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Muscle synergies during bench press

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DOI (link to publication from Publisher):
10.5278/vbn.phd.med.00042

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Kristiansen, M. V. (2015). Muscle synergies during bench press. Aalborg Universitetsforlag. (Ph.d.-serien for Det Sundhedsvidenskabelige Fakultet, Aalborg Universitet). DOI: 10.5278/vbn.phd.med.00042

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MUSCLE SYNERGIES DURING BENCH PRESS

BY
MATHIAS KRISTIANSEN

DISSERTATION SUBMITTED 2015

AALBORG UNIVERSITY
DENMARK

MUSCLE SYNERGIES DURING BENCH PRESS

Ph.D Thesis

by

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AALBORG UNIVERSITY
DENMARK

DISSERTATION SUBMITTED TO DEPARTMENT OF HEALTH SCIENCE AND TECHNOLOGY AT AALBORG UNIVERSITY

Thesis submitted: October 2, 2015

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PhD Series: Faculty of Medicine, Aalborg University

ISSN (online): 2246-1302
ISBN (online): 978-87-7112-378-4

Published by:
Aalborg University Press
Skjernvej 4A, 2nd floor
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

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Printed in Denmark by Rosendahls, 2015

CURRICULUM VITAE

PhD thesis title: Muscle synergies during bench press

PhD Student: Mathias Kristiansen

Supervisor: Associate Prof. Ernst Albin Hansen,

Co-supervisors: Prof. Pascal Madeleine and
Associate Prof. Afshin Samani

List of published/submitted articles:

I. **Kristiansen, M.**, Samani, A., Madeleine, P., Hansen, E. A. Muscle synergies during bench press are reliable across days. J*ournal of electromyography and kinesiology, in revision*.

II. **Kristiansen, M.**, Madeleine, P., Hansen, E. A., Samani, A. 2015 Inter-subject variability of muscle synergies during bench press in power lifters and untrained individuals. *Scandinavian Journal of Medicine and Science in Sports, 25, 1, 89-97*.

III. **Kristiansen, M.**, Samani, A., Madeleine, P., Hansen, E. A. Effects of five weeks of bench press training on muscle synergies – A randomized controlled study. *Journal of strength and conditioning research, in revision*.

ENGLISH SUMMARY

Strength training, in various forms, is a widely practiced form of physical training. It is generally thought that both morphological mechanisms and neurological mechanisms play a role in the increase in strength following training. As the human body represents a linked mechanical system, postural activity specific to the task, bracing, and proper setup of a base of support, is critical for the expression of maximal strength. Thus, the precise activation and timing of agonist, synergist, and antagonist muscles is of paramount importance to forceful execution of the task at hand. This can be referred to as inter-muscular coordination. The general aim of this thesis was to provide further insight into inter-muscular coordination during bench press. This aim was pursued by investigating the reliability of inter-muscular coordination, differences in inter-muscular coordination between groups of different training status, and the effects of upper-body strength training on inter-muscular coordination. For that purpose, muscle synergies were extracted from electromyography data recorded during submaximal bench press by means of nonnegative matrix factorization. Currently, there is a lack of knowledge regarding the reliability of muscle synergy extraction, and the effects of various training modalities on muscle synergies.

In Study (I), the between-day reliability of extracting muscle synergies during bench press was assessed and found to be strong to very strong. In Study (II), a cross-sectional study design was used to asses if differences in muscle synergies reside in subject groups of very different training status. Expert powerlifters were found to exhibit larger inter-subject variability in the synergy activation coefficient and less inter-subject variability in the muscle synergy vectors responsible for the concentric phase of the bench press, compared to untrained subjects. In Study (III), a randomized controlled trial was carried out in an attempt to establish a causal relationship between training and alterations in muscle synergies. Performing a cross-validation test of the extracted muscle synergies, revealed that changes had occurred in the muscle synergies of the group that performed strength training for five weeks, while no changes had occurred in the control group.

The present thesis provided novel data on the between-day reliability of muscle synergies. Further, it was documented that distinct differences in muscle synergies were present between expert powerlifters and untrained subjects, and that five weeks of strength training induced changes in muscle synergies during bench press.

DANSK RESUMÉ

Styrketræning i forskellige former er en meget udbredt form for fysisk træning. Den generelle opfattelse er at en øgning i styrke som følge af styrketræning, er forårsaget af både morfologiske og neurologiske mekanismer. Da den menneskelige krop repræsenterer et forbundet mekanisk system, betyder det at specifik postural aktivitet og opspænd er kritisk i forhold at udøve maksimal kraft. Det vil sige at den præcise aktivering og timing af agonist, synergist, og antagonist muskulatur er af afgørende betydning for udviklingen af kraft i en given øvelse. Dette samspil mellem musklerne, kaldes for inter-muskulær koordination. Det overordnede mål for denne PhD afhandling var at opnå yderligere indsigt i den inter-muskulære koordination ved øvelsen bænkpres. Dette blev gjort ved at undersøge pålideligheden af inter-muskulær koordination, forskellen i inter-muskulær koordination imellem grupper af forskellig træningsstatus, og effekten af styrketræning på inter-muskulær koordination. For at opnå dette blev der udtrukket muskel synergier fra elektromyografisk data, der var blevet optaget ved submaksimal bænkpres, ved brug af en nonnegativ matrix factorization algoritme. Generelt mangler der viden vedrørende pålideligheden af muskel synergier og trænings effekt på muskel synergier.

I studie (I), blev pålideligheden af muskel synergier under bænkpres vurderet til at være stærk til meget stærk. I studie (II), blev et tværsnits studiedesign anvendt til at undersøge forskellen i muskel synergier for to grupper med meget forskellig træningserfaring. Her blev det vist at styrkeløftere på eliteniveau, udviste større variabilitet i den synergi aktiverings koefficient, og mindre variabilitet i de muskler synergi vektorer, som repræsenterede den koncentriske fase i bænkpres, end de forsøgspersoner som var utrænede. I studie (III), blev der udført et randomiseret kontrolleret forsøg, med det mål at etablere at kausalt forhold mellem træning og ændringer i muskel synergier. Udførelsen af en kryds-valideringstest resulterede i at der var sket ændringer i muskel synergierne hos den gruppe som udførte styrketræning i fem uger, hvorimod der ingen ændringer var sket i kontrol gruppen.

Denne afhandling præsenterer nye resultater vedrørende pålideligheden af muskel synergier. Endvidere dokumenteres det at der er tydelig forskel i muskel synergier for styrkeløftere på eliteniveau og utrænede, og at fem ugers styrketræning kan inducere ændringer i muskel synergier under bænkpres.

ACKNOWLEDGEMENTS

Completion of the current thesis would not have been possible without the generous economic support of: The Ministry of Culture Committee on Sports Research in Denmark, The Danish Rheumatism Association, Danish Council for Independent Research | Technology and Production Sciences (FTP), and Otto Mønsted Fonden.

I also wish to thank Aalborg Sportshøjskole for loan of the lifting equipment used during data collection for Study (II). Similarly, I wish to thank Erik Rasmussen from ER-Equipment, for his generous sponsorship of the lifting equipment used during data collection of Study (I) and (III).

Furthermore, I would like to acknowledge the support and encouragement that I have received from my supervisors. I would like to thank: Ernst Albin Hansen, for his bluntly feedback, irrepressible perfectionism and superb guidance. Pascal Madeleine, for his supreme project leadership skills, ability to see one step ahead, and vast high level scientific experience. And Afshin Samani, for his excellent technical and mathematical support and guidance, as well as his hard working ethics. I have gained a tremendous amount of knowledge and experience from working with you all, and for this I am truly thankful.

Last but not least, I would like to acknowledge the love and support I have received from friends and family. Especially, I would like to thank my wife Louise, for her endless support, encouragement and belief in me. This would not have been possible without you.

PREFACE

The present studies were carried out in the period 2012 to 2015 at the Physical Activity and Human Performance group, SMI, Department of Health Science and Technology, Aalborg University, Denmark. The current PhD stipend was funded by Aalborg University.

The thesis is based on the following three articles. In the text these are referred to as Study (I), Study (II), and Study (III) (full-length articles in Appendix).

Study (I):	Kristiansen, M., Samani, A., Madeleine, P., Hansen, E. A. Muscle synergies during bench press are reliable across days. *Journal of electromyography and kinesiology, in revision.*
Study (II):	Kristiansen, M., Madeleine, P., Hansen, E. A., Samani, A. 2015 Inter-subject variability of muscle synergies during bench press in power lifters and untrained individuals. *Scandinavian Journal of Medicine and Science in Sports, 25, 1, 89-97.*
Study (III):	Kristiansen, M., Samani, A., Madeleine, P., Hansen, E. A. Effects of five weeks of bench press training on muscle synergies – A randomized controlled study. *Journal of strength and conditioning research, in revision*.

This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific articles which are listed above. Parts of the articles are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

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LIST OF ABBREVIATIONS

3RM	: Three repetition maximum
C	: Synergy activation coefficient
$C_{\mathrm{Pre\_FixW}}$	: Recomputed synergy activation coefficient for pretest
$C_{\mathrm{Post\_FixW}}$	: Recomputed synergy activation coefficient for posttest
$\mathrm{C}_{\mathrm{preW\text{-}postW}}$	: Correlation of muscle synergy vectors from the pretest and posttest
$\mathrm{C}_{\mathrm{preW\text{-}prefixW}}$	: Correlation of the original and the recomputed muscle synergy vectors from the pretest
$\mathrm{C}_{\mathrm{postW\text{-}postfixW}}$	: Correlation of the original and the recomputed muscle synergy vectors from the posttest
$\mathrm{CC}_{\mathrm{preC\text{-}postC}}$	: Cross-correlation of synergy activation coefficients from the pretest and posttest
$\mathrm{CC}_{\mathrm{preC\text{-}prefixC}}$	: Cross-correlation of the original and the recomputed synergy activation coefficients from the pretest
$\mathrm{CC}_{\mathrm{postC\text{-}postfixC}}$	: Cross-correlation of the original and the recomputed synergy activation coefficients from the posttest
CON	: Control group, Study (III)
e	: Residual error matrix
E	: Initial matrix
EMG	: Electromyography
EXP	: Expert powerlifter group, Study (II)
$\mathrm{ICC}_{3,1}$	: Intraclass correlation coefficient
SEM	: Standard error of measurement
SD	: Standard deviation
TRA	: Training group, Study (III)
UNT	: Untrained subject group, Study (II)
VAF	: Variance accounted for
$\mathrm{VAF}_{\mathrm{Fix\_A}}$	: Recomputed VAF by fixing the synergy activation coefficient, Study (I)
$\mathrm{VAF}_{\mathrm{Fix\_V}}$	: Recomputed VAF by fixing the muscle synergy vector, Study (I)
$\mathrm{VAF}_{\mathrm{Fix\_W}}$	: Recomputed VAF by fixing the muscle synergy vector, Study (III)
$\mathrm{VAF}_{\mathrm{Fix\_C}}$	: Recomputed VAF by fixing the synergy activation coefficient, Study (III)
$\mathrm{VAF}_{\mathrm{muscle}}$	: Variance accounted for of an individual muscle
W	: Muscle synergy vector
$W_{\mathrm{Pre\_FixC}}$	: Recomputed muscle synergy vector for pretest
$W_{\mathrm{Post\_FixC}}$	: Recomputed muscle synergy vector for posttest
ρ_{max}	: Maximum Spearman cross-correlation value
r_{max}	: Maximum Pearson cross-correlation value (r-value)
t_{max}	: Lag time, taken when the correlation value is maximal

1 INTRODUCTION

1.1 STRENGTH TRAINING IN GENERAL

Strength training, in various forms, is a widely practiced form of physical training (19). Strength training is a key component in developing athletic performance (87), in which power output, agility, and reaction time are important parameters. In addition, strength training may also be used as an important part of injury prevention. For instance, specific strength training may counteract muscle strength imbalances. Such imbalances in thigh and hip muscle strength can be predictive of an increased risk of hamstring injury in elite-level Australian football players (10) and adductor muscle strains in professional ice hockey players (80), respectively. Strength training may also serve to combat age-induced declines in muscle strength and function, as elderly also have been shown to respond very well to strength training (22, 60). In particular for the elderly population, maintenance of strength is a key component in the ability to perform normal activities of daily living. Consequently, a decline in strength among elderly individuals has a major impact on their ability to maintain an independent lifestyle, causes physical frailty (20), and induces an increased risk of fall related injuries (85). As described above, the positive effects of strength training are numerous and the practical applications are widespread, underlining the importance of a deeper understanding of the underlying mechanisms responsible for increase and maintenance of strength.

1.2 ADAPTATIONS TO STRENGTH TRAINING

Overall, the mechanisms responsible for the expression of muscular strength levels may be divided into two categories; morphological mechanisms and neurological mechanisms (19). It is generally regarded that the primary morphological adaptation resulting from prolonged strength training, is skeletal muscle hypertrophy. Therefore, muscle hypertrophy following strength training has been widely documented (33, 52). However, during the early stages of a strength training program, only relatively small increases in muscle hypertrophy can be observed (59), whereas strength will typically increase to a much greater extent (24, 44). This creates a mismatch in the time course of strength gain and muscle hypertrophy, as the increase in strength is much higher than what can be explained by the significant, but very small increase in muscle mass. Consequently, the sole increase in muscle hypertrophy cannot account alone for the increase in strength, suggesting that neurological adaptations must play an important role in the expression of strength.

