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„The effect of mental stress on human motor control during familiar and unfamiliar movement tasks“

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Abstract

Muscle synergies are cooperating patterns of muscle activation that are used to perform certain movements. The related muscle synergy theory suggests that the central nervous system does not activate each muscle individually but rather coordinates groups of muscles within multiple motor modules through a common activation command, which reduces the complexity of motor control.

The aim of this thesis was to determine how stress affects movement control. It was hypothesized that i) synergy vectors are not influenced by mental stress, ii) trial-to-trial variability of activation coefficients increases with mental stress and iii) trial-to-trial variability of temporal spatial parameters also increases with mental stress. The data was recorded in four three-minute-long test runs using the treadmill: forward movement without stress, forward movement with stress, backward movement without stress and backward movement with stress. Mental stress was induced using the *Paced Auditory Serial Addition Task* and surface EMGs were used to determine muscle activity of lower extremities.

The results show that the synergy vectors as well as the trial-to-trial variability of activation coefficients did not differ between trials with and without stress. The trial-to-trial variability of temporal spatial parameters showed a significant difference when comparing trials with and without stress for the familiar (forward), but not for the unfamiliar (backward) movement.

Participants exhibited high percentages of shared synergies in both familiar (90%) and unfamiliar (80%) movements, indicating that fundamental movement control mechanisms remain unchanged under stress. Contrary to expectations, trial-to-trial variability of synergy activation coefficients did not differ significantly between the stress and no stress conditions. However, increased trial-to-trial variability in temporal spatial parameters was observed in the forward task under stress, suggesting reduced movement consistency. No significance was found in backward walking, likely due to the heterogeneous nature of unfamiliar movements.

Zusammenfassung

Muskelsynergien sind zusammenwirkende Muster der Muskelaktivierung, die zur Ausführung bestimmter Bewegungen verwendet werden. Die damit zusammenhängende Muskelsynergie-Theorie besagt, dass das zentrale Nervensystem nicht jeden Muskel einzeln aktiviert, sondern Muskelgruppen innerhalb mehrerer motorischer Module durch einen gemeinsamen Aktivierungsbefehl koordiniert und dadurch die Komplexität der motorischen Kontrolle reduziert.

Ziel dieser Arbeit war es zu untersuchen, wie mentaler Stress die Bewegungskontrolle beeinflusst. Es wurde die Hypothese aufgestellt, dass i) Synergievektoren durch Stress nicht beeinflusst werden, ii) die trial-to-trial Variabilität der Aktivierungskoeffizienten mit Stress zunimmt und iii) die trial-to-trial Variabilität der zeitlich-räumlichen Parameter mit Stress ebenfalls zunimmt. Die Daten wurden in vier dreiminütige Testläufe auf dem Laufband erfasst: Vorwärtsbewegung ohne Stress, Vorwärtsbewegung mit Stress, Rückwärtsbewegung ohne Stress und Rückwärtsbewegung mit Stress. Mentaler Stress wurde mithilfe des *Paced Auditory Serial Addition Task* induziert und Oberflächen-EMGs wurden zur Bestimmung der Muskelaktivität der unteren Extremitäten verwendet.

Die Resultate zeigen, dass sich die Synergievektoren und trial-to-trial Variabilität der Aktivierungskoeffizienten nicht zwischen Durchgängen ohne Stress und mit Stress unterschieden. Die trial-to-trial Variabilität der zeitlich-räumlichen Parameter zeigte beim Vergleich von trials ohne Stress und mit Stress einen signifikanten Unterschied bei der gewohnten (vorwärts), jedoch nicht bei der ungewohnten (rückwärts) Bewegung.

Die Proband*innen zeigten einen hohen Prozentsatz gemeinsamer Synergien sowohl bei gewohnten (90 %) als auch bei ungewohnten (80 %) Bewegungen, was darauf hindeutet, dass die grundlegenden Mechanismen der Bewegungskontrolle unter Stress unverändert bleiben. Entgegen den Erwartungen unterschied sich die trial-to-trial Variabilität der Aktivierungskoeffizienten nicht signifikant zwischen Durchgängen ohne Stress und mit Stress. Allerdings wurde bei vorwärts mit Stress eine erhöhte trial-to-trial Variabilität der zeitlich-räumlichen Parameter beobachtet, was auf eine geringere Bewegungskonsistenz schließen lässt. Bei rückwärts wurde keine Signifikanz festgestellt, was wahrscheinlich auf die Heterogenität der ungewohnten Bewegungen zurückzuführen ist.

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1 Introduction

1.1 Human motor control

Muscle synergies were first discovered by Bernstein in 1967 and have since gained significant attention in the field of neuroscience. The word "synergy" originates from Greek, meaning "working together" (Bergius, 2019), which hints at the role of muscle synergies. The human body, with its infinite degrees of freedom, does not make it quite easy to understand how the central nervous system (CNS) manages movement control. To make the complexity of muscle activation for known movement patterns simpler and facilitate movement control, the number of degrees of freedom is reduced for each specific task. The related muscle synergy theory suggests that the CNS does not activate each muscle individually but coordinates groups of muscles within multiple motor modules through a common activation command instead, which leads to reducing the complexity of movement coordination. These groups of co-active muscles are referred to as synergy vectors. Synergy vectors are spatially defined and activated through the activation coefficient. A combination of common as well as specific synergies across movements leads to realization of the motion. Each synergy defines a uniform activation pattern for the motor neurons, which then innervate a specific group of muscles. To sum up, muscle synergies are coordinated patterns of muscle activation used to perform specific movements or tasks, organized by motor cortex areas and afferent systems (Tresch et al., 1999; d'Avella & Bizzi, 2005; Ting & Macpherson, 2005; Ting & McKay, 2007; Cheung et al., 2009; Bizzi & Cheung, 2013).

