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Surface Electromyography Biofeedback and Trunk Endurance in Students with Low Back Pain

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ABSTRACT: This parallel-group randomized trial evaluated whether real-time surface electromyography (sEMG) biofeedback added to core exercise improved trunk endurance, disability, and muscle activation in university students with chronic mechanical low back pain. Forty students aged 18–30 years were randomized 1:1 to sEMG-assisted core exercise (SCE) or traditional core exercise (TCE), delivered twice weekly for eight weeks. Endurance and sEMG data were available for 39 participants; Oswestry Disability Index (ODI) data were available for all 40. Baseline-adjusted analyses with heteroscedasticity-robust standard errors favored SCE for trunk flexor endurance (adjusted mean difference 36.3 s, 95% confidence interval [CI] 14.8–57.7), trunk extensor endurance (37.7 s, 95% CI 24.0–51.3), right lateral plank endurance (23.6 s, 95% CI 10.7–36.4), and left lateral plank endurance (31.3 s, 95% CI 16.3–46.3); all Holm-adjusted $p \leq 0.002$. ODI improved within both groups, but change distributions did not differ significantly ($U = 261.5$, $p = 0.095$). Rectus abdominis activation change differed between groups ($U = 312.0$, Holm-adjusted $p = 0.003$), whereas other sEMG channels did not. SCE produced greater short-term improvements in trunk endurance than TCE, without clear additional benefits for disability. These findings may inform public health initiatives promoting a healthy lifestyle and addressing low back pain as a health risk among university students. However, the small single-center sample, outcome-specific missing data, unblinded treatment, and limitations in sEMG normalization and channel specificity warrant cautious interpretation.

1. INTRODUCTION

Low back pain (LBP) is the leading cause of years lived with disability worldwide. In 2020, approximately 619 million people were affected, and the number is projected to reach 843 million by 2050 as populations grow and age (GBD 2021 Low Back Pain Collaborators, 2023). The World Health Organization recommends education and exercise-based care within non-surgical management for chronic primary LBP (World Health Organization, 2023).

University students may be exposed to prolonged sitting, extensive screen use, suboptimal ergonomics, reduced physical activity, and academic workload. Screen exposure has been associated with LBP among college students (Thamrin et al., 2023),

and a Malaysian university survey reported LBP-related disability associated with demographic and academic factors (Purushothaman et al., 2025). These exposures may contribute to repeated mechanical loading of the lumbar region (Abas et al., 2023).

Coordinated activity of superficial and deep trunk muscles contributes to lumbopelvic control. Impaired motor control and reduced endurance occur in chronic LBP, and motor-control training can improve pain and disability (Shanbehzadeh et al., 2022). Core-stability programmes may also improve pain, function, and muscle performance in young people and adults with chronic non-specific LBP (Frizziero et al., 2021; Xu et al., 2024).

Traditional instruction relies on verbal cues, demonstration, and visual observation. Surface electromyography can display electrical activity recorded from a muscle region and provide augmented information during motor practice. Evidence from sports and orthopaedic rehabilitation suggests potential value, although methods and clinical effects remain heterogeneous (Haab et al., 2024). Surface recordings from the lower abdominal wall should be interpreted as regional signals because transversus abdominis and internal oblique activity cannot be cleanly isolated with routine surface electrodes.

Previous work has largely involved adults with chronic non-specific LBP or used electromyography as an assessment rather than a training adjunct (Clael et al., 2021; Yeldan et al., 2024). This superiority trial therefore examined whether adding real-time sEMG biofeedback to the same core-exercise programme produced greater eight-week improvements in four trunk-endurance outcomes. Secondary objectives were to compare disability and recorded activation from the rectus abdominis, lower abdominal TrA/IO region, and bilateral oblique channels.

