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Research article

Effects of Maximal Eccentric Trunk Extensor Exercise on Lumbar Extramuscular Connective Tissue: A Matched-Pairs Ultrasound Study

Andreas Brandl [1,2,3], Jan Wilke [4], Christoph Egner [2], Tobias Schmidt [5,6,†] and Robert Schleip [2,7,†] ✉
[1] Department of Sports Medicine, Institute for Human Movement Science, Faculty for Psychology and Human Movement Science, University of Hamburg, Hamburg, Germany; [2] Department for Medical Professions, Diploma Hochschule, Bad Sooden-Allendorf, Germany; [3] Vienna School of Osteopathy, Vienna, Austria; [4] Department of Movement Sciences, University of Klagenfurt, Klagenfurt, Austria; [5] Osteopathic Research Institute, Osteopathie Schule Deutschland, Hamburg, Germany; [6] Institute of Interdisciplinary Exercise Science and Sports Medicine, MSH Medical School Hamburg, Hamburg, Germany; [7] Department of Sport and Health Sciences, Conservative and Rehabilitative Orthopedics, Technical University of Munich, Munich, Germany. [†] These authors contributed equally to this work

Abstract

Recently, it has been shown that the extramuscular connective tissue (ECT) is likely involved in delayed onset muscle soreness (DOMS). Therefore, the aim of the present study was to investigate the effects of maximal trunk extension eccentric exercise (EE) on ECT thickness, self-reported DOMS, ECT stiffness, skin temperature, and possible correlations between these outcomes. Healthy adults ($n = 16$, 29.34 ± 9.87 years) performed fatiguing EE of the trunk. A group of highly active individuals (TR, $n = 8$, > 14 h of sport per week) was compared with a group of less active individuals (UTR, $n = 8$, < 2 h of sport per week). Ultrasound measurements of ECT thickness, stiffness with MyotonPro and IndentoPro, skin temperature with infrared thermography, and pain on palpation (100 mm visual analog scale, VAS) as a surrogate for DOMS were recorded before (t_0), immediately (t_1), 24 h (t_{24}), and 48 h (t_{48}) after EE. ECT thickness increased after EE from t_0 to t_{24} (5.96 mm to 7.10 mm, $p = 0.007$) and from t_0 to t_{48} (5.96 mm to 7.21 mm, $p < 0.001$). VAS also increased from t_0 to t_{24} (15.6 mm to 23.8 mm, $p < 0.001$) and from t_0 to t_{48} (15.6 mm to 22.8 mm, $p < 0.001$). Skin temperature increased from t_1 to t_{24} (31.6° Celsius to 32.7° Celsius, $p = 0.032$) and t_1 to t_{48} (31.6° Celsius to 32.9° Celsius, $p = 0.003$), while stiffness remained unchanged ($p > 0.05$). Correlation analysis revealed no linear relationship between the outcomes within the 48-hour measurement period. The results may confirm previous findings of possible ECT involvement in the genesis of DOMS in the extremities also for the paraspinal ECT of trunk extensors. Subsequent work should focus on possible interventions targeting the ECT to prevent or reduce DOMS after strenuous muscle EE.

Key words: DOMS, ultrasound, connective tissue, eccentric exercise.

Introduction

Recent studies have shown that extramuscular connective tissue (ECT), referred to as deep fascia, may be involved in delayed onset muscle soreness (DOMS; Wilke et al., 2022; Tenberg et al., 2022). Traditionally, most research on DOMS focused exclusively on skeletal muscle and assumed that it was a process involving sarcomere damage (Fridén et al., 1981), lactate production (Gleeson et al., 1998), or free radicals (Close et al., 2004). However, there is a lack of evidence that these mechanisms are involved in the development of pain in the pathogenesis of DOMS, which brought the deep fascia surrounding the muscles into the focus of research (Vincent and Vincent, 1997; Newton et al., 2008; Wilke et al., 2022; Tenberg et al., 2022).

The ECT is characterized by a close mechanical relationship with the adjacent muscle , which allows force transmission between these myofascial tissues (Ajimsha et al., 2022). Here, fascia is considered to be a support in handling heavy loads on the muscle by distributing and absorbing mechanical forces (Wilke et al., 2018). Specifically, the thoracolumbar fascia (TLF) wraps around the underlying erector spinae (ES) muscle in the lumbar region (in addition to their multilayered architecture and multiple connections to other anatomical structures) and may help the muscle produce a higher and/or more precise force (Bojairami and Driscoll, 2022; Brandl et al., 2022). Fascia is not just a packaging organ, however. For example, the TLF is highly innervated and most of the free nerve endings appear to have a nociceptive, proprioceptive or autonomic regulatory function (Mense, 2019; Schleip and Stecco, 2021).