In what follows, several studies on that topic are described below. Muscle synergies are obtained from electromyography (EMG) recordings of the relevant muscles. A commonly used method to investigate the complexity of movement control is the total variance in muscle activity accounted for (tVAF) by a given number of synergies. The tVAF indicates how much of the total variability in muscle activity data is explained by the identified muscle synergies. A lower tVAF implies a better representation of the movement and is associated with a more complex motor control (Bizzi & Cheung, 2013; Rabbi et al., 2020).

Following studies explored the effects of brain injuries and neurological disorders, such as cerebral palsy and strokes, on muscle movement. Kim et al. (2022) investigated muscle synergy variability in walking under constraints, comparing children with typical development to those with cerebral palsy. The conditions were introduced in two ways: by altering walking speed and by restricting the foot width. They found that healthy subjects exhibited relatively consistent patterns between strides. Children with cerebral palsy showed more affected muscle activation patterns and thus were more sensitive to changes in the external walking environment. Others also investigated the effects of cerebral palsy, especially trying to find out whether individuals with CP exhibit lower complexity in neuromuscular control during walking compared to unimpaired individuals, and if these changes could be associated with functional ability. They concluded that impaired individuals needed fewer synergies during gait compared to healthy individuals and the tVAF also increased with the severity of the CP. These changes were linked to functional impairments and measures, such as strength and spasticity. This suggests that people with CP use less synergies and simpler motor control during gait (Steele et al., 2015). Shuman et al. (2019) examined whether a variety of treatments used to improve gait had an impact on muscle synergies. Despite changes in walking after receiving treatment, changes in synergies were minor. The number of synergies remained mostly unchanged, as well as the tVAF indicating that the motor control remains constant. The changes occurring in individuals with CP, were also related to stroke survivors. Van Criekinge et al. (2020) investigated studies, concluding that following a stroke, less synergies are needed to describe activity during gait. Here too, a higher tVAF was observed.

Turpin et al. (2011) compared rowers and untrained individuals to find out whether rowing expertise is associated with specific muscular coordination patterns. They found slight differences in the composition of the muscle synergies between both groups, but the temporal organization of the synergies was quite similar. These findings suggest that developing new muscle synergies is not necessary for rowing expertise. In healthy cyclists, a study has shown that the synergies and tVAF remain nearly unchanged under varying mechanical constraints, such as torque and posture and there were only slight adaptations of activation coefficients (Hug et al., 2011).

Researchers have identified comparable motor modules across various movements in which similar synergy vectors were engaged. These “shared synergies” represent common movement components and seem to be used when different movement tasks share similar mechanical subtasks (Barroso et al., 2014; Nazifi et al., 2017). Different studies have found shared synergies between non-identical movements. For example, Nazifi et al. (2017) analyzed data from subjects both walking and slipping and compared the synergies and activation coefficients between both, discovering two shared synergies among four synergies. The activation coefficients for the two shared synergies were alike during walking and slipping in the beginning, differing later which indicates that muscle synergies are activated in response to a slip. Another study also wanted to see if Nordic walking demands task-specific muscle coordination compared to conventional walking. The results showed that the number of muscle synergies did not differ between both activities and four muscle synergies were shared (Boccia et al., 2017). Furthermore, a study from Sawers et al. (2015) showed that when comparing overground walking and beam walking in ballet dancers versus novices, the experts used more motor modules and more shared synergies. This could be indicating a broader generalization of motor module function across various movements. Shared synergies were also found in cycling and walking (Hug et al., 2010), standing reactive balance tasks and walking (Allen et al., 2020) and stepping and non-stepping postural behaviors (Chvatal et al., 2010). In bench press exercises, experts showed consistent muscle synergy vectors, unlike their untrained counterparts. Experts also exhibited a larger inter-subject variability in their activation coefficients (Kristiansen et al., 2016).

Few researchers have investigated learning through specific muscle synergies. Cheung et al. (2020) collected electromyographic signals from both older and younger people playing virtual bowling. In older adults, improvements in scores were linked to changes in the variability of activation timing for specific synergies. In young adults, these improvements were associated with changes in the variability of both the activation profile and the synergies themselves. Sylos-Labini et al. (2022) investigated the activation coefficients of synergies during walking across various age groups. Their findings revealed that as locomotor development progresses, there is a marked increase in the consistency of activation coefficients from trial to trial. The learning process for simple and fast acquired tasks differs from that of complex movements. Kaufmann et al. (2024) addressed the question of more complex movements by studying skateboarding tricks. The team concluded that both the number of shared synergies and tVAF remained consistent across tricks of varying difficulty. They also found that inter-subject variability was high in complex movements and identified the presence of both shared and task-specific synergies in various skateboard tricks.