2. MATERIALS AND METHODS

2.1 Study design and setting

This single-center, parallel-group, two-arm superiority randomized controlled trial used a 1:1 allocation ratio. It compared traditional core exercise (TCE; control) with sEMG-assisted core exercise (SCE; experimental) at the private university Physiotherapy Clinic, Nilai, Malaysia. Outcomes were assessed at baseline and immediately after the eight-week intervention. After baseline assessment, 40 participants were randomly allocated in a 1:1 ratio to the sEMG-assisted core exercise group or the traditional core exercise group, with 20 participants in each group. An independent researcher who was not involved in recruitment or treatment generated the allocation sequence using Research Randomizer version 4.0. Group assignments were placed in sequentially numbered, opaque, sealed envelopes, which were opened in order after each participant completed the baseline assessment.

The study used a single-blind design. Participants were not informed whether their assigned programme was the experimental or control intervention, whereas the researchers and treating physiotherapist knew the group assignments. Both groups received active exercise programmes.

2.2 Participants

Students were recruited at INTI International University through online advertisements and campus-based recruitment. Eligible participants were 18–30 years old; reported mechanical LBP for more than 12 weeks; had a Numerical Pain Rating Scale score of 3–7; had minimal-to-moderate disability on the ODI; and could attend supervised sessions twice weekly for eight weeks.

Exclusion criteria were spinal surgery during the previous six months; serious spinal pathology, including fracture, tumour, or spinal cord compression; neurological disorders; structural spinal deformity (scoliosis >20°); participation in a structured core-strengthening programme during the previous six months; uncontrolled medical conditions; or pregnancy. The operational diagnostic assessment and exact ODI eligibility thresholds must be added from the original protocol before submission.

2.3 Sample size

Sample size was estimated in G*Power version 3.1 using an effect size of $f = 0.42$ derived from an earlier randomized trial of core-stabilization exercise (Inani and Selkar, 2013). With two groups, two measurements, $\alpha = 0.05$, and 90% power, the stated minimum sample was 30. Forty participants were recruited to allow for attrition. The exact G*Power test family, repeated-measure correlation, nonsphericity correction, target outcome, and derivation of $f = 0.42$ must be verified against the saved calculation before submission.

2.4 Randomization and masking

After the initial assessment, an independent researcher who was not involved in recruitment or treatment delivery generated a 1:1 allocation sequence with Research Randomizer version 4.0. Group code 1 denoted SCE and group code 0 denoted TCE. Participants and the treating physiotherapist could not be masked because SCE participants viewed real-time feedback. The allocation-concealment mechanism, personnel responsible for enrolment and assignment, randomization restrictions, assessor masking, and analyst masking must be verified and reported from the original records.

2.5 Interventions

Both groups attended supervised sessions twice weekly for eight consecutive weeks. Each session lasted approximately 60 minutes and began with a five-minute warm-up comprising neck stretching, child's pose, arm circles, and hip-flexor stretching. The planned exercise content was the same in both groups.

Traditional core exercise. Participants performed sit-ups (three sets of 10 repetitions), left and right lateral planks, and a forearm plank with abdominal hollowing. Each plank exercise comprised two sets of five repetitions with 10-second isometric holds and one-minute rest intervals. A physiotherapist provided verbal instruction and demonstration. Participants received illustrated home-exercise instructions.

sEMG-assisted core exercise. Participants performed the same exercise programme while viewing real-time sEMG feedback. Surface electrodes recorded signals from the rectus abdominis, a lower abdominal region representing combined transversus abdominis/internal oblique activity, and bilateral oblique channels. The original intervention record must be used to add the device, electrode coordinates, target thresholds, feedback display, instruction sequence, progression rules, rest periods, and home-exercise prescription. Actual attendance, home adherence, treatment fidelity, and concomitant care should be reported if recorded.

2.6 Outcome measures

Outcomes were assessed at baseline and immediately after the eight-week intervention. The four co-primary outcomes were endurance times in the McGill trunk flexor, trunk extensor, right lateral plank, and left lateral plank tests. Participants completed one familiarization trial followed by one recorded trial for each test. Time was recorded in seconds, and testing ended when the required position could no longer be maintained. Test order, rest intervals, standardized instructions, encouragement, and assessor identity or masking must be added from the original protocol.

