

Bodily maps of exercise-induced sensations

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Abstract

Physical exercise is a strong physiological and mechanical stimulus that elicits various bodily sensations. They shape the affective experience and in turn contribute to the psychological benefits of exercise. Despite the centrality of interoception and somatosensation in generating subjective sensations and the capacity for physical exercise in altering the bodily states, there is a paucity of data on bodily experiences and sensations evoked by physical exercise. Here we mapped bodily sensations evoked by exercise in two studies. In the first proof-of-concept study we asked participants (n=305; 143 females) to imagine undergoing aerobic or strength training and report the expected bodily sensations. In the second field study we mapped participants' (n=133; 105 females) emotions and bodily sensations before and after actual exercise sessions. Both studies utilised visual analogue scales for sensation rating and a topographical self-report tool for mapping bodily sensations: participants were asked to colour on a human body silhouette all the bodily regions where each specified sensation (e.g. "Energized") was felt. The findings revealed a wide array of mostly positive exercise-induced bodily sensations with distinct topographies, consistent across individuals. The field experiment confirmed that bodily sensations of activity and exhaustion intensified following exercise in topographically specific manner, and that experience of exhaustion in the body mapping was linearly associated with physiological and subjective indices of exertion. Altogether these results show that different exercise-induced sensations have distinct bodily topographies, suggesting that the exercise-induced emotions may arise from the interoceptive and somatosensory pathways.

Introduction

Bodily sensations and emotions are inherent part of physical exercise. Exercise is a strong physiological and mechanical stimulus that elicits changes throughout the biological circuits in the body. Being subjectively aware in physiological and biomechanical state of the body not only help to regulate exercise performance but also shape the affective experience of exercise [1–3]. Exercise is an effective behavioural strategy for self-regulation of mood and emotions [4–8], and consequently it is also beneficial for improving symptoms of depression, anxiety and psychological distress [9].

Emotions prepare the mind and body for action by automatically adjusting activity in the central and peripheral nervous system to maximize survival odds and well-being [10]. Emotions are also important predictors of long-term exercise engagement [11,12]. While exercise is typically associated with mood elevation, the spectrum of feelings, sensations and emotional states induced by exercise is complex and ranges from anger and disgust [13] to the invigorating euphoria or "runner's high" [14,15]. Exercise-induced positive emotions such as joy and pleasure act as positive reinforcers promoting exercise motivation and maintenance of regular exercise routines [16–21], whereas negative emotions such as pain act as negative reinforcers discouraging future exercise [22]. These negative emotions may be particularly important when beginning routine exercise, as discomfort and pain are common when switching from sedentary to active lifestyle. However, strict adherence to the exercise program will rapidly shift the even the initially negative exercise-induced feelings to positive, thus promoting exercise motivation [16,23,24]. Moreover, positive mood is associated with greater likelihood of exercising which then again results in improved mood, creating a positive loop [25,26].

Emotions are tightly intertwined in the body, as they adjust behavioural priorities, central nervous system states, skeletomuscular systems, and autonomic activity to promote survival and well-being [27]. Both classic and modern emotion theories also posit that the subjective experience of emotions (e.g. "I feel good") is based on the interoceptive and somatosensory feedback from the current bodily state [28–30]. Different emotions as well as cognitive and somatic states have discernible and consistent "feeling signatures" in the body [30–32]. These findings are based on distinct topographical maps derived from simple self-reports of phenomenological bodily

sensations to demonstrate how basic and more complex emotions are represented in the body. Importantly, the more pleasurable a mental or homeostatic state is the more strongly it is experienced in the body [31], highlighting the corporal nature of emotions.

Muscles generate power and heat during exercise, and the associated metabolic changes alongside with accumulation of lactate and other muscle metabolites lead to sensations of fatigue and exhaustion in the muscles and in the mind [33]. For example the Borg's 15-point rating of perceived exertion (RPE) scale [34], the most commonly used psycho-physical measure for evaluating the subjective perception of whole-body exertion during exercise, yields a net index of several integrated physiological mechanisms, including cardiopulmonary variables, cerebral and peripheral metabolism, neural drive from motor cortex area, core and skin temperature and mechanical strain [35]. Thus, by altering the physiological processes which may subsequently be forwarded to consciousness via interoceptive pathways, exercise results in various embodied sensations such as sweating, cramping muscles, pounding heart, feeling "the buzz", "the pump", and pain, which shape affective experience of exercise [2,36]. Based on subjective interpretation of these sensations, even negative emotions such as pain may ultimately trigger positive feelings that promote future exercise engagement [2,36]. Despite the i) centrality of interoception and somatosensation in generating subjective sensations and ii) the capacity for physical exercise in altering the bodily states, there is a paucity of data on bodily experiences and sensations evoked by physical exercise. Unravelling the topographical organization of the exercise-evoked sensations would be important, as the bodily sensations triggered by exercise could be potential mediators for both adherence to and termination of exercising.

