sahrman test

Core stability was measured via the Sahrman test. To perform this test the inflatable pad of a pressure biofeedback unit is placed in the natural lordotic curve of the back, and is inflated to 40 mm Hg whilst the participant is lying supine (21). The subject activates the stabilising musculature via the abdominal hollowing technique, and if performed correctly will result in either no change in pressure or a slight decrease in pressure from the initial 40 mm Hg (22). The test consists of five levels with each level increasing in difficulty (21). In order to attain each increasing level on the Sahrman test, the lumbar spine position must be maintained by a change of no more than 10 mm Hg in pressure on the analogue dial of the pressure biofeedback unit (21). The ability of the core musculature to stabilise the spine can be indirectly measured by changes in the pressure applied to the biofeedback unit as the subject must maintain core activation during increased motion of the lumbopelvic complex with each level (16).

Level one: Abdominal presetting is performed with no movement being produced. The participant then raises one leg to 100° of hip flexion with comfortable flexion of the knee. The other leg is then brought to the same position. This became the initial position for subsequent levels. If the participant could maintain stability when raising one leg but not both, a score of 0.5 was awarded (21).

Level two: From the start position, the participant slowly lowers the heel of one foot to the floor, slides the leg out to fully extend the knee, and then returns to the start position.

Level three: The heel of one foot is lowered to 12 cm from the floor, the leg slides out to fully extend the knee and then returns to the start position.

Level four: From the start position, the participant lowers both heels to contact the floor, both legs slide out to fully extend the knees, and then return to the start position.

Level five: From the start position, the participant lowers both heels to 12 cm from the floor, the legs slide out to fully extend both knees, and then return to the start position (21).



Figure S2.5 The Sahrman test (level 1)