Motor-evoked pain on a background of widespread muscle strain: a novel model simulating everyday activities

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Original Experimental

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Abstract

Objectives: Musculoskeletal pain is among the most prevalent types of pain. However, experimental models that induce acute musculoskeletal pain by everyday activities – on top of sustained daily muscular strain – in a controlled and moderate manner are still lacking. Such models are essential for investigating underlying mechanisms of musculoskeletal pain and evaluating treatment approaches. The present study proposes a novel experimental model to address this gap.

Methods: A total of 43 pain-free participants completed two motor (lifting objects) and two sensory (hot water immersion, noxious pressure) pain challenges. Participants were randomly assigned to either an experimental group, who wore a suit that induced widespread muscle strain through limb weights and joint restrictions, or a control group without the suit. Both groups performed the additional pain challenges. Numerical pain ratings, pain-related facial expressions (Facial Action Coding System, FACS), heart rate (HR) and its variability (HRV), as well as electrodermal activity (EDA), were recorded.

Results: Wearing the experimental suit to induce muscle strain led to increased pain ratings during motor challenges when further muscle power was required (weightlifting). Additionally, pain-specific facial responses and autonomic markers (heart rate and tonic EDA) were significantly elevated in the experimental group during motor tasks. No significant group differences were observed during the sensory pain challenges.

Conclusion: This study introduces a novel and effective experimental model for inducing acute musculoskeletal pain by applying light weightlifting on top of sustained muscular strain, with both stressors designed to reflect everyday motor activities. This approach offers a promising tool for future research into pain-relieving interventions and the mechanisms of musculoskeletal pain, including studies involving affected patient populations.

Keywords: musculoskeletal pain; experimental pain model; inducing muscle pain; aging suit

Introduction

Musculoskeletal pain ranks among the most common types of pain [1]. For many individuals, it affects widespread body regions and occurs across multiple anatomical sites. To identify factors that may moderate musculoskeletal pain and could be targeted in pain treatment, researchers have employed experimental models that induce musculoskeletal pain under controlled conditions [2].

Such experimental models offer the advantage of standardized and well-defined pain stimuli, while also allowing systematic investigation of covariates commonly associated with musculoskeletal pain (e.g., age, gender, depression, and deficient conditioned pain modulation). The most widely used model for inducing clinically relevant musculoskeletal pain through exercise is delayed onset muscle soreness (DOMS) [3]. DOMS typically peaks 24–48 h after intensive or unfamiliar exercise and is characterized by soreness, swelling, stiffness, temporary strength loss, and mild to moderate musculoskeletal pain [4, 5]. Using DOMS protocols, numerous studies have identified factors that moderate musculoskeletal pain, such as pain catastrophizing, depression, and sex [6–8]. However, most experimental protocols have focused on regional muscle strain, involving specific muscle groups through exercises such as presses, pulls, or isometric holds [e.g. 9–11].

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Only a few studies have attempted to induce more widespread pain using DOMS protocols that stimulate multiple sites within a single session [7]. Yet, these approaches still require prolonged exercise to produce soreness across sites. Consequently, there remains a lack of experimental protocols capable of inducing generalized muscle strain and in consequence musculoskeletal pain within a short period.

To address this gap, we employed an age simulation suit to induce muscle strain in several muscles. Such suits are designed to mimic age-related motor limitations by incorporating sewn-in weights and joint range restrictions, resulting in reduced muscle strength and increased fatigue [12, 13]. Unlike previous studies focusing on specific muscle groups, the GERontologic Simulator (GERT) [14] enables simultaneous activation of multiple muscle groups throughout the body. Our participants wore the GERT suit while performing everyday activities in our living lab (e.g., sitting, walking, and changing body positions while sitting or lying in bed), which likely induced widespread muscle strain and ultimately muscle fatigue – a state that increases vulnerability to musculoskeletal pain.

To examine whether and how this state influences the pain response system, we employed two types of pain-inducing challenges: (i) Motor pain challenges: Participants lifted weights from a shelf and lifted a box, tasks that imposed additional short-term muscle load on top of the ongoing strain. (ii) Sensory pain challenges: Participants were exposed to experimental pressure and heat pain, allowing assessment of non-motor-related pain responses.

Both types of challenges were repeated once (Round 1 and Round 2) with an interval of roughly 20 min to observe changes over time with prolonged muscle strain. Alongside self-reported pain ratings, we recorded facial expressions of pain as a more reflexive and objective measure. Additionally, heart rate, heart rate variability, and electrodermal activity were recorded as indicators of autonomic pain responses. Perceived exertion ratings were collected as manipulation checks to verify physical strain and fatigue.

A randomized controlled design was implemented: half of the participants completed the two rounds of motor and sensory pain challenges while wearing the GERT suit (experimental group), and the other half performed the same tasks without the suit (control group). Based on this design, we tested the hypothesis that participants would exhibit increased pain responses during motor pain challenges only after experimentally induced muscle strain, while their pain responses to sensory pain challenges would remain unchanged.