Here we mapped bodily sensations evoked by physical exercise using two different approaches: conventional Likert-scale responses different somatic sensations (e.g. active, strong, relaxed...) and using novel topographical self-report tool where the subjects indicated on a blank human body where they experienced each of the sensations [30,31]. In the first study we asked a large sample of subjects to estimate the sensations evoked by imaginary aerobic and strength training workout and in the second field study we collected the corresponding sensation reports from subjects before and after a session of exercise (e.g., running, spinning etc.). We show that exercise induces a wide range of mostly positive bodily sensations with distinct bodily topographies. As specific bodily sensation patterns were associated with objective (heart rate) and subjective (RPE) indicators of cardiovascular load, suggesting that the bodily mapping tool might provide a novel approach for measuring exercise-induced exertion and mood and aid in planning exercise and recovery schedules.

Materials and Methods

Experiment 1

The first experiment was a proof-of-concept study for the feasibility of mapping bodily sensations resulting from exercise. Instead of measuring sensations immediately after exercise, we asked subjects to imagine undergoing either aerobic exercise or strength training and report the bodily sensations they would feel following the workout.

Methods

Subjects were recruited from Prolific (<https://www.prolific.co>) and the experiment was run on the gorilla.sc online experiment platform (<https://gorilla.sc>). Subjects provided informed consent, after which they filled in background information regarding demographics and physical exercising. This yielded a sample of 143 females and 162 males with a mean age of 27 years (SD= 7.27) and mean BMI of 26.46 years (SD =14.65). Median years of regular exercise was 4. Median weekly time (hours) spent exercising was 3 for heavy exercise and 4 for light exercise. Participants reported enjoying exercise (MD= 8 out of 10), reported being in average fit (MD=5 out of 10) being in good mood (MD = 7 out of 10).

Bodily sensation mapping

The subjects were asked to imagine that they had completed a vigorous 60-minute exercise. To standardize imagery and maximize the brevity of responses, half of the subjects were instructed to imagine aerobic exercise (e.g. jogging, cycling, dancing, tennis, aerobics...) and half to imagine strength training workout (e.g. using free weights, kettlebells, resistance bands, gym machines...). They were then provided a list of 52 somatic sensations and asked to evaluate, using a visual analogue scale (VAS), whether the exercise session would increase or decrease the feeling of each sensation. After completing the VAS scales, the subjects completed the bodily sensation mapping tool (Nummenmaa et al., 2014; Nummenmaa et al., 2018). The subjects were shown a blank human body and the name of a single sensation (e.g. “Energized”). They were asked to colour all the bodily regions where they would feel that sensation. Again, the subjects were instructed to imagine they had completed the aerobic (50%) / strength training session (50%) and indicate bodily regions where they would experience each of the sensations following the training session. Due to the large number of tokens, each participant was randomized to report only half (26 out of 52) tokens pertaining bodily sensations. Topographical maps for each token were averaged, and the mean maps were subjected to mass univariate t tests against zero to reveal regions where each experience increased statistically significantly. False Discovery Rate (FDR) correction was applied to control for multiple comparisons.

Results

Fig 1 shows the mean distribution of the rated sensations. No statistically significant differences were found between the aerobic and strength training conditions, and the feeling-wise ratings across the conditions were almost perfectly ($r = 0.99$) correlated; these data were subsequently analysed together. Exercise increased particularly the experience of positive emotions and bodily sensations such as sweatiness, thirst, pride, and decreased the experience of negative emotions such as shame, disappointment, anger and sadness. All differences from zero were statistically significant ($t_s > 1.90$, $p_s < 0.05$) except for shaky, cool, tingling, and tight.