The neurological mechanisms responsible for increases in strength involve both intra-muscular adaptations and inter-muscular adaptations. Several studies have investigated intra-muscular adaptations following strength training. For instance, strength training has been shown to cause an increase in neural drive (1, 23, 70, 84), motor unit firing rate (34, 58), and motor unit synchronization (66) within the agonist muscles. Intuitively, a larger activation of agonist muscles, caused by changes in descending drive, should result in a higher force output, all other things being equal. However, strength is often expressed through the use of multi-joint free weight exercises. In such a setting, the increased force producing capabilities of agonist muscles are not the only important parameter necessary to produce adequate task performance. As the human body represents a linked mechanical system, postural orientation and postural equilibrium are two important factors that must be controlled prior to execution of forceful task (26). Therefore, bracing and postural activity specific to the task are critical for the expression of maximal strength and have thus been shown to adapt following strength training (62). Further, the adaptations in strength have been shown to be highly specific to the postures utilized in training (86). Thus, the precise activation and timing of agonist, synergist, and antagonist muscles are of paramount importance to forceful execution of the task at hand (64). This means that the expression of maximal strength can be viewed as a skilled act, in which the coordination of all the task-relevant muscles must be learned, trough practice. This skilled and learned act can be referred to as inter-muscular coordination. The literature on adaptations in inter-muscular coordination following strength training is rather limited, and has primarily been concentrated on studying the agonist-antagonist relationship during single joint movements. It has thus been shown that strength training may cause an increased coactivation of synergist muscles and a reduced coactivation of antagonist muscles (12, 22). In general, single joint exercises are considered to be simple, and only to a lesser extent influenced by the skill of the subject. However, it has been shown that during submaximal isometric contractions of the knee extensor muscles, subjects adopted various strategies to accomplish the task (56). More specifically, considerable inter-subject and inter-trial variability was present in the contribution of the mono- and biarticular muscles of the thigh. Similar findings on movement variability have also been documented in both a sport (4) and an ergonomic setting (48, 49). This underlines the importance of inter-muscular coordination in the expression of strength while also raising the point of the musculoskeletal system being highly redundant (40).

1.3 REDUNDANCY OF THE MUSCULOSKELETAL SYSTEM

The successful execution of any movement necessitates that the timing and pattern of activation of the involved muscles are precisely coordinated. However, due to the abundance of muscles capable of influencing each joint, and the ability of the central nervous system to adjust the contribution of each of these muscles, any given task can be accomplished using an infinite combination of muscle recruitment. This is commonly referred to as the redundancy of the musculoskeletal system, and was first described by Bernstein (6) and has later received further attention (4, 40, 41, 61, 82). In the framework of the present PhD project, the central nervous system is faced with multiple options for recruiting muscles during the multi-joint strength training exercises utilized. As multi-joint exercises involve many muscles, and as each muscle comprise a large number of motor units, a multi-joint exercise poses a heavy computational burden to the central nervous system. Rather than meticulously controlling each of the thousands of involved motor units during a movement or exercise, it has been theorized that the central nervous system to a large extent controls human movement, through the flexible combination of a few basic activation patterns, also known as motor modules or muscle synergies (6, 32, 38).

1.4 MUSCLE SYNERGIES AS A FRAMEWORK FOR MOTOR CONTROL

A muscle synergy can be characterized as a low dimensional organizational structure, capable of controlling multiple muscles. It is theorized that a muscle synergy can be activated by a single control signal, thus alleviating the computational burden on the central nervous system (68). These neural coordinative structures are thought to be located at the spinal level, and to be controlled by the motor cortical areas and the afferent systems (8). Consequently, muscle synergies have been suggested to provide a simplified strategy for the nervous system to control movements (6, 15, 27, 32, 73, 74). The current research within this field has shown that a few basic patterns/muscle synergies can adequately describe a number of various movements in humans such as: standing (36, 74), walking (30, 47), running (11), pedalling (17, 28, 29), rowing (78, 79), and backward giant swing (21). Further, this approach has also been applied in stroke patients (13) as well as in the presence of acute pain (54). Muscle synergies are also reported to be consistent across a variety of postural perturbations in cats (73) and to be robust in human balance control across different biomechanical contexts in humans (75). However, the effect of strength training on muscle synergies has not been investigated in either a cross-sectional or a longitudinal study design.

1.5 EXTRACTING MUSCLE SYNERGIES USING NONNEGATIVE MATRIX FACTORIZATION

Muscle synergies can be extracted from multiple surface EMG signals using the nonnegative matrix factorization algorithm (42). Thus, the EMG data recorded from multiple muscles is decomposed into the summed activation of a small number of muscle synergies (21, 27, 73, 79), and thus used to study inter-muscular coordination during movements. A muscle synergy consists of two components. The first component is a muscle synergy vector, which represents the relative weighting of each muscle within each synergy (21). The second component is a synergy activation coefficient, which represents the recruitment of the muscle synergy over time (21). The extraction of muscle synergies offers unique insight into the combined timing and activation patterns of multiple muscles during movements, and may thus be used to evaluate inter-muscular coordination in a multi-joint free weight strength training exercise. Currently, there is a lack of knowledge regarding the reliability of muscle synergy extraction, and the effects of various training modalities on muscle synergies.

1.6 AIMS OF THE PHD PROJECT

The general aim of this thesis was to provide further insight into inter-muscular coordination during bench press, possible differences in inter-muscular coordination between groups of different training status, and effects of strength training on inter-muscular coordination. This was accomplished by extracting muscle synergies from EMG data recorded during submaximal bench press by means of nonnegative matrix factorization.

The specific aims of the PhD project were:

1. To investigate the between-day reliability of muscle synergies by applying nonnegative matrix factorization to EMG data collected during bench press (Study I).
2. To elucidate the role of expertise on inter-subject variability of muscle coordination during bench press in groups of expert powerlifters and untrained subjects (Study II).
3. To assess the effect of five weeks of upper body strength training on muscle synergies obtained during bench press.

In Study (I), the absolute and relative between-day reliability of extracting muscle synergies during bench press was assessed. It was hypothesized that muscle synergies extracted during bench press were reliable across days. In Study (II), a cross-sectional study design was used to asses if differences in muscle synergies reside in subject groups of considerably different training status. It was hypothesized, that expert power lifters would display less inter-subject variability in muscle synergies compared to untrained subjects. In Study (III), a randomized controlled trial was carried out in an attempt to establish a causal relationship between training and alterations in muscle synergies. It was hypothesized that inter-and intra-subject alterations in muscle synergies would occur in the group performing training, while the control group would remain unaffected.

2 METHODS

The following section provides an overview of the methods used in the three studies.

2.1 SUBJECTS (STUDY I-III)

In total, 73 subjects participated in the three studies. An overview of number of subjects for each study, as well as baseline training status, strength, anthropometric measures and age can be seen in Table 1. All subjects were healthy males with no history of injuries in the upper extremities requiring surgery. In study (I) all subjects had performed full-body strength training 2-3 times per week for at least 2 years prior to data collection. In study (II), 11 of the subjects comprised elite-level powerlifters, having achieved a mean Wilks-score of 143.3 ± 18.5 in bench press, during an official powerlifting competition. The Wilks-score is a validated method for comparing the performance of lifters from different weight categories (83). The rest of the subjects in study (II), and all of the subjects in study (III) had no experience with strength training prior to data collection. All subjects gave their written informed consent after having been explained the experimental methods and risks according to the Helsinki declaration. The studies were approved by the local ethics committee of North Denmark Region (N-20120036). Besides, Study (III) has been registered as a randomized controlled trial in the International Standard Randomized Controlled Trial Number Register (ISRCTN10375612).

Table 1: Baseline characteristics of the 73 subjects enrolled for the three studies

	Study		
	(I)	(II)	(III)
Number of subjects	21	22 (11+11)	30 (17+13)
Training status	Strength Trained	**A:** Untrained **B:** Powerlifters	**A:** Untrained **B:** Untrained
Strength (3RM in bench press) (kg)	109.2±26.1	**A:** 61.1±11.7 **B:** 163.0±19.9	**A:** 55.2±12.6 **B:** 56.5±19.6
Age (years)	24.5±2.2	**A:** 25.5±3.4 **B:** 28.6±5.8	**A:** 22.9±2.7 **B:** 25.6±4.9
Body mass (kg)	89.0±12.8	**A:** 79.9±10.2 **B:** 102.4±16.5	**A:** 77.2±11.1 **B:** 77.2±16.2
Height (m)	1.81±0.07	**A:** 1.84±0.59 **B:** 1.79±0.43	**A:** 1.80±0.79 **B:** 180.0±0.66

2.2 STRENGTH TESTING (STUDY I-III)

To test the strength of the subjects, a 3RM test was carried out in bench press. The 3RM test consisted of lifting increasingly heavier loads in bench press, until the maximum load which could be lifted three times was found. The protocol was inspired by a previously reported approach (69). Further, similar maximal strength tests, for 1RM (67), 5RM (65), and 8RM (69) has previously been deemed reliable. In general, the subjects started by performing 8–10 repetitions of bench press with a 20 kg barbell. Subsequently, the load was increased by 5–40 kg depending on the estimated capacity of the subject, while the number of repetitions was decreased to five. The load was then increased by another 5–30 kg, and the number of repetitions was further decreased to three. In the following sets, the load was increased by 2.5-10 kg per set of 3 repetitions, until the 3RM load was found. In study (I), subjects were tested twice, with an average of 8.2±2.9 days in between test sessions. In study (II), subjects were tested once. In study (III), subjects were tested before and after a five week period of either upper-body strength training or normal activities of daily living. Strength tests were applied in all three studies as shown in Table 2.

Table 2: Overview of the methods used in the three studies

	Study		
	(I)	(II)	(III)
Strength test	X	X	X
EMG recordings	X	X	X
Extraction of muscle synergies	X	X	X
Barbell acceleration		X	
Barbell displacement	X		X
Upper-body strength training			X

2.3 DATA COLLECTION (STUDY I-III)

To obtain a representative pattern of cyclic muscle activation, 20-40 cycles are commonly used (27, 28, 57). Therefore, all participants performed three sets of eight repetitions at 60% of 3RM. In these sets, the participants were instructed to follow an auditory signal set to 1 Hz, by timing the top and bottom position of the barbell to the signal. This yielded a total of 24 repetitions with a cyclic activation pattern consisting of approximately 1-s eccentric phase and 1-s concentric phase. The data obtained during these repetitions were used for extraction of muscle synergies. To avoid excessive fatigue influencing the data, the intensity of lifting was kept to 60% and 5 min of rest was provided before and between the sets. The first bench press cycle of each set was removed from the data, resulting in a total of 21 complete cycles per participant. The 21 cycles were concatenated to preserve the inter-cycle variability in the data (13, 71).

2.4 NORMALIZATION OF THE TIME SCALE (STUDY I-III)

To enable a point-by-point comparison of EMG activity within or between subjects, a time normalizing technique was used (27). In study (I) and (III) a potentiometer (Model KS60, NTT Nordic Transducer, Hadsund, Denmark) was connected to the middle of the barbell for measurement of the vertical displacement. This enabled a bench press cycle to be defined as the period between two successive top positions. In study (II), an accelerometer (Bang & Olufsen Technology, Struer, Denmark;

diameter 17.6 mm, mass 2.9 g, sensitivity 30 pC/ms−2, linear transmission in the frequency range 0.1–800 Hz) coupled with a charge amplifier (Brüel & Kjaer, NEXUS Conditioning Amplifier Type 2692-C, Naerum, Denmark) was attached to the end of the barbell. A bench press cycle was then defined as the period between two successive maximal peaks of the barbell velocity.

2.5 ELECTROMYOGRAPHIC RECORDINGS (STUDY I-III)

In study (I) and (III), EMG was recorded from 13 muscles, and in study (II), from nine muscles (Table 3). All recordings were done on the right side of the body. Before mounting the EMG electrodes (Ambu Neuroline, 720 01-K/12, Ag/AgCl, inter electrode distance 20 mm, Ambu A/S, Ballerup, Denmark) over the muscles, the skin was shaved, abraded, and cleaned with alcohol. Following data analysis, all data of Trapezius Inferior (TI) were disregarded because of insufficient quality.

Table 3: Overview of the muscles used for EMG recording.

		Study		
Muscle	(Abbreviation)	(I)	(II)	(III)
Pectoralis Major	(PM)	X	X	X
Anterior Deltoideus	(AD)	X	X	X
Biceps Brachii	(BB)	X	X	X
Triceps Brachii Lateral head	(TBL)	X	X	X
Triceps Brachii Medial head	(TBM)	X		X
Latissimus Dorsi	(LD)	X	X	X
Erector Spinae	(ES)	X	X	X
Rectus Femoris	(RF)	X		X
Biceps Femoris	(BF)	X		X
Gastrocnemius Lateral head	(GML)	X		X
Soleus	(SOL)	X	X	X
Vastus Lateralis	(VL)	X	X	X
Vastus Medialis	(VM)	X		X
Trapezius Inferior	(TI)		X	

Most of the electrodes were mounted according to the SENIAM recommendations (25). For PM and LD, which are not listed by SENIAM, the electrodes were mounted four fingerbreadths below the clavicle, medial to the anterior axillary border and 3 fingerbreadths distal to and along the posterior axillary fold, parallel to the lateral border of scapula (43), respectively. A reference electrode was mounted on the ankle, at the lateral malleolus in study (I) and (III). In study (II), two reference electrodes were mounted on the bony prominence of the proximal part of fibula and on the bony prominence of clavicula, respectively.

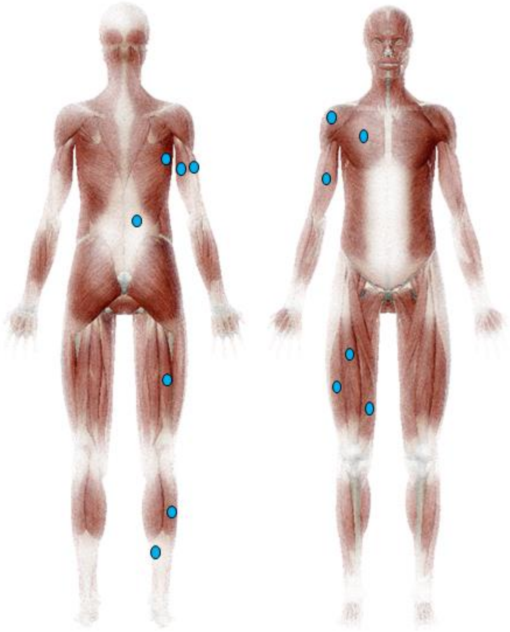

Figure 1: EMG data was recorded from the muscles marked with a blue circle in study (I) and (III).

