Universidade de Lisboa

Faculdade de Motricidade Humana

Intermuscular Coordination in Strength Training:

A transversal study with power clean

Dissertação elaborada com vista à obtenção do Grau de Mestre em Treino de Alto Rendimento

Orientador:

Professor Doutor Pedro Luís Camecelha de Pezarat Correia

JÚRI:

Presidente

Doutora Maria João de Oliveira Valamatos

Professora Auxiliar da Faculdade de Motricidade Humana da Universidade de Lisboa

Vogais

Doutor Pedro Luís Camecelha de Pezarat Correia

Professor Associado com Agregação da Faculdade de Motricidade Humana da Universidade de Lisboa

Doutor João Pedro Casaca da Rocha Vaz

Professor Auxiliar da Universidade Europeia

Paulo Duarte Guia dos Santos

2019

Agradecimentos

Apesar deste capítulo ser aquele em relação ao qual me posso dar ao luxo de escrever de uma forma mais desconcentrada, sem grande atenção aos pormenores, e quase na ausência de pensamento que alguma fadiga mental provoca, é aqui que revejo aquilo que foi todo um processo de fases definidas no seu tempo, espaço e sobretudo nos recursos humanos que colaboraram para a sua galvanização. O que quero dizer é que apesar de ter um documento escrito, fruto de muitas horas de trabalho, nesse documento não estão contempladas as pessoas e tudo o que elas representaram nesta primeira viagem um pouco mais formal pelas Ciências do Desporto, e sei que ao ser impresso, este manuscrito ficará a ganhar pó na biblioteca, provavelmente ninguém se interessará mais por ele, mas sei também que as pessoas que estiveram presentes, em quaisquer que fossem os momentos desta jornada, não serão esquecidas, e continuando com uma presença mais ou menos regular certamente que se tornam em conjunto naquela que considero ser a componente mais enriquecedora que se originou com a elaboração deste trabalho. Neste pequeno texto, terei de ser muito conciso porque o tempo é curto, e correndo já o risco de me esquecer de alguém, peço logo desculpa no primeiro parágrafo para que saibam que não é por mal! Reforço ainda a sensação de alguma ansiedade que sinto por estar prestes a finalizar esta etapa, pois daqui a uns tempos será engraçado voltar a ler isto e recordar de que forma o meu sistema límbico atuava no controlo de emoções primárias, nomeadamente de fuga!

Tal como no power clean, identifico três principais sinergias que então contribuíram para que agora esteja aqui a escrever uns disparates e a apelar a algum tipo de emoções que por norma não me costuma ser característico. As três sinergias (desta vez não definidas pela VAF) são as correspondentes ao trabalho, à família e aos amigos, e sei que a sua participação conjunta, atuando alguns elementos em mais do que uma dessas sinergias, foi preponderante nas várias fases do trabalho.

Em primeiro lugar, é difícil separar aquilo que foi o mestrado, daquilo que é o trabalho na Pós-Graduação. Estas duas diferentes, mas dependentes vertentes da minha vida fizeram com que nos últimos dois anos e meio tivesse uma grande evolução a nível de conhecimento e responsabilidade, e as pessoas que têm "culpa" disso ter acontecido são o Professor Pedro Pezarat, o Professor Pedro Mil-Homens e a Professora Maria João Valamatos, e por isso lhes agradeço. Ao Professor Pedro Mil-Homens por ter sido a pessoa que falou comigo para me candidatar à oportunidade de trabalhar como bolseiro no Laboratório de Função Neuromuscular, e que tantos dias passou comigo e com o Paulo (já lá chego!) a testar circuitos elétricos, a preparar aulas e outras tantas coisas que me trazem boas recordações daquele início em que tudo parecia novo para mim quando acabei a licenciatura. À Professora Maria João por estar também comigo quase que diariamente e por se encontrar sempre disponível para tudo o foi, o que é e (antecipando-me) o que será preciso, e por só se chatear um bocadinho comigo nas ocasiões em que me apanhou na sua cadeira.

Ao Professor Pedro Pezarat, que merece um particular destaque neste texto por ser o meu orientador neste percurso. Relembro as aulas de Anatomofisiologia e de Cinesiologia, que quer pelo conteúdo, quer pela forma de serem dadas pelo Professor, me cativaram desde o início para a parte da investigação. Por toda a disponibilidade, a facilidade com que me conseguiu fornecer todas as condições para fazer o melhor trabalho possível, o tempo despendido quando me surgiam dúvidas (algumas com sentido, outras apenas fruto da minha inexperiência), o saber, e outras tantas valências e momentos que para mim foram sendo peças chave para a evolução pessoal, aqui lhe agradeço, e sabendo que espero vir a agradecer novamente daqui a uns 5 anos no culminar da próxima etapa.