1.2 Stress and the hypothalamic-pituitary-adrenal axis

Although the intensity may vary, we are often exposed to stressful situations. In these situations, the hypothalamic-pituitary-adrenal axis plays an important role in regulating the body. Regardless of whether the stress is physical or mental, it triggers a reaction by activating various systems. When a stressor, which may pose a threat to physical or mental well-being, is perceived the hypothalamus is activated. This region of the brain produces and releases the corticotropin-releasing hormone (CRH), which then sets off the stimulation of an endocrine gland, the pituitary gland, which in turn releases adrenocorticotropin (ACTH). The ACTH then travels through the blood to the adrenal glands, which activate the production and release of

glucocorticoids, primarily cortisol. Cortisol is a stress hormone that sets off a variety of reactions in the body that serve to adapt to stress and can be very important. However, excessive and long-term activation can lead to negative effects. These include hypertension, autoimmune disease or major depression (Smith & Vale, 2006). The hormones activated by stress also activate the sympathetic nervous system, which triggers a variety of reactions. These can be an increased heart rate and the constriction of blood vessels in the skin and internal organs in order to divert blood to the muscle supply (Berlit, 2011; Speckmann et al., 2013). Furthermore, the sympathetic nervous system causes an increased body temperature and emotional reactions, which can cause people to sweat more and increase skin conductivity (Berlit, 2011; Horslen & Carpender, 2011; Speckmann et al., 2013).
Exposure to stress can impact posture and movement. Acute stress can lead to freezing gait behaviors (Richer et al., 2024) and a change in temporal and spatial gait parameters (Ramírez & Gutiérrez, 2021). It has also been found that various forms of mental stress and cognitive demands can activate increased muscle activity for example in the trapezius (Ekberg et al., 1995; Lundberg et al., 1994; Svebak et al., 1993; Waersted et al., 1996). As far as the effect of stress on muscle synergies, there is still very little research, but Asemi et al. (2024) investigated whether the internal or environmental stress experienced by individuals in signature verification systems affected muscle synergy patterns. They concluded that the patterns of muscle synergies related to emotion and stress were consistent, as they were nearly equal in both conditions (with and without stress).

1.3 Aim and Hypothesis

The aim of this master's thesis was to determine how mental stress affects movement control. Due to the lack of research in this area, this thesis attempts to address a research gap by analyzing human motor control during familiar and unfamiliar movement, more specific forward and backward motion on a treadmill, in relation to the effect of a mental stress situation. For this purpose, in both movement tasks, one trial was carried out with and one without a stress condition. It was hypothesized that i) synergy vectors are not influenced by mental stress a) in familiar movement b) in unfamiliar movement, ii) trial-to-trial variability of activation coefficients increases with mental stress a) in familiar movement and b) in unfamiliar movement iii) trial-to-trial variability of temporal-spatial parameters increases with mental stress a) in familiar movement and b) in unfamiliar movement.

2 Materials and Methods

2.1 Participants

Fifteen sports-oriented participants, aged 18 to 40, were recruited. To be included in the study, the individuals had to engage in physical activities at least once a week. All participants had to be injury- and pain-free at the time of data collection and were not allowed to have any known medically diagnosed neurological disorders. No individuals from protected groups were included in the study. The study got approved by the ethics committee of the University of Vienna (reference number: 00953).

Seven people had to be excluded from the study. Two people could not be included in the analysis due to problems with the skin conductance/ electrodermal activity data (EDA) and the remaining people had to be excluded due to errors in the Vicon recording and electromyography (EMG) signals. In total, eight people (23.7 ± 2.8 years; four women and four men) were involved in the results of this study. Prior to data collection, participants were informed of the procedures, asked to sign a declaration of consent and indicate whether recordings were allowed.

2.2 Experimental Setup and Data Collection

Before data collection, the demographic and anthropometric data of all subjects were recorded. Reflective markers and surface electromyography (sEMG) electrodes (eleven PicoEMG and two Mini Wave Infinity, Wave Plus wireless EMG system, Cometa, Milan, Italy) were then attached to the subjects to record muscle activities. Following the Seniam guidelines (Seniam.org), the sEMGs were placed on the lower body, targeting following muscles: gluteus medius (glut_med), vastus medialis (vast_med), tibialis anterior (tib_ant), gastrocnemius medialis (gast_med), rectus femoris (rect_fem), biceps femoris (bic_fem), and gluteus maximus (glut_max). While subjects were laying relaxed on their back on a massage table, a baseline EMG signal of a few seconds was taken. To collect data, we used the standard Vicon Plug-in-Gait marker set (Vicon, Oxford, UK), consisting of 23 reflective individual markers as well as four cluster markers. Heel and toe markers were attached to the participants' shoes. Marker trajectories at a sampling rate of 200 Hz, EMG data at 1000 Hz and ground reaction forces from a force plate at 1000 Hz (Kistler Instrumente, Winterthur, Switzerland) were simultaneously recorded by a 12-camera 3D motion capture system (Vicon, Oxford, UK). Additionally, participants wore in-shoe force sensor insoles (loadsol®, Novel, Munich, Germany) to determine stance phases. The data from the insoles were captured at 200 Hz utilizing the loadsol-s application (version 1.7.63) on a mobile phone (iPhone 12 mini, Apple, California, USA). To minimize sensor drift errors, the data was zeroed before each trial. Foot contact instances were identified using custom scripts based on vertical contact forces exceeding 30 N. By having participants step on the force plate prior to each trial, time synchronization between the insole and Vicon data was achieved. Foot contact instances and skin conductance were synchronized using the data collection start times. The experimental data was recorded and worked on using Vicon Nexus 2.12 software (Vicon, Oxford, UK), with following analyses using Gnu Octave version 6.2.0 and MATLAB (R2022a, MathWorks Inc., Natick, USA).

Participants were asked to undergo four conditions. At the beginning, each proband had to walk for at least three minutes on the treadmill (cardiostrong) while familiarizing with the machine and choosing their own speed for both the familiar (forward gait) and unfamiliar (backward gait) testing. The chosen speed was maintained for all test runs.