2.5.1 EMG DATA PROCESSING

All surface EMG signals collected in Study (I-III) were amplified using a 128-channel surface EMG amplifier (EMG-USB, LISiN - OT Bioelectronica, Turin, Italy) with a subject-specific gain factor [500-2000], band-pass filtered [10-750 Hz], and sampled at 2048 Hz. Following complete acquisition, all EMG data were further processed using a digital band-pass filter (Butterworth, 4th order, 10-400 Hz). Furthermore, a notch filter (4th order Butterworth band stop with rejection width of 1 Hz centered at the first three harmonics of the power line frequency of 50 Hz was used to remove line interference. The linear envelopes of the EMG measurements recorded at 60% of 3RM, were computed over one bench press cycle and then interpolated into 100 time points. This was done for all cycles.

2.5.2 NORMALIZATION OF EMG

The use of surface EMG is challenged by inter- and intra-individual differences in conductivity, creating the need for a normalization procedure. In such a procedure, the EMG data can be normalized with respect to a maximum or a reference voluntary contraction. However, during a dynamic cyclic task, in this case bench press, the optimal normalization approach is still a matter of debate (9). In the online supplementary material for Study (II), five different normalization approaches were evaluated. Based on this, the submaximal dynamic normalization procedure was chosen. This entailed a submaximal set in bench press performed solely for normalization purposes, following the 3RM test. In this set, three repetitions were performed at 75% of the 3RM load. The first and last half a second of these EMG measurements were excluded, and the linear envelopes were computed (low pass filter, Butterworth, 4th order, cut off frequency at 5 Hz) and averaged across 100 ms non-overlapping intervals. The maximum of these averaged values were used as normalization factors.

2.6 NONNEGATIVE MATRIX FACTORIZATION (STUDY I-III)

For the extraction of muscle synergies, a nonnegative matrix factorization was applied to the concatenation of the 21 bench press cycles (57) obtained at 60% of 3RM, using the Lee and Seung algorithm (42) in agreement with previous studies (21, 28, 29, 53, 57, 74, 79). Nonnegative matrix factorization decomposes the initial matrix E, into two multiplication matrices (W and C), while enforcing nonnegativity of the elements of those two matrices. The nonnegative matrix factorization is essentially an optimization problem and can be formulated as: Min$\left| E - WC \right|$FRO, with W and $C \geq 0$. Where E is a p-by-n matrix, p is the number of muscles (13 or 9 muscles) and n is the number of time points (100 time points times 21 cycles = 2100 time points). W is a p-by-s matrix, where s is the number of synergies. The C matrix is a s-by-n matrix. $\left|\;\right|$FRO denotes the Frobenius norm (square root of sum of an array's elements squared). The columns of W consist of the muscle synergy vectors, which represents the relative weighting of each muscle within each synergy. Muscle synergy vectors are denoted on a scale ranging from 0 to 1. C represents the synergy activation coefficient, which represents the recruitment of the muscle synergy over time.

2.6.1 VARIANCE ACCOUNTED FOR

The number of synergies chosen for further analysis is dependent on the variance accounted for (VAF). Letting e be the residual error matrix, $e = E - WC$ which is also a p-by-n matrix like E. VAF was calculated using the following equation:

$$VAF = 1 - \frac{\sum_{i=1}^{p} \sum_{j=1}^{n} (e_{i,j})^2}{\sum_{i=1}^{p} \sum_{j=1}^{n} (E_{i,j})^2} \qquad [1]$$

VAF indicates the amount of variability that is accounted for by the synergy activation coefficients and muscle synergy vectors in the matrix *E*. A VAF of 100% indicates a 100% reconstruction of matrix *E* using the *WC*-matrix factorization model, meaning that the residual error *e* is a 0-vector. In line with previous work (28, 74, 79), the smallest number of synergies that provided a VAF ≥ 90% for all participants was accepted.

2.6.2 FUNCTIONAL SORTING

The smallest number of muscle synergies that described ≥90% of VAF, were functionally sorted (74). Functional sorting is an important procedure, as the order of the muscle synergies may be swapped among participants following application of the nonnegative matrix factorization. The muscle synergies were sorted based on the similarity of their muscle synergy vector and synergy activation coefficients to those of a reference muscle synergy (initially a reference subject). This procedure was iterated until no change in the sorting of the muscle synergy parameters occurred. In study (III), the synergy parameters were subsequently sorted across the groups. After each iteration, the reference muscle synergy was updated by averaging the muscle synergy parameters across the subjects.

2.7 CROSS-VALIDATION OF MUSCLE SYNERGIES (STUDY I-III)

To evaluate changes of the extracted synergy activation coefficients and muscle synergy vectors from pretest to posttest in study (I) and (III), a cross-validation analysis similar to that performed by Frère and Hug (21) was performed. In this iterative procedure, the muscle synergy vectors extracted in the pretest were recomputed, using the fixed synergy activation coefficients from the posttest as follows:

$$W_{ij}^{(n)} = W_{ij}^{(n-1)} \left(\frac{\left(E * C_{fixed}^{T}\right)_{ij}}{\left(W^{(n-1)} * C_{fixed} * C_{fixed}^{T}\right)_{ij}} \right) \qquad [2]$$

where C was fixed, W was being recomputed, n was the iteration counter, and i and j were indices corresponding to the row and column elements of the matrices. This yielded a new variable, termed $W_{\text{Pre\_FixC}}$. This iteration process continued until the reconstruction error converged. $W^{(n)}$ was initially randomized in each of the above formulations. T was the transposed matrix. A similar procedure was then performed to re-compute the muscle synergy vectors extracted in the posttest using the fixed synergy activation coefficients from the pretest. This yielded a second new variable, termed $W_{\text{Post\_FixC}}$. The new recomputed muscle synergy vectors were then compared to their original versions in each test, using correlation analysis. The outcome of the correlation analysis was termed $\mathrm{C}_{\text{preW-prefixW}}$ and $\mathrm{C}_{\text{postW-postfixW}}$. A similar procedure, as described above, was carried out for the synergy activation coefficients, as they were recomputed, using the fixed muscle synergy vector from either the pretest or the posttest as follows:

$$C_{ij}^{(n)} = C_{ij}^{(n-1)} \left(\frac{\left(W_{fixed}^{T} * E\right)_{ij}}{\left(W_{fixed}^{T} * W_{fixed} * C^{(n-1)}\right)_{ij}} \right) \qquad [3]$$

where W was fixed, and C was being recomputed. This yielded a third and a fourth new component termed $C_{\text{Pre\_FixW}}$ and $C_{\text{Post\_FixW}}$, respectively. The new recomputed synergy activation coefficients were then compared to their original versions in each test using the maximum of the cross-correlation function. The outcomes of the cross-correlation analyses were termed $\mathrm{CC}_{\text{preC-prefixC}}$ and $\mathrm{CC}_{\text{postC-postfixC}}$.

Lag times were calculated as the absolute time delay between the two waveforms of synergy activation coefficients, where the cross-correlation function was maximal within an approx. 200 ms time window around the zero lag. This was to account for a possible minor distortion in the time line of the recomputed synergy activation coefficients (29, 79).

In study (II), intra-group similarity of muscle synergy vectors and synergy activation coefficients was assessed using a similar analysis as the one described above. The purpose of the analysis was to check that the muscle synergies extracted from one subject account for the overall and individual EMG pattern of each of the other subjects in that group. First, the muscle synergy vectors extracted from one subject was held fixed while the synergy activation coefficient of the compared subject is free to vary. Using an iteratively update rule, the EMG matrix is then updated until convergence. The process was performed for each of the 72 pairs in UNT (nine subjects compared with the eight others) and each of the 90 pairs in EXP (ten subjects compared with the nine others). The success of the fixed muscle synergy vectors and the computed activation coefficients in reconstructing the EMG patterns were based on the overall VAF and $\mathrm{VAF}_{\text{muscle}}$. A $\mathrm{VAF}_{\text{muscle}} \geq 75\%$ has previously been found to be satisfying (74). Following this procedure, a similar analysis was carried out in which the synergy activation coefficients were held fixed and the muscle synergy vectors were free to vary.

2.8 STRENGTH TRAINING PROTOCOL (STUDY III)

In study (III), 17 subjects completed a five week upper-body strength training intervention designed to increase their 3RM in bench press. Subjects trained three times per week (Monday, Wednesday, and Friday), with each session lasting approximately one hour. All training sessions were supervised by personal trainers in order to ensure correct exercise technique and compliance to the specified training program. The main exercise in the training program was bench press, which was trained in all 15 training sessions. Three submaximal sets in bench press constituted the warm-up before every training session, with increasing load and decreasing repetitions per set (12 repetitions in the first set, 10 repetitions in the second set, and 8 repetitions in the third set). The training program was progressive and can be seen in table 4.

Table 4: Overview of the strength training regimen for bench press applied in Study (III)

	Week 1-2	Week 3-4	Week 5
Training sessions per week	3	3	3
Training sets per session	3	3	4
Repetitions per set	6	5	3
Load	7RM	6RM	4RM

Three min of rest were applied between sets. If the load was either too heavy or too light during the work sets, the personal trainers adjusted the load for the next set. Additionally, six assistance exercises were performed per week. Five different back exercises (bend over rows, seated rows, neutral grip latissimus dorsi pull down, face pull, and bend over reverse dumbbell flies) were incorporated to prevent injuries occurring from excessive training of the anterior muscles relative to the posterior muscles of the upper body. One assistance exercise (push down) was used to strengthen the Triceps Brachii muscles. Assistance exercises can be seen in table 5. Two min of rest were applied between sets of assistance exercises.

Table 5: Overview of the assistance exercises used in the strength training program in Study (III)

Monday	Training sets per session	Repetitions per set	Load
Barbell bent over row	4	12	14RM
Face pull	3	12	25RM
Wednesday	Training sets per session	Repetitions per set	Load
Push down	3	12	14RM
Latissimus dorsi pull down	3	12	25RM
Friday	Training sets per session	Repetitions per set	Load
Seated row	3	12	14RM
Bend over reverse dumbbell flies	3	12	25RM

2.9 STATISTICS

For the statistics applied in the three studies, the reader is referred to the articles/manuscripts of Study (I-III). In addition, further statistical analyses have been performed for the present thesis. The data from all the strength measurements of Study (I-III) have been compared across groups using a one-way ANOVA, with a Tukey post hoc test. SPSS Version 22.0 (IBM Corp; Armonk, NY, USA) was used for all statistical analyses. Statistical significance was accepted at $p \leq 0.05$. Results are presented as median [25th;75th]percentile, unless otherwise indicated.

3 RESULTS

The main results of the three studies are summarized in this section. The reader is referred to the original articles/manuscripts for further details.

3.1 STRENGTH (STUDY I-III)

In study (I), the 3RM in bench press was not different in the pre and posttest session ($p>0.05$) for the strength trained subjects. In study (II), EXP was significantly stronger than UNT ($p \leq 0.05$). And in study (III), TRA significantly increased 3RM in bench press with 19.0% [10.3%;21.7%] ($p<0.001$), while no change occurred in CON. However, applying the one-way ANOVA statistics, as shown in figure 2, resulted in the strength level of TRA in study (III), measured at the posttest, not being significantly different from the other groups of untrained subjects, despite the significant increase in 3RM.

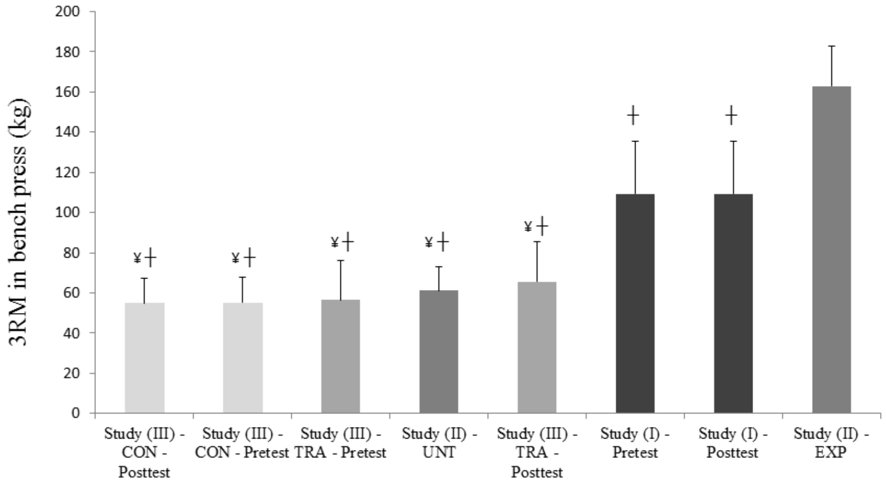

Figure 2: All results of the 3RM bench press test for all groups in the three studies, presented as mean ± SD. The elite powerlifters from the EXP group of Study (II) were significantly stronger than all other groups. The strength trained subjects from Study (I), was significantly stronger than all groups containing untrained subjects, including TRA from Study (III). ¥ significantly different from Study (I) – Pretest ($p \leq 0.05$) and Study (I) –Posttest ($p \leq 0.05$). ┼ significantly different from Study (II) –EXP ($p \leq 0.05$).