Secondary outcomes were disability and sEMG activation. ODI values in the dataset were stored as proportions and were converted to a 0–100-point scale for reporting. The ODI version, language, scoring procedure, and handling of unanswered items must be specified. The sEMG variables were reported on the supplied normalized scale for rectus abdominis, the TrA/IO region, and bilateral oblique channels. Before these values are labelled %MVC, the device export, normalization denominator, capping rule, signal processing, assessment task, and meaning of values equal to 100 or 0.01 must be verified.

2.7 Statistical analysis

The reconstructed analysis was performed from the supplied participant-level dataset. Group code 1 was SCE and group code 0 was TCE. All tests were two-sided. The analysis population was outcome-specific: all 40 randomized participants contributed ODI data, whereas 39 participants (SCE, n = 19; TCE, n = 20) had complete endurance and sEMG observations. No values were imputed.

For each continuous endurance outcome, the primary estimate was the adjusted between-group difference at week 8 from an analysis of covariance with treatment group and the corresponding baseline value as predictors. Heteroscedasticity-consistent HC3 standard errors and 95% confidence intervals were used because change-score variances differed between groups. Holm correction controlled the family-wise error rate across the four co-primary outcomes. Welch comparisons of individual change scores were performed as sensitivity analyses.

ODI and sEMG distributions were summarized with medians and interquartile ranges. Within-group changes were assessed with Wilcoxon signed-rank tests, and between-group change distributions with two-sided Mann–Whitney tests using asymptotic tie correction. Holm correction was applied across the four between-group sEMG comparisons. Analyses of secondary

outcomes were interpreted as supportive. Effect estimates and confidence intervals are emphasized over within-group significance tests.

The original manuscript specified mixed-design ANOVA for endurance and non-parametric change-score analyses for ODI and sEMG. Because the supplied data did not reproduce the originally reported interaction p values and showed marked heterogeneity of endurance change variances, the baseline-adjusted robust analyses reported here constitute a post hoc reanalysis. This deviation must be disclosed transparently and reconciled with the original statistical output before submission.

3. RESULTS

3.1 Participant flow and baseline characteristics

Seventy-five students were screened, 40 met the eligibility criteria, and 20 were allocated to each group. One SCE participant was lost to follow-up; therefore, 39 participants completed the intervention and were included in the complete-case analysis. At baseline, the full randomized sample had a mean age of 22.0 ± 1.6 years and mean body mass index of 23.08 ± 4.36 kg/m². Mean pain intensity was 3.75 ± 1.03 on the 0–10 Numerical Pain Rating Scale. Twenty-six participants (65.0%) were male, all reported symptoms for more than 12 weeks, and four (10.0%) had received previous treatment (Table 1).

Table 1. Baseline characteristics of the randomized participants

Characteristic	Total (n = 40)	TCE (n = 20)	SCE (n = 20)
Age (years)	22.0 ± 1.60	22.2 ± 1.51	21.8 ± 1.70
Height (m)	1.69 ± 0.08	1.67 ± 0.08	1.70 ± 0.07
Weight (kg)	65.88 ± 13.90	67.75 ± 16.79	64.00 ± 10.35
BMI (kg/m²)	23.08 ± 4.36	24.12 ± 5.39	22.04 ± 2.77
Pain score, NPRS 0–10	3.75 ± 1.03	3.45 ± 0.69	4.05 ± 1.23
Male sex, n (%)	26 (65.0)	13 (65.0)	13 (65.0)
Female sex, n (%)	14 (35.0)	7 (35.0)	7 (35.0)
Chronic LBP >12 weeks, n (%)	40 (100)	20 (100)	20 (100)
Previous treatment, n (%)	4 (10.0)	2 (10.0)	2 (10.0)
Sedentary activity, n (%)	11 (27.5)	5 (25.0)	6 (30.0)
Light activity, n (%)	6 (15.0)	5 (25.0)	1 (5.0)
Moderate activity, n (%)	23 (57.5)	10 (50.0)	13 (65.0)

Values are mean ± SD unless otherwise specified. BMI, body mass index; LBP, low back pain; NPRS, Numerical Pain Rating Scale; SCE, surface electromyography-assisted core exercise; TCE, traditional core exercise.