The data was then recorded in four three-minute-long test runs using the treadmill: (i) forward movement without stress, (ii) forward movement with stress, (iii) backward movement without stress, (iv) backward movement with stress. The test subjects were randomly assigned, so that half of them had to complete the forward trials first and the other half the backward trials. During the three-minute rounds, probands were instructed to let their arms swing as loosely as possible and only hold on to the treadmill if necessary. Both stress runs were carried out using a three-minute audio (mp3) recording of the PASAT (Paced Auditory Serial Addition Task), which is a method for measuring cognitive functions, that assess the speed and flexibility of auditory information processing, as well as the ability to calculate, and is thus intended to trigger a stress situation in the test subjects (Gronwall, 1977). In order to further increase the stress situation, the PASAT was additionally backed with white noise. During the stress trials, subjects were instructed to say the results of the test loud and clear. To prevent possible preparation, participants were not informed in advance about the use of the chosen test. However, if asked, they were told that cognitive tasks are to be solved while walking on the treadmill. Through non-stress trials, participants were asked to remain silent. Each run was followed by a break of at least two minutes. The time period used for analysis was between 60-150 of the overall 180 collected seconds.

2.3 EMG Processing

Surface electromyography (EMG) data was exported in c3d format and analyzed using Octave 6.2.0. Initially, the raw EMG signals underwent high-pass filtering at 20 Hz with a 4th-order Butterworth zero-lag filter. The signals were then removed of artefacts, demeaned, full-wave rectified, and further low-pass filtered at 8 Hz using the same filter type (Hug et al., 2012; Potvin & Brown, 2004). Both filtered and raw EMG signals for each step and muscle were thoroughly checked for artefacts, for example in the movement, and excluded if necessary. Negative values post-filtering were set to zero. Subsequently, the signals were time-normalized to 61 data points for the stance phase and 40 data points for the swing phase, representing 100% of each phase. Amplitude normalization was based on the mean values from 85-95% of all steps (Bianco et al., 2018). The analysis focused on data recorded between 60 and 150 seconds of EDA measurement.

Table 1

EMG used muscles/ participant, left and right

P01	tib_ant, gast_med, vast_med, rect_fem, no, no, glut_max
P02	tib_ant, gast_med, no, rect_fem, bic_fem, glut_med, glut_max
P05	tib_ant, no, no, rect_fem, bic_fem, glut_med, glut_max
P06	tib_ant, no, vast_med, no, bic_fem, glut_med, glut_max
P08	tib_ant, gast_med, vast_med, rect_fem, bic_fem, glut_med, glut_max
P09	tib_ant, gast_med, no, rect_fem, bic_fem, no, glut_max
P13	tib_ant, no, no, rect_fem, bic_fem, glut_med, glut_max
P14	tib_ant, no, no, rect_fem, bic_fem, glut_med, no

2.4 Skin conductance

Electrodermal activity, which measures skin conductance and quantifies electrical changes that occur during sweat production, is used as a physiological measure of emotional arousal. The reason why is because stressed individuals often sweat more (Baghestani et al., 2024). In this study, skin conductance was recorded on the non-dominant hand (Shimmer3 GSR+ Unit and ConsensysPRO Software) with sensors (625A) attached to the middle phalanx of the index and middle finger. Prior to data recording, a breathing test was carried out to make sure the electrodes detected the changes in stress level. Trials in which the subjects were not exposed to mental stress were used for baseline data. Between the trials, a break of at least two minutes was taken to ensure that the skin conductance levels returned to normal. The raw data was then converted into physiodate files using Matlab, analyzed and filtered with the PhysioData Toolbox (4 Hz, 250 ms resolution) and the Resampled Tonic Skin Conductance Level (SCL) converted into Z-scores. Skin conductance and loadsol data was synchronized using data collection start times. The analyzed time was between 60-150 s of the conducted data.

2.5 Synergy extraction and analyses

The processed EMG signals from all trials were concatenated for every participant (Hug et al., 2011; Hagio et al., 2015), and muscle synergies using the spatial/ synchronous synergy model in which the motor control of muscle activations is portrayed as a linear combination of fixed spatial synergy vectors and time-varying activation coefficients, were extracted (Turpin, 2021). For extracting the muscle synergies, non-negative-matrix-factorization (NNMF) has been used as it is a suitable method in walking tasks (Rabbi et al., 2020). This NNMF produced muscle synergy vectors as well as synergy activation coefficients. To extract 1 to muscle number -2 muscle synergies, the "nmf_bpas" octave function has been used (Paatero & Tapper, 1994; Seung & Lee, 1999; Kim & Park, 2008). Specifically, iterations with a minimum of 50 and maximum of 5000 were permitted, thus achieving a convergence criterion of 10^{-6}. Each calculation was repeated 30 times and for further analysis the output with the highest tVAF was used.

There were two inputs. On the one hand, each synergy was calculated individually to obtain the synergies for each of the four conditions (Syn_con), forward without stress (FW NORM), forward with stress (FW STRESS), backward without stress (BW NORM), backward with stress (BW STRESS). This process was essential for the first hypothesis to calculate the synergy vector and compare them between NORM and STRESS. To examine the activation coefficients and thus the third hypothesis, the synergies were not calculated for each condition individually, but for each task (FW or BW), regardless of NORM or STRESS, which was named Syn_tsk. An adjusted knee-point analysis was used on the overall tVAF curve to calculate the number of synergies (NoS) in every condition (Syn_con) and task (Syn_tsk). The point on the tVAF curve with the lowest angle between three following points is the so-called knee-point (v). When using this method, it is assumed that beyond this point, all further synergies only describe unstructured data or noise (Tresch et al., 2006). If the second smallest angle was at most 15° greater than the smallest angle, we chose the lower number of synergies, unless the tVAF difference between the two was over 5%, in which case we opted for the higher number.