The group of strength trained subjects from study (I) was significantly stronger than all other groups containing untrained subjects, as well as TRA from study (III) ($p \leq 0.05$). However, the EXP group from Study (II) was significantly stronger than all other groups ($p \leq 0.05$). This indicates that five weeks of strength training is enough to produce a significant increase in strength compared to untrained subjects, but not enough to make up for the minimum of two years of training experience possessed by the strength trained subjects in study (I). Similarly, the strength of EXP was significantly larger than the strength of the strength trained subjects from study (I), indicating that years of training are needed to develop elite strength levels.

3.2 VARIANCE ACCOUNTED FOR (VAF)

A VAF >90% is required for optimal reconstruction of the original matrix E, when extracting muscle synergies. It was common for all three studies, that two muscle synergies were required, in order for all participants to be above this this level. VAF values of all three studies can be seen in figure 3.

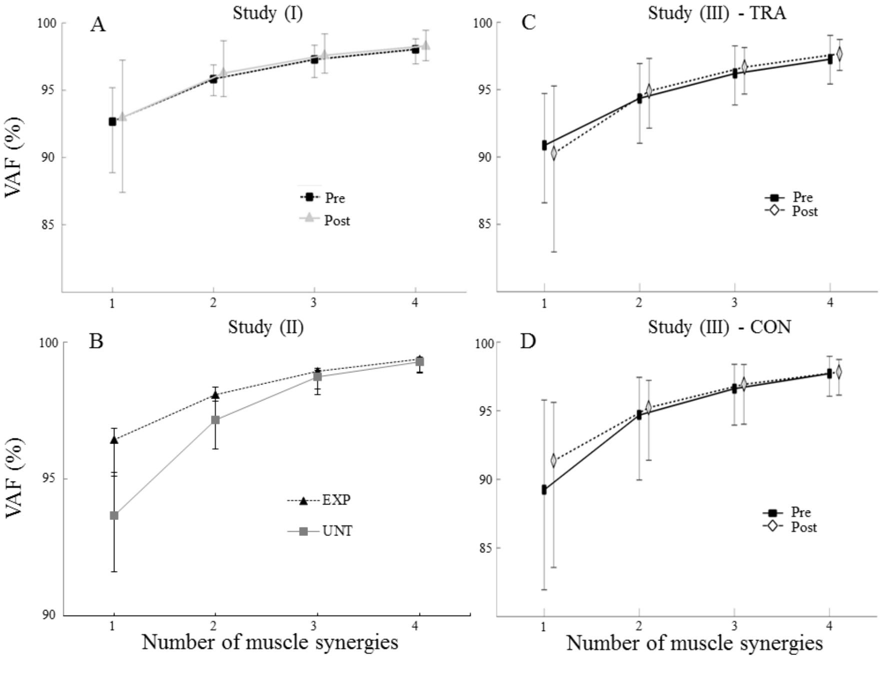

Figure 3: The percentage of variance accounted for (VAF, %) depicted as a function of the number of extracted muscle synergies for all three studies. In all studies, two muscle synergies were needed for VAF >90%. In A, C, and D, values are presented as mean ± minimum and maximum values. In B, values are presented as median ± 25^{th} and 75^{th} percentile. Adopted from study (I), (II), and (III).

3.3 MUSCLE SYNERGIES (STUDY I-III)

In general of Study (I-III), the first muscle synergy reflected the eccentric phase of the bench press, while the second muscle synergy reflected the concentric phase. In study (I), the peak activity of synergy activation coefficient 1, representing the eccentric phase, occurred just before the 50th time point. The peak activity of synergy activation coefficient 2, representing the concentric phase, occurred in the second half of the bench press cycle, between the 50th and 100th time point. This is shown in figure 4. In the eccentric phase, the muscle synergy vectors, which were weighted the highest, belonged to the lower extremities (i.e. VM, Vl, SOL, and GML). In the concentric phase the muscle synergy vectors representing the agonist muscles (i.e. PM, AD, TBL, and TBM), were weighted the highest.

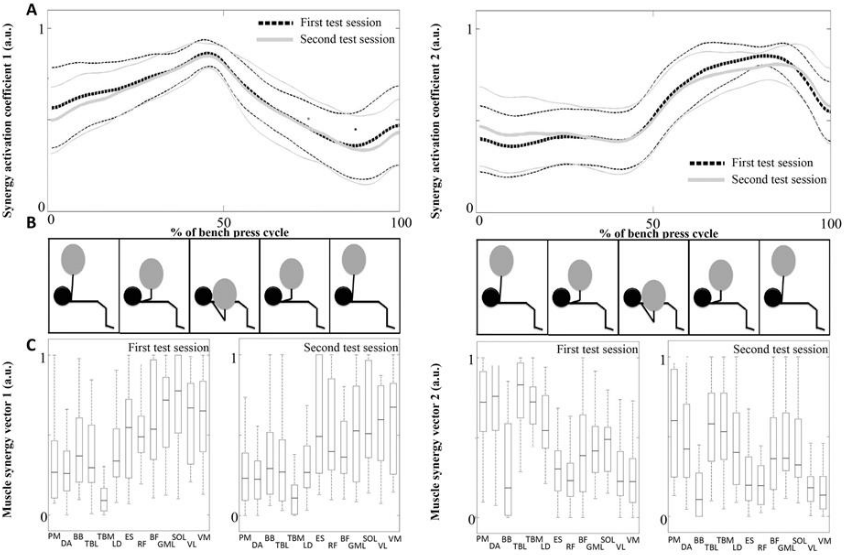

Figure 4: Synergy activation coefficient 1 and 2 (A, left and right panel, respectively) and muscle synergy vector 1 and 2 (C, left and right panel, respectively) of the first and second test session in study (I). (B) represents a graphical illustration of the bench press cycle. The thin lines in A represent 25th and 75th percentiles. The bottom and top of the boxes in C represent 25th and 75th percentiles. The band inside the box represents the median. Box whiskers extend to the most extreme data. For muscle abbreviations, se table 3. Adopted from study (I).

In study (II), the peak activity in synergy activation coefficient 1, occurs just prior to the peak activity of synergy activation coefficient 2, as depicted in figure 5. It should be noticed that the start of the bench press cycle is shifted, due to the use of the accelerometer for normalization of the time scale. The onset of the synergy activation coefficients was calculated from the point of maximal velocity, which occurred approximately in the middle of the eccentric phase. In the eccentric phase, the muscle synergy vectors were weighted relatively evenly. ES, TB and VL were the primary contributors in EXP and BB the primary contributor in UNT. In the concentric phase of the bench press cycle the muscle synergy vectors weighted the highest were the primary agonist muscles (i.e. PM, AD, and TB) for both EXP and UNT.

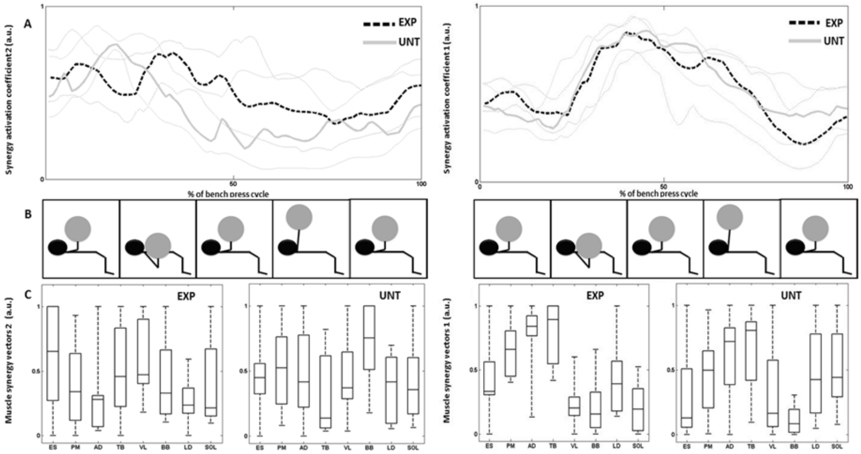

Figure 5: Synergy activation coefficient 1 and 2 (A, left and right panel, respectively). The dashed and solid lines indicate the synergy activation coefficient for expert power lifters and untrained subjects, respectively. Thin dashed line represent 25th and 75th percentile. (B) Graphical presentation of the range of motion in bench press. Box plot of muscle synergy vectors 1 and 2 (C, all panels). The bottom and top of the box represents [25th and 75th percentiles]. The band inside the box represents the median. Whiskers extend to the most extreme data. For muscle abbreviations, se table 3. Adopted from Study (II).

In Study (III), the general pattern of the synergy activation coefficients and muscle synergy vectors were similar to that found in Study (I). Again, this meant that the peak activity of synergy activation coefficient 1, representing the eccentric phase, occurred just before the 50th time point for both TRA and CON, as depicted in figure 6.

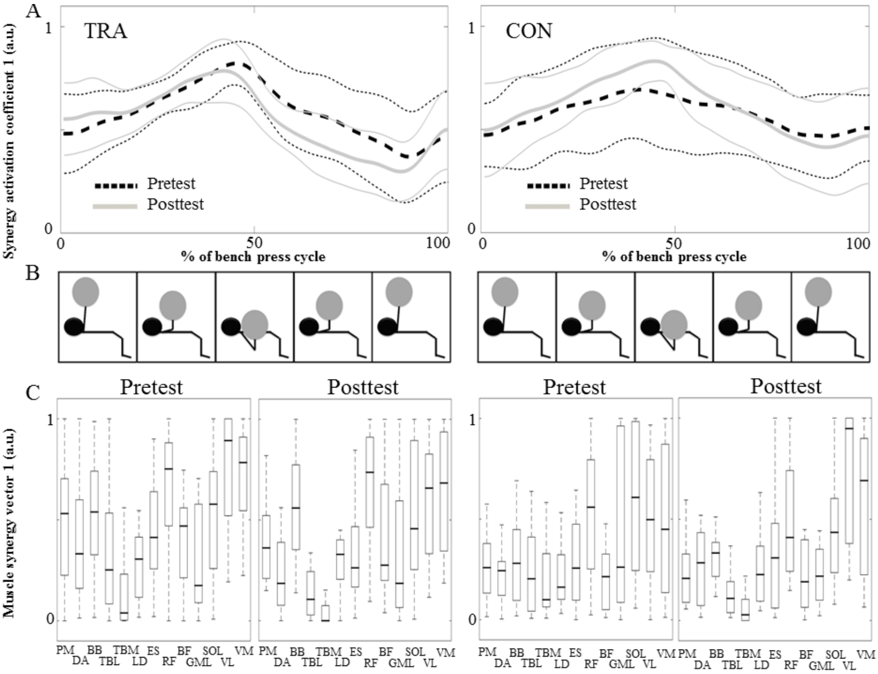

Figure 6: Synergy activation coefficient 1 (A, left and right panel, respectively) and muscle synergy vector 1 (C, all panels) for the pretest and posttest of the training group (TRA) and the control group (CON). (B) Graphical presentation of the range of motion in bench press. Muscle synergy 1 mainly involved the eccentric phase of the bench press cycle. The thin lines in A represent 25th and 75th percentiles. The bottom and top of the boxes in C represent 25th and 75th percentiles. The band inside the box represents the median. Box whiskers extend to the most extreme data. For muscle abbreviations, se table 3. Adopted from Study (III).

Similarly, the peak activity of synergy activation coefficient 2, representing the concentric phase, occurred between the 50^{th} and 100^{th} time point. This was the case for both TRA and CON, and is depicted in figure 7. As seen in Study (I), the muscle synergy vectors weighted the highest in the eccentric phase, belonged to the lower extremities (i.e. VM, Vl, SOL, and RF). In the concentric phase the muscle synergy vectors representing the agonist muscles (i.e. PM, AD, TBL, and TBM), were weighted the highest.

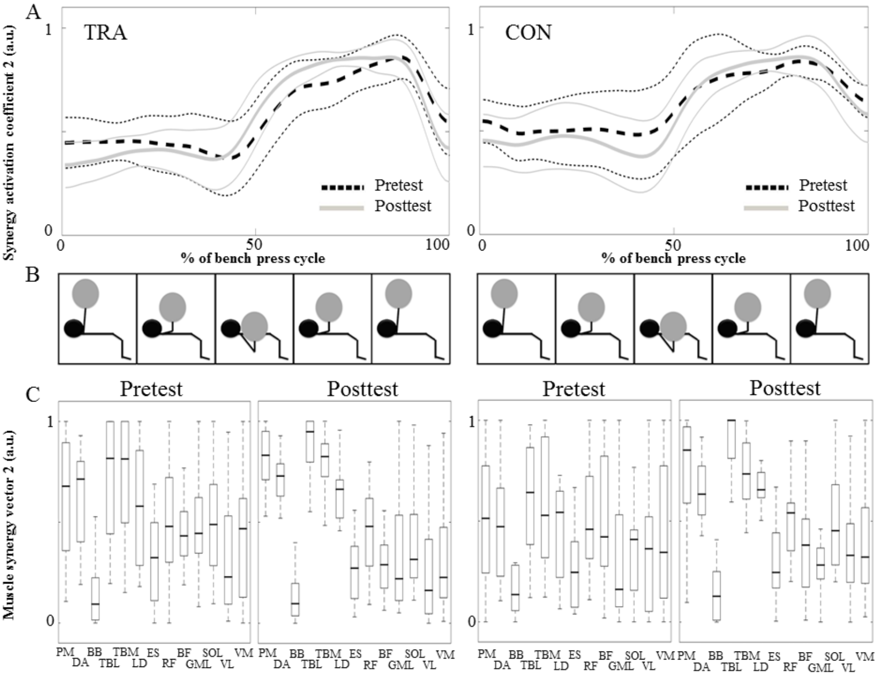

Figure 7: Synergy activation coefficient 2 (A, left and right panel, respectively) and muscle synergy vector 2 (C, all panels) for the pretest and posttest of the training group (TRA) and the control group (CON). (B) Graphical presentation of the range of motion in bench press. Muscle synergy 2 mainly involved the concentric phase of the bench press cycle. The thin lines in A represent 25th and 75th percentiles. The bottom and top of the boxes in C represent 25th and 75th percentiles. The band inside the box represents the median. Box whiskers extend to the most extreme data. For muscle abbreviations, se table 3. Adopted from Study (III).