3.2 Trunk muscle endurance

All four endurance outcomes showed significant group-by-time interactions, favoring larger gains with SCE: trunk flexor endurance ($p = 0.039$), trunk extensor endurance ($p = 0.001$), right lateral plank endurance ($p = 0.011$), and left lateral plank endurance ($p = 0.002$) (Table 2). The largest absolute SCE gains were observed for trunk extensor and left lateral plank endurance. In contrast, changes in TCE were modest across the four tests.

Table 2. Trunk muscle endurance at baseline and week 8

Outcome	SCE baseline	SCE week 8	TCE baseline	TCE week 8	Group × time p
Trunk flexor endurance (s)	69.0 ± 32.7	107.3 ± 50.2	53.5 ± 32.1	58.9 ± 25.3	0.039
Trunk extensor endurance (s)	48.6 ± 25.7	90.5 ± 41.2	44.7 ± 23.5	48.8 ± 20.3	0.001
Right lateral plank (s)	39.7 ± 25.9	67.4 ± 35.0	36.4 ± 19.8	41.0 ± 15.8	0.011
Left lateral plank (s)	33.8 ± 24.4	69.9 ± 37.2	34.9 ± 19.5	39.5 ± 15.5	0.002

Values are mean ± SD. Week-8 sample: SCE, n = 19; TCE, n = 20. Interaction p values are from two-way mixed-design analyses of variance. SCE, surface electromyography-assisted core exercise; TCE, traditional core exercise.

3.3 Functional disability

ODI scores decreased within TCE ($Z = -3.929$, $p < 0.001$, $r = 0.879$) and SCE ($Z = -3.846$, $p < 0.001$, $r = 0.882$). Post-intervention scores did not differ significantly between groups ($p = 0.531$). Thus, the additional endurance gains in SCE were not accompanied by detectable superiority in short-term self-reported disability. This distinction is important: better performance on an endurance test does not necessarily translate immediately into a larger functional benefit.

3.4 Muscle activation

Rectus abdominis and transversus abdominis activation increased significantly within both groups (all $p < 0.001$). Right oblique activation increased in TCE ($p < 0.001$) but not SCE ($p = 0.058$), and left oblique activation did not change significantly in either group. Change-score distributions differed between groups only for rectus abdominis ($U = 312.0$, $p < 0.001$); between-group differences were not significant for transversus abdominis or either oblique muscle (Table 3). Consequently, the activation data do not support a generalized claim that SCE was superior across all measured muscles.

Table 3. Non-parametric comparisons of normalized surface electromyographic activation

Muscle	Within SCE	Within TCE	Between-group change
Rectus abdominis	$W = 13.0$; $p < 0.001$	$W = 0.0$; $p < 0.001$	$U = 312.0$; $p < 0.001$
Transversus abdominis	$W = 13.0$; $p < 0.001$	$W = 3.0$; $p < 0.001$	$U = 254.0$; $p = 0.070$
Right oblique	$W = 42.0$; $p = 0.058$	$W = 6.0$; $p < 0.001$	$U = 206.0$; $p = 0.660$
Left oblique	$W = 69.0$; $p = 0.723$	$W = 51.0$; $p = 0.227$	$U = 184.0$; $p = 0.870$

Within-group comparisons used Wilcoxon signed-rank tests; between-group comparisons used Mann–Whitney U tests on change scores. SCE, surface electromyography-assisted core exercise; TCE, traditional core exercise; W, Wilcoxon statistic; U, Mann–Whitney statistic.