Agradecimentos particulares ao Professor Sandro Freitas, com quem gosto muito de partilhar dúvidas, pois me transmite sempre conhecimento, dando opiniões que me deixam a pensar e que me fazem compreender certos aspetos de vários temas; ao Professor Jorge Infante, que ao manusear ferramentas tão bem ou melhor do que a bola de vólei nos proporcionou tardes de engenhocas, algo em que eu confirmei não ter jeito nenhum; ao Professor Gonçalo Mendonça, com quem aprendi bastante quer ao colaborar em alguns projetos, quer em conversas mais informais; ao Professor Raul Oliveira por todo o apoio que deu quando precisei, assim como pela partilha de conhecimentos noutros projetos. Um agradecimento também à Joana Reis e ao Pedro Fatela por todas as palavras de incentivo, que por conhecerem o meu lado obscuro de reações vagais, apresentam sempre uma enorme vontade de me ver na defesa. Agradeço também ao Laboratório de Biomecânica e Morfologia Funcional, nomeadamente ao Professor António Veloso, à Professora Sílvia Cabral e à Professora Filipa João. Um agradecimento particular ao Bruno Pedro pelas sessões de V3D e não só, espero que nos possamos continuar a ajudar mutuamente.

Um agradecimento especial ao João Vaz, também meu orientador, mesmo que de forma não formal, e que disponibilizou muitas tardes para me ensinar, tirar dúvidas, discutir decisões e acalmar uma ou outra crise existencial que possa ter tido. Uma pessoa por quem desenvolvi um grande apreço e sem a qual esta tese teria sido impossível. Espero que continue esta colaboração, tanto ao nível do doutoramento como noutros projetos paralelos, e que cada vez tenha mais autonomia para poder diminuir o número de mails a chatear. Mais um agradecimento especial para o Paulo Correia, que teve um percurso com timings idênticos ao meu e com quem nos últimos três anos partilhei diariamente um espaço, frustrações, conquistas e outras palavras de cariz filosófico. Juntos aprendemos muita coisa (a verdade é que desaprendi outras tantas!), e sendo o meu "colocador oficial de elétrodos" e tendo participado em todas as recolhas, tem um papel fundamental neste trabalho. Mas atenção, se procrastinas essa sina e o tempo passa, não termina… e quando pensas no avanço, ele bloqueia e rebobina… vê lá se te vem a mística benfiquista para acabares a tese que eu não quero apresentar sozinho!

Agradeço também aos outros ajudantes em recolhas, o Paulo Carvalho e o Miguel Gomes. Para além disso agradeço o apoio do pessoal da caverna (no qual o Fred se inclui), e todas as pessoas aqui da faculdade que diariamente coabitam os mesmos espaços que eu (cantina/"bar", corredores e por aí fora). Um sentimento de empatia especial por todos os que partilham comigo esta fase: Dália, Miguel, Lino, Vasco, Carlos e André!

Deixo aqui também umas palavras relativas ao apoio dado pelos meus pais em tudo o que tem a ver com a elaboração deste trabalho. Sei que o meu pai estará seguro de que terei 21 numa escala até 20, e que por outro lado a minha mãe estará ainda mais nervosa que eu (difícil!), mas é mais uma etapa que espero celebrar com eles no Solar dos Presuntos. Por fim, agradeço também à Ayala pela leitura assídua de todos os capítulos da tese (só que não), mas brincadeiras à parte, sem o seu apoio e confiança em mim (por vezes mais do que eu próprio) teria sido muito mais difícil, e a sua presença faz com que o cansaço pese menos

Com bastante alegria por poder escrever em português de novo, desta forma termino, referindo mais uma vez que este processo foi definido pelas pessoas que nele intervieram, e que este documento (que apenas os mais corajosos se atreverão a ler) é o culminar de uma etapa perfeita na sua imperfeição, com defeitos e procrastinação, mas sobretudo enriquecedora e sempre percorrida numa harmoniosa SINERGIA.

Intermuscular Coordination in Strength Training:

A transversal study with power clean

Coordenação intermuscular em Treino de Força:

Estudo transversal com o power clean

Abstract

Muscle synergy extraction has been utilized to investigate muscle coordination in human movement, namely in sports field. However, there is a lack of information regarding strength training complex motor tasks. Thus, the aim of this thesis was to ensure that this procedure is reliable within- and between-days, and to compare neural strategies adopted by two populations with different levels of expertise. Twelve unexperienced participants and 7 weightlifters performed sets of power cleans, and muscle synergies were extracted from electromyography (EMG) data of 16 muscles. First, we analyzed muscle synergies reliability within the untrained subjects. Then, we compared them with the weightlifters to look for different coordination strategies. We observed that synergistic organization of muscle coordination during power clean remained stable across repetitions, sets and days in unexperienced subjects with slight time adjustments and muscle weightings variations within each synergy. In the other hand, although the same number of synergies has been extracted, all synergies presented slight time shifts between groups, and muscle weightings within each synergy were highly variable. Therefore, these results point to an interventional approach to identify how unexperienced subjects modify coordination over time.