3.4 RELIABILITY OF MUSCLE SYNERGIES (STUDY I)

Comparing the synergy components from the first and second test session of study (I) resulted in strong correlations for muscle synergy vectors (*r*-values of 0.58 and 0.62) and very strong correlations for synergy activation coefficients (*r*-values of 0.84 and 0.89) according to previously defined categories (51) (Table 6).

Moreover, the original components were compared to the recomputed components of the first and second test session by the use of correlation as can be seen in Table 6. This showed a very strong correlation for muscle synergy vectors and synergy activation coefficients in all instances (*r*-values of 0.74-0.88). For muscle synergy vectors, $ICC_{3,1}$-values were almost perfect (0.85 and 0.95) according to previously proposed categories (39). SEM values were 0.10 and 0.16. For synergy activation coefficients, $ICC_{3,1}$-values were substantial (0.70) and almost perfect (0.90), with SEM values being 0.06 in both cases.

For lag times, $ICC_{3,1}$-values were substantial (0.69 and 0.80), and SEM values were 75 ms and 84 ms. In general, the two muscle synergies that described the eccentric and concentric phases of the bench press, were reliable across days, as indicated by the high correlation coefficients, high $ICC_{3,1}$-values, and low SEM values.

Table 6 Comparison of muscle synergies across test sessions and comparison of original and recomputed components of muscle synergies consisting of muscle synergy vectors, synergy activation coefficients, and lag times. Adopted from Study (I).

	Muscle synergy vector 1	Muscle synergy vector 2
First vs second test session (r)	0.58±0.42	0.62±0.41
Recomputed component vs original component for:		
First test session (r)	0.74±0.46	0.75±0.46
Second test session (r)	0.75±0.41	0.82±0.36
$ICC_{3,1}$	0.95	0.85
SEM (r)	0.10	0.16

	Synergy activation coefficient 1	Synergy activation coefficient 2
First vs second test session (r_{max})	0.84±0.22	0.89±0.13
Recomputed component vs original component for:		
First test session (r)	0.86±0.22	0.75±0.46
Second test session (r)	0.88±0.19	0.82±0.36
$ICC_{3,1}$	0.90	0.70
SEM (r)	0.06	0.06

	Lag time (t_{max}) Synergy activation coefficient 1	Lag time (t_{max}) Synergy activation coefficient 2
First vs second test session (ms)	110±158	134±188
Recomputed component vs original component for:		
First test session (ms)	102±176	78±142
Second test session (ms)	82±124	122±202
$ICC_{3,1}$	0.69	0.80
SEM (ms)	84	75

3.5 EFFECT OF EXPERTISE ON MUSCLE SYNERGIES (STUDY II)

Following data acquisition in study (II), three subjects (one from EXP and two from UNT) were omitted from the data analysis due to lost data. Comparing the inter-subject variability between EXP and UNT for synergy activation coefficient 1 and muscle synergy vector 1 revealed no significant differences, in study (II). For synergy activation coefficient 2, the median ρ_{max} was significantly lower in EXP (0.59 [0.49;0.77]) than in UNT (0.83 [0.71;0.88]) ($p \leq 0.001$) as shown in table 7. This point at significantly higher inter-subject variability in the activation pattern responsible for the concentric phase of the bench press in EXP compared with UNT. No significant differences were present when comparing muscle synergy vector 1 between groups. However, for muscle synergy vector 2, the median ρ in EXP (0.48 [0.02;0.70]) was significantly higher than in UNT (0.15 [−0.08;0.46]) ($p = 0.03$). This indicates a more similar contribution of the same muscles in the concentric phase for EXP compared with UNT.

In UNT, VAF_{muscle} was significantly lower when the muscle synergy vectors were fixed, compared to when the synergy activation coefficients were fixed ($p \leq 0.001$). This was not the case in EXP, and no differences were found between VAF_{muscle} values, when either the muscle synergy vectors or the synergy activation coefficients were held fixed.

Table 7: Cross-correlation coefficients (ρ_{max}) of synergy activation coefficients, correlation coefficients (ρ) of muscle synergy vectors and lag times (t_{max}) for EXP and UNT. EXP: expert power lifters (N=10), UNT: untrained subjects (N=9). Adopted from Study (II).

Variables	EXP		UNT		*p*-value
	Median	25th;75th percentile	Median	25th; 75th percentile	
Synergy activation coefficient 1 (ρ_{max})	0.65	[0.52;0.79]	0.71	[0.58;0.85]	0.190
Synergy activation coefficient 2 (ρ_{max})	0.59	[0.49;0.77]	0.83	[0.71;0.88]	**<0.001**
Variables	Median	25th; 75th percentile	Median	25th; 75th percentile	*p*-value
Muscle synergy vectors 1 (ρ)	-0.02	[0.32;0.40]	0.08	[-0.33;0.30]	0.951
Muscle synergy vectors 2(ρ)	0.48	[0.02;0.70]	0.15	[-0.08;0.46]	**0.029**
Variables	Median	25th; 75th percentile	Median	25th; 75th percentile	*p*-value
Lag time (ms) activation coefficient	21	[5.5;32]	8	[4.3;21.3]	0.076
Lag time (ms) activation coefficient	8	[3.5;15.5]	3.5	[0;13]	0.073

3.6 EFFECT OF STRENGTH TRAINING ON MUSCLE SYNERGIES (STUDY III)

In study (III), all 17 subjects in TRA completed all training sessions causing adherence to be 100%. Inter-group differences in muscle synergies were evaluated by comparing all VAF-values, cross-correlation values, and correlation values across groups. In the pretest, $\mathrm{VAF}_{\mathrm{Fix\_W}}$, was significantly lower in TRA compared to CON (*p*=0.033). No other significant differences were present between TRA and CON.

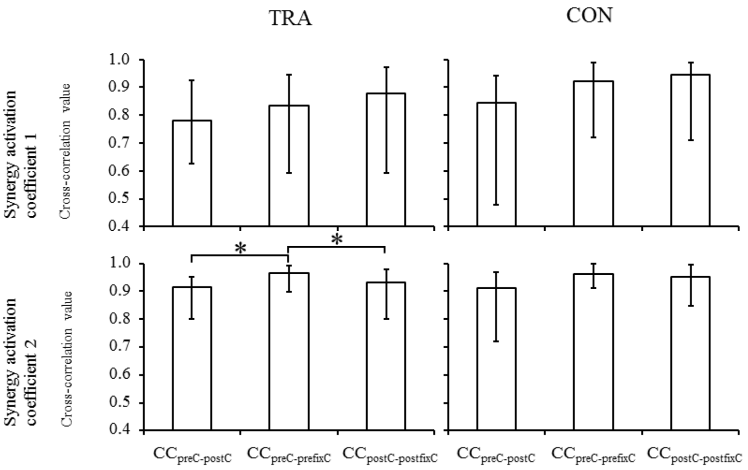

Figure 8: Bar plot of cross-correlation values for synergy activation coefficient 1 and synergy activation coefficient 2 in the pretest and the posttest for the training group (TRA) and the control group (CON) of study (III). In each group cross-correlations were made between pretest and posttest, pretest and C_{Fix_W}, and posttest and C_{Fix_C}. Top of bar represents median cross-correlation value. Whiskers extend to 25th and 75th percentiles. $*p \leq 0.05$, for intra-group comparisons. Adopted from Study (III).

A cross-validation procedure was used to evaluate intra-group changes from pretest to posttest. The recomputed variables were calculated, by fixing either the muscle synergy vector or the synergy activation coefficient, where after they were cross-correlated with their original counterpart. The results of the statistical comparison of the obtained *r*-values can be seen in figure 8 for synergy activation coefficients, figure 9 for lag times, and figure 10 for muscle synergy vectors. In TRA, this resulted in no significant changes observed for synergy activation coefficient 1. However, for synergy activation coefficient 2, $CC_{preC\text{-}postC}$ was significantly lower than $CC_{preC\text{-}prefixC}$ (p=0.009) (Figure 8). This significant change indicates that the pretest synergy activation coefficient 2, representing the concentric phase, is somewhat different than the one from the posttest. $CC_{postC\text{-}postfixC}$ was also significantly lower than $CC_{preC\text{-}prefixC}$ (p=0.033). No difference was observed between $CC_{preC\text{-}postC}$ and $CC_{postC\text{-}postfixC}$. In CON, there were found no significant differences in the obtained *r*-values. This indicates that roughly the same synergy activation coefficients were applied at both test sessions for the subjects in CON.

In TRA, lag times for $CC_{preC\text{-}prefixC}$ in synergy activation coefficient 2, were significantly lower than the lag times obtained for $CC_{preC\text{-}postC}$ (p=0.027) (Figure 9). Further, lag times for $CC_{preC\text{-}prefixC}$ in synergy activation coefficient 2, were also significantly lower than for $CC_{postC\text{-}postfixC}$ (p=0.045). This is indicative of a change in the synchrony of synergy activation coefficient 2 from pretest to posttest. No differences were observed in the lag times obtained for $CC_{\text{preC-postC}}$ and for $CC_{\text{postC-postfixC}}$. In CON, no differences were observed, indicating that the synchrony remained intact between pretest and posttest.

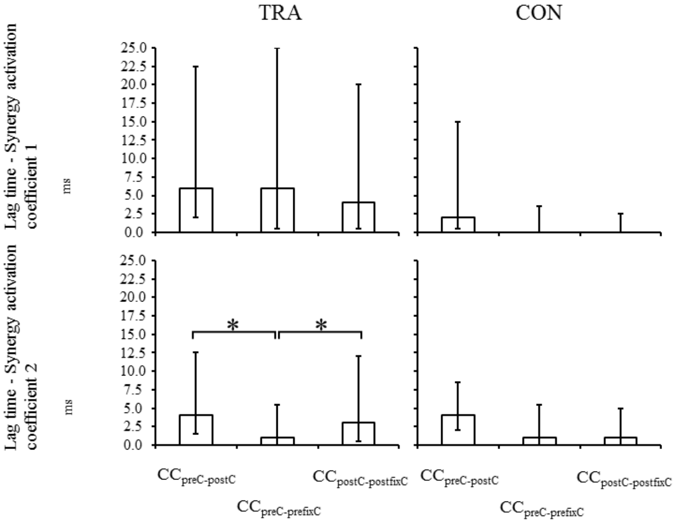

Figure 9: Bar plot of lag time values for synergy activation coefficient 1 and synergy activation coefficient 2 in the pretest and the posttest for the training group (TRA) and the control group (CON) in study (III). In each group lag times were calculated following cross-correlations between synergy activation coefficients from pretest and posttest, from pretest and C_{PreFix_W}*, and from posttest and* $C_{PostFix\_C}$*. Top of bar represents median cross-correlation value. Whiskers extend to 25th and 75th percentiles. ** $p \leq 0.05$*, for intra-group comparisons. Adopted from Study (III).*

For TRA, the correlation value of $C_{\text{preW-postW}}$ in muscle synergy vector 1, was significantly lower than $C_{\text{preW-prefixW}}$ (p=0.009), and $C_{\text{postW-postfixW}}$ (p=0.015). For muscle synergy vector 2, the correlation value of $C_{\text{preW-postW}}$ was significantly lower than the correlation values obtained for $C_{\text{preW-prefixW}}$ (p<0.001) and for $C_{\text{postW-postfixW}}$ (p=0.030). Further, the correlation value obtained for $C_{\text{postW-postfixW}}$ was also lower than $C_{\text{preW-prefixW}}$ (p=0.05) (Figure 10). These results indicate that a significant change has occurred in the weighting of muscle synergy vector 1 and 2 from pretest to the posttest in TRA. In CON, the correlation value obtained for $C_{\text{preW-postW}}$ in muscle synergy vector 1, was significantly lower than the value for $C_{\text{preW-prefixW}}$ (p=0.009), but not different from $C_{\text{postW-postfixW}}$ (p=0.084). No significant differences were observed for muscle synergy vector 2 (Figure 10).

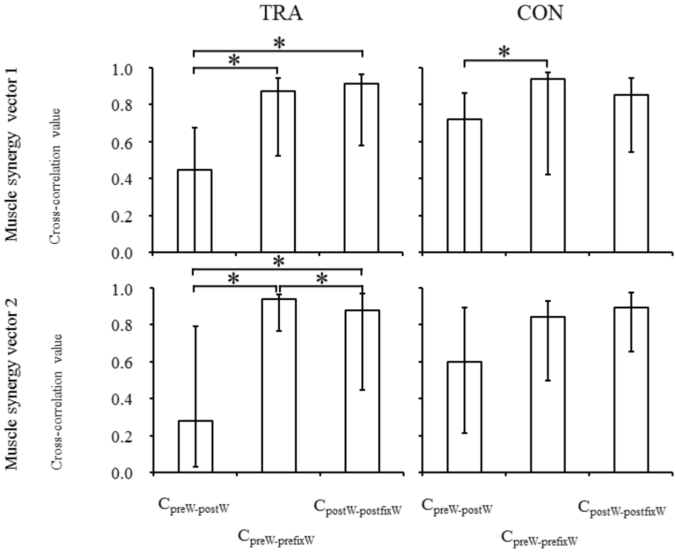

*Figure 10: Bar plot of correlation values for muscle synergy vector 1 and muscle synergy vector 2 in the pretest and the posttest for the training group (TRA) and the control group (CON) in study (III). In each group, correlations were made between muscle synergy vectors from pretest and posttest, from pretest and C_{Fix_W}, and from posttest and C_{Fix_C}. Top of bar represents median cross-correlation value. Whiskers extend to 25th and 75th percentiles. * $p \leq 0.05$, for intra-group comparisons. Adopted from Study (III).*

4 DISCUSSION

The aim of the current thesis was to provide further insight into inter-muscular coordination during bench press through extraction of muscle synergies using nonnegative matrix factorization. To this extent three studies were carried out, all including EMG data recordings from multiple muscles during bench press at 60% of 3RM. The main findings of the three studies were as follows: Muscle synergies extracted during bench press on different days, can be reliably quantified. Synergy activation coefficients and muscle synergy vectors displayed very strong and strong correlations, respectively (I). Significant differences in inter-subject variability of muscle synergies are present between EXP and UNT. In EXP, higher inter-subject variability is present in the synergy activation coefficient responsible for the concentric phase compared to UNT. Furthermore, EXP displays a more similar contribution of the same muscles in the concentric phase compared to UNT, as reflected by the higher similarity of the muscle synergy vectors (II). Five weeks of bench press training did not lead to significant inter-group changes in muscle synergies between CON and TRA. However, significant changes was seen when a cross-validation procedure was applied, indicating that changes in muscle synergies did occur in TRA, but not in CON (III). The following chapter will provide an in depth discussion of the main findings, limitations and perspectives of the thesis.