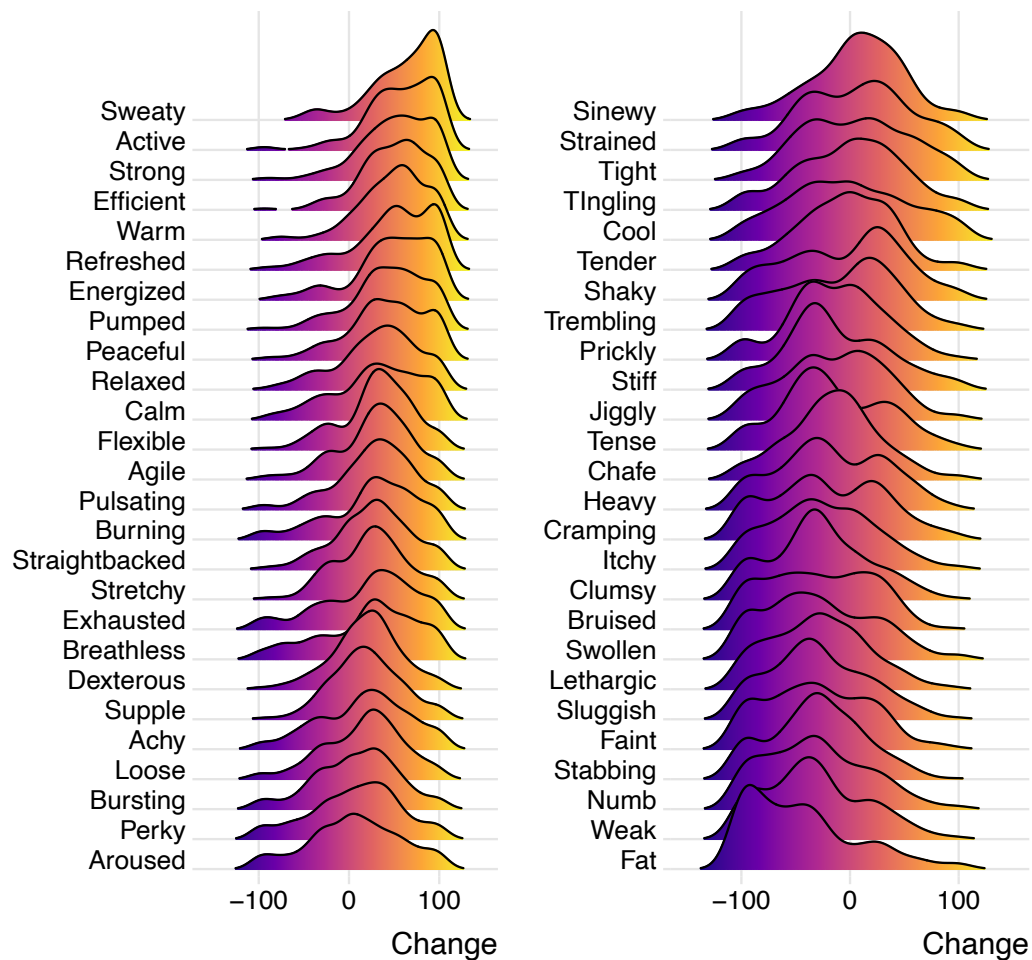


Fig 1 Distributions of the intensity of the sensations in descending order. All differences from zero are statistically significant ($t_s > 1.90$, $p_s < 0.05$) except for shaky, cool, tingling and tight.

Cluster analysis (hierarchical clustering with Ward method) revealed a clear six-cluster structure for the similarity of the feelings (**Fig 2**). Torso-focused sensations (aroused, fat, straight-backed and stabbing) formed one cluster, similarly low-intensity feelings (calm, faint, peaceful, cool) grouped together. Cardiovascular sensations (sweaty, breathless, bursting, pulsating) formed one cluster and clearly whole-body sensations (e.g., uncomfortable, exhausted, chafed) grouped together. Limb-centred feelings (Dexterous, shaky, trembling) formed one cluster and the remaining sensations formed the final, largest cluster (e.g., swollen, bruised, jiggly, supple...).