Methods

Participants

We recruited 43 young participants via flyers and emails distributed at the University of Bamberg. Participants were randomly assigned to the experimental and the control group based on sex and appointment time (morning or afternoon). Thus, 22 participants were assigned to the experimental group and 21 participants to the control group. We based our sample size calculations (Sample Power 2.0, SPSS Inc., Chicago, IL, USA) on the expectation of large effect sizes (f=0.40) and a power of 0.9, which resulted in an n=20 per group. As can be seen in Table 1, experimental and control groups did not differ with regard to the self-reported frequency of habitual exercise and activity level. Although the two groups significantly differed in age, the difference was less than two years and thus, should not be of relevance. Exclusion criteria were acute and chronic pain conditions, other physical and mental illnesses, and the habitual use of psychotropic drugs and analgesics. Participants were instructed not to consume CNS-active drugs or alcohol 24 h prior to testing. No caffeinated beverages or nicotine were to be consumed 2 h prior to testing. Participants received either 40 euros or course credit for their participation. Participants provided written informed consent before participation. The study protocol was approved by the ethics committee of the University of Bamberg (2021-04/18).

Procedures and materials

All tests were performed between 9:00 am and 6:00 pm. Light (simulated daylight; 5,500 K) and temperature were kept constant (21 °C) in our lighting- and temperature-controlled living lab. The testing procedure is displayed in Figure 1A. It

Table 1: Sample characteristics.

	Experimental group (wearing GERT suit)	Control group	Group differences
n	22	21	
Female/male	10/12	10/11	X^2 (p=0.882)
Age (mean (SD))	21.41 (3.20)	22.52 (2.16)	t-test (p=0.029)
regular exercise[a] (yes/no)	18/4	18/3	X^2 (p=1)
activity level[b] (more/as active/ less)	4/14/4	6/14/1	X^2 (p=0.337)

[a]Do you exercise regularly? [b]Compared to others your age, do you consider yourself more active, about as active, or less active? SD, standard deviation.

included first a pre-survey (demographic data and question-naires, 5 min), a preparation phase (attaching the electrodes for the physiological responses, 5 min; suiting up the GERT in the experimental group and a pause of similar duration in the control group, 5 min), followed by a brief rest period (10 min). Thereafter, a series of everyday whole-body exercises were scheduled to bring the GERT into action and induce muscle strain, which were bed-repositioning tasks with extra arm movements and straight as well as curve walking (10 min). Finally, the two sensory challenges (experimental pressure pain and heat pain, 10 min) and the two motor challenges (lifting tasks A and B, 10 min) took place. Next, a second round of the strain-inducing exercises as well as of the motor (10 min) and the sensory challenges (10 min) was performed, followed by a second brief rest period (10 min) and a short debriefing and post-survey (5 min). In total, the entire testing lasted between 85 and 95 min.

Sustained widespread and generalized muscle strain – experimental group

Wearing the GERonTologic Simulator (GERT suit [14]) was used to induce sustained muscle strain all over the body in the experimental group (see Figure 1B). The GERT suit consists of 11 components, which were a neck brace, elbow, and knee bandages to restrict the range of motion and mobility, as well as a weight vest (10 kg), wrist weight cuffs (1.5 kg), and ankle weight cuffs (2.3 kg) to increase the physical effort required for movement. Additionally, special gloves were used to decrease grasping ability. Participants wore the GERT suit over a thin T-shirt and light trousers. Most GERT components are made of non-insulating synthetic materials like polyamide (nylon) or polyester. And thus, we do not expect any meaningful thermal insulation or impact on body temperature.