Following synergy analyses were computed with Syn_con. Shared synergies between both conditions within one task (NORM – STRESS) were quantified using the Pearson correlation coefficient (r) among all combinations of vectors. If the correlation was higher than the critical r value at sign level 0.01, the synergies were considered shared. The percentage of shared synergies was then calculated using the formula 100*(number of shared synergies/ smaller NoS between conditions). Subsequent synergy analyses were performed using Syn_tsk each at NoS_tsk. With the use of the Pearson correlation coefficient (r), the activation coefficient trial-to-trial variability was explored (Ivanenko et al., 2004; Barroso et al., 2014; Hug et al., 2011; Turpin et al., 2017). All pairwise combinations of activation coefficients from different trials within each synergy for each condition were determined. This procedure was done to explore the overall trial-to-trial variability of activation coefficients. High trial-to-trial similarity was indicated by a high r. The r values were then z-transformed with the fisher transformation. Overall, the analyzed time was between 60-150s of the EDA data.

2.6 Statistical analyses

The statistics were conducted using Jasp 0.18.0.0 (Amsterdam, Netherlands). Normality was examined using the Shapiro-Wilk test. To investigate the effect of mental stress on all parameters, both forward (FW: vw_o - vw_s) and backward (BW: rw_o - rw_s) trials were compared within each other. All parameters were analyzed with a paired samples t-test. A p-value of less than 0.05 was viewed as statistically significant ($p < 0.05$). Additionally, descriptive statistics were provided for all parameters, including the mean, standard deviation, minimum and maximum.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, ChatGPT (https://chatgpt.com) was used to validate the grammar and improve the manuscript's readability. After using this service, the content was carefully reviewed and revised, assuming full responsibility for its accuracy.

3 Results

All participants included in the study completed four three-minute trials: (i) forward movement without stress (FW NORM), (ii) forward movement with stress (FW STRESS), (iii) backward movement without stress (BW NORM), (iv) backward movement with stress (BW STRESS). In the following sections, the forward and backward trials are referred to as *tasks*, and whether stress-induced or not is referred to as *stress*. To be considered significant, the results had to reach a p-value of $p < 0.05$.

3.1 Stress analyses

Tonic skin conductance and thus stress level was indicated by EDA_z. The results were calculated using a paired samples t-test. The mean EDA_z value for FW NORM was -1.156 ± 4.957 and for BW NORM -3.413 ± 4.414. During the STRESS trials, the average value for FW was 4.648 ± 5.246 and for BW -0.389 ± 6.888. Normal distribution was given, and the paired samples t-test revealed a significant result ($p = 0.002$) for familiar movement (FW). Looking at the unfamiliar movement (BW), the p-value of 0.230 was not significant. This indicates that there was a difference between FW NORM and FW STRESS in skin conductance, but not between BW NORM and BW STRESS. Additionally, FW NORM and BW NORM were compared, as well as FW STRESS and BW STRESS. Both measures showed no significance.

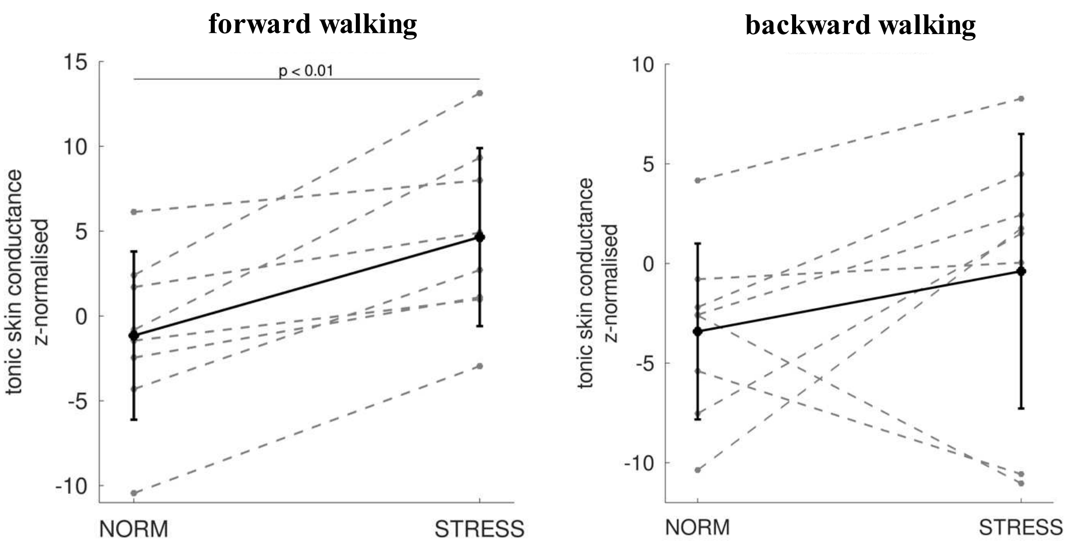

Figure 1. *Stress Level.* Note: left = FW, right = BW, dashed lines = individual participants, thick lines = mean and standard deviation across participants, The x-axis shows the tonic skin conductance z-normalized. The y-axis shows NORM and STRESS.