It has been previously found that untrained and resistance-trained participants experience almost the same degree of DOMS after a similar maximal eccentric exercise (EE) protocol (Vincent and Vincent, 1997; Newton et al., 2008). However, plasma creatine kinase activity, which is a marker of muscle damage, was increased 20-fold in untrained participants compared to trained participants (Newton et al., 2008). Thus, the authors already argued 25 years ago that muscle soreness is not a good correlate to presumed muscle damage and that other mechanisms must cause DOMS (Vincent and Vincent, 1997; Newton et al., 2008).

A systematic review found that structural fascial damage is present in approximately one-third of all muscle injuries (Wilke et al., 2019) and most of these are due to excessive muscle stretching during eccentric contractions (Wilke et al., 2022). A study by Tenberg et al. (2022) that examined thickening of the ECT during an eccentric exercise (EE) protocol is consistent with these findings. They observed a significant increase in ECT thickness of the biceps brachii after heavy eccentric loading and concluded that this was likely due to edema and swelling resulting from fascial micro-injury. Wilke et al. (2022) reported a significant increase in ECT stiffness of the biceps femoris

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muscle after EE and also linked this response to micro-injury induced edema. Moreover, both studies found an association between thickening or stiffness increase and higher levels of self-reported DOMS. In contrast, the muscle does not appear to increase in thickness after EE (Vieira et al., 2018). However, these studies, like most research examining DOMS, focused on muscles and connective tissue of the extremities, such as the elbow or knee flexors (Wilke et al., 2022; Tenberg et al., 2022), and few studies addressed the paraspinal muscles (Hanada et al., 2022).

Recent studies have observed an increase in thermographic skin surface temperature during DOMS and have linked it to muscle damage (da Silva et al., 2021; Dindorf et al., 2022). As described earlier, there is a lack of evidence for such a mechanism. Therefore, inflammation caused by microinjury may be present in fascial tissue rather than muscle (Vincent and Vincent, 1997; Newton et al., 2008).

The recruitment strategies of the ES might be negatively altered during DOMS and reduce the ability of the muscles to counteract movement perturbations (Abboud et al., 2021). A study by Brandl et al. (2022) showed that TLF may have an effect on ES recruitment during tasks involving paraspinal muscles under pathological conditions. They suggested an underlying mechanism of ECT stiffening associated with a loss of shear capacity of the TLF and ES. In a recent study, a strong negative correlation was found between the deformability of the TLF and the performance achieved in the deadlift. This was highest in athletes who regularly trained with lifting tasks (A. Brandl et al., 2023). The cause-effect triangle between lower deformability, stiffness increase and swelling due to edema of the ECT is therefore of particular interest.

The aim of this study was to investigate the effect of an EE protocol on ECT thickening in DOMS. We hypothesized an increase of ECT thickness, e.g., as a result of swelling and edema (H1), self-reported DOMS (H2) and myofascial stiffness (H3), as well as likely inflammation would increase skin temperature (H4). We further assume that there is no difference between untrained and trained participants in ECT thickness and self-reported DOMS (H5), and that self-reported DOMS is correlated with ECT thickness and myofascial stiffness (H6).

Methods

The article was a matched-pairs study of a maximal trunk extensor eccentric exercise protocol using repeated-measures, between-within-subject design. The study protocol was prospectively registered with the German Clinical Trials Register (DRKS00031201). The study, which adhered to the STROBE Statement, was reviewed, and approved by the ethical committee of the Diploma Hochschule, Germany (Nr.1065/2023). It was conducted in accordance with the declaration of Helsinki (World Medical Association., 2013) and all participants provided written informed consent.

Setting and participants

The study was conducted in a school of physiotherapists, in a medium-sized city in middle Germany. The number of participants was calculated based on two studies measuring deep fascia thickening and palpation pain after maximal eccentric exercises (Cohen's f = 0.35, α err = 0.05, 1-β err = 0.8) and was set at 14 (Wilke et al., 2022; Tenberg et al., 2022). Assuming a drop-out rate of 15%, n = 16 participants (8 matched pairs) were included. The acquisition was carried out via direct contact, a notice board, and the distribution of information material in the school. The study groups consisted of highly physically active (trained) participants (TR; n = 8) and minimally physically active (untrained) participants (UTR; n = 8). Group members were matched by age (±5 years), sex, and BMI (2 classes: "normal," BMI between 18.5 - 24.9; "pre-obesity," BMI between 25.0 - 29.9).