Keywords: 1. muscle synergies; 2. electromyography; 3. muscle coordination; 4. power clean; 5. strength training; 6. reliability; 7. expertise; 8. nonnegative matrix factorization; 9. olympic weightlifting; 10. muscle patterns

Resumo

As sinergias neuromusculares têm sido investigadas para uma melhor compreensão do movimento humano, nomeadamente, no ramo do desporto. No entanto, existe pouca informação relativa a tarefas complexas no âmbito do treino de força. Deste modo, o objetivo desta tese foi, em primeiro lugar, assegurar a reprodutibilidade do procedimento, e em segundo, comparar as estratégias neurais adotadas por duas populações com níveis de desempenho diferenciados. Doze sujeitos destreinados e sete halterofilistas realizaram séries de power cleans, e as sinergias foram extraídas de sinais eletromiográficos provenientes de dezasseis músculos. Por um lado, analisámos a reprodutibilidade das sinergias para cada sujeito destreinado, e por outro, comparámo-las com as de halterofilistas, com o intuito de encontrar diferentes estratégias coordenativas. Observámos que a organização sinérgica da coordenação muscular durante o power clean em sujeitos destreinados permaneceu estável entre repetições, séries e dias, apenas com pequenos ajustes temporais e espaciais. Por sua vez, entre grupos, embora o mesmo número de sinergias tenha sido extraído, todas apresentaram desfasamentos na sua ativação, tendo sido também encontradas diferenças ao nível da sua composição. Deste modo, os resultados apontam para a estruturação de uma intervenção para identificar como é que sujeitos destreinados modificam as estratégias coordenativas ao longo do tempo.

Palavras-chave: 1. sinergias neuromusculares; 2. eletromiografia; 3. coordenação; 4. power clean; 5. treino de força; 6. reprodutibilidade; 7. expertise; 8. factorização não-negativa de matrizes; 9. halterofilismo; 10. padrões de ativação

Index of Contents

List of Figures

Chapter B – Review of Literature

Chapter D – General Methodology

Chapter E – Study 1

Chapter F – Study 2

List of Tables

List of Acronyms

BB – Biceps Brachii

BF – Biceps Femoris

CI – Confidence Interval

CMJ – Countermovement Jump

CNS – Central Nervous System

CPG – Central Pattern Generators

CST – Cluster Strength Training

CUE – Cluster Unexperienced

DOF – Degrees of Freedom

EDC – Extensor Digitorum Communis

EMG – Electromyography

ES – Erector Spinae

EXP – Experienced group

FDS – Flexor Digitorum Superficialis

GL – Lateral Gastrocnemius

Gmax – Gluteus Maximus

ICA – Independent Component Analysis

ICC – Intraclass Correlation

LD – Latissimus Dorsi

LPF – Low-pass Filter

NMF – Nonnegative Matrix Factorization

OE – External Oblique

OWL – Olympic Weightlifting

PCA – Principal Component Analysis

PM – Pectoralis Major

RA – Rectus Abdominis

RFD – Rate of Force Development

RM – Repetition Maximum

ST – Semitendinosus

TA – Tibialis Anterior

TB – Triceps Brachii Lateral Head

TS – Upper Trapezius

UA – Arbitrary Units

UNE – Unexperienced group

VAF – Variance Accounted For

VL – Vastus Lateralis of Quadriceps

VQ – Vector Quantization

A – Structure of the thesis

The present thesis has the major topic the motor control of human movement, particularly in sports science field. We generally aimed to understand how motor systems behave in different populations, ensuring in first place the reliability of the data collection and the processing methodology in subjects that could be submitted to a training process.

The present document is organized according the following structure:

Chapter B is dedicated to the presentation of the state of art, focusing in three principal aspects: Olympic Weightlifting; Neuromuscular adaptations to training; Muscle Synergies.

In **Chapter C** are described the objectives of each study.

Chapter D regards to general aspects of the methodological procedures.

Chapter E and **F** are dedicated to the presentation of each study in a journal article format. The specific topic of each study is introduced, and the methodology will be described, presenting redundant information previously described in **Chapter D**. Furthermore, results are presented and discussed. Each of these chapters has also their own and specific reference list.

Chapter G corresponds to general considerations, regarding limitations, general conclusions, perspectives and practical applications.

Chapter H regards to the references used in **Chapter B** and **G.** Note that references list for **Chapter E** and **F** are independent for this section and are presented at the end of each of the aforementioned chapters.

B – Review of Literature

1. OLYMPIC WEIGHTLIFTING CONSIDERATIONS

1.1. *Strength Training and Olympic Weightlifting*

Strength and power play a key role in sports performance, and the training of these physical qualities has become more relevant among trainers and physical coaches. Maximal strength is a physical quality associated to the maximal capacity in an isometric contraction independently the time, while power regards to the capacity of force production in a fast way. Both are related to the neuromuscular output and appear to promote specific benefits in performance parameters while complementing the main purpose of a particular sport. Nevertheless, this association is more evident in sports such as athletic throws or Olympic weightlifting (OWL). Thus, strength training effects, which include gains in muscle mass, increases in strength and power or better posture and balance, have been linked to the optimization of specific sport valences, not only being possible predictors of success in professional sports, but also preventing injuries and rehabilitating athletes so they can return to competition.

With the intention of developing strength, power, speed and agility, OWL movements have been used in the practice of strength training. The introduction of OWL movements in training protocols developed to increase muscle strength and power in other sports besides OWL is becoming increasingly popular. This evidence is mainly due to the relationship between OWL movements performance and other performance variables that may predict success in sports (like power, speed or agility). OWL movements promote an whole-body muscles recruitment at high speeds, while lifting high loads, which might explain why weightlifters present greater rate of force development and higher power outputs, when compared for example, with sprinters and powerlifters (Mcbride, Triplett-Mcbride, Davie, & Newton, 1999).