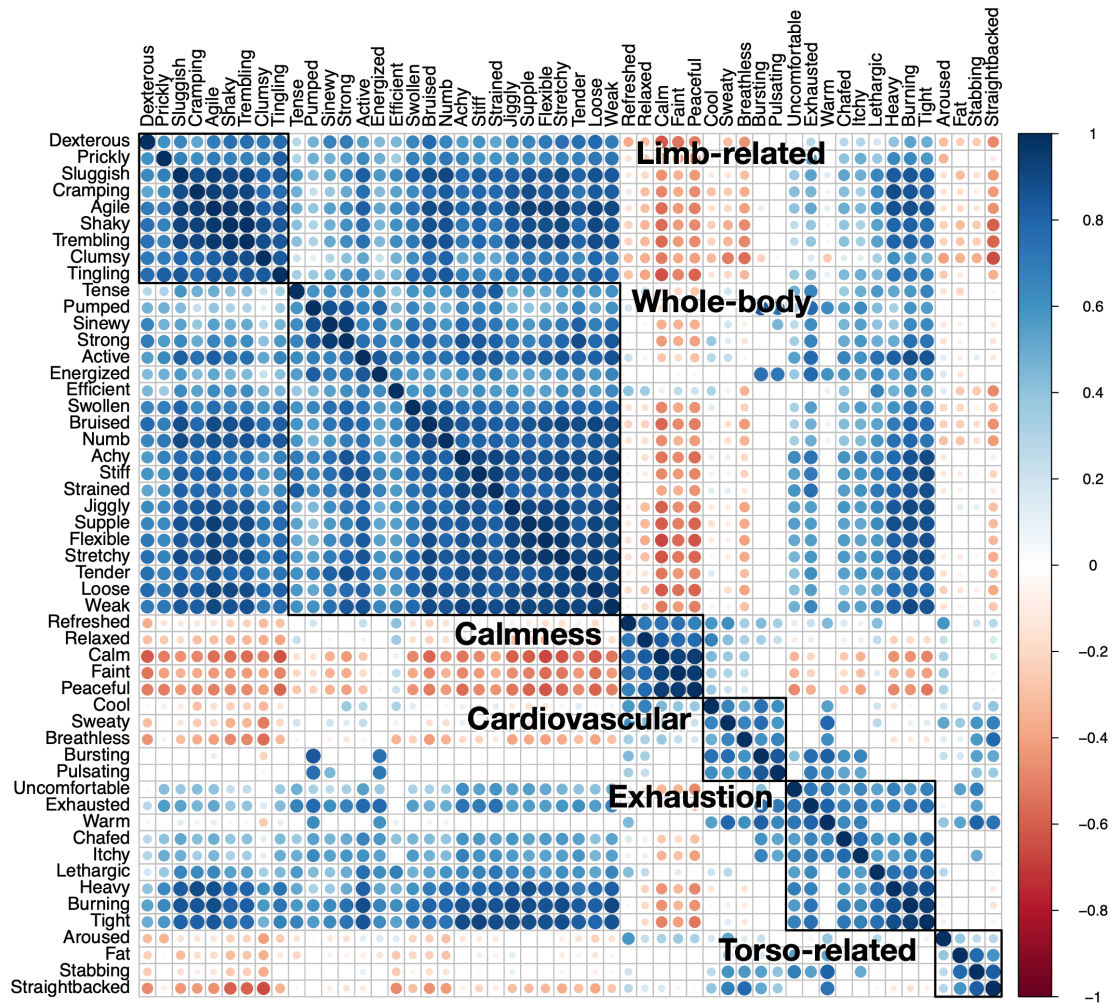


Fig 2 Similarity structure (Pearson correlation) of the bodily sensations. Only statistically significant ($p < 0.001$) correlations are shown.

We next analysed the bodily sensation maps for the exercise-induced bodily sensations (**Fig 3**). Physical exercise was associated with consistent experience of bodily sensations across subjects, and the intensity as well as the bodily topography of these sensations varied significantly from sensation to sensation. Some sensations such as warmth, sweatiness and exhaustion were felt throughout the whole body, whereas others such as strength, agility and flexibility were felt in the limbs. In turn, some sensations such as breathlessness and pulsation were felt in the upper torso, and others (such as discomfort, sluggishness, and numbness) were experienced only rarely. Finally, calmness and peacefulness were experienced primarily in the head area, likely reflecting the psychological rather than embodied basis of these experiences.

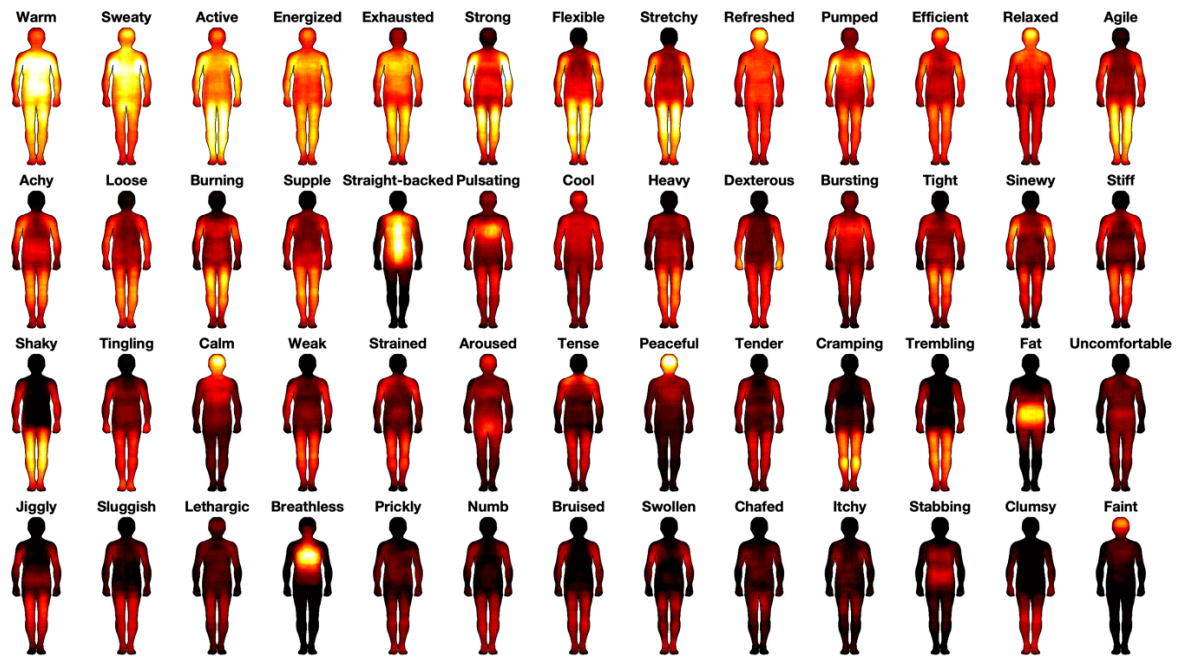


Fig 3 Bodily sensation maps for physical exercise. Pixel intensities show t-values. The data are arranged per total coloured bodily area and thresholded at $p < 0.01$ FDR corrected.

To further visualize the embodied nature of the exercise-evoked feelings, we computed the mean number of pixels coloured in head and body regions for each sensation [37]. We considered colouring of the body region implying the bodily component of the sensations, and colouring of the head to imply mentation, here called mental component. This is based on our previous work on 100 core feelings showing how mental phenomenological experience of subjective states or physiological changes is associated with sensations in the head area [31]. This revealed clear gradients both in the mental and bodily component of the feelings (**Fig 4**). Sensations of warmth, activeness, sweatiness, and energy were most saliently felt in the body, whereas faintness, clumsiness, itchiness and chafedness were devoid of the bodily component. Peacefulness, calmness, sweatiness and relaxation were most saliently experienced in the mind, whereas shakiness, stabbing, cramping and bruises were lacking the mental component.