Inclusion criteria were: (a) generally healthy constitution; (b) BMI between 18 and 29.9; (d) female or male participants aged 18 to 50 years; (e) for TR, a score on the International Physical Activity Questionnaire (IPAQ) (Meh et al., 2021) of more than 14 hours of strenuous exercise per week and for UTR, less than 2 hours per week.

Exclusion criteria were: (a) generally valid contraindications to exhausting trunk extension exercises (i.e., fractures, tumors, infections, severe cardiovascular, neural, and metabolic diseases); (b) pregnancy; (c) rheumatic diseases; (d) taking medication that affects blood circulation, pain or mind; (e) taking muscle relaxants; (f) skin changes (e.g. neurodermatitis, psoriasis, urticaria, decubitus ulcers, hematoma); (g) overuse disorders, surgery or other scars in the lumbar region; (h) previous mental illness; (i) surgery in the last three months; (j) acute inflammation.

The investigators and statisticians were blinded to the group membership of the participants.

Eccentric exercise protocol

Using a back extension bench (Finnlo Tricon, Hammer Sport AG, Neu-Ulm, Germany), participants bend their trunk from the starting position parallel to the floor into a 40° flexion position for 3 seconds and then return it to the starting position as quickly (ca. 1 second) as possible (Figure 1 A). The set consisted of 25 repetitions of trunk flexion–extension with a rest period in flexion position of 10 seconds (Figure 1 B). The sets were repeated under time announcement of the examiner until the participants could not continue the exercise.

Outcomes

Extramuscular connective tissue (ECT) thickness (H1), self-reported DOMS (H2), Myofascial stiffness with the MyotonPro device (H3) and skin temperature (H4) were measured before (t_0), immediately after EE (t_1), and one day (t_{24}) and two days (t_{48}) consecutively. Indentometrical myofascial stiffness (H3) was assessed at time points t_0, t_{24}, and t_{48} (Figure 1 C).

Extramuscular connective tissue thickness

High resolution ultrasound (US) measurement (Philips Lumify linear transducer L12 - 4, 12 MHz; Philips Ultrasound Inc., Bothell, WA) was used to evaluate ECT thickness. Participants lay prone on a treatment table. First, the transvers process of the second lumbar vertebra was located with a display depth of 6.5 cm. The transducer was then placed 4 cm lateral of the spinous processes at that height.

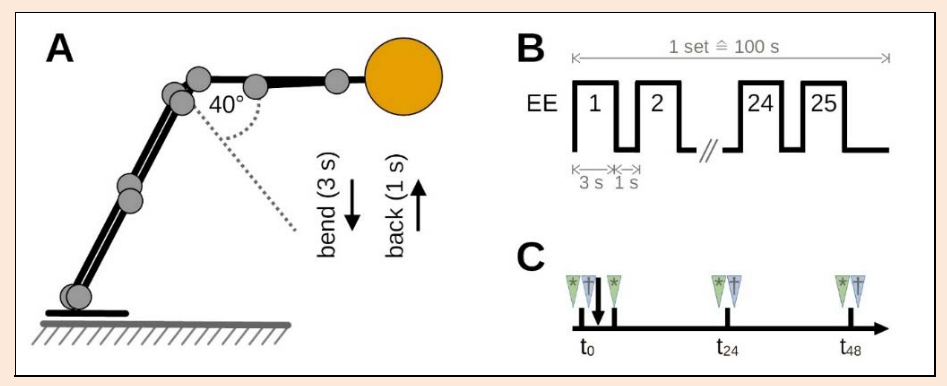

Figure 1. Excentric exercise. A Schematic drawing of the exercise. B Protocol for excentric exercise. C Experimental schedule. EE, excentric exercise; s, second; t_0, baseline; t_1, post-exercise; t_{24}, 24 h after exercise; t_{48}, 48 h after exercise; * (green arrow), ECT thickness, self-reported DOMS, myofascial stiffness measured with MyotonPro device, and skin temperature measurement; † (blue arrow), indentometrical myofascial stiffness.

An artificial shadow was created in the US image using a 4 mm wide plastic adhesive tape placed on the skin at the center of the image section, which served as a reference for the subsequent measurement (Mohr et al., 2021). To avoid measurement uncertainties due to varying pressure to the inside of the transducer, the force of the transducer on the gel-wetted skin was kept constant at 1 N ± 0.2 N. For this purpose, a force gauge (ZP-50N, Baoshishan Electronic Ltd., China) was attached to the transducer with a custom-made bracket and held in a vertical position with a spirit level. This method has also been described in detail by Ishida et Watanabe (Ishida and Watanabe, 2012) and Jafari et al. (Jafari et al., 2018) and has shown high interrater reliability (ICC 0.84 - 0.96) (Bartsch et al., 2023). Acquisition of three static images was performed when the deep fascia was clearly visible as a hyperechoic region over the ES with a display depth of 3 cm. All images were immediately visually inspected for artifacts such as beam width or echo, and if necessary, the image was repeated.