The effects of power training incorporating OWL movements in some performance parameters, namely the association with vertical jump height and force production, have been studied. The incorporation of this kind of exercises during 10 weeks of off-season of football players combined with sprint and agility training has demonstrated efficiency to improve some physical abilities (Hoffman, Cooper, Wendell & Kang, 2004). In this study, the group who performed OWL (against the group performing powerlifting) in training showed greater improvement in sprint and vertical jump, being this probably associated with the mechanical similarities of the pulling action with vertical jumps, reflecting the triple extension of lower-limbs. Besides, the power output gains were higher, which is possibly related to the high rate of force development and improved contractile speed when training with high loads (>80%RM) at high speeds, reflecting specificity in the adaptations.

When comparing recreational athletes either performing OWL movements or vertical jump exercises, both groups had significant increases in peak power during jump testing and in the first 10m of a 20m sprint test, which resulted in better sprint test times, not existing, however, significant differences between groups (Teo, Newton, Newton, Dempsey & Fairchild, 2016). Also, in high school boys, an OWL movements program of 8 weeks showed no significant differences in vertical jump height when compared to a powerlift program (Channell & Barfield, 2008).

The incorporation of OWL movements in child (between 10 and 12 years-old) training programs has been also studied, and either Olympic weightlifting or plyometric training showed to be equal or more effective to traditional resistance training for enhancing performance after a 12-week training period. These types of training involve explosive contractions (high contraction speed and consequently increases in neural component demands commonly associated with strength gains in children) and have higher balance demands (Chaouachi et al., 2014).

On the other hand, not every study has found advantages when applying OWL programs. An OWL program of 8 weeks showed to be ineffective to increase muscle power of lower limbs in vertical jump when compared with a free weight strength and power training, and motorized strength and power training in hockey, volleyball and badminton players (Helland et al., 2017). However, in this particular study, the OWL program included just OWL exercises, not integrating other nuclear exercises such as squats. Furthermore, the almost inexistent eccentric phase in all exercises can lead to lower volume and lower muscle recruitment. Nevertheless, another possibility to justify these findings concerns the technical level and the initial strength levels of the athletes performing OWL movements (James et al., 2018), since technique is an important prerequisite and OWL can be more relevant for athletes with higher values of maximal strength when performing training protocols developed to improve muscle power and speed of lower-limbs (Helland et al., 2017).

Finally, concluding with the results from two meta-analyses describing the effects of OWL and plyometric training (Hackett, Davies, Soomro & Halaki, 2016; Berton, Lixandrão, Pinto & Tricoli, 2018), some studies have demonstrated that we can expect adaptation in some performance parameters, namely vertical jumps, when performing a training protocol that includes OWL movements. OWL training can induce 3,5 times greater CMJ improvement in comparison to traditional resistance training probably because of the specificity of the movement (triple extension of lower-limbs) and greater power outputs produced. When comparing OWL to plyometric training, the gains in vertical jumps were equally effective, and it is verified that the enhancement after OWL training can be associated with increased muscular power capacity whilst the enhancement due to plyometric training can be associated with improvement in stretch-shortening cycle efficiency. However, when applying this kind of protocols using OWL movements, it is essential to ensure the technical proficiency of the athletes and initial levels of maximal strength, considering the specificity of the sport in question.

1.2. Power clean

The power clean is a derivative exercise of the full clean and one of the most used exercises in strength and power training in sports.

Power clean starts with the bar above the anterior third of the foot, gripping the barbell with the palm of the hand downwards and adopting a slightly lordotic posture of the spine. The first phase of the exercise, known as first pull, regards to the moment when the athlete applies force against the floor and consequently the bar starts rising. The knees are extended and moved backwards so the barbell may pass while the hip and the shoulder rise keeping the same vertical distance (Pires & Mendonça, 2015). The second pull begins as the barbell reaches near mid-thigh position, and the barbell should reach the highest velocity (Winchester, Erickson, Blaak & McBride, 2005), which means that the acceleration of the barbell during the second pull should be higher than in the first pull and this plays a key role in the success of the movement. The forward displacements of the barbell should be minimized, and the athletes should generate a more backward-directed force during the second pull (Kipp & Meinerz, 2017). During the second pull, the center of pressure moves from the heel to the toes. Figure 1 illustrates first and second pulls of power clean.

Figure 1 - First and second pull

After, the barbell continues to rise, and the lifter performs a triple extension of the lower-limbs and the elbows and fists begin to flex – third pull. When the barbell reaches the highest position the catch phase begins and the lifter should transition the body under the barbell, holding it in the anterior region of the shoulders, with the elbows in maximal flexion and pointed forward. The exercise ends when the lifter extends the knees and stands with the barbell. Figure 2 illustrates third pull and catch of power clean.

Figure 2 - Third pull and catch

The main difference between this exercise and the full clean is the front squat during the catch phase. In power clean the hip and knee joints do not reach maximum flexion angles as in full clean. Therefore, the catch phase during the power clean is performed at a higher height than the clean, which means that the barbell must have a greater rise requiring more vertical velocity, and does not allow to use loads as heavy as in the clean (Storey & Smith, 2012).