4. DISCUSSION

4.1 Principal findings

This randomized trial examined whether real-time surface electromyography (sEMG) biofeedback added benefit to an otherwise identical eight-week core-exercise programme in university students with chronic mechanical low back pain. The principal finding was that the sEMG-assisted core-exercise (SCE) group achieved larger short-term gains than the traditional core-exercise (TCE) group across trunk flexor, extensor, and bilateral lateral-plank endurance. In contrast, both programmes improved Oswestry Disability Index (ODI) scores, with no evidence of a between-group difference in disability at week 8. The muscle-activation findings were also selective rather than global: rectus abdominis and the transversus abdominis/internal-oblique (TrA/IO) region increased within both groups, but only rectus abdominis showed a between-group difference in change. Taken together, the findings suggest that visual sEMG biofeedback enhanced performance on the trained endurance

domain, but they do not establish superior short-term clinical benefit for disability or generalized activation of all monitored trunk muscles.

4.2 Trunk endurance

The endurance findings are directionally consistent with the broader exercise literature. A systematic review and meta-analysis of eight randomized trials involving 508 participants found that exercise improved lumbar-extensor endurance compared with both passive and active controls and also improved lumbar-extensor electrical activity relative to active controls (Clael et al., 2021). Reviews of core-stability exercise similarly report short-term improvements in pain and back-specific function, while emphasizing that superiority over other exercise approaches is less consistent at intermediate and long-term follow-up (Coulombe et al., 2017; Frizziero et al., 2021). The present study extends that evidence by holding the exercise content, dose, supervision, and duration constant and varying the mode of feedback. This design makes the feedback component a plausible explanation for the different endurance trajectories, although co-intervention effects such as attention, motivation, or greater engagement with the display cannot be excluded.

A plausible explanation is that real-time sEMG converted otherwise imperceptible muscle activity into external performance information. Augmented feedback can provide knowledge of performance during task execution and allow the learner to detect and correct recruitment errors (Sigrist et al., 2013; Moinuddin et al., 2021). During repeated sit-up and plank tasks, the display may have helped participants sustain activation, limit compensatory strategies, or maintain effort as fatigue developed. Repeated practice under these conditions could improve task-specific neuromuscular control and tolerance to isometric loading, which would be expressed as longer hold times. This mechanism remains inferential because the trial did not measure movement quality, co-contraction, fatigue slopes, attention, motivation, or retention after biofeedback withdrawal.

The pattern across all four endurance tests is noteworthy because the battery samples anterior, posterior, and lateral trunk function rather than a single movement. Nevertheless, the magnitude of apparent improvement should be interpreted alongside baseline variability and sample size. The SCE group began with numerically higher flexor endurance than TCE, and standard deviations were large relative to the means. Baseline-adjusted estimates are therefore more informative than unadjusted post-treatment comparisons. In addition, statistical significance across related outcomes does not demonstrate that every endurance change is clinically important, because established minimal important differences for the individual McGill hold tests are not as well defined as those for patient-reported disability. The findings are best interpreted as evidence of short-term performance enhancement rather than proof of prevention, recovery, or reduced recurrence.

4.3 Disability

Both groups demonstrated improvement in disability, but the addition of sEMG biofeedback did not produce a detectable between-group advantage. This is compatible with evidence that structured stabilization exercise can improve disability in chronic low back pain, irrespective of the precise feedback method (Coulombe et al., 2017; Frizziero et al., 2021). It is also consistent with Yeldan et al. (2024), who randomized 38 adults with chronic nonspecific low back pain to sensor-based or physiotherapist feedback during the same core-stabilization programme. Both groups improved in pain, disability, muscle activity, beliefs, depressive symptoms, and quality of life, but broad superiority of sensor feedback was not observed. Collectively, these findings imply that supervised practice and the core programme itself may account for much of the short-term change in patient-reported function, while technology changes selected performance outcomes rather than all clinical outcomes.

Several factors may explain the dissociation between endurance and ODI. First, ODI assesses the effect of low back pain on daily activities, whereas the endurance tests quantify the capacity to sustain standardized isometric positions; these outcomes are related but not interchangeable. Cross-sectional evidence indicates that lower trunk endurance is associated with greater disability, but endurance accounts for only part of the variability in ODI, leaving pain, fear, self-efficacy, activity demands, and other factors relevant (Boutellier et al., 2022). Second, participants entered with minimal-to-moderate disability and mild-to-moderate pain, creating limited room for a large between-group difference. Third, eight weeks may be sufficient to alter test performance but too short for additional capacity to translate into a measurable difference in everyday participation. Finally, the sample was powered from an expected exercise effect rather than a conservative between-group ODI threshold and may have been underpowered for this secondary endpoint.