Sensory challenges

Pressure pain. We applied pressure stimuli using a pressure algometer (Algometer Type II, SOMEDIC Electronics, Hörby, Sweden) with a probe area of 1 cm^2 following a protocol of Bunk et al. [15]. Four different pressure intensities were applied with ascending intensity levels (50, 200, 400, and 500 kPa) to the left and right shoulder (above the trapezius muscle, midway between the neck and shoulder line) and the left and right inner forearm (midway between the wrist
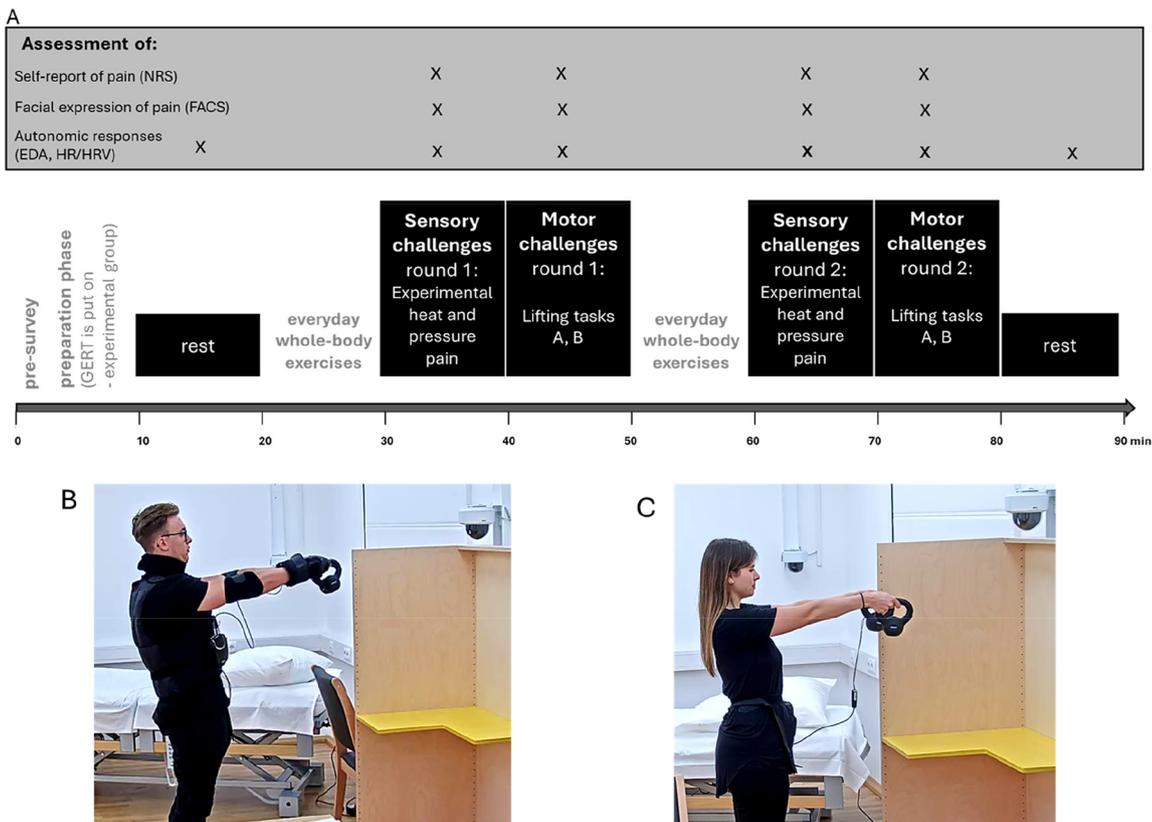

Figure 1: Assessments, the experimental protocol, and participants during motor challenge. (A) Timeline of the testing schedule, (B) example of a participant wearing the GERonTologic Simulator (GERT) suit for inducing muscle strain in several muscles, to which the Lift Task A added further muscle load for a short time (experimental group); (C) a participant was shown without GERT during the same lift task A. *Note*. Both participants provided written consent for the use of their images in scientific publications.

and elbow flexion). This resulted in a total of 16 pressure stimuli (4 intensities × 2 body sides × 2 stimulation sites). In each area, pressure was increased steadily for 2 s until the desired intensity was reached and was then kept constant for 5 s.

Heat pain. Participants were asked to immerse their right hand approximately 2 cm above the wrist into a water-filled sink with a thermostatically (Sous-Vide Cooker SV 100 Professional from Steba) controlled temperature of 46.5 °C [16] for 3 s. The immersion was repeated three times before a 10-s pause for a total of nine immersions (3–3–3).

Motor challenges

Lift Task A. (see Figure 1). Participants stood in front of a shelf and were instructed to lift two kettlebells of 2 kg with outstretched arms from the middle board (86 cm) to shoulder height as well as to the top edge of the shelf (160 cm) and hold this position for 5 s before placing the kettlebells back on the middle board (adapted from Thibault et al. [17]). Next, participants placed the kettlebell on the bottom board (9 cm) and, after a pause of 5 s, they lifted the weight onto the middle board again. Each challenge was performed twice, once at closer distance (28 cm) and once at further distance (60 cm) from the shelf. This motor task was inspired by the idea of simulating everyday motor activity activities, such as handling or reorganizing heavy pots/pans on a kitchen shelf.

Lift Task B. Based on a protocol by Lussanet [18], participants were asked to lift a box (40 × 30 x 22 cm) with both hands weighted with sandbags (8 kg) from the floor on his/her right, remain upright for 1 s, and placed the box back on the floor on his/her left side and stand up straight again. The box was then lifted from the left side and had to be placed on the right side. Altogether, 10 trunk rotation movements were performed. This motor task was inspired by the idea of simulating everyday motor activity activities, such as lifting a crate of drinks.

Both lifting tasks were set up to further increase the muscle load for a short time to add strain to the muscles in the experimental group or to test singular effects of muscle activation in the control group.