OWL movements are beneficial to many athletes considering biomechanical profiles of the exercises involving triple extension of the hip, knee and ankle. The clean exercises are associated with high force generation and muscle power output. Thus, neuromuscular adaptations, such as increased recruitment of high-threshold motor units, may accompany a training program incorporating these exercises. The power output obtained during OWL movements is influenced by the rate of force development (RFD), and when comparing to vertical jumps, the power clean at 70% 1RM presented a greater RFD, suggesting that the increase of jumping height after an OWL program may be associated with gains in explosive strength (MacKenzie, Lavers & Wallace, 2014). The approximate relative intensity that elicits peak power among experienced subjects in power clean is around 80% 1RM, and this marker can be used as an optimal relative intensity in weightlifting exercises to enhance muscle power (Caldwell, 2015). The relationship between power clean (with the 1RM normalized to bodyweight) and other exercises with pulling actions of the ground, namely the squat and vertical jumps, present Pearson's correlations of r = 0.88 and r = 0.75 (Channel & Barfield, 2008), and significant relations with sprinting and agility tests were also found (Storey & Smith, 2012).

However, not all studies suggest similarities between vertical jumps and power clean. Mackenzie and colleagues (2014) measured electromyographic signals of lower-limb muscles and verified that during power clean the knee extensors (*vastus medialis* and *rectus femoris*) presented less activation in the first half of the movement than the vertical jumps. Moreover, it was demonstrated a substantial increase corresponding to the triple extension in the later phase of power clean. In the same phase of the movement, *gluteus medius* and *medial gastrocnemius* showed an activation peak, both significantly later than in the jumps. The activation of the *biceps femoris* was not significantly different in power clean and loaded jumps, and differences were found when comparing to vertical jumps not loaded, revealing a later activation during the power clean. Considering the kinematic parameters, differences were also found in knee and ankle displacement between the two exercises. In the first half of the ascendant phase the knee and ankle showed significantly more extension, and in the beginning of the second half the two joints showed a flexion period before the complete extension of the lower-limbs. Regarding the hip joint, the extension occurred later in power clean. Thus, vertical jumps and power clean ascendant phase are not similar in what concerns kinematic and electromyographic parameters, considering that differences in lower-limb joints angular displacement and in activation timings of muscles were demonstrated (MacKenzie et al., 2014). At different phases of the power clean the *rectus abdominis* and *obliquus internus* showed generally little activation, while the *transversus abdominis* was clearly targeted during the lift, showing increased activation in the highest positions of the barbell. By contrast the *erector spinae* was more active in the lower positions of the barbell (Eriksson Crommert, Ekblom & Thorstensson, 2014).

2. NEUROMUSCULOSKELETAL SYSTEM CONTROL AND ADAPTATIONS

2.1. *Neuromuscular adaptations to strength training*

Regular practice of strength training is associated to increases in maximal strength, changes in neuromuscular function and muscle morphology. When submitted to strength training, previously untrained subjects tend to augment significantly the maximum amount of force they can produce, and to increase substantially the size of skeletal muscle (Ahtiainen, 2006).

The morphological adaptations that result from strength training involve increases in the cross-sectional area of the muscle, mainly through the hypertrophy of muscle fibers (increase in myofibrillar size and number). This phenomenon is associated with proliferation and fusion of satellite cells with existing fibers which consequently increase in numerical density of myonuclei. Other morphological adaptations, such as changes in muscle architecture (namely in pennation angle) and fascicle length, in fiber type and in tendons structure may occur (Folland & Williams, 2007). Particularly, weightlifters showed greater pennation angles of *vastus lateralis* than resistance trained adults while no significant differences in anatomical and physiological muscle thickness existed between groups. Nonetheless, the former group presented greater ability to generate and sustain peak force of isometric contractions (Storey, Wong, Smith & Marshall, 2012). Regarding the muscle fiber type, weightlifting performance is not dependent on type IIX fibers. These athletes exhibit high percentages of *vastus lateralis*' type IIA muscle fibers instead, reflecting myosin heavy chain IIa isoform (Fry et al., 2003; Storey & Smith, 2012). The percentage of type II fibers appears to be no different from untrained individuals. However, the cross-sectional area of these fibers is considerably larger. A positive relation between IIA fibers and snatch performance and a negative relation between IIX fibers and clean & jerk performance were found (Fry et al., 2003).

On the other hand, there is evidence that neural adaptations to strength training occur earlier than muscle adaptations, which reflects that the initial gains in strength that are not accompanied by increase in muscle size. Besides, learning and changes in coordination emerging from the specificity of training and the cross-training effect are other indirect evidences of neurological adaptations. Changes in the neural drive to the muscle have been inferred from surface electromyography (EMG) studies that show increases in EMG signal of the agonist muscle during first weeks of training (Folland & Williams, 2007;

Sale, 1988; Sale, 2003; Moritani & DeVries, 1979; Duchateau, Semmler & Enoka, 2006). This increase in EMG reflects increases in fiber recruitment or firing frequency, and is sensitive to changes in synchronization (Folland & Williams, 2007). It appears that motor unit recruitment thresholds are reduced in response to training (Griffin and Cafarelli, 2005; Folland & Williams, 2007; Sale, 2003). Cortical adaptations, like primary motor cortex changes in movement representation and increased corticospinal excitability, nerve conduction velocity, reflex function and motoneuron excitability may be other neurological adaptations promoted by strength training (Griffin & Cafarelli, 2005; Sale, 2003).