4.1 STRENGTH

From figure 2, it is apparent that significant differences resided in the 3RM in bench press of the subject groups enlisted for this PhD project. Subjects in EXP (Study II) were significantly stronger than all other subject groups. This is expected, due to the subjects in this group having at least six years of strength training experience, and all of them belonging to the Danish powerlifting elite and the Danish national team in powerlifting. The subjects recruited for Study (I), all had at least two year’s experience with full body strength training. As a result, they were significantly stronger than the untrained subjects recruited for study (II) and Study (III). The subjects in TRA, managed to significantly increase their 3RM in bench press, while no change occurred in the 3RM of the subjects in CON (III). However, despite this increase in strength, it was not enough to significantly separate TRA from the untrained subjects in Study II and III, when the ANOVA statistics were applied for a multiple comparison. This indicates that the strength level in TRA was only modestly improved, as expected after only five weeks of strength training. From these results, it can be inferred that elite strength levels (EXP), are only achievable following many years of rigorous training. The distribution of neural and morphological adaptations to such high performance strength levels is not easily assessed. Muscle hypertrophy, certainly plays a role in the expression of maximal strength, as can be seen from table 1. Here the mean body mass is 102.4 kg in EXP and only 79.9 kg in UNT. However, neural adaptations are also bound to affect the strength increments attained following many years of strength training.

4.2 VAF AND NUMBER OF MUSCLE SYNERGIES

To determine the number of extracted muscle synergies, the widely used criterion of VAF > 90% was used (74). In all three studies, this resulted in the extraction of two muscle synergies. In general, the first muscle synergy reflected the eccentric phase of the bench press, while the second muscle synergy reflected the concentric phase. These results imply, that the muscle synergies extracted during bench press of 73 strength trained or untrained subjects represent a general neural strategy underlying the inter-muscular coordination of bench press.

The cross-validation procedure allowed for recomputing the VAF-values, depending on whether the synergy activation coefficients or muscle synergy vectors were fixed. In Study (I), VAF_{Fix_A} for both test sessions (92.7% and 92.4%), resulted in higher VAF-values than VAF_{Fix_V} (86.8% and 84.9%). In study (II), fixing the muscle synergy vector (median VAF-value of 84.4%) resulted in lower VAF-values than fixing the synergy activation coefficient VAF-value of 87.8%) for EXP. In UNT, fixing the muscle synergy vectors (VAF-value of 72.6%) similarly resulted in lower VAF-value than when fixing the synergy activation coefficients (VAF-value of 87.8%). The same was true in Study (III), where VAF_{Fix_W} was significantly lower than VAF_{Fix_C}, in the pretest for TRA, and in the posttest for TRA and CON. In general this was not expected as the opposite has been shown during a backward giant swing (21). Namely that higher VAF-values were obtained when muscle synergy vectors were fixed compared to when synergy activation coefficients were fixed. In fact, several studies have reported similar results (21, 29, 63, 74), and it has thus been suggested that muscle synergies are spatially fixed while their temporal patterns of recruitment can vary (63). However, this idea is challenged by the results of the present thesis, which indicates that muscle synergies during bench press are temporally fixed while the spatial dimension is free to vary (I, II, III). Other studies support the notion that the temporal recruitment patterns are invariant, while the spatial dimension is free to vary (11, 30, 31). One possible explanation of the diverging results can be found in the experimental procedures of the studies. The studies advocating for spatially fixed recruitment patterns did not control the tempo of execution during giant backswing (21), maximal sprint cycling (29), or various postural perturbations (63, 74). In contrast, the studies advocating for a fixed temporal pattern of recruitment, did control the tempo of execution during bench press (I, II, III), walking (30, 31), and running (11). It is therefore possible that the controlled tempo of execution in the studies of the present thesis (I, II, III), guided by the metronome, provided a temporal reference point for the synergy activation coefficients, thereby fixing the temporal recruitment patterns during bench press (III).

4.3 RELIABILITY OF MUSCLE SYNERGIES (STUDY I)

The reliability of EMG data during closed kinetic chain upper body pressing exercises has previously been reported to be good to excellent (16). However, due to the complexity of the nonnegative matrix factorization algorithm, one cannot directly conclude about the reliability of muscle synergy components based on the reliability of the rectified EMG. Further, it is of paramount importance to test the between-day reliability of this method, if it is to be used for quantification of changes in inter-muscular coordination over time.

The results of Study I showed that the between-day reliability of muscle synergy vectors and synergy activation coefficients were strong and very strong, respectively. Muscle synergy vectors were slightly less reliable than synergy activation coefficients. This can be explained by the fact that the cross-correlation of synergy activation coefficients is calculated from 100 samples, while only 13 samples are used for muscle synergy vectors. This creates a computational difference, when comparing the reliability of the two components. Due to this difference, a larger estimation variance is expected in muscle synergy vectors compared to synergy activation coefficients (I) (50). Another explanation is that the musculoskeletal system displays profound redundancy (40), enabling any movement to be performed using a wide variety of different muscle recruitment options. The fact that muscle synergy vectors were slightly less reliable, may indicate that the relative weighting of each of the muscles within each synergy is subject to small variations between the first and second test session, as a result of the musculoskeletal redundancy (I). In spite of this difference, the reliability of the muscle synergy vectors was still strong, indicating good between-day reliability. Similarly, the synergy activation coefficients displayed very strong correlations between the first and second test session (I). This supports our main hypothesis, indicating that muscle synergies are reliable across days, and that the same basic motor output patterns were responsible for the inter-muscular coordination in the first and second test session.

In addition to the correlation analysis, a cross-validation procedure was performed in which each of the muscle synergy vectors and synergy activation coefficients were recomputed (I). This procedure was carried out to verify the within-subject reliability of the extracted muscle synergies. The cross-validation procedure also served the purpose of providing data for calculating $ICC_{3,1}$-values SEM-values. This is of particular importance as the correlation coefficient is not an appropriate statistical tool for assessment of test-retest reliability, due to an inability in detecting systematic bias (3). Further, the correlation coefficient depends greatly on the range of values in the sample, underlining the downside of purely relying on this measure. Reliability studies should both report absolute and relative reliability of the extracted parameters (3). Consequently, the $ICC_{3,1}$ were used as an index of relative reliability while the SEM served as an index of absolute reliability. The very strong correlation of the r-values (between original and recomputed components), the high $ICC_{3,1}$ values and the low SEM values further indicated that the within-subject reliability of the extracted muscle synergies across test sessions was high (I). These data provide novel information on the robustness of the low dimensional structure of inter-muscular coordination across days (I). The results are supported by previous studies having shown that muscle synergies are consistent across a variety of postural perturbations in cats (73), and are robust in human balance control across different biomechanical contexts (75). Further, the consistency of muscle synergies has also been shown during pedalling at different resistive torques and postures (29).

It therefore seems that at least for strength trained individuals, the neural control of bench press is stable. This indicates that extracting muscle synergies from EMG data using nonnegative matrix factorization is a reliable method for studying muscle coordination during bench press (I). In addition, these results point towards important implications for the use of nonnegative matrix factorization as an assessment tool of inter-muscular coordination.

4.4 EFFECT OF EXPERTISE ON MUSCLE SYNERGIES (STUDY II)

In Study (II), the gross neuromuscular strategy applied during bench press was the same for UNT and EXP, as depicted by the choice of two muscle synergies. These results support the hypothesis that muscle synergies may reflect a neural control strategy. The results are also in line with similar studies indicating that muscle synergies are consistent across expert participants during cycling (28), backward giant swings (21), and rowing (78).

It was hypothesized, that EXP would display less inter-subject variability in muscle synergies compared to UNT. The results, however, unexpectedly showed that synergy activation coefficient 2, representing the concentric phase of the bench press, was more variable among EXP than UNT. Based on this finding, the hypothesis was rejected. On the other hand, EXP displayed less inter-subject variability in the contribution of muscle synergy vectors for the concentric phase compared with UNT as hypothesized (II). It is possible that the higher inter-subject variability in the synergy activation coefficient representing the concentric phase of the bench press in EXP is caused by the application of highly individualized motor strategies following years of strength training. Thus, the gross motor control has most likely been modulated to fit the anthropometry and muscle architecture of the individual, thereby creating a more effective activation pattern, capable of producing higher forces in the specific task (II). The ability to coordinate all the involved muscles in a task, including those used to stabilise the body, have large implications for the ability to lift heavy weights (62). On a further note, skill learning has previously been shown to be able to modify both muscle synergy vectors and synergy activation coefficients in rats (35). This may help explain why the EXP displays significant larger inter-subject variability in synergy activation coefficient 2 compared to UNT. In further support of this, considerable inter-subject variability has been shown in javelin throwers (4), along with considerable inter-subject and inter-trial variability in the contribution of the mono- and biarticular muscles of the thigh during submaximal isometric contractions of the knee extensor muscles (56). Moreover, variability in motor patterns (kinematics of the upper extremity) has been shown to increase with experience in butchers (49). Thus, it may be possible that EXP apply individually modulated muscle synergies while UNT are relying on intrinsic muscle synergies used in similar motor tasks, seeing as they have never tried the bench press exercise before (II).

Regarding muscle synergy vectors, the variability of these were less in EXP compared to UNT for the concentric phase. As muscle synergy vectors represent the relative weighting of each muscle within each synergy, this may imply that during the concentric phase of bench press, the collective activation of the major agonist muscles (PM, AD, and TB) is important for subjects at the elite level.

4.5 EFFECT OF STRENGTH TRAINING ON MUSCLE SYNERGIES (STUDY III)

To investigate the effects of strength training on muscle synergies during bench press, both inter-group and intra-group comparisons were carried out. The inter-group comparison was performed by correlating synergy activation coefficients and muscle synergy vectors between TRA and CON, at pretest and posttest. No significant differences were observed between TRA and CON, despite a significant increase in 3RM bench press by on average 19% in TRA (III). The significant increase in strength in TRA, advocates that either neural or morphological adaptations, or a combination hereof, must have taken place. It has previously been shown that strength training can increase motor unit firing rate (34, 58), motor unit synchronization (66), and neural drive (1, 23, 70, 84) within a similar time frame (III). Similarly, muscle hypertrophy is reported to occur readily after one single bout of strength training exercise (59). It is therefore possible that the majority of the strength increase in TRA, can be attributed to the above mentioned neural and morphological adaptations, and to a lesser extent adaptations in muscle synergies. Further, it is possible that subtle changes may have occurred in inter-muscular coordination, but that the extraction of muscle synergies was not sensitive enough to these changes. It has previously been suggested that “during more complex multi-joint or whole-body movements, the level of antagonist activation may be greater, perhaps providing more opportunity for a reduction in coactivation with training” (19). When properly performed, bench press requires the coordinated activation of all major muscles of the legs, back, and upper body. Plantar flexion of the ankle joint and extension of the knee joint is necessary to create and maintain a stable setup of the body. The hyperextension of the spinal column creates an arch that elevates the chest, which decreases the range of motion of the barbell. The muscles of the upper back (i.e. trapezius, levator scapulae, and rhomboideus) are responsible for maintaining shoulder joint integrity through postural control of the scapula. The agonist muscles of the upper body (i.e. pectoralis major, triceps brachii, and deltoideus anterior) are responsible for exertion of force to the barbell (III). Thus, due to the large number of phasic and postural muscles involved throughout the body during bench press, adaptations in inter-muscular coordination may take longer than five weeks to be manifested.

Intra-group comparisons were performed using the cross-validation approach described in the methods section. In short, this involved recomputing the muscle synergy vectors from the pretest by fixing the synergy activation coefficients from the posttest. The muscle synergy vectors from the posttest were recomputed using the synergy activation coefficients from the pretest. The same procedure was applied to the synergy activation coefficients. The recomputed components were then correlated with their original counterpart, to evaluate if changes had occurred. If the same structure of the synergy components were present at both the pretest and the posttest, the recomputed component would be very similar to the original, thereby resulting in a high correlation value. On the other hand, if changes had occurred in the structure of the synergy components from pretest to posttest, this would result in a weak correlation value.