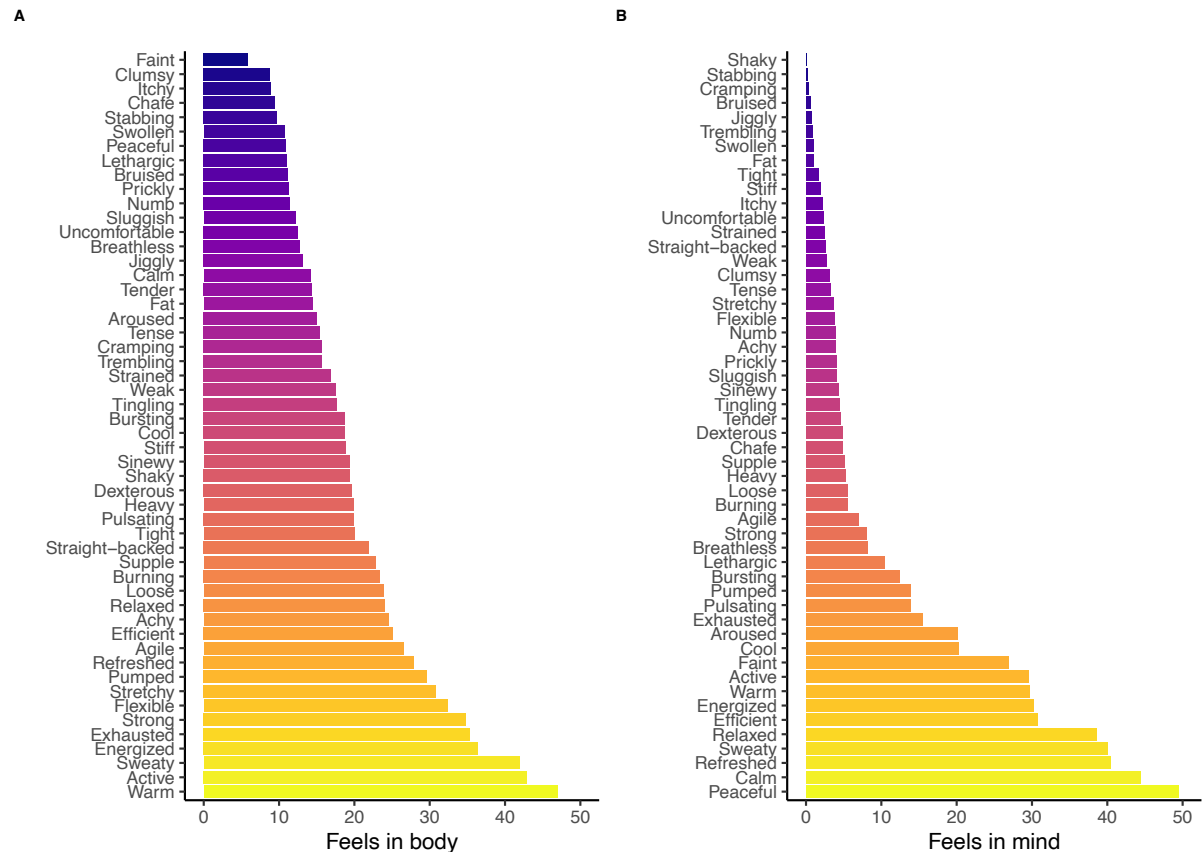


Fig 4 Bodily (left) and mental (right) components of the exercise-induced sensations. Note that the data are ordered separately for the left and right panels.

Experiment 2

Experiment 1 suggested that subjects estimate exercise to induce a wide variety of bodily sensations, and that these sensations are evaluated consistently across subjects. In the second field experiment we mapped the exercise-induced emotional and bodily feelings in naturalistic training setting. Subjects were recruited from different sport clubs, training groups, and workout / dance halls. We decided to use self-selected voluntary sports as the experimental model, as it is more representative of natural recreational exercise than laboratory-based or experimenter-led exercise sessions. To minimize the interference of the experiment to the exercise classes, we trimmed the adjective list for the VAS and bodily mapping task from Experiment 1 down so that the experiment could be completed in approximately 10 minutes.