In an initial phase of the training process the nervous system has to adapt itself to the specific required movements and it involves the ability to develop qualitative changes in coordinative patterns of muscle activation, being the optimization of coordination between agonists, antagonists and synergists essential to produce the desired movement output, in what concerns to angular amplitudes and velocities of the joints (Sale, 2003; Pezarat-Correia, 2012). For example, six weeks of different multi-finger training programs promoted increased pressing strength, decreased force errors regarding a target force value (20% maximal voluntary contraction) and decreased independence of the fingers that resulted from neuromuscular adaptations specific of the training protocol (Shim, Hsu, Karol, & Hurley, 2008). In order to promote gains in strength performance three mechanisms are described regarding neural adaptations in intermuscular coordination: increased activation of agonists, decreased activation of antagonists and activation of synergists.

Training also allows recruitment of fast-twitch muscle fibers innervated by higher threshold motoneurons (type II fibers) which results in a increase in motor unit firing rates, particularly at the onset of ballistic contractions, which promotes greater rate of force development. The activation of antagonists depends on muscle group, velocity, type of muscle contraction, intensity and joint angle, opposing the torque developed by the agonists. Nevertheless, antagonist activation is an important mechanism to maintain joint stability, stop and bring precision to movement. The antagonist muscles appear to reduce their activation at the same force production after training, causing a decrease in antagonist/agonist activation ratio, which is observed in older individuals (Häkkinen et al., 1998). These changes may be related with the ability to focus motor command to the main muscles involved in the task and inhibiting antagonists (Duchateau et al., 2006).

Finally, for the optimization of movement it is required that all muscle involved, including fixators to achieve postural requirements of the task, activate with the right intensity and in the exact timing for the performed action (Rutherford & Jones, 1986). The coordination of all muscles would allow to produce the required joint moments in the intended direction to perform specific movements, promoting specific strength gains (Sale, 2003; Folland & Williams, 2007; Duchateau et al., 2006; Griffin & Cafarelli, 2005).

During whole-body and power movements, like in OWL, the level of activation of antagonists may be greater as compared with less complex movements. Therefore, in this case it is essential that the nervous system is able to control unwarranted co-contraction between agonists and antagonists, that may possibly reduce power output (Arabatzi & Kellis, 2012; Folland & Williams, 2007). A study regarding an 8-week OWL training program showed differences in activation patterns of knee muscles, promoting higher vertical jumps when compared to a traditional resistance training group. It would be expected that OWL could improve motor unit recruitment in agonists inhibiting at the same time the antagonist muscle action. In this particular study, a reduction of the antagonist/agonist ratio was observed in the OWL, possibly indicating increases in knee extension torque at propulsion in vertical jumps, in contrast to the traditional resistance training group, which exhibited a higher ratio of activation (Arabatzi & Kellis, 2012).

Regarding the described mechanisms of neuromuscular adaptations to strength training, it is plausible to conclude that morphological adaptations become the dominant factor in the late stage of the training program, mainly after the first month. The neural factors are determinant in the initial voluntary strength increment, considering intermuscular and intramuscular adaptations to training (Moritani & DeVries, 1979; Sale, 1988). Strength gains in advanced training stages are associated to continued muscle adaptations. Figure 3 illustrates the timings of muscular and neural adaptations to strength training. However, regarding to complex movements expertise, the role of training in the refinement of these tasks and the possible timings of skill acquisition are issues that remain unexplored.

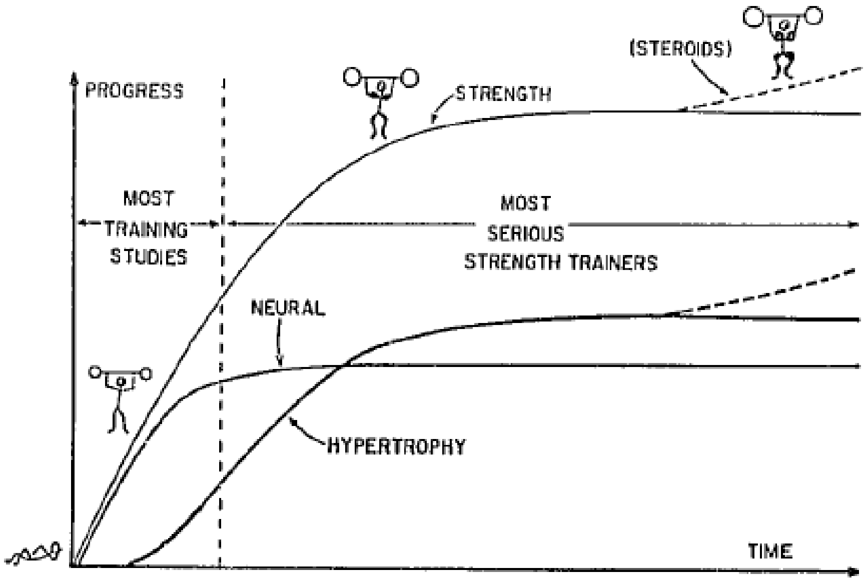

Figure 3 - The relative roles of neural and muscular adaptation to strength training. In the early phase of training neural adaptation predominates. This phase also encompasses most training studies. In intermediate and advanced training, progress is limited to the extent of muscular adaptation that can be achieved, notably hypertrophy – hence the temptation to use anabolic steroids when it becomes difficult to induce hypertrophy by training alone (reprinted from Sale, 1988).