As described in the results section, significant changes were present in TRA for synergy activation coefficient 2, muscle synergy vector 1 and 2, and lag times for synergy activation coefficient 2. In CON, only one significant change was found for muscle synergy vector 1. This indicates that for CON, roughly the same muscle synergies were applied at pretest and posttest, while this was not the case for TRA (III). Of particularly interest is the low cross-correlation values obtained in $C_{\text{preW-postW}}$ of muscle synergy vector 1 (*r*-value of 0.45) and muscle synergy vector 2 (*r*-value of 0.28) in TRA (III). These values indicate a low correlation, which means that the contribution of the recorded muscles changed from pretest to posttest in TRA. This may be explained by the increased force production capability in bench press attained by the subjects in TRA following the strength training intervention. In study (II), less inter-subject variability was shown for the muscle synergy vectors in the concentric phase of the bench press. Therefore, the results of Study (II) and (III) may indicate that deliberate bench press training modulates the contribution of muscle synergy vectors during bench press as a way of attaining higher force outputs. Such an inter-muscular learning effect has previously been documented during a strength training intervention (62). Further, results from skill training in rodents have shown that muscle synergies can be modulated as a result of training (35). On the other hand the observed changes in TRA, could also be explained by peripheral changes affecting the obtained EMG signals to a greater extent than changes in the neural drive (2) (III). Nonetheless, the cross-validation procedure indicated significant changes in the muscle synergies from pretest to posttest in TRA, but not in CON. Considering that the cross-validation procedure applied in Study (I), indicated substantial to almost perfect reliability of muscle synergies when the cross-validation procedure was applied, it is apparent that the changes observed in TRA is very likely to be the result of the training intervention. Further, the inter-group differences between EXP and UNT in muscle synergies of study (II), combined with the results of study (III) may indicate that the timeframe of adaptations in inter-muscular coordination is long term. However, it should be noted that due to the cross-sectional study design applied in Study (II), causality cannot be inferred between many years of strength training in EXP, and the observed inter-group differences between EXP and UNT.

4.6 METHODOLOGICAL CONSIDERATIONS

The topic of the current thesis falls within the scientific realm of motor control. One of the goals of motor control science is to determine the fundamental output of the central nervous system. More specifically, to determine whether the central nervous system controls the activation of individual motor units, individual muscles, or groups of muscles (76). The hypothesis in support of muscle synergies, argue that the central nervous system produce movements through the flexible combination of low-dimensional modules (6, 32, 38). Currently, evidence exist both in support of and oppose to this hypothesis (76). Proponents argue that muscle synergies provide a solution to the redundancy of the musculoskeletal system, by producing the desired movement through the combination of a few basic activation patterns rather than individually controlling thousands of motor units (7, 14, 72). It is further argued that muscle synergies are part a hierarchical control strategy allowing simplified control of movements, through identification and activation of relevant muscle groupings (45, 46). In contrast, opponents of the hypothesis argue that muscle synergies reflect task constraints, rather than a neural control strategy (37, 81). Similarly it is evident that volitional control of single muscles, single motor units and individual neurons is attainable through practice (18), inferring that muscle synergies are not required for motor control. However, several studies have demonstrated that even complex movements can be performed using a combination of muscle synergies. For instance it has been shown, that a set of extracted muscle synergies from the frog hind limb may produce an efficient and similar control, as to that obtained through the use of individual muscles (5). And a similar study, has extracted muscle synergies from humans during locomotion and then successfully used these synergies to drive a complex musculoskeletal model to perform well coordinated walking (55). Thus, the methods applied in the current thesis and their theoretical background has support, albeit some also oppose the use of such methods for investigation of motor control during movement.

In addition, the research investigating muscle synergies has primarily applied statistical analyses of EMG data recorded during movement, such as nonnegative matrix factorization. It is important to clarify that several different matrix factorization algorithms exist for this purpose, such as: principal component analysis, maximum likelihood factor analysis with varimax rotation, independent component analysis, and probabilistic independent component analysis. This variety in matrix factorization algorithms makes the interpretation of different results difficult even though the algorithms display general agreement in their basic conclusions (77).

4.7 STRENGTHS AND LIMITATIONS

The current thesis has focused on extraction of muscle synergies during bench press. To the best of the author's knowledge, such an approach has not previously been applied in order to investigate neural adaptations in inter-muscular coordination following strength training. Similarly, this thesis presents the first data on between-day reliability of extracting muscle synergies using nonnegative matrix factorization. However, when interpreting the current results, certain limitations should be taken into account.

One limitation is that the tempo of execution during bench presses in Study (I) – (III), was slightly modified. Subjects were instructed to follow an auditory signal set to 1 Hz by timing the top and bottom position of the barbell to the signal. As this mode of performing bench press may not have fitted with the normal tempo of execution, especially in EXP, it may have represented a small perturbation.

In study (II), an accelerometer was used for normalizing the timescale. This was done by calculating the period between two successive maximal peaks of the barbell velocity. Whereas, a potentiometer helped define the period between two successive top positions in study (I) and (III). This resulted in an offset between the starting points of the time scale. In study (II), the timescale started at the point of maximal velocity, approximately half way in to the eccentric phase, while the timescale in study (I) and (III) started from the top position. The integration of the accelerometer data caused a segmentation bias, resulting in the synergy activation coefficients being more rugged, compared to the segmentation done when using the potentiometer. In addition, the point of maximum velocity may have differed between participants inducing some bias. However, visual examinations of the EMG traces showed high consistency between trials and participants. Instead of using the filtered signal and its zero crossing points to segment the surface EMG signal, a double integration of the acceleration signal should have been used to define the precise onset of the eccentric and concentric phase (II).

The number and choice of muscles may impact the results of the muscle synergy analyses (68). Therefore it is a limitation that EMG was recorded from nine muscles in study (II), while recordings were made from 13 muscles in study (I) and (III). As the study design used in study (II) is cross-sectional, it is not possible to infer a causal relationship between the differences in muscle synergies displayed by EXP compared to UNT, and the years of athletic training performed by this group. Finally, the addition of kinematic analyses would have supported the current results, as a direct measure of the actual movement performed by the subjects.

5 CONCLUSIONS

The general aim of this thesis was to provide further insight into inter-muscular coordination during bench press. To accomplish this, muscle synergies were extracted from EMG data recorded during submaximal bench press, using nonnegative matrix factorization.

Study (I) demonstrated that muscle synergies are reliable across days, in strength trained young men. The correlations of muscle synergy vectors and synergy activation coefficients between two test sessions were strong to very strong, and further analysis indicated that $ICC_{3,1}$ values ranged from substantial to almost perfect combined with low SEM values. This demonstrates the consistency of the motor strategy used by the nervous system to control movements like bench press (I).

Study (II) demonstrated significant differences in terms of inter-subject variability in muscle coordination between EXP and UNT. EXP showed larger inter-subject variability than UNT in the synergy activation coefficient representing the concentric phase, as reflected by the lower cross-correlation coefficient. This indicates that EXP applies highly individualized motor strategies after years of training. On the other hand, EXP displayed less variability than UNT in the muscle synergy vectors representing the concentric phase, as reflected by the higher correlation coefficient. This indicates that the similar contribution of certain muscles is important for high performance during bench press (II).

Study (III) demonstrated that five weeks of bench press training, supplemented with assistance upper body strength training, did not induce significant changes in muscle synergies obtained during bench press as compared to a control group, despite a significant increase in 3RM bench press performance. However, significant changes in correlation values for intra-group comparisons indicated that the synergy components changed in TRA, while not in CON.

All in all, these results provide new insights into the neural adaptations underlying inter-muscular coordination during bench press. Although extractions of muscle synergies possess limitations, the valuable knowledge generated in this thesis may act as a starting point for future studies on adaptations in inter-muscular coordination following strength training.

6 PERSPECTIVES

The studies presented in the current thesis contribute to the understanding of how neural adaptations modulate inter-muscular coordination, following strength training. As the use of extracting muscle synergies during strength training exercises are not widely used, this thesis may provide a scientific foundation from which more research can be done within this particular field.

Certainly more research is needed to improve our understanding of the timeframe, in which these neural adaptations occur as well as their specificity to strength training exercises. The five week strength training intervention applied in study (III), proved to elicit significant increases in 3RM bench press, but it was not sufficient to induce direct changes in muscle synergies as investigated via the use of correlation analysis across groups. Only through the use of the cross-validation analysis was it clear that changes had occurred in TRA but not in CON. Future studies, should apply longer strength training interventions with multiple test sessions during the period, in an attempt to map the timeframe of neural adaptations in inter-muscular coordination. In the light of the results presented in the current thesis, it is this author's opinion that such adaptations may take a long time to develop, and thus be partly responsible for performance enhancements into the later stages of a strength and power athlete's career.

Most neural adaptions that result in increased expression of force, exhibit high training exercise-specificity, training velocity-specificity, and range of motion-specificity. Muscle synergies are thought to be flexible building blocks, which can be adapted to fit a wide variety of movements. Future studies should therefore investigate if performance increases, partly caused by modulation of muscle synergies, exhibits the same specificity as other neural adaptations. For instance, it is plausible that the same muscle synergies utilised in the bench press, could be flexibly recruited in the performance of an overhead press. But would strength training in one of the exercises also cause changes in the muscle synergies of the other exercise or does these adaptations occur specifically to the exercise that is trained?

7 THESIS AT A GLANCE

Title of study	Primary aim	Method	Main findings
Study I:			
Muscle synergies during bench press are reliable across days.	To assess the between-day reliability of muscle synergies in strength trained subjects.	Extracting muscle synergies from EMG data obtained during bench press at 60% of 3RM.	Between-day reliability of muscle synergies were found to be strong to very strong.
Study II:			
Inter-subject variability of muscle synergies during bench press in power lifters and untrained individuals.	To asses if differences in muscle synergies reside in subject groups of very different training status.	Extracting muscle synergies from EMG data obtained during bench press at 60% of 3RM.	EXP were found to exhibit larger inter-subject variability in the synergy activation coefficient and less inter-subject variability in the muscle synergy vectors responsible for the concentric phase of the bench press, compared to UNT.
Study III:			
Effects of five weeks of bench press training on muscle synergies – A randomized controlled study.	To establish a causal relationship between training and alterations in muscle synergies	Extracting muscle synergies from EMG data obtained during bench press at 60% of 3RM.	Five weeks of strength training induced changes in muscle synergies during bench press.

8 REFERENCES

References

1. Aagaard, P, Simonsen, EB, Andersen, JL, Magnusson, P, and Dyhre-Poulsen, P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J Appl Physiol* 93: 1318-1326, 2002.

2. Arabadzhiev, TI, Dimitrov, VG, and Dimitrov, GV. The increase in surface EMG could be a misleading measure of neural adaptation during the early gains in strength. *Eur J Appl Physiol* 114: 1645-1655, 2014.

3. Atkinson, G, and Nevill, AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine* 26: 217-238, 1998.

4. Bartlett, R, Wheat, J, and Robins, M. Is movement variability important for sports biomechanists? *Sports Biomechanics* 6: 224-243, 2007.

5. Berniker, M, Jarc, A, Bizzi, E, and Tresch, MC. Simplified and effective motor control based on muscle synergies to exploit musculoskeletal dynamics. *Proc. Natl. Acad. Sci. U. S. A.* 106: 7601-7601-7606, 2009.

6. Bernstein, N. The Coordination and Regulation of Movements. New York; Pergamon Press, 1967.

7. Bizzi, E, D'Avella, A, Saltiel, P, and Tresch, M. Modular Organization of Spinal Motor Systems. *The Neuroscientist* 8: 437-442, 2002.

8. Bizzi, E, and Cheung, VCK. The neural origin of muscle synergies. *Frontiers in Computational Neuroscience* 7: DOI: 10.3389/fncom.2013.00051, 2013.

9. Burden, A. How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. *J Electromyogr Kinesiol* 20: 1023-1035, 2010.

10. Cameron, M, Adams, R, and Maher, C. Motor control and strength as predictors of hamstring injury in elite players of Australian football. *Phys Ther Sport* 4: 159-166, 2003.

11. Cappellini, G, Ivanenko, YP, Poppele, RE, and Lacquaniti, F. Motor patterns in human walking and running. *J Neurophysiol.* 95: 3426-3437, 2006.

12. Carolan, B, and Cafarelli, E. Adaptations in coactivation after isometric resistance training. *J Appl Physiol* 73: 911-917, 1992.

13. Clark, DJ, Ting, LH, Zajac, FE, Neptune, RR, and Kautz, SA. Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. *J Neurophysiol* 103: 844-857, 2010.

14. d'Avella, A, Saltiel, P, and Bizzi, E. Combinations of muscle synergies in the construction of a natural motor behavior. *Nat. Neurosci.* 6: 300-308, 2003.

15. D'Avella, A, and Bizzi, E. Shared and specific muscle synergies in natural motor behaviors. *Proc. Natl. Acad. Sci. U. S. A.* 102: 3076-3081, 2005.

16. de Araújo, RC, Tucci, HT, de Andrade, R, Martins, J, Bevilaqua-Grossi, D, and de Oliveira, AS. Reliability of electromyographic amplitude values of the upper limb muscles during closed kinetic chain exercises with stable and unstable surfaces. *J Electromyogr Kinesiol* 19: 685-694, 2009.

17. Dorel, S, Drouet, J-, Couturier, A, Champoux, Y, and Hug, F. Changes of pedaling technique and muscle coordination during an exhaustive exercise. *Med Sci Sports Exerc* 41: 1277-1286, 2009.

18. Fetz, EE. Volitional control of neural activity: implications for brain-computer interfaces. *J. Physiol. (Lond.)* 579: 571-571-579, 2007.

19. Folland, JP, and Williams, AG. The Adaptations to Strength Training. *Sports Med* 37: 145-168, 2007.

20. Fougère, B, Vellas, B, Van Kan, GA, and Cesari, M. Identification of biological markers for better characterization of older subjects with physical frailty and sarcopenia. *Transl Neurosci* 6: 103-110, 2015.

21. Frère, J, and Hug, F. Between-subject variability of muscle synergies during a complex motor skill. *Front Comput Neurosci* 6: DOI: 10.3389/fncom.2012.00099, 2012.