3.2 Muscle synergy analyses

3.2.1 Synergy vectors

The probands had an average number of synergies (NoS) of 4.250 ± 0.886 for FW NORM and 3.875 ± 0.835 for FW STRESS. For BW, an average of 2.625 ± 1.061 for NORM and 2.875 ± 1.246 for STRESS was determined. The minimum number of synergies was 3 for FW and 2 for BW. The highest number of synergies for FW and BW was 5.

The percentage of shared synergies shown by the subjects during FW and BW (NORM vs. STRESS each) ranged between 50 and 100%. 100% of shared synergies in one task (FW or BW) meant that all synergies used by the subject for this movement were used in both NORM and STRESS. On average, the subjects had 90% shared synergies in the familiar movement and 80% in the unfamiliar movement. Subjects 1, 4, 6 and 8 had 100% shared synergies in both the FW and BW runs. Subject 2 had 75% of shared synergies in the FW task and 100% in the BW task. Subject 5 had 66.667% for FW and 100% for BW, while both subjects 9 and 13 had 100% for FW and 50% for BW. Subject 14 had the fewest shared synergies overall, with 66.667% for FW and 50% for BW.

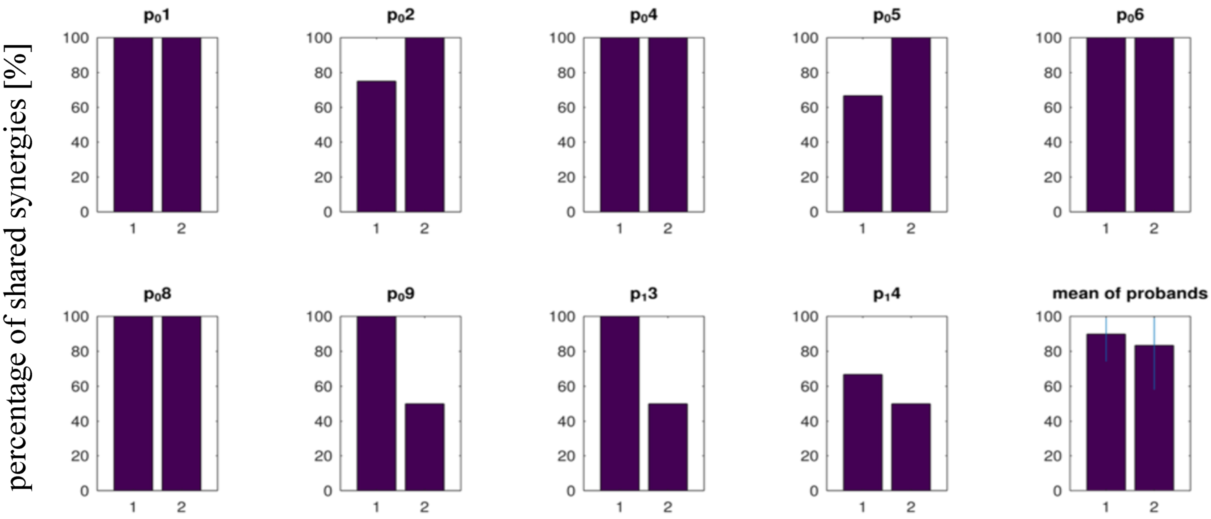

Figure 2. *Percentage of Shared Synergies.* Note: The x-axis shows the percentages of shared synergies from 0 to 100. On the horizontal axis, 1 stands for the familiar movement (FW) and 2 for the unfamiliar movement (BW).

3.2.2 Trial-to-trial variability of activation coefficients

The trial-to-trial variability of activation coefficients showed a mean and standard deviation of 1.484 ± 0.181 for FW NORM and 1.488 ± 0.143 for FW STRESS. The values for BW NORM were 1.328 ± 0.282 and 1.401 ± 0.304 for BW STRESS. Both FW and BW were not significant in the assumption check, indicating no deviation from the normal distribution. The paired samples t-test results for both tasks were not significant, suggesting the trial-to-trial variability of activation coefficients did not fulfill NORM < STRESS in the FW and BW task.

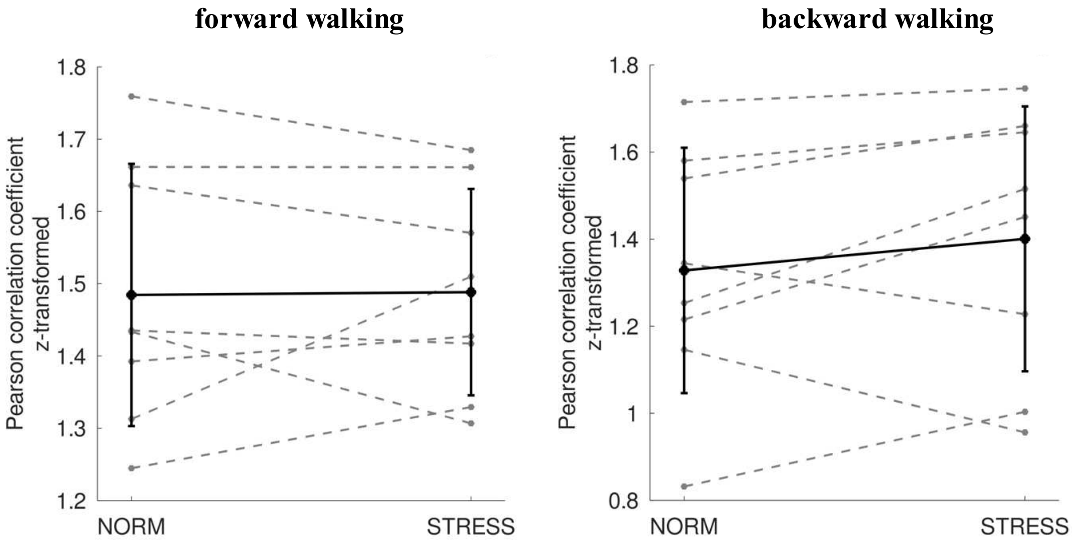

Figure 3. *Activation Coefficient Variability.* Note: left = FW, right = BW, dashed lines = individual participants, thick lines = mean and standard deviation across participants. The x-axis shows the Pearson correlation coefficient z-transformed. The y-axis shows NORM and STRESS.