2.2. *Muscle coordination*

The control of movement that enables the performance of coordinated actions implies the existence of functional relations between all the components of the system, i.e., muscles and other structures organize themselves in order to perform movement and complete a desired task. However, there is more than one way that the CNS can adopt to perform some motor task, and this redundancy associated to motor control refers to the degrees of freedom problem, proposed by Bernstein (1967). The musculoskeletal system has infinite solutions to perform an action, regarding how the elements of the system interact with each other. Also, it has been demonstrated that the human body has more elements than it should be necessary to perform a particular motor task (Latash, Scholz, & Schöner, 2007).

Thus, according to Bernstein (1967), when learning some new skill, the neuromuscular system adapts to the motor possibilities manipulating the degrees of freedom (DOF) and promoting an approach that leads to an optimal solution constructed to minimize the cost to the CNS (Hirashima & Oya, 2016). During skill acquisition an intermittent reduction and release of DOF may be observed. In early stages of this process the CNS will reduce the number of DOF, stiffening the movement but controlling the excess of DOF that could possibly add to much variability to the system. With practice, some of these DOF are released, smoothing the movement and increasing it efficiency (Latash et al., 2007; Passos & Barreiros, 2013).

The abundance of DOF allows to the neuromuscular system to ensure stability of important performance variables and flexibility to adapt to internal and external changes of the environment, and the redundancy of DOF may be used to compensate errors that arise from unpredictable acting forces (Latash et al., 2007; Latash, Krishnamoorthy, Scholz, & Zatsiorsky, 2005; Latash, 2015; Oliveira & Shim, 2008). In other words, the permanent elimination of DOF does not occur. Instead, those alternative DOF are used to minimize changes of the movement and to promote a functional adapted motor control.

According to the previous statements, we can assume that coordination regards to the interaction between all the components of neuromusculoskeletal system, and it is though that each one can be controlled individually (Bernstein, 1967; Passos & Barreiros, 2013). Thus, the control of locomotive system is achieved through the refinement of redundant DOF that group themselves and allow the system to perform coordinated movements. In response to practicing and training many elements of the nervous system may adapt and therefore produce specific muscle patterns of muscle recruitment. Particularly and in the vast majority of cases, strength training is implemented in order to optimize how the CNS recruit muscles so the performance levels in some tasks may be increased.

It should be noted that strength training induces some supraspinal adaptations, which ensure that the task is performed in the most efficient way possible. For example, a reduction in cortical activation and therefore a decrease in the interference of other areas of the brain with the execution of movement will be observed. With the increase of force production capacity of muscles fewer descending fibers will be activated for a given task, controlling the muscle in a more effective way. In other words, with training the relation between brain activity and force production will change resulting in less brain activity being necessary for the same kinetic output (Carson, 2006). During skill acquisition, neural connections between primary motor cortex and other areas (long term potentiation of synapses), and between cortico-spinal cells and motoneurons will be altered (Carroll, Riek, & Carson, 2001; Carson, 2006).

The choice and adjustment of DOF by the CNS, the combination of joint angles to produce the required movement or the selection of individual motor units and the consequent muscular output, are problems referring fewer constraints than elements, helping to reduce DOF that the nervous system must control (Bernstein, 1967; Latash et al., 2005). Thus, it appears the concept of functional synergies, ensembles of elements forming coordinative structures that allow the performance of coordinated movements (Passos & Barreiros, 2013; Latash et al., 2007).

3. MUSCLE SYNERGIES

3.1. *Muscle Synergies for motor control*

Muscle synergies represent a mechanism organizing a system with high number of elements, reducing the cost for the CNS and simplifying motor control (Figure 4). Thus, the coordination of different elements of musculoskeletal system, i.e., various muscles, can be recruited by a single neural command, representing just one variable that may be controlled. The contribution of various elements to each synergy reveals its sharing character and ensure that one alteration in the function of one element will be compensated by other, which means that synergies adapt themselves to different tasks even when recruiting the same elements (Latash, 2008). The combination of recruitment of multiple synergies will result in the production of a wide range of possible complex movements, that is, specific tasks can be achieved by modulating neural commands specifying spatiotemporal patterns of muscle activation that can produce natural motor behaviors (Safavynia, Torres-Oviedo, & Ting, 2011; Ting & McKay, 2007).

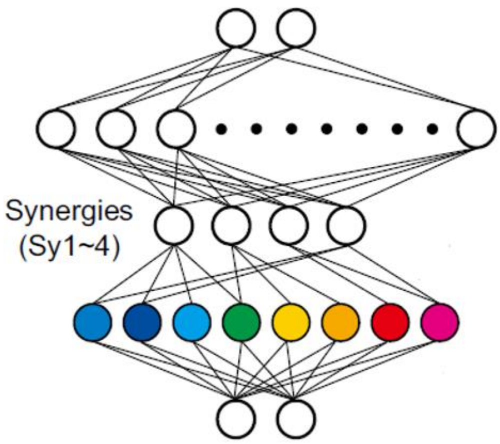

Figure 4 - Synergy Model (reprinted from Hirashima & Oya, 2016)