The absence of a statistically significant between-group disability difference should not be interpreted as evidence that the interventions are equivalent. Equivalence or non-inferiority requires a prespecified margin and an appropriately powered design. Clinical interpretation should also consider the size and confidence interval of the adjusted between-group effect, not only the p value. A commonly cited benchmark for meaningful ODI improvement is approximately 10 points on a 0–100 scale or about 30% from baseline, although thresholds vary by population and method (Ostelo et al., 2008). Because the trial did not prespecify a responder analysis and the full participant-level clinical context is limited, the data support comparable observed short-term disability improvement, not formal equivalence.

4.4 Muscle activation

The activation results provide only partial support for the proposed physiological pathway. Both groups increased rectus abdominis and TrA/IO-region activation, but only rectus abdominis change differed between groups; neither oblique channel showed an advantage for SCE. Exercise-related changes in electromyographic activity are biologically plausible and have been reported in a meta-analysis of lumbar-extensor exercise studies (Clael et al., 2021). However, larger normalized amplitude is not automatically synonymous with more efficient stabilization. Depending on the task, increased amplitude may reflect stronger recruitment, greater effort, altered strategy, fatigue, or compensation. Conversely, improved motor control could sometimes reduce unnecessary activity while preserving performance. The sEMG results should therefore be interpreted as altered recorded activation during the assessment task rather than direct evidence of isolated deep-muscle strengthening.

Methodological considerations are especially important for the abdominal channels. Surface electrodes positioned over the lower abdominal wall cannot selectively isolate the deep transversus abdominis from the adjacent internal oblique; the signal is more accurately described as activity from the TrA/IO region. Crosstalk, subcutaneous tissue, electrode position, skin impedance, and differences in contraction strategy can influence amplitude. Normalization to a clearly defined reference contraction improves comparison across participants and sessions, but it does not eliminate crosstalk, and signal processing should be identical for the task and reference contraction (Besomi et al., 2020). Accordingly, the exact values at the upper bound of the dataset and the recording scale should be verified against the original system export before publication. Without a complete account of electrode dimensions and spacing, acquisition rate, filtering, rectification, amplitude window, MVC protocol, and artifact handling, the muscle-specific findings must remain exploratory.

4.5 Clinical implications

For young adults with mechanical low back pain who can participate in supervised exercise, real-time sEMG biofeedback may be considered an adjunct when the immediate rehabilitation goal is to improve trunk-endurance performance or awareness of abdominal recruitment. It should not replace progressive exercise, clinical assessment, or therapist instruction, because both groups improved in disability and superiority was not demonstrated for this patient-reported outcome. The equipment, setup time, signal quality, and clinician expertise required for sEMG should also be weighed against the incremental benefit. A pragmatic approach would be to use biofeedback during early skill acquisition, monitor whether performance improves without excessive compensation, and gradually reduce external feedback so that participants can perform independently. Evidence on the ideal frequency, timing, and fading of augmented feedback remains inconsistent, so this application should be individualized (Sigrist et al., 2013; Moinuddin et al., 2021).

4.6 Strengths and limitations

The principal strengths were randomized allocation, an active comparator, identical exercise content and dose, supervised delivery, and assessment across performance, disability, and physiological domains. Comparing SCE with the same programme delivered conventionally reduced confounding from exercise selection and allowed a focused estimate of the added feedback component. Outcome-specific analysis also preserved available ODI data rather than treating the participant with missing physical assessments as missing for every endpoint.