Methods

Research assistant contacted the subjects upon arriving to the sports facility and enquired about their willingness to participate. Upon enrolling, subjects provided informed consent and were given instructions and a private code for logging on to the experimental platform. Subjects were encouraged to complete the experiment on their own device; iPads were also available for those who preferred them. The sampling resulted in 133 young adult volunteers (29 males, 105 females) with mean BMI of 23.01 (SD 3.32). Subjects reported to exercise 4.59 (SD = 1.68) hours/week and assessed their cardiorespiratory fitness on 1 (extremely poor) – 7 (extremely good) scale as being above average ($M = 4.74$, $SD = 0.92$). Upon logging on to the experiment before the exercise, subjects provided background information and reported their current feelings using 12 adjectives describing emotional and somatic states. Subsequently they completed the bodily mapping task for six sensations that resulted in distinctive maps in Experiment 1 (Active,

Uncomfortable, Painful, Exhausted, Relaxed, and Sinewy). The main difference to Experiment 1 was that now the subjects were asked to paint the regions in their body where they currently experienced each sensation. The subjects then completed their exercise, after which they immediately re-evaluated their subjective state using the 12 adjectives and completed the bodily mapping task for their current sensations. Subjects were also asked to evaluate the strenuousness of the exercise session on Borg RPE 6-20 scale and how much they enjoyed the exercise session on 1-7 scale (1 extremely little; 7 enormously). Subjects wearing personal heart rate monitors were asked to enter their mean heart rate during the exercise session to the electronic form; these data were obtained from 44 subjects. Subjective sensations in the pre and post exercise measurements were compared using two-sample t-test. The bodily maps were generated as previously, but to assess exercise-induced changes in bodily sensations, the post-test maps were compared with pre-test maps using repeated measures t-tests. To assess the relationship between bodily sensation maps and self-reported exertion and fitness level, we computed the total number of pixels coloured for each sensation to indicate the net bodily sensation; these values were subsequently correlated with the Borg scale scores, the mean heart rates during the exercise, self-assessed fitness level, and weekly hours of exercise.

Results

Most subjects did aerobic exercise in group (93) or on their own (6), some also participated in body maintenance in group (19), strength training in group (5) or alone (10). Mean RPE was 14.02 (SD=2.9) and heart rate 132.6 bpm (SD = 22.41, $n = 44$) suggesting a moderate-intensity exercise, and the modal length for the exercise session was 57 minutes. On a scale 1-7, exercise was “liked very much” (mean 5.62; SD 9.43). In general, exercise increased the experience of positive feelings and decreased experience of negative feelings. We observed statistically significant increases in experience of healthiness, happiness, pride, perkiness, energeticness and attractiveness, and significant decreases in the experience of exhaustion, stress, lethargicness, anxiety, depression, and embarrassment ($t_s > 1.92$, $p_s < 0.05$; **Fig 5**).

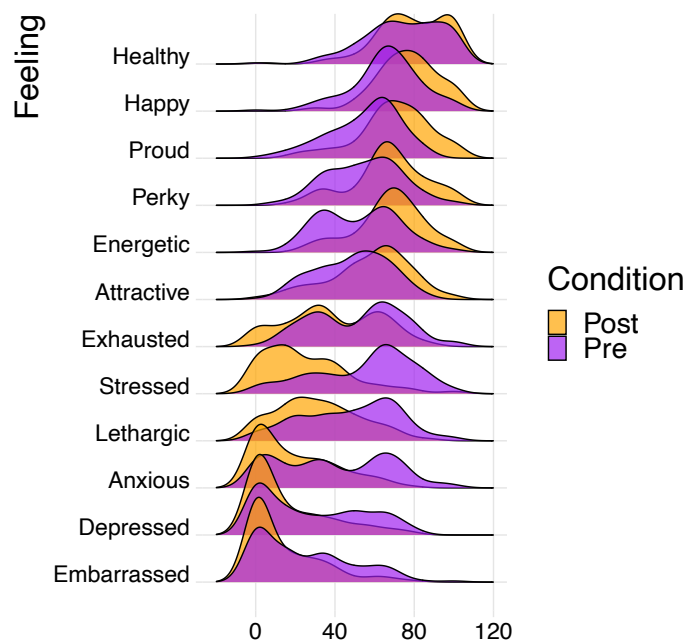


Fig 5 Distributions of emotional and somatic feelings before and after the workout. Differences in all sensations between pre and post measurements are statistically significant at $p < 0.01$.

The bodily sensation maps revealed distinctive topographical experience patterns for different sensations (**Fig 6**). Exercise increased experience of activeness and sinewiness in the chest and back areas, while it led to increased experience of exhaustion in feet and relaxation in the head. Conversely, experience of exhaustion decreased in the head and shoulder area, whereas uncomfortable and painful sensations decreased in the upper torso region.

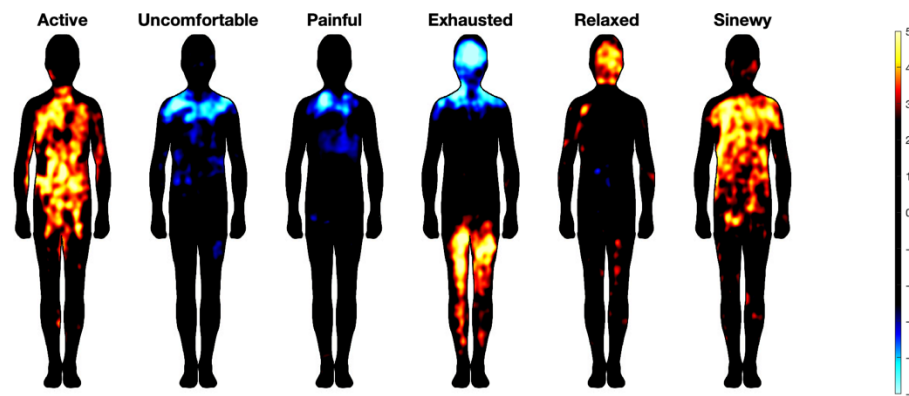


Fig 6 Bodily maps of exercise-induced sensations. The maps show regions where experience of each sensation increased (hot colours) or decreased (cool colours) in comparison with the baseline state. Pixel intensities show t-values. The data are thresholded at $p < 0.05$ FDR corrected.