Assessment of pain responses

Self-report of pain. After each stimulus (pressure pain) or after completing each task (heat pain, lift tasks A and B), participants were asked to report their maximum pain experienced on an 11-point Numerical rating scale (NRS) ranging from 0 (*no pain)* to 10 (*worst pain imaginable*). For further analyses, pain ratings were averaged (i) across both

sensory challenges as well as (ii) across both motor challenges, separately for round 1 and round 2.

Facial expression of pain. Twelve cameras recorded the entire experiment. The respective frontal camera view of the face was used to analyze facial expressions using the facial action coding system (FACS [19]). The FACS allows the motion analysis of facial muscles and distinguishes between 44 different action units (AUs). Two certified FACS coders evaluated the frequency and intensity (5-point scale) of 44 AUs in an offline analysis. Interrater reliability (using the Ekman–Friesen formula [19]) between the coders was high at 0.76. We used the program Observer Video-pro (Noldus Information Technology, Wageningen, The Netherlands) for FACS coding. Given the enormous time it takes to FACS code the data (1 min of video material takes approximately up to 2 h to process [19]), we only coded segments within each sensory and motor challenges. More precisely, time segments of 3 s heat pain (time of hand immersion) and Lift B task (approximate time for each trunk rotation movement), and 5 s pressure pain (plateau of target intensity) and Lift A task (duration of lifting the kettlebell) were selected for FACS coding. Frequency and intensity values of each AU were multiplied to form the product for each AU and the product of those AUs indicative of pain [20], namely AU4 (corrugator muscle), AU 6_7 (orbicularis oculi muscle), AU 9_10 (levator muscle), and AU25_26_27 (orbicularis oris muscle) were combined (averaging) to form one pain-indicative facial expression composite score as done in previous studies [21]. For further analyses, pain-indicative facial composite scores were averaged (i) across both sensory as well as (ii) across both motor challenges; separately for round 1 and 2.

Autonomic Responses. We assessed the electrocardiogram (ECG) and electrodermal activity (EDA) using the wireless NeXus-10 MKII biosignal system (MindMedia, Herten, The Netherlands; sampling rate: 256 Hz) during all challenges.

ECG. Self-adhesive ECG electrodes were placed according to Lead II setup (the ground electrode was placed just below the left clavicle, the positive electrode below the left rib cage, and the negative electrode just inferior to the right clavicle). Mean heart rate (HR) and heart rate variability (square root of the mean squared differences between successive RR intervals, RMSSD; in ms) were analyzed using Kubios HRV Premium (version 4.0.2) software [22]. Before data analysis, we visually inspected the ECG data for anomalies and artifacts and applied low threshold artifact correction (0.35 s [23]).

EDA. Electrodermal activity (EDA) was measured using finger electrodes (index and middle finger). The skin conductance level (SCL) was recorded within a range of 2–20 μS, with specific attention to its change (1–3 μS). The

data were analyzed using Continuous Decomposition Analysis (CDA) via the Ledalab toolbox for MATLAB. For this study, the mean tonic activity (CDA.Tonic) was used as the primary variable for analysis. If the skin conductance values are above 20 μS, the values indicate excessive noise or artifacts (BIOPAC Systems, Inc., n.d.) most likely due to measurement errors and were therefore excluded. For that reason, three participants were excluded from the EDA analysis, leaving us with 21 participants in the experimental group and 19 participants in the control group.

For each sensory and motor task, the 30 s preceding the task completion were chosen as time segments for ECG and EDA analyses. One-minute baselines were averaged from the 8th minute of each rest period. We then computed delta values (task values – baseline values) for each task. For further analyses, delta values were averaged (i) across both sensory as well as (ii) across both motor challenges, separately for round 1 and round 2.

Manipulation check (Self-report of physical exertion). An 11-point Numerical Ratings Scale (NRS) was used, where participants were asked to rate the maximum physical exertion during each motor task performed (0=*no exertion*, 10=*maximum imaginable exertion*). Given that the sensory challenges did not require noteworthy motor activity, we did not assess exertion after pressure and heat stimulation. For further analyses, the exertion ratings were averaged across both motor challenges; separately for round 1 and 2.

Statistical analysis

Effect of performing everyday whole body exercises while wearing the GERT suit (manipulation check). Repeated measurement ANOVAs (within-subject factor round 1 and round 2) were conducted to compare the effect of wearing the GERT suit between groups (between-subject factor) on self-report of exertion.

Impact of muscle strain on pain responses evoked by motor and sensory challenges (hypothesis testing). To investigate whether pain responses differed between experimental (wearing the GERT suit) and control groups, repeated measure ANOVAs with the between-subject factor GERT and the within-subject factor round (round 1 and round 2) were conducted; pain indicative outcome variables were pain ratings, pain-indicative facial expressions, electrodermal activity (EDA), heart rate (HR) and heart rate variability (RMSSD)) separately for (i) the motor challenges and (ii) the sensory challenges.