ImageJ software (Image J 1.53t, USA) was used to calculate the ECT thickness. In each of the US images, four regions of interest (ROIs) were defined once at the left and right edges of the shadow of the artificial reference and 1 cm adjacent to each (Figure 2A, 2B). The average of the ROIs in all three images was chosen to determine the ECT thickness. Previous studies have shown that measuring fascia thickness using Image J with three averaged images achieves high inter- and intraday reliability (ICC 0.86 - 0.98) (Cheng et al., 2012), and that reliability increases with the number of ROIs (Bisi-Balogun et al., 2016).

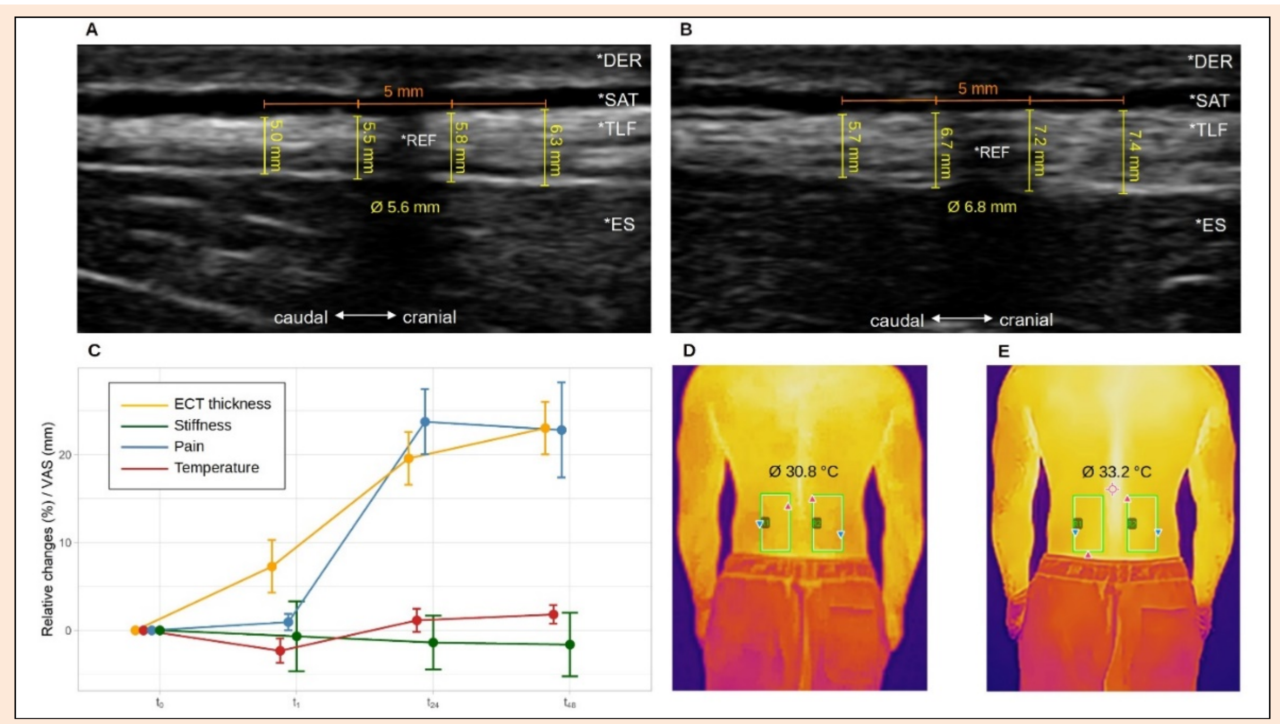

Figure 2. High resolution ultrasound and thermography assessment. A Pre-measurement ECT thickness. B 48 h-measurement ECT thickness. C Outcomes (error bars show the non-parametric 95% confidence interval). D Post-exercise-measurement skin temperature. E 48 h-measurement skin temperature. *REF, artificial reference by adhesive tape; *DER, dermis; *SAT, subcutaneous adipose tissue; *TLF, posterior layer of the thoracolumbar fascia; *ES, erector spinae muscle; ECT, extramuscular connective tissue; t0, baseline; t1, post-exercise; t24, 24 h after exercise; t48, 48 h after exercise.