Next, we tested if the intensity of the bodily sensations of exhaustion (as indexed with total % of pixels coloured) was associated with physiological (heart rate) and subjective estimates of perceived exertion (RPE). Significant correlations ($r_s > 0.33$, $p_s < 0.05$) were found for both estimates indicating that more intensive exercise was linked with stronger experience of exhaustion in the body (**Fig 7**). Finally, self-reported physical fitness was negatively associated with bodily experience of pain ($r = -0.25$, $p < 0.05$) and uncomfortable sensations ($r = -0.30$, $p < 0.05$). No correlations were found between weekly hours of exercise and bodily sensations.

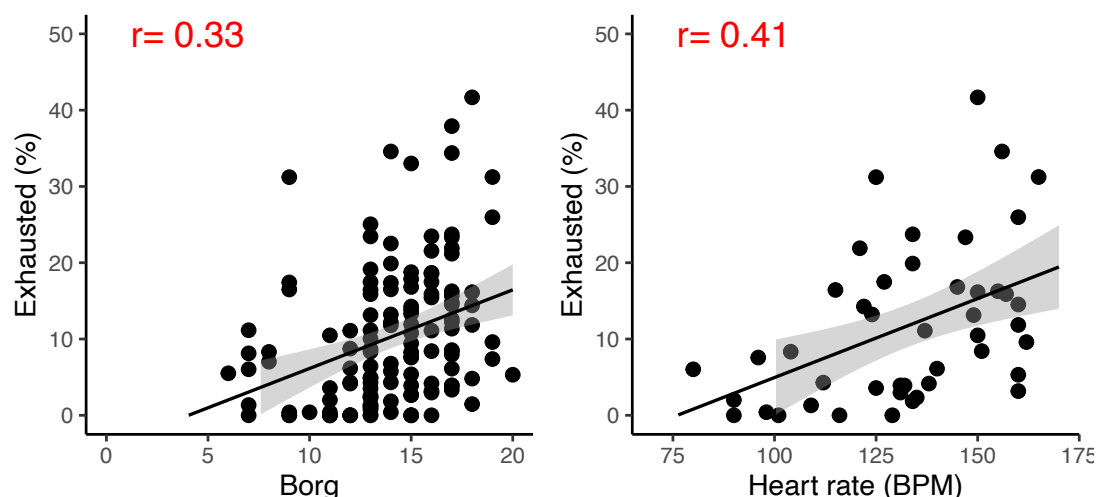


Fig 7 Association between bodily exhaustion (as indicated by the BSM) and exhaustion indexed by self-report based on the Borg RPE scale (A) and mean heart rate during exercise (B).

Discussion

Our main finding was that physical exercise induces a wide array of somatovisceral sensations, whose topography was consistent across individuals. Exercise-induced sensations were predominantly positive, and the experience of negative sensations decreased following exercise. These sensations were associated with distinct bodily topographies, ranging from whole-body experiences (warm, sweaty...) to regionally specific bodily feelings (agile, shaky...). Some sensations (calm, faint...) localised mostly to the head region, likely reflecting the predominantly mental nature of the sensations. The field experiment confirmed that bodily sensations of activity and exhaustion intensified following exercise in topographically specific manner, and that experience of exhaustion in the body mapping was linearly associated with physiological (heart rate during exercise) and subjective (RPE) indices of exertion. Altogether these results show how different exercise-induced sensations have distinct bodily topographies. Exercise-induced emotions may arise from the interoceptive and somatosensory pathways, and the resultant topographical sensations may provide important feedback when planning exercise and recovery schedules.

Bodily sensations and physical exercise

Exercise was primarily associated with increase in positively (e.g. active, strong, energized) and decrease in negatively valenced sensations (weakness, sluggishness, numbness). This accords with a large bulk of data on the relationship between moderate-intensity aerobic exercise and positive mood [8,38,39] that may regulate exercise performance, continuation, and subsequent engagement in exercise. The bodily sensations reported using Likert scales formed six distinct clusters ranging from whole-body experiences to sensations in the limbs, torso, and cardiovascular system. Calmness and exhaustion/arousal related sensations were also separated into distinct clusters. The bodily sensation mapping revealed distinguishable topographies for exercise-induced sensations, ranging from whole-body experience of warmth, sweating, and activeness to regionally specific sensations of strength, agility and flexibility, suggesting that people can consistently access the nonverbal interoceptive sensations triggered by exercise [40]. These somatosensory and interoceptive sensations are also regionally specific. For example, strength was experienced only in the limbs, breathlessness in the chest area and so forth. Because emotions and sensations evoked by exercise are important determinants of sports performance [3,41–43] and exercise engagement [16,17,19,20,44] the bodily mapping approach could reveal whether sensations in specific bodily regions (such as aching in the limbs or exhaustion in the chest area) are associated with exercise motivation and mood changes following exercise.