Analyzes of variances were performed using the ez R package [24]. For F Tests, we reported generalized eta-squared ($\eta^2 G$) as effect sizes [25]. If significant interaction effect (GERT × round) were found, we conducted post-hoc *t*-tests using the emmeans R package and reported Cohen's d as effect size [26, 27]. Findings were considered to be statistically significant at α<0.05.

Results

Effect of performing everyday whole body exercises while wearing the GERT suit on self-report of exertion (manipulation check): With regard to self-report of physical exertion, the ANOVA revealed a significant main effect for "GERT" (F(1, 41)=16.74, p<0.001, $\eta^2 G$=0.28), with higher self-reported exertion ratings in the experimental group (round 1: 5.5 ± 2.1; round 2: 5.9 ± 2.0) compared to the control group (round 1: 3.2 ± 1.9; round 2: 3.3 ± 1.9). This main effect shows that our manipulation of inducing muscle strain seems to have been subjectively successful. There was no significant effect for "round" (F(1, 41)=3.20, p=0.081, $\eta^2 G$<0.01) and no significant "GERT" x "round" interaction effect (F(1, 41)=0.74, p=0.393, $\eta^2 G$<0.01).

Impact of muscle strain on self-report of pain evoked by motor and sensory pain challenges

Self-report of pain – motor challenges: During motor challenges, when the participants had to rate the painfulness of the additional muscle load due to lifting weights, we found a significant main effect for "GERT" (F(1, 41)=4.89, p=0.033, $\eta^2 G$=0.10), with higher pain ratings in the experimental group (see Figure 2A). There was no significant effect for "round" (F(1, 41)=0.07, p=0.793, $\eta^2 G$<0.01) and no significant "GERT" x "round" interaction effect (F(1, 41)=0.30, p=0.586, $\eta^2 G$<0.01). Thus, induction of muscle strain led to increased pain ratings during the motor pain challenges.

Self-report of pain – sensory challenges: During the sensory challenges, when the participants had to rate the painfulness of experimental pressure and heat pain, we did not find a significant effect for "GERT" (F(1, 41)=0.04, p=0.844, $\eta^2 G$<0.01). Thus, groups did not differ in their pain ratings (see Figure 2B). The ANOVA yielded a significant main effect for round (F(1, 41)=4.25, p=0.046, $\eta^2 G$<0.01), with slightly lower NRS-pain ratings for round 2 compared to round 1. The "GERT" x "round" interaction effect (F(1, 41)=1.77, p=0.191, $\eta^2 G$<0.01) was not significant. Thus, induction of muscle strain did not affect pain ratings of experimental pain stimuli.
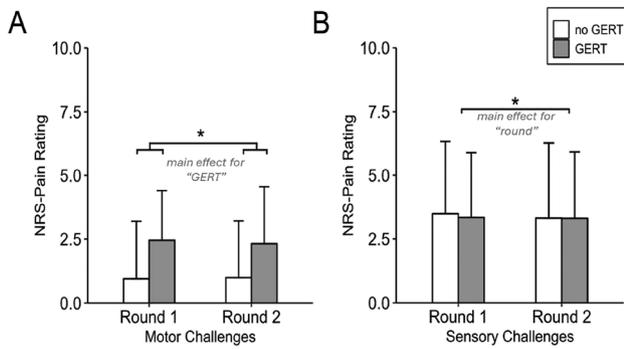
Figure 2: Mean and standard deviation of NRS-pain ratings during motor challenges (A) and during sensory challenges (B), shown separately for experimental (GERT) and control (no GERT) groups and separately for the two rounds. *Note*. NRS=numerical rating scale (0=*no pain*, 10=*worst pain imaginable*). *p<0.05.

Impact of muscle strain on facial expression of pain evoked by motor and sensory pain challenges

Facial expression of pain – motor challenges: During motor challenges (weightlifting), the ANOVA revealed a significant main effect for "GERT" (F(1, 41)=4.63, p=0.037, $\eta^2 G$=0.10), with increased facial expressions of pain in the experimental group compared to the control group (see Figure 3A). No significant main effect was observed for "round" (F(1, 41)=1.56, p=0.219, $\eta^2 G$<0.01), nor was there a significant "GERT" x "round" interaction effect (F(1, 41)=0.54, p=0.466, $\eta^2 G$<0.01). Thus, induction of muscle strain led to increased facial expressions of pain during the motor pain challenges.

Facial expression of pain – sensory challenges: During the sensory challenges, we observed no significant difference in facial expression of pain between groups (F(1, 41)

=0.40, p=0.530, $\eta^2 G$=0.01), between rounds (F(1, 41)=0.55, p=0.462, $\eta^2 G$<0.01) or "GERT" x "round" interaction effect (F(1, 41)=0.02, p=0.885, $\eta^2 G$<0.01). Thus, facial response to experimental pain did not differ between groups nor across rounds (see Figure 3B).