Self-reported DOMS

The method of Lau et al. (Lau et al., 2015) was used to quantify DOMS. Here, an investigator palpated the ES at the level of the tape marking in longitudinal direction and applied a pressure of about 400 kPa with the tips of the middle and index fingers of the right hand, which was repeated for three times. A 100-mm analog scale (VAS) was used to ask participants to indicate the level of pressure pain. Thereby, 0 indicates no pain and 100 indicates maximum pain. The experimenter was trained with a force gauge prior to data collection to ensure that the correct pressure was applied with at least 5% variation between trials (Lau et al., 2015).

Myofascial stiffness

Myofascial stiffness was measured using a digital indentometer (IndentoPro, Fascial Research Group, University of Ulm; Institute of Human Movement Sciences, University of Chemnitz, Germany) with an indentation depth of 8 mm and a circular probe with a diameter of 11.3 mm. It was assumed that deeper myofascial tissue, which is likely to be more affected by muscle stiffness, could be measured under these measurement conditions (Bartsch et al., 2023). Another digital palpation device (MyotonPro, MyotonAS; Tallinn, Estonia) with a 3-mm-diameter probe and a shallower indentation depth when applied at 0.18 N was used to determine likely higher, subcutaneous, or fascial tissue (Bartsch et al., 2023). Three measurements were taken with these instruments at the level of the transverse process of L2 (marked with the tape) for each participant at every measurement time point. Both instruments are considered highly reliable and showed highest interrater reliability (ICC 0.75 - 0.99) and validity (r 0.97 - 0.99) (Bartsch et al., 2023).

Infrared thermography

An infrared thermographic camera with a resolution of 256 × 192 with a total of 49,152 pixels (Hikmicro W-Pocket2, Hikmicro Sensing Technology Ltd., Hangzhou, China) was used to measure skin temperature with a noise equivalent temperature difference (NETD) < 0.04 °C and a measurement uncertainty of ±2° Celsius or 2%. At least 10 min before the assessments, the camera was turned on to allow the electronic components to stabilize. Images were taken at a distance of 1 m from the lumbar region with perpendicular lens alignment. All images were taken while participants were standing still and muscles were exposed. To ensure adequate adaptation to room temperature, a 10 min acclimatization period was first given. An anti-reflection plate was placed behind the participant to avoid interference from radiation emanating from a non-neutral background. Software (Hikmicro Analyzer v1.2.0.3, Hangzhou Microimage Software Ltd., China) was used to define two rectangular ROIs to the left and right of the ES, from the 12th rib to the iliac crest (Figure 2 D, 2 E). The approximate pixel number of the ROIs was 3300, and the mean value of the skin temperature data was based on the average of the values for the pixels within the ROIs. All thermal images were acquired in a thermally controlled environment: Room temperature 23.0 ± 1.5 °C and humidity 48.5 ± 2.0%. All image acquisitions were performed by the same researcher according to the TISEM checklist (Moreira et al., 2017). Infrared thermography with averaged temperature measurement of ROIs has been shown to be highly reliable (ICC 0.86 - 0.98) (Bouzas Marins et al., 2014; Fernández-Cuevas et al., 2015).

Statistical analysis

Mean, standard deviation, 95% confidence interval (95% CI), median, and interquartile range were determined for all parameters.

The ICC within the rater of ECT thickness measured by high resolution ultrasound, 95% CI, and minimal detectable changes (MDC) (Furlan and Sterr, 2018) were calculated using the R package "irr" version 0.84.1 based on a 2-way mixed-effects model with absolute agreement. Variables were normally distributed as assessed by the Shapiro-Wilk test ($p > .05$). Resulting ICC values were interpreted according to Fleiss (Ref) as ‘poor’ (< 0.4), ‘fair to good’ (0.4 to 0.75), and ‘excellent’ (> 0.75).

Friedman tests for omnibus comparisons and Durbin-Conover tests for pairwise post hoc comparisons were used for outcomes for violation of the assumptions for parametric testing (ECT thickness, H1; palpation pain, H2; stiffness (H3); skin temperature (H4); TR/UTR comparisons of ECT thickness, H5). Kendall’s coefficient of concordance (W) was calculated for effect size. Repeated measures ANOVA and pairwise comparisons were performed with Bonferroni correction for parametric outcomes (TR/UTR comparisons of palpation pain, H5).

Partial Spearman correlation coefficients adjusting for baseline covariates (sex, age, BMI) were calculated for the non-normally distributed data assessed with the Shapiro-Wilk test ($p < 0.05$) to detect possible relationships between the changes of ECT thickness, myofascial stiffness, and self-reported pain (H6). Significant resulting values were interpreted according to Cohen [44] as ‘weak’ (> 0.09, < 0.30), ‘medium’ (> 0.29, < 0.50), and ‘strong’ (>= 0.50).

All analyses were performed using Jamovi 2.3 (The jamovi project, https://www.jamovi.org).