22. Häkkinen, K, Kallinen, M, Izquierdo, M, Jokelainen, K, Lassila, H, Mälkiä, E, Kraemer, WJ, Newton, RU, and Alen, M. Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. *J Appl Physiol* 84: 1341-1349, 1998.

23. Häkkinen, K, Alen, M, Kallinen, M, Newton, RU, and Kraemer, WJ. Neuromuscular adaptation during prolonged strength training, detraining and re-strength-training in middle-aged and elderly people. *Eur J Appl Physiol* 83: 51-62, 2000.

24. Hansen, S, Kvorning, T, Kjær, M, and Sjøgaard, G. The effect of short-term strength training on human skeletal muscle: The importance of physiologically

elevated hormone levels. *Scandinavian Journal of Medicine and Science in Sports* 11: 347-354, 2001.

25. Hermens, HJ, Freriks, B, Disselhorst-Klug, C, and Rau, G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol* 10: 361-374, 2000.

26. Horak FB, MJ. Postural orientation and equilibrium. In: Handbook of physiology: section 12 exercise: regulation and integration of multiple systems. Rowell LB, SJ, ed. New York: Oxford University Press, 1996. pp. 255.

27. Hug, F. Can muscle coordination be precisely studied by surface electromyography? *J Electromyogr Kinesiol* 21: 1-12, 2010.

28. Hug, F, Turpin, NA, Guével, A, and Dorel, S. Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? *J Appl Physiol* 108: 1727-1736, 2010.

29. Hug, F, Turpin, NA, Couturier, A, and Dorel, S. Consistency of muscle synergies during pedaling across different mechanical constraints. *J Neurophysiol* 106: 91-103, 2011.

30. Ivanenko, YP, Poppele, RE, and Lacquaniti, F. Five basic muscle activation patterns account for muscle activity during human locomotion. *J Physiol* 556: 267-282, 2004.

31. Ivanenko, YP, Cappellini, G, Dominici, N, Poppele, RE, and Lacquaniti, F. Coordination of locomotion with voluntary movements in humans. *J Neurosci* 25: 7238-7253, 2005.

32. Ivanenko, YP, Poppele, RE, and Lacquaniti, F. Motor control programs and walking. *Neuroscientist* 12: 339-348, 2006.

33. Jones, DA, Rutherford, OM, and Parker, DF. Physiological changes in skeletal muscle as a result of strength training. *Q. J. Exp. Physiol.* 74: 233-256, 1989.

34. Kamen, G, and Knight, CA. Training-related adaptations in motor unit discharge rate in young and older adults. *J Gerontol A Biol Sci Med Sci* 59: 1334-1338, 2004.

35. Kargo, WJ, and Nitz, DA. Early Skill Learning Is Expressed through Selection and Tuning of Cortically Represented Muscle Synergies. *Journal of Neuroscience* 23: 11255-11269, 2003.

36. Krishnamoorthy, V, Latash, ML, Scholz, JP, and Zatsiorsky, VM. Muscle synergies during shifts of the center of pressure by standing persons. *Exp Brain Res* 152: 281-292, 2003.

37. Kutch, JJ, Kuo, AD, Bloch, AM, and Rymer, WZ. Endpoint force fluctuations reveal flexible rather than synergistic patterns of muscle cooperation. *J. Neurophysiol.* 100: 2455-2471, 2008.

38. Lacquaniti, F, Ivanenko, YP, and Zago, M. Development of human locomotion. *Curr Opin Neurobiol* 22: 822-828, 2012.

39. Landis, JR, and Koch, GG. The measurement of observer agreement for categorical data. *Biometrics* 33: 159-174, 1977.

40. Latash, ML, Scholz, JP, and Schöner, G. Motor control strategies revealed in the structure of motor variability. *Exercise Sport Sci. Rev.* 30: 26-31, 2002.

41. Latash, ML. Movements that are both variable and optimal. *Journal of human kinetics* 34: 5-5-13, 2012.

42. Lee, DD, and Seung, HS. Learning the parts of objects by non-negative matrix factorization. *Nature* 401: 788-791, 1999.

43. Lehman, GJ, MacMillan, B, MacIntyre, I, Chivers, M, and Fluter, M. Shoulder muscle EMG activity during push up variations on and off a Swiss ball. *Dyn Med* 5:7: DOI: 10.1186/1476-5918-5-7, 2006.

44. Lexell, J, Downham, DY, Larsson, Y, Bruhn, E, and Morsing, B. Heavy-resistance training in older Scandinavian men and women: short- and long-term effects on arm and leg muscles. *Scand. J. Med. Sci. Sports* 5: 329-341, 1995.

45. Lockhart, DB, and Ting, LH. Optimal sensorimotor transformations for balance. *Nat. Neurosci.* 10: 1329-1336, 2007.

46. Loeb, GE, Brown, IE, and Cheng, EJ. A hierarchical foundation for models of sensorimotor control. *Experimental Brain Research* 126: 1-18, 1999.

47. MacLellan, MJ, Ivanenko, YP, Massaad, F, Bruijn, SM, Duysens, J, and Lacquaniti, F. Muscle activation patterns are bilaterally linked during split-belt treadmill walking in humans. *J Neurophysiol* 111: 1541-1552, 2014.

48. Madeleine, P, Mathiassen, SE, and Arendt-Nielsen, L. Changes in the degree of motor variability associated with experimental and chronic neck-shoulder pain during a standardised repetitive arm movement. *Exp. Brain Res.* 185: 689-698, 2008.

49. Madeleine, P, Voigt, M, and Mathiassen, SE. The size of cycle-to-cycle variability in biomechanical exposure among butchers performing a standardised cutting task. *Ergonomics* 51: 1078-1095, 2008.

50. Mak, TK. Estimating variances for all sample sizes by the bootstrap. *Compu Stat Data An* 46: 459-467, 2004.

51. Martínez-Valencia, MA, Linthorne, NP, and Alcaraz, PE. Effect of lower body explosive power on sprint time in a sled-towing exercise. *Science and Sports* 28: e175-e178, 2013.

52. McDonagh, MJN, and Davies, CTM. Adaptive response of mammalian skeletal muscle to exercise with high loads. *Europ. J. Appl. Physiol.* 52: 139-155, 1984.

53. Muceli, S, Boye, AT, D'Avella, A, and Farina, D. Identifying representative synergy matrices for describing muscular activation patterns during multidirectional reaching in the horizontal plane. *J. Neurophysiol.* 103: 1532-1542, 2010.

54. Mucelli, S, Falla, D, and Farina, D. Reorganization of muscle synergies during multidirectional reaching in the horizontal plane with experimental muscle pain. *J Neurophysiol* 111: 1615-1630, 2014.

55. Neptune, RR, Clark, DJ, and Kautz, SA. Modular control of human walking: A simulation study. *J. Biomech.* 42: 1282-1282-1287, 2009.

56. Nozaki, D, Nakazawa, K, and Akai, M. Uncertainty of knee joint muscle activity during knee joint torque exertion: The significance of controlling adjacent joint torque. *J. Appl. Physiol.* 99: 1093-1103, 2005.

57. Oliveira, AS, Gizzi, L, Farina, D, and Kersting, UG. Motor modules of human locomotion: Influence of EMG averaging, concatenation, and number of step cycles. *Front. Human Neurosci.* 8, 2014.

58. Patten, C, Kamen, G, and Rowland, DM. Adaptations in maximal motor unit discharge rate to strength training in young and older adults. *Muscle Nerve* 24: 542-550, 2001.

59. Phillips, SM. Short-term training: When do repeated bouts of resistance exercise become training? *Can J Appl Physiol* 25: 185-193, 2000.

60. Reeves, ND, Narici, MV, and Maganaris, CN. Effect of resistance training on skeletal muscle-specific force in elderly humans. *J Appl Physiol* 96: 885-892, 2004.

61. Robins, M, Wheat, J, Irwin, G, and Bartlett, R. The effect of shooting distance on movement variability in basketball. *J. Hum. Mov. Stud.* 50: 217-238, 2006.

62. Rutherford, OM, and Jones, DA. The role of learning and coordination in strength training. *Eur. J. Appl. Physiol. Occup. Physiol.* 55: 100-105, 1986.

63. Safavynia, SA, and Ting, LH. Task-level feedback can explain temporal recruitment of spatially fixed muscle synergies throughout postural perturbations. *J Neurophysiol* 107: 159-177, 2012.

64. Sale, DG. Neural adaptation to strength training. In: Strength and Power in Sport, Second Edition. Komi, PV, ed. Oxford, UK: Blackwell Science Ltd, 2003. pp. 281.

65. Sascha, G, and Künzell, S. Reliability of a 5-repetition maximum strength test in recreational athletes. *Dtsch. Z. Sportmed.* 65: 314-317, 2014.

66. Semmler, JG, and Nordstrom, MA. Motor unit discharge and force tremor in skill- and strength-trained individuals. *Exp Brain Res* 119: 27-38, 1998.

67. Seo, DI, Kim, E, Fahs, CA, Rossow, L, Young, K, Ferguson, SL, Thiebaud, R, Sherk, VD, Loenneke, JP, Kim, D, Lee, MK, Choi, KH, Bemben, DA, Bemben, MG, and So, WY. Reliability of the one-repetition maximum test based on muscle group and gender. *J. Sports Sci. Med.* 11: 221-225, 2012.

68. Steele, KM, Tresch, MC, and Perreault, EJ. The number and choice of muscles impact the results of muscle synergy analyses. *Frontiers in Computational Neuroscience* 7, 2013.

69. Taylor, JD, and Fletcher, JP. Reliability of the 8-repetition maximum test in men and women. *J. Sci. Med. Sport* 15: 69-73, 2012.

70. Tillin, NA, Pain, MTG, and Folland, JP. Short-term training for explosive strength causes neural and mechanical adaptations. *Exp. Physiol.* 97: 630-641, 2012.

71. Ting, LH, Chvatal, SA, Safavynia, SA, and Lucas Mckay, J. Review and perspective: Neuromechanical considerations for predicting muscle activation patterns for movement. *Int. J. Numer. Methods Biomed. Eng.* 28: 1003-1014, 2012.

72. Ting, LH, and Macpherson, JM. A Limited Set of Muscle Synergies for Force Control During a Postural Task. *J. Neurophysiol.* 93: 609-609-613, 2004.

73. Torres-Oviedo, G, Macpherson, JM, and Ting, LH. Muscle synergy organization is robust across a variety of postural perturbations. *J. Neurophysiol.* 96: 1530-1546, 2006.

74. Torres-Oviedo, G, and Ting, LH. Muscle synergies characterizing human postural responses. *J. Neurophysiol.* 98: 2144-2156, 2007.

75. Torres-Oviedo, G, and Ting, LH. Subject-specific muscle synergies in human balance control are consistent across different biomechanical contexts. *J. Neurophysiol.* 103: 3084-3098, 2010.

76. Tresch, MC, and Jarc, A. The case for and against muscle synergies. *Curr. Opin. Neurobiol.* 19: 601-607, 2009.

77. Tresch, MC, Cheung, VCK, and d'Avella, A. Matrix Factorization Algorithms for the Identification of Muscle Synergies: Evaluation on Simulated and Experimental Data Sets. *J. Neurophysiol.* 95: 2199-2212, 2006.

78. Turpin, NA, Guével, A, Durand, S, and Hug, F. No evidence of expertise-related changes in muscle synergies during rowing. *J Electromyogr Kinesiol* 21: 1030-1040, 2011.

79. Turpin, NA, Guével, A, Durand, S, and Hug, F. Effect of power output on muscle coordination during rowing. *Eur J Appl Physiol* 111: 3017-3029, 2011.

80. Tyler, TF, Nicholas, SJ, Campbell, RJ, and McHugh, MP. The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. *Am J Sports Med* 29: 124-128, 2001.

81. Valero-Cuevas, FJ, Venkadesan, M, and Todorov, E. Structured variability of muscle activations supports the minimal intervention principle of motor control. *J. Neurophysiol.* 102: 59-68, 2009.

82. Van Emmerik, REA, and Van Wegen, EEH. On the functional aspects of variability in postural control. *Exerc. Sport Sci. Rev.* 30: 177-183, 2002.

83. Vanderburgh, PM, and Batterham, AM. Validation of the Wilks powerlifting formula. *Med. Sci. Sports Exerc.* 31: 1869-1875, 1999.

84. Vangsgaard, S, Taylor, JL, Hansen, EA, and Madeleine, P. Changes in H reflex and neuromechanical properties of the trapezius muscle after 5 weeks of eccentric training: A randomized controlled trial. *J Appl Physiol* 116: 1623-1631, 2014.

85. Wickham, C, Cooper, C, Margetts, BM, and Barker, DJP. Muscle strength, activity, housing and the risk of falls in elderly people. *Age Ageing* 18: 47-51, 1989.

86. Wilson, GJ, Murphy, AJ, and Walshe, A. The specificity of strength training: the effect of posture. *Europ. J. Appl. Physiol.* 73: 346-352, 1996.

87. Young, WB. Transfer of strength and power training to sports performance. *Int J Sports Physiol Perform* 1: 74-83, 2006.

9 APPENDICES

I. **Kristiansen, M.**, Samani, A., Madeleine, P., Hansen, E. A. Muscle synergies during bench press are reliable across days. J*ournal of electromyography and kinesiology, in revision*.

II. **Kristiansen, M.**, Madeleine, P., Hansen, E. A., Samani, A. 2015 Inter-subject variability of muscle synergies during bench press in power lifters and untrained individuals. *Scandinavian Journal of Medicine and Science in Sports, 25, 1, 89-97.*

III. **Kristiansen, M.**, Samani, A., Madeleine, P., Hansen, E. A. Effects of five weeks of bench press training on muscle synergies – A randomized controlled study. *Journal of strength and conditioning research, in revision*.

ISSN (online): 2246-1302
ISBN (online): 978-87-7112-378-4

AALBORG **UNIVERSITY PRESS**