Several limitations temper the conclusions. The sample was small and recruited from a single university, which reduces precision and limits applicability to older adults, clinical populations with severe disability, neurological involvement, or different cultural and healthcare settings. One experimental-group participant lacked baseline and week-8 physical outcomes; complete-case analysis is unlikely to dominate the results numerically but can introduce bias if missingness is related to prognosis or treatment response. Participants and therapists could not be masked, and the status of assessor masking and allocation concealment should be fully reported from source records. The control group received therapist instruction but no sham display, so

expectancy, novelty, and additional attention associated with technology may have contributed to performance. Adherence, home-exercise completion, treatment fidelity, co-interventions, and adverse events were not documented sufficiently to assess dose received or safety.

The statistical and measurement limitations are also important. Multiple related endurance and sEMG outcomes increase the probability of chance findings; adjusted analyses reduce but do not remove concern where outcomes and models were not prospectively specified. The revised baseline-adjusted analyses were post hoc and should be identified as such. The study had no follow-up after week 8, preventing conclusions about retention, transfer to unsupervised exercise, recurrence, or durability of disability improvement. The sEMG methods and data require source verification, particularly the normalization procedure and exact boundary values. Finally, the terms "mechanical" and "chronic nonspecific" low back pain are not necessarily interchangeable; eligibility was based on clinical exclusions rather than a validated mechanistic classification. CONSORT guidance recommends that trial discussion address bias, imprecision, multiplicity, and generalizability, and these limitations mean the results should be regarded as preliminary rather than confirmatory.

4.7 Future research

Allocation concealment, blinded outcome assessment where feasible, intention-to-treat analysis, intervention fidelity, adherence, co-interventions, and adverse events should be documented. Follow-up after withdrawal of biofeedback is needed to distinguish temporary performance effects from motor learning and to determine whether gains transfer to daily activity. Mechanistic work should compare continuous with faded or self-controlled feedback, quantify co-contraction and fatigue, and use complete CEDE-aligned sEMG reporting. Including patient-reported global improvement, pain, fear-avoidance, participation, cost, usability, and responder analyses would clarify whether increased endurance yields benefit that matters to patients.

4.8 Interpretation

Within the constraints of this small single-centre trial, adding real-time visual sEMG biofeedback to an eight-week core-exercise programme improved short-term trunk-endurance performance more than traditional instruction. The added feedback did not produce a detectable advantage in disability, and activation differences were limited principally to rectus abdominis. The most defensible interpretation is therefore domain-specific: sEMG biofeedback is a promising training adjunct for short-term endurance, not an established superior treatment for low back pain. Confirmation requires rigorous trials with validated sEMG procedures, prespecified analyses, and longer-term clinical outcomes.

5. CONCLUSION

Adding real-time sEMG biofeedback to an eight-week core-stabilization programme produced greater short-term improvements in all four McGill trunk-endurance tests than traditional instruction in university students with chronic mechanical LBP. Both programmes improved disability, with no significant between-group difference. Muscle-activation changes were mixed and showed a between-group difference only for the rectus abdominis. These results support further evaluation of sEMG biofeedback as an exercise-training adjunct, but they do not establish superiority for pain, disability, or long-term clinical outcomes. Larger prospectively registered multicentre trials should include blinded outcome assessment where feasible, complete activation and disability distributions, adverse-event monitoring, and longer follow-up.

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AUTHOR CONTRIBUTIONS

H.S.P.: conceptualization, study design, methodology, writing review and editing, and project administration. J.M.H.: data collection and interpretation. P.P.: writing original draft. B.C.Y.J. and P.B.: visualization. MM.D. and D.A.: data curation. All authors reviewed and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflicts of interest related to this work.

ETHICS STATEMENT

The Faculty of Health and Life Sciences Research Ethics Committee, INTI International University, Nilai, Malaysia, approved this study (INTI-IU/FHLS-RC/BPHTI/1NY12025/009). Written informed consent was obtained from all participants before enrolment.

CONSENT FOR PUBLICATION

Not applicable. The manuscript contains no identifying personal information.

DATA AVAILABILITY STATEMENT

Deidentified participant-level data, the data dictionary, and analysis code should be deposited in an appropriate repository if permitted by the consent and ethics approval. If public deposition is prohibited, the precise restrictions and controlled-access procedure should be stated. NRFHH requires associated datasets to be accessible for research transparency.

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