As Experiment 1 was based on self-reports of hypothetical somatic consequences of exercise, we cannot conclude whether these sensations reflect actual experiences during exercise. Field experiment 2 however confirmed that actual physical exercise evokes distinct topographies of different sensations. Following exercise, increased (in relation to baseline) experience of activeness and sinewiness was felt in the torso area, whereas experience of relaxation was increased in the head area. Sensations of pain and discomfort decreased in shoulder and back area, supporting the role of exercise in pain management [45]. Interestingly, experience of exhaustion increased in the lower limbs but decreased in the head area, likely reflecting the mental component of the exertion. This accords with the notion that physical and mental fatigue may be decoupled, and that increased pleasurable physical exhaustion may decrease the experience of mental exhaustion. Indeed, exercise is often described to increase feelings of energy and revitalisation [46–49]. These bodily sensations were also directly linked with subjective (RPE) and physiological (heart rate) indicators of exercise load. Given the well-established regulatory role of exercise intensity on affective responses of exercise [8,38], it is not surprising that exercise intensity modulates also the overall bodily experience of exhaustion. Moreover, we found that higher self-assessed fitness level was associated with greater reductions of bodily sensations of pain and discomfort after exercise, which

may be linked with greater exercise-induced endogenous opioid release observed in individuals with higher cardiorespiratory fitness and physical activity level [50]. Although these are just simple one-dimensional indicators, they however suggest that the self-reported bodily sensations have physiological basis [30], as previously shown for RPE [35,51]. Future studies could aim at linking the sensations maps directly with a broader array of physical parameters, such as body temperature, breathing rates and muscle power. The field experiment also revealed that exercise caused exhaustion but also increased experience of positive emotions (feeling healthy, happy, proud, perky, energetic, and attractive) while decreasing the experience of negative emotions (feeling stressed, lethargic, anxious, depressed, and embarrassed). This accords with the overall pattern of results in Experiment 1, as well as the literature on the mood-lifting capacity of exercise [8,38]. Interestingly, although embarrassment related to one's body may lower exercise motivation [52], our study actually shows that engaging in voluntary self-selected physical exercise is an effective way of tackling embarrassment and increase the feelings of pride and attractiveness.

A variety of bodily sensations have been implicated in the performance-optimising flow state experienced by elite athletes during sports performance [3,43]. Monitoring the sensations and bodily experience of pain is also important for pacing strategy during races [41]. While coping with extreme sensations of pain is essential for elite athletes, learning to adapt to uncomfortable bodily sensations is crucial also for novice exercisers adopting new training routines [53]. As a consequence, bodily sensations like pain, fatigue and arousal may eventually contribute to the "hurt so good" effect of exercise [2,36], potentially due to endogenous opioid release [14,54]. However, subjective experience of exercise-induced sensations varies across individuals. While some people prefer high exercise intensities [55], the mechanical strain, increased heart rate, and sweating result in unpleasant feelings in others [49]. All in all, our data show that the bodily sensation mapping tool is sensitive to detecting exercise-induced regional changes in bodily sensations. From practical standpoint, the tool might be useful in tracking e.g. regional changes in muscle strain or exhaustion, for monitoring and improving performance and recovery, and designing pleasant and tolerable exercise programs that would foster adoption of sustainable exercise routines.

Limitations

The field experiment was conducted in naturalistic settings and subjects were recruited from exercise studios, dance classes and so forth. This led to variation in the types of exercise the subjects did, yet it ensured that all subjects were exercising in their preferred way, which has been associated with more positive affective experience [56]. Affective responses during and after exercise can be markedly different [38]. Our findings only apply to the changes (pre-post) in bodily feelings induced by the exercise session. Heart rate measurements were only recorded from a subset of the subjects using consumer-level heart rate monitors, yet they were robustly associated with exhaustion measures derived from the body maps. We only measured a limited number of bodily sensations in the field experiment to minimize subject discomfort. Future studies using standardized exercise protocol should be conducted using the full array of sensations in Experiment 1. Our field study involved moderately fit, normal weight participants with regular exercise background. Given that obesity [57,58], poor cardiorespiratory fitness [59], and low level of regular exercise [60] are all associated with more negative affective responses to exercise, our findings cannot directly be extended to these population groups. Finally, as the study was based on self-reports, we do not know whether the bodily sensation pattern relate to changes in the activity of specific physiological systems. However, the association between bodily patterns of exhaustion and heart rate indicates that at least some of the subjective sensation patterns are linked with the underlying physiological processes induced by exercise. Future studies using, for example, total-body positron emission tomography perfusion measurements [61] could resolve this issue.

Conclusions

We conclude that bodily sensations are core component of the exercise-driven affect. The bodily sensation mapping provides a novel tool for understanding the integration between bodily signals and emotional processing in physical exercise. Moreover, it provides a new method for quantifying exercise load and concomitant emotions and may prove valuable when evaluating the psychological and somatic effects of exercising.

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