Impact of muscle strain on electrodermal activity evoked by motor and sensory pain challenges

Electrodermal activity (EDA) – motor challenges: We found no significant main effects for "GERT" (F(1, 38)=2.95, p=0.094, $\eta^2 G$=0.07) or "round" (F(1, 38)=1.84, p=0.184, $\eta^2 G$<0.01). However, the interaction between "GERT" x "round" was significant (F(1, 38)=9.55, p=0.004, $\eta^2 G$<0.01). Post hoc tests showed a significant increase in EDA from round 1 to round 2 only in the experimental group (GERT; t(38)=−3.23, p=0.003, d=−0.52), but not for the control group (t(37)=1.20, p=0.239, d=0.19). Moreover, EDA response was significantly increased in the experimental compared to the control group in round 2 (t(38)=−2.03, p=0.025, d=−0.64) but not in round 1 (t(38)=−1.36 p=0.182, d=−0.43), as can be seen in Figure 4A. Thus, induction of muscle strain led to increased skin conductance responses during weightlifting the longer the test session lasted.

Electrodermal activity (EDA) – sensory challenges: During the sensory challenges, we observed no significant
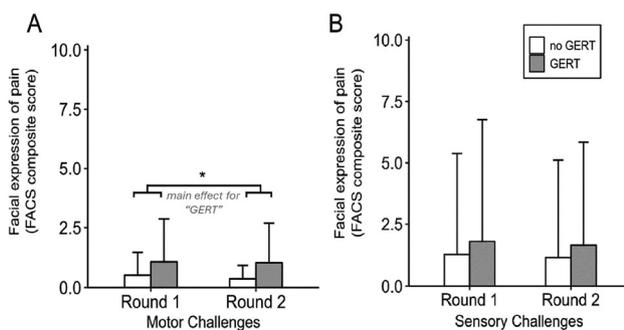

Figure 3: Mean and standard deviation of facial expressions of pain during motor challenges (A) and during sensory challenges (B), shown separately for experimental (GERT) and control (no GERT) groups and separately for the two rounds. *Note*. FACS=Facial Action Coding System. *p<0.05.
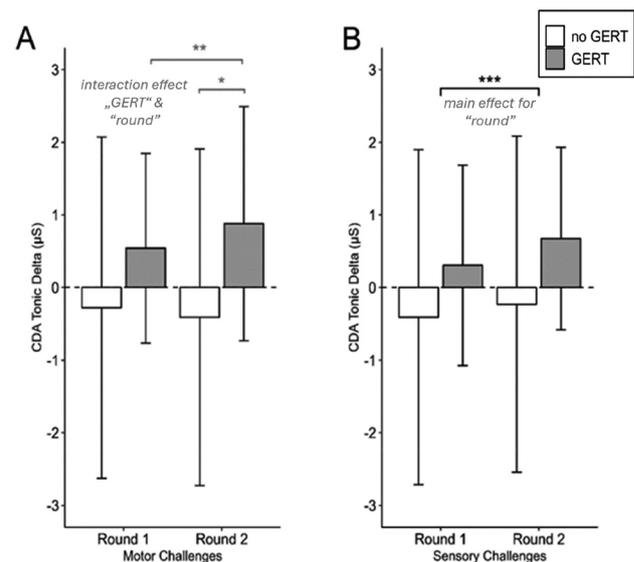

Figure 4: Mean and standard deviation of EDA (CDA tonic) during motor challenges (A) and during sensory challenges (B), shown separately for experimental (GERT) and control (no GERT) groups and separately for the two rounds. *Note*. CDA=continuous decomposition analysis. ***p<0.001, **p<0.01, *p<0.05.

difference in EDA between groups ($F_{(1, 38)}$=1.95, p=0.171, $\eta^2 G$=0.05) and no significant "GERT" x "round" interaction effect ($F_{(1, 38)}$=2.74, p=0.106, $\eta^2 G$<0.01).There was only a significant main effect for "round" ($F_{(1, 38)}$=22.13, p<0.001, $\eta^2 G$=0.01), with increased EDA responses in round 2 (see Figure 4B). Thus, induction of muscle strain did not affect EDA responses to experimental pain stimulation.

Impact of muscle strain on heart rate responses evoked by motor and sensory pain challenges

HR/HRV (RMMSD) – motor challenges: We found a significant main effect "GERT" ($F_{(1, 41)}$=5.29, p=0.027, $\eta^2 G$=0.11), with increased HR responses in the experimental compared to the control group (see Figure 5A). Moreover, there was also a significant effect for "round" ($F_{(1, 41)}$=23.63, p<0.001, $\eta^2 G$=0.03), with HR responses increasing over time. The interaction between "GERT" x "round" was not significant ($F_{(1, 41)}$=0.19, p=0.662, $\eta^2 G$<0.01). Regarding the heart rate variability (RMSSD), no significant main effect of "round" ($F_{(1, 41)}$=3.76, p=0.060, $\eta^2 G$=0.01) or "GERT" ($F_{(1, 41)}$=1.25, p=0.270, $\eta^2 G$=0.03) and no significant "GERT" x "round" interaction

effect ($F_{(1, 41)}$=0.06, p=0.804, $\eta^2 G$<0.01) was found. Thus, induction of muscle strain led to increased HR responses (but no change in HRV) during the motor pain challenges.