3.2.3 Trial-to-trial variability of temporal spatial parameter

The relationship between stance and swing phase, the step relation (SREL), was calculated as the duration of the stance phase in seconds divided by the total duration of the step in seconds. The average step relation of the test subjects at FW NORM was 0.651 ± 0.015, at FW STRESS 0.652 ± 0.014, at BW NORM 0.677 ± 0.014, and at BW STRESS 0.686 ± 0.023. The trial-to-trial variability of the SREL had following mean ± standard deviation: FW NORM 1.738 ± 0.185, FW STRESS 2.231 ± 0.547, BW NORM 3.295 ± 0.920 and BW STRESS 3.188 ± 0.736. A normal distribution was assumed. The hypothesis was tested directionally, with the assumption that NORM < STRESS. The paired samples t-test showed a significant result for the FW task with $p = 0.012$ ($p < 0.05$), therefore the trial-to-trial variability of temporal spatial parameters in the familiar movement (FW) was affected by inducing stress. The unfamiliar movement (BW) was not significant, indicating the parameter was not higher in STRESS than NORM.

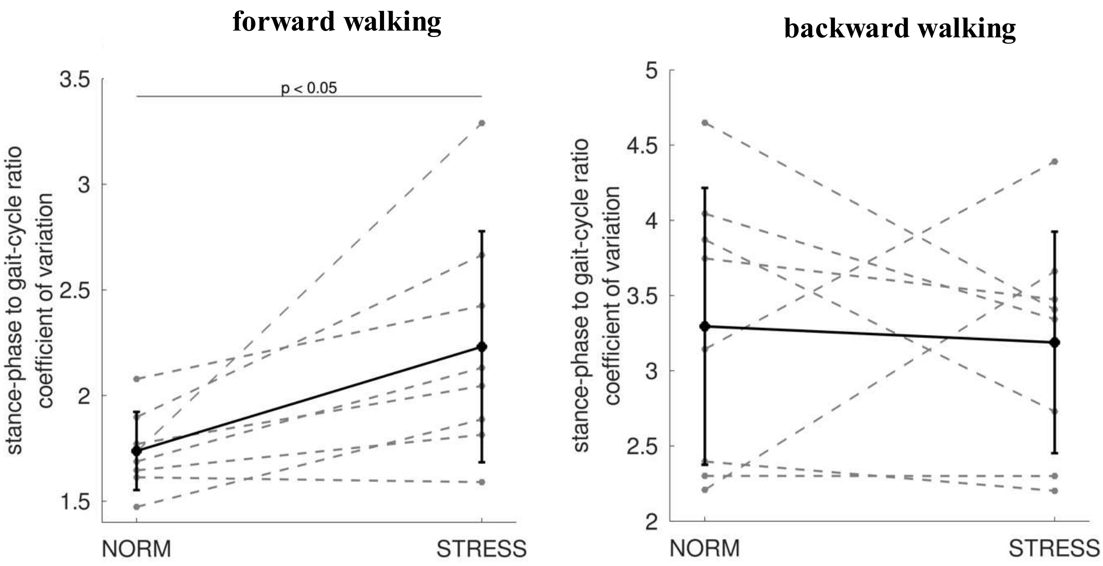

Figure 4. *Temporal Spatial Gait Variability.* Note: left = FW, right = BW, dashed lines = individual participants, thick lines = mean and standard deviation across participants. The x-axis shows the stance-phase to gait-cycle ratio coefficient of variation. The y-axis shows NORM and STRESS.

4 Discussion

Muscle synergies, first identified by Bernstein in 1967, refer to coordinated patterns of muscle activation that facilitate movement control. The term "synergy" emerged from the Greek meaning "working together" and highlights its role (Bergius, 2019). To manage the complexity of motion, the central nervous system reduces the degrees of freedom by activating groups of muscles through common commands rather than individually. This theory suggests that muscle synergies are patterns of muscle activation used to efficiently perform specific movements (Tresch et al., 1999; d'Avella & Bizzi, 2005; Ting & Macpherson, 2005; Ting & McKay, 2007; Cheung et al., 2009; Bizzi & Cheung, 2013).

The aim of this thesis was to examine the impact of mental stress on movement control. For this purpose, human motor control during familiar and unfamiliar movements (forward and backward treadmill motion) was investigated under the influence of stress. Each movement task was conducted with and without a stress condition. It was hypothesized that i) synergy vectors are not influenced by mental stress, ii) trial-to-trial variability of activation coefficients increases with mental stress and iii) trial-to-trial variability of temporal spatial parameters increases with mental stress.