Results

As per the a priori sample size calculation, 16 participants took part in the study. The baseline characteristics were (mean ± SD): age, 29.34 ± 9.87 years; height, 174 ± 12.9 cm; weight, 72.25 ± 14.67 kg; Body Mass Index (BMI), 23.63 ± 3.41 kg/m^2. No adverse events or drop-outs were recorded.

The ICC within the rater of the ECT thickness showed excellent agreement, ICC = 0.98, 95% - CI[0.96, 0.99], $F(15, 28) = 191$, $p < 0.001$. The MDC was calculated based on the standard error of the mean (SEM), 0.26 mm with 0.72 mm.

Significant changes over time were found for H1, ECT thickness ($X^2 = 17.2$, $p < 0.001$, $W = 0.36$). Pairwise post hoc comparisons showed that ECT thickness was systematically higher at 24 h (5.96 mm to 7.10 mm, $p = 0.007$) and 48 h (5.96 mm to 7.21 mm, $p < 0.001$) after exercise (Figure 2C).

There were also significant changes over time for H2, self-reported DOMS ($X^2 = 33.9$, $p < 0.001$, $W = 0.71$). Pairwise post hoc comparisons showed that DOMS was systematically higher at 24 h (VAS, 15.6 mm to 23.8 mm, $p < 0.001$) and 48 h (VAS, 15.6 mm to 22.8 mm, $p < 0.001$) after exercise (Figure 2C).

No Significant changes over time were found for H3, myofascial stiffness, measured with MyotonPro ($X^2 = 0.684$, $p = 0.877$, $W = 0.03$) and measured with IndentoPro ($X^2 = 0.143$, $p = 0.931$, $W = 0.01$).

Skin temperature (H4) changed significantly over time ($X^2 = 8.89$, $p = 0.031$, $W = 0.19$). Pairwise post hoc comparisons showed that skin temperature was systematically higher at 24 h (31.6 °C to 32.7 °C, $p = 0.032$) and 48 h (31.6 °C to 32.9 °C, $p = 0.003$) compared to post-exercise measurement (Figure 2C).

Repeated-measures ANOVA revealed no differences for the parametric outcome of ECT thickness between TR and UTR (H5), $F(3, 21) = 0.57$, $p = 0.639$, partial $\eta^2 = 0.006$. There was also no significant difference between TR and UTR in the Friedman test regarding the non-parametric outcome of self-reported DOMS (H5), $X^2 = 4.10$, $p = 0.251$, $W = 0.06$.

Partial Spearman correlation (H6) adjusting for baseline covariates (sex, age, BMI) showed no significant association between Δ ECT thickness ($r_s(14) = 0.328$, $p = 0.274$) or Δ myofascial Stiffness ($r_s(14) = 0.049$, $p = 0.819$) and Δ self-reported DOMS.

Descriptive statistics are presented in Table 1. Relative changes over time are shown in Figure 2C.

Table 1. Descriptive statistics (n = 16).

		95% Confidence Interval					
		Mean	**Lower**	**Upper**	**Median**	**SD**	**IQR**
ECT thickness (mm)	t_0	5.96	4.84	7.09	5.69	2.09	2.71
	t_1	6.07	5.12	7.02	5.78	1.77	2.40
	t_{24}	7.10	5.63	8.57	6.29	2.76	2.16
	t_{48}	7.21	5.82	8.60	6.70	2.60	3.70
Pain (VAS, mm)	t_0	0.15	-0.07	0.38	0.00	0.43	0.00
	t_1	0.09	-0.10	0.29	0.00	0.37	0.00
	t_{24}	2.37	1.58	3.16	2.50	1.48	1.87
	t_{48}	2.28	1.12	3.43	1.75	2.16	2.37
Stiffness (MyotonPro) (N/m)	t_0	331.01	289.23	372.79	334.00	78.41	101.43
	t_1	329.57	271.53	387.61	301.75	108.92	122.50
	t_{24}	321.93	285.35	358.51	334.50	68.64	108.87
	t_{48}	320.23	284.50	355.97	329.50	67.06	104.12
Stiffness (IndentoPro) (N/m)	t_0	1.83	1.57	2.09	1.89	0.46	0.56
	t_{24}	1.91	1.62	2.19	1.90	0.54	0.82
	t_{48}	1.73	1.49	1.97	1.58	0.43	0.69
Temperature (°C)	t_0	32.38	31.61	33.15	32.63	1.44	1.47
	t_1	31.58	30.83	32.33	31.75	1.41	1.75
	t_{24}	32.70	31.99	33.41	33.02	1.33	1.83
	t_{48}	32.94	32.10	33.78	32.75	1.58	2.48

VAS, visual analogue scale; ECT, extramuscular connective tissue; SD, standard deviation; IQR, interquartile range; t_0, baseline; t_1, post-exercise; t_{24}, 24 h after exercise; t_{48}, 48 h after exercise.