HR/HRV (RMMSD) – sensory challenges: During the sensory challenges, we observed no significant difference in HR ($F_{(1, 41)}$=2.30, p=0.137, $\eta^2 G$=0.04) or in HRV ($F_{(1, 41)}$=1.45, p=0.235, $\eta^2 G$=0.03) between groups. We found significant effects for "round", with HR increasing ($F_{(1, 41)}$=29.83, p<0.001, $\eta^2 G$=0.13) and HRV decreasing ($F_{(1, 41)}$=4.54, p=0.039, $\eta^2 G$=0.01) across rounds (see Figure 5B–D). The interaction between "GERT" x "round" interaction effect was neither significant for HR ($F_{(1, 41)}$=006, p=0.811, $\eta^2 G$<0.01) nor for HRV ($F_{(1, 41)}$=0.45, p=0.505, $\eta^2 G$<0.01). Thus, induction of muscle strain did not affect HR and HRV responses to experimental pain stimulation.

Summary

In sum, wearing the GERT and hereby inducing muscle strain at multiple sites (experimental group) resulted in increased self-reported pain, facial expressions of pain, electrodermal activity, and heart rate responses during additional motor pain challenges (i.e., weight and object
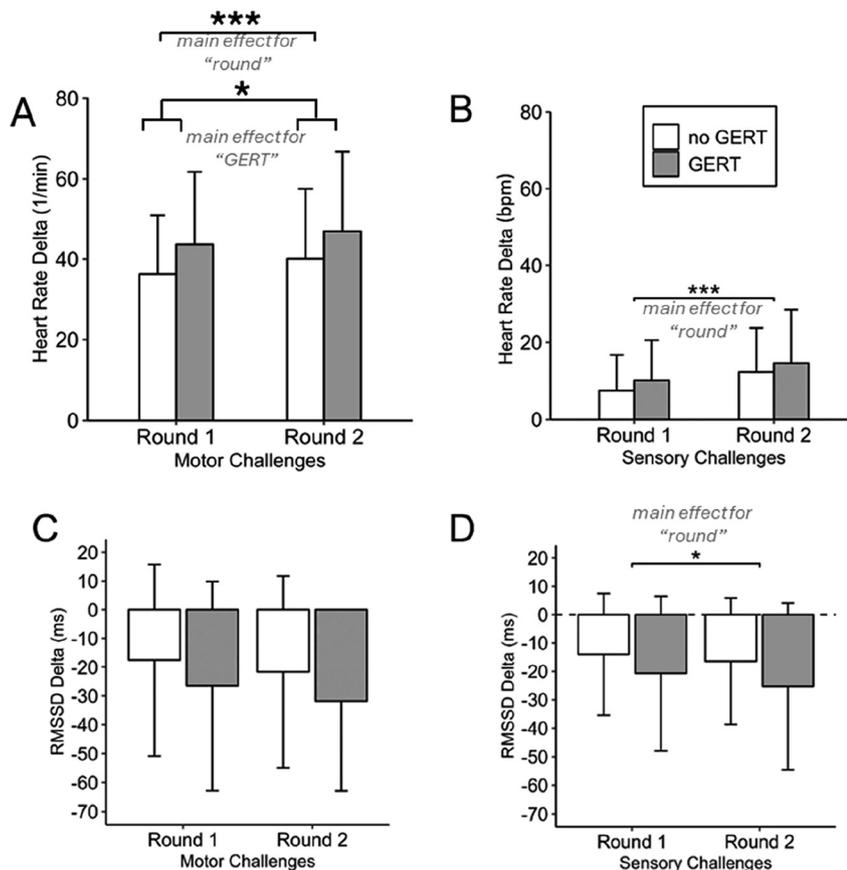

Figure 5: Mean and standard deviation of heart rate during motor challenges (A) and during sensory challenges (B) and heart rate variability (RMSSD) during motor challenges (C) and during sensory challenges (D), shown separately for experimental (GERT) and control group (no GERT) across the two rounds. *Note.* ***p<0.001, *p<0.05.

lifting) compared to the control group. In contrast, no group differences emerged during the sensory pain challenges (painful heat and pressure stimulation); only time effects (round 1 vs. round 2) were observed.

Discussion

In the present study, we examined the impact of sustained, multisite muscle strain lasting more than an hour (induced by the GERonTologic Simulator (GERT) [14], a suit equipped with limb and body weights and joint-movement restrictions) on the pain system. To evaluate its pain-related effects, we introduced everyday motor challenges (e.g., lifting objects such as when reorganizing heavy pots on a kitchen shelf or moving a crate of drinks) as well as sensory challenges (e.g., hot-water immersion, noxious pressure) that are typically associated with pain.