Shared synergies refer to the activation of the same synergy vectors during different movements. This implies that different movement tasks, such as cycling and walking (Hug et al., 2010) share common mechanical subtasks (Barroso et al., 2014; Nazifi et al., 2017). Similar synergies have been found in unperturbed and perturbed walking (Chvatal & Ting, 2013), as well as walking and slipping (Nazifi et al., 2017), which indicates that shared muscle synergies create a motor framework for movement. To date, no studies have examined the relationship between mental stress and shared synergies. However, inducing emotional stress could be considered a form of perturbation. It was hypothesized that synergy vectors would not differ between NORM and STRESS in FW and BW tasks, which was confirmed by the results. Participants showed an average of 90% shared synergies in familiar movements and 80% in unfamiliar movements. Notably, four out of eight participants exhibited 100% shared synergies in both tasks, indicating they used the same synergies in both NORM and STRESS.

Trial-to-trial variability of temporal activation coefficients might be essential for effective movement control (Sylos-Labini et al., 2022; Kaufmann et al., 2023). By examining muscle activity data from stepping neonates, infants, preschoolers and adults, Sylos-Labini et al. (2022) concluded that as modular organization becomes more complex with age, the corresponding variability diminishes. This is linked to potential advantages in learning locomotor tasks. Similarly, Kaufmann et al. (2023) found that when examining tasks with different levels of proficiency, the trial-to-trial similarity increased as movement skills were learned. They also concluded that increasing trial-to-trial similarity, and thus reducing trial-to-trial variability, is important for motor learning. These findings align with the second hypothesis of this thesis, which proposed that trial-to-trial variability of synergy activation coefficients would be lower in NORM and increase with induced stress. Higher variability would indicate more heterogeneous outcomes. Surprisingly, this was not the case, as these parameters did not significantly differ between NORM and STRESS conditions. This might suggest that even though, adjustments to movement are made due to stress, the fundamental mechanisms of movement control stay unchanged.

Induced stress can lead to freezed gait behaviors (Richer et al., 2024) and altered temporal and spatial gait parameters (Ramírez & Gutiérrez, 2021). In this study, it was assumed that trial-to-trial variability of temporal spatial parameters, specifically the relationship between the stance and swing phases, increases under the influence of stress. To test this, the trial-to-trial variability of the step relation was analyzed and showed a significant result for the FW task, indicating that NORM and STRESS differ in familiar movement (NORM < STRESS). Increased variability suggests reduced movement consistency. The authors Ramírez and Gutiérrez (2021) examined the relationship between cognitive impairment and gait. They investigated whether dual-task gait can predict cognitive impairment in older adults by analyzing twelve studies. Consistent with the findings of this thesis, they found significant associations between cognitive decline over time and trial-to-trial variability of temporal spatial parameters. No significant results were observed in the BW task. A possible explanation for this could be that unfamiliar movements, such as walking backwards are inherently more variable. As a result, the data in the NORM condition might already be more heterogeneous, lowering the impact of induced stress. Hak et al. (2012) examined how individuals adapt their gait to regain stability in response to balance perturbations and found that participants primarily adjusted their step length and step frequency. Stokes and colleagues (2017) also studied perturbed walking and concluded that participants exhibited more variable strides and increased variability in postural sway when faced with disturbances. Perturbations and unfamiliar movements could thus lead to an unnatural gait and higher variability.

Some limitations need to be mentioned. The first and most consequential one is that EDA z-scores were used to ensure that the participants were more stressed during the stress trials. However, for BW, the EDA z-scores did not show a significant difference between NORM and STRESS. This could potentially be because walking backward, which is an unfamiliar movement, may have caused stress even without the PASAT, thereby reducing the differentiation between NORM and STRESS conditions. To examine this consideration, a paired samples t-test was conducted to compare FW NORM with BW NORM, as well as FW STRESS with BW STRESS. The statistical results showed no significant results for either comparison. Thus, it remains unclear why the induced stress did not have a significant effect during the BW task. The results and their interpretation should therefore be viewed critically. Another limitation is, that although the order of the trials was randomized so that half of the participants completed BW and the other half FW tasks first, the stress trials were conducted in the same manner (three-minute PASAT audio). This might have caused the participants to become accustomed to the procedure during the second time, resulting in them being less stressed. Additionally, walking on the treadmill was unfamiliar for many participants. Even though they were given time to acclimate to the treadmill at the beginning, it is possible that the walking on the machine itself induced more stress than would be the case under normal circumstances, meaning that treadmill walking may not be fully representative of natural gait.

Researching stress, the associated mechanisms and the effects on those affected is a relevant topic. Stress is considered to play a particularly important role in the development of various diseases (Silverman & Sternberg, 2012). Especially in the context of health, it would be interesting to further examine the effects of stress on movement control. This could reveal whether and how negative emotions generally impact rehabilitation and recovery, for instance, in the orthopedic field. Additionally, it would be important to investigate the effects of stress on more complex movements than walking. Further findings in these areas could also be utilized to better understand human motor control in high-pressure performance contexts. All findings in this area are essential to better understand our control of motion.

5 Conclusion

The aim of this thesis was to investigate the effects of stress on movement control. It can be said that inducing mental stress did not influence the synergy vectors in either the familiar or the unfamiliar movement. On average, the subjects had 90% shared synergies in the familiar movement and 80% in the unfamiliar movement. Similarly, the trial-to-trial variability of the activation coefficients in the FW and BW tasks remained unaffected. The trial-to-trial variability of temporal spatial parameters increased significantly in the familiar movement due to stress, but there was no effect in the unfamiliar movement. To date, the impact of stress on motor control remains largely unexplored, highlighting the need for further investigation in this domain.

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Explanation

„I declare that I have composed this work independently and only used the indicated aids. This work has not been submitted elsewhere (e.g. for other courses) or presented by other individuals (e.g. works by other people from the internet)."

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