Discussion

Some recent studies give reason to associate ECT with mechanisms of DOMS development (Wilke et al., 2022; Tenberg et al., 2022). However, these works focused on muscles and connective tissues in the upper and lower extremities and not on the paraspinal regions. To the best of the authors' knowledge, the present work is the first to address the trunk, specifically the ECT of the ES and the myofascial mechanisms behind EE-induced DOMS.

One of the main findings of this study was a 23% relative increase in ECT thickness (H1) following EE. This may confirm the results of a previous study in which the ECT of the biceps brachialis increased in thickness by 13% after an EE protocol (Tenberg et al., 2022). Here, the values after 24 h (+1.14 mm) and 48 h (+1.25 mm) were also above the MDC of 0.72 mm, indicating that the increase in thickness was not random. Other researchers investigating these phenomena linked the thickening and increase in stiffness to edema and swelling caused by micro-injuries to the fascia (Wilke et al., 2022; Tenberg et al., 2022). The results of this study were able to confirm this hypothesis to a certain extent. However, neither indentometry at deeper penetration depths nor myotonometry at presumably more superficial tissues measured significant changes in stiffness (H3). Therefore, at first glance, an alternative hypothesis could be discussed. Exercise in general stimulates the production of hyaluronic acid (Mridha and Ödman, 1985). This alone would increase stiffness by increasing fluid viscosity, but this is counteracted by the mechanical influence on viscosity and the decrease in stiffness due to the thixotropic nature of hyaluronic acid (Pavan et al., 2014). Wilke et al. (2022) demonstrated a significant increase in stiffness after EE of the biceps femoris muscle using shear wave elastography. A recent reliability study found that stiffness changes of the posterior layer of the TLF, which was preferentially measured in this study, could not be detected by perpenticular measurement with the IndentoPro or MyotonPro device (Bartsch et al., 2023). Therefore, at this time, the authors tend to hypothesize that edema and swelling caused by fascial micro-injuries lead to thickening of the ECT and a subsequent increase in stiffness, which the devices in this study (contrarily to elastography) were unable to measure. Therefore, further work with ultrasound elastography is recommended to detect supposed stiffness changes in the ECT.

Self-reported DOMS increased as expected, with the highest values at 24 h (+22.8 mm) and 48 h (+21.9 mm; Table 1) after EE (H2). Interestingly, the increase in palpation pain was almost at the same level in a previous study by Wilke et al. (2022) who used a similar protocol. Tenberg et al. (2022) demonstrated that this palpation pain was correlated with thickening of the ECT three days after EE. Although this has been studied in the extremities, these mechanisms could also occur in the lumbar region. However, our study found no such correlations for shorter periods up to 48 hours (H6), but it might be possible that this would be the case if the follow-up period were longer and the tested sample larger. Further studies need to consider this, and it is recommended that longer follow-up periods up to at least 96 hours be included to detect such suspected correlations.

Skin temperature decreased immediately after EE (-0.8 °C), but not significantly (H4). There was, however, a significant increase of 1.12 °C 24 h and 1.36 °C 48 h after EE compared to post-exercise measurement. Dindorf et al. (2022) found a decrease in skin temperature after exercise, but no interaction with muscle fatigue. This is consistent with other studies that examined a relationship between skin temperature and muscle fatigue and also found no support for such a relation (Priego-Quesada et al., 2020; Alburquerque Santana et al., 2022). In contrast, other studies that investigated skin temperature and DOMS reported an increase after EE in the following days (Fidut-Wrońska et al., 2019; Priego-Quesada et al., 2020). Since fascial inflammation is known to cause an increase in skin temperature (Stecco et al., 2013; Pavan et al., 2014; Fidut-Wrońska et al., 2019), the authors hypothesize that the thermographically observed results are likely caused by micro-injury induced inflammation that also leads to edema and swelling.

As expected, there were no significant differences between TR and UTR in terms of ECT thickness of self-reported DOMS (H5). This is consistent with previous studies by Vincent and Vincent (1997) and Newton et al. (2008) and confirms previous findings on DOMS. Both groups, TR and UTR, perceived almost the same level of DOMS after similar EE. This study showed that ECT thickening was also the same between these groups. Therefore, we hypothesized that changes in ECT rather than muscle (where mentioned studies found up to 20-fold higher creatine kinase activity, which is a marker of muscle destruction after EE) lead to DOMS.