Based on this design, we hypothesized that participants would experience pain and sympathetic arousal during additional muscular exertion only when their muscles had already been activated for an extended period and had become fatigued. In contrast, we expected pain responses during sensory pain challenges to remain unaffected.

Our findings support this hypothesis. Motor-related pain tasks elicited increased pain ratings in participants wearing the GERT suit, accompanied by a similar pattern in pain-related facial expressions. Heart rate (HR) and electrodermal activity (EDA) responses were likewise elevated during motor pain tasks in the experimental group, but not during sensory challenges. Notably, heart rate variability (HRV) did not show significant effects related to muscle strain.

These results indicate that even a brief period of sustained multisite muscle activation is sufficient to induce muscle strain and, consequently, musculoskeletal pain when additional exertion is required. This pain response was accompanied by clear signs of sympathetic nervous system arousal. Importantly, this state does not reflect a generalized hyperalgesia, as pain responses to non-motor (sensory) stimuli (pressure, heat) remained unaffected.

Although it may seem intuitive that fatigued muscles produce pain when further exerted, the significance of this study lies in its objective validation using nonverbal and behavioral pain indicators, such as pain-specific facial expressions. The accompanying increase in HR and EDA further reinforces the interpretation of a pain-related, sympathetic response. This aligns with findings by Greco et al. [28], who demonstrated that phasic and tonic EDA responses can predict muscle fatigue.

On this basis, we propose a novel experimental musculoskeletal pain model consisting of two key components: (i) the induction of multisite muscle strain through everyday activities performed while wearing the GERT suit, and (ii) the application of additional acute muscle load via moderate weightlifting, ultimately producing subjective, behavioral, and autonomic indicators of pain.

Previous models have largely focused on regional muscle pain, such as Delayed Onset Muscle Soreness (DOMS), which typically arises 24–72 h after unaccustomed or strenuous activity [29, 30]. While DOMS models typically target localized muscle groups, our model activates multiple sites simultaneously, offering a closer approximation of the physical demands of daily life and providing an opportunity to study widespread musculoskeletal pain.

Wearing the GERT suit for only a few minutes and inducing multisite muscle strain may be enough to prime individuals for pain when further exertion is required. The suit can be used in naturalistic environments, facilitating research on how everyday activities induce pain [31], even in pain-free individuals.

We assessed the specificity of this pain model in two ways: (i) by evaluating pain-specific outcomes, and (ii) by comparing motor vs. sensory pain challenges. Regarding (i), facial expressions provide a reliable and pain-specific behavioral measure that is neither biased nor easily influenced by general arousal. Prior research has identified facial Action Units (AUs) that uniquely characterize pain and differentiate it from other negative emotional states [20, 32–34]. In our study, participants wearing the GERT suit exhibited activation of these pain-specific AUs during additional motor challenges, indicating that the observed responses reflect pain rather than mere fatigue or discomfort. Regarding (ii), as hypothesized, we found no evidence of generalized hyperalgesia; the increased pain sensitivity was specific to the musculoskeletal system and emerged only during motor, not sensory, pain challenges.

Taken together, our experimental model increases vulnerability to musculoskeletal pain without inducing general discomfort or general pain hypersensitivity. The establishment of this technical and methodological framework provides a viable tool for assessing both pharmacological and non-pharmacological pain interventions. Moreover, it allows direct comparisons between pain-free individuals and those with clinical musculoskeletal pain, particularly regarding their capacity to tolerate and respond to pain elicited by everyday motor tasks.

Limitations

Several limitations should be acknowledged. First, we did not account for individual fitness levels in our analyses,

although prior research suggests that higher fitness may reduce pain susceptibility [35–37]. Moreover, we did not include direct physiological markers of muscle fatigue such as surface electromyography (EMG), a robust method for assessing muscle fatigue [38]; which limits the mechanistic interpretation of the induced strain. Furthermore, because this represents the first evaluation of our paradigm, we tested only young students. Now that the proof of principle has been established, extending the paradigm to individuals at ages when chronic musculoskeletal pain commonly first emerges could yield particularly valuable insights.

Conclusions

Activating muscles at multiple body sites for just a few minutes by wearing weighted garments and restricting joint movement, can induce muscle strain and make even pain-free individuals vulnerable to pain during subsequent everyday motor activities. In contrast, sensory pain challenges (e.g., heat or pressure) did not elicit increased pain responses in this vulnerable state.

The combination of elevated subjective pain ratings, increased pain-specific facial expressions, and heightened autonomic responses (HR and tonic EDA) during motor tasks confirms the utility of this experimental model. This model of acute widespread musculoskeletal pain is well suited for use in naturalistic settings and provides a robust framework for investigating pain mechanisms and interventions in both healthy and clinical populations.

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