The results of this study could have implications for coaches and sports professionals, especially in competitive sports where recovery time is a crucial factor for performance. Infrared thermography has been proposed to monitor the recovery of elite soccer players after a competitive season (Rodrigues Júnior et al., 2021). It could equally be a simple tool to monitor changes in skin temperature presumably indicative of inflammation after EE and identify appropriate new recovery strategies. In addition, ECT-targeted treatments such as foam rolling, which has been shown to prevent fascial inflammation (Pablos et al., 2020), or myofascial release techniques, which improve fascial mobility and microcirculation (Brandl et al., 2021; Brandl et al., 2023), are promising methods to recover after fatiguing EE. Finally, the ECT itself could be addressed through adapted exercises to prevent or reduce swelling, as it is known that the ECT is able to adapt to mechanical stress (Zügel et al., 2018).

The results of this study must be seen in the light of some shortcomings. First, high-resolution ultrasound with a 12 MHz transducer was used to measure ECT thickness. It is well known that the measurement of tissue thickness with ultrasound is highly dependent on the pressure with which the transducer is pressed on the tissue and its angular variation between measurements (Ishida and Watanabe, 2012; Porra et al., 2015). An attempt was made to solve this problem by using a defined force of 1 N ± 0.2 N and a spirit level to keep the settings constant. However, with three consecutive days of data collection, variations cannot be completely ruled out. Ishida and Watanabe (2012) reported a measurement difference of 0.1 mm between 1 N and 2 N transducer pressure and give the ICC for a 4 to 10 mm thickness measurement with 1 N as 0.98 - 0.99. The intrarater reliability for the US thickness measurement in this study also reached an ICC of 0.98 and a MDC of 0.72 mm was calculated. The total ECT thickness increase here was 1.25 mm (5.96 mm to 7.21 mm). It can therefore be assumed with some confidence that the measurement procedure was reliable. In further studies, explicit control of interrater reliability should be considered. Second, the skin temperature increased significantly by 1.36° Celsius with DOMS and also exceeded the measurement error of 2%. However, with devices with lower measurement error, e.g., 1% and higher resolution, even increased precision could be achieved. Finally, the sample size was relatively small. Maximally strenuous exercise is a demanding challenge even for healthy participants, particularly untrained individuals. Therefore, the required sample was carefully calculated based on the effect sizes of two studies with a similar protocol (Wilke et al., 2022; Tenberg et al., 2022). Statistical power was further increased by a matched-pairs design. Our results showed moderate to large effect sizes for ECT thickness measurements and self-reported DOMS, indicating that the sample size chosen was large enough to reveal significant within-subject differences.

Conclusion

A maximal EE protocol for trunk extensors increased ECT thickness, skin temperature, and self-reported DOMS. This reinforces the hypothesis that extramuscular connective tissue is more of a factor in DOMS development than the muscle itself. Coaches and sports professionals should therefore consider addressing ECT through adapted exercises to prevent or reduce DOMS after strenuous muscle EE.

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Key points

- Eccentric exercise increases the thickness of lumbar extramuscular connective tissue.
- The results may confirm previous findings on the involvement of fascia in DOMS.
- A focus on fascial interventions for prevention or reduction of DOMS could be promising.

AUTHOR BIOGRAPHY

Andreas BRANDL
Employment
PhD student at the Department of Sports Medicine, Institute for Human Movement Science, Faculty for Psychology and Human Movement Science, University of Hamburg, Hamburg, Germany
Degree
MSc
Research interests
Fascia and Muscle Physiology
E-mail: andreas.brandl@edu.ioesr.org

Jan WILKE
Employment
University of Klagenfurt, Department of Movement Sciences, Klagenfurt am Wörthersee, Austria
Degree
PhD
Research interests
Exercise & Training
E-mail: jan.wilke@aau.at

Christoph EGNER
Employment
Department for Medical Professions, Diploma Hochschule, Bad Sooden-Allendorf, Germany
Degree
PhD
Research interests
Physiotherapy
E-mail: christoph.egner@diploma.de

Tobias SCHMIDT
Employment
Institute of Interdisciplinary Exercise Science and Sports Medicine, MSH Medical School Hamburg, Hamburg, Germany
Degree
PhD
Research interests
Exercise & Training
E-mail: tobias.schmidt@medicalschool-hamburg.de

Robert SCHLEIP
Employment
Department of Sport and Health Sciences, Conservative and Rehabilitative Orthopedics, Technical University of Munich, Munich, Germany
Degree
PhD
Research interests
Fascia Research
E-mail: robert.schleip@tum.de

✉ **Robert Schleip**
Department for Medical Professions, Diploma Hochschule, Bad Sooden-Allendorf, Germany