Muscle patterns of activation are the result of simultaneous and independent recruitment of muscle synergies, that are combined, scaled in amplitude and shifted in time (d'Avella, Saltiel, & Bizzi, 2003). The simplification of motor control is related to shared muscle synergies across tasks. In other words, a variety of motor behaviors may be achieved through combination of small number of the same low-level discrete elements, being them explicative of a large fraction of the variation of data (d'Avella & Bizzi, 2005; Bizzi & Cheung, 2013; Prevete, Donnarumma, d'Avella, & Pezzulo, 2018). Namely, freely moving frogs presented small number of synchronous and time-varying muscle synergies that represented the variation across swimming, jumping and walking tasks, reflecting the inherent shared structure of neural modulation, and implementing behavior specific modules to efficiently achieve the biomechanical requirements of the task (d'Avella et al., 2003; d'Avella & Bizzi, 2005). It is important to emphasize that synergies may be synchronous, representing fixed spatial relation of muscle activation in a given time, or time-varying, denoting stereotypical temporal activation profiles shared across muscles during the whole movement. The combination of these two types of low-level circuits that implement descending motor commands and reflex contributions, construct coordinated muscle activity and release the higher structures of the CNS, namely in the brain, to operate on other specific variables of the task (Delis, Hilt, Pozzo, Panzeri, & Berret, 2018). The spatial synergies will be considered in this thesis (Figure 5), and these basic temporal pattern synergies have a fixed base represented by the weightings of the muscles. The timing of activation of the muscles' synchronous recruitment made by the synergy is variable.

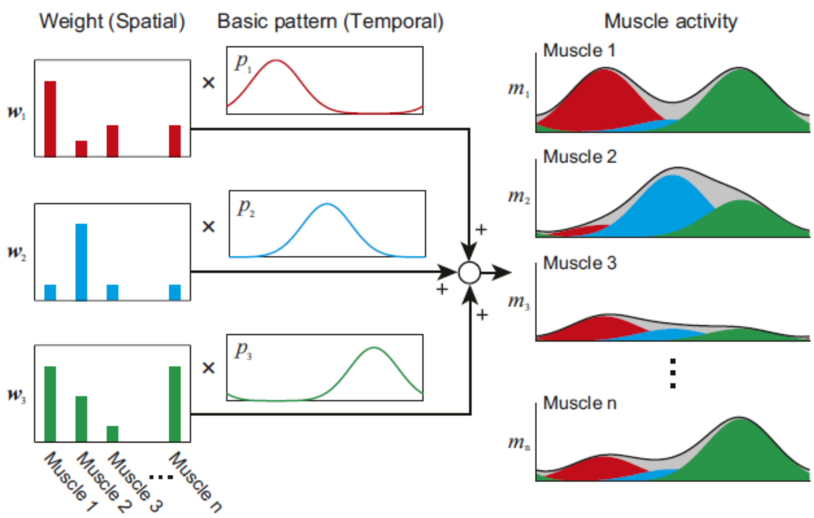

Figure 5 - Low dimensional spatiotemporal structure of muscle synergies basic activation patterns (temporal structure) with distribution weights (spatial structure) (reprinted from Aoi & Funato, 2016).

3.2. *Origin of Muscle Synergies*

Muscle synergies origin has been suggested as being neural, recruited by functional units of spinal interneurons that request specific activation of muscles and a consequent motor output. The combination of these motor modules allows the performance of an unlimited number of movements (Bizzi & Cheung, 2013).

Chemical and electric stimulation in several vertebral species have been the main approaches to study the representation of muscle synergies in spinal cord (Bizzi & Cheung, 2013). The simultaneous electrical stimulation of two sites of the spinal cord in frogs resulted in equivalent generated forces when compared to the summation of each of the two sites stimulated separately (Mussa-Ivaldi, Giszter, & Bizzi, 1994). Neuronal discharges in the spinal cord gray of frogs at the L2/L3 zone activated motor primitives rather than individual muscles (Hart & Giszter, 2010). Premotor interneurons in the primate cervical spinal cord showed spatiotemporal properties correlated with muscle synergies during voluntary hand movements (Takei, Confais, Tomatsu, Oya, & Seki, 2017). Chemical stimulation with N-methyl-D-aspartate (NMDA) glutamate excitatory receptors, by application of iontophoresis in the interneuronal regions of the lumbar spinal cord of frogs, elicited EMG patterns that revealed to be grouped in muscle synergies (Saltiel, Wyler-Duda, D'Avella, Tresch, & Bizzi, 2001). In cats, muscle synergies identified by cluster analysis were the same before and after spinal transection, revealing, however, differences in timing of certain synergies and suggesting the importance of afferent inputs for the expression of some muscle synergies (Desrochers, Harnie, Doelman, Hurteau, & Frigon, 2019). Intra-cortical microstimulation applied to motor cortical areas of macaques evoked hand movements, revealing muscular activations reducible to summations of few basic patterns representing muscle synergies (Overduin, d'Avella, Carmena, & Bizzi, 2012), and similar synergistic organization of the brain was verified for grasping different objects (Hao et al., 2017).

Regarding the studies mentioned above, muscle synergies have been proposed to be structured in brainstem and spinal cord (Bizzi & Cheung, 2013; Bruton & O'Dwyer, 2018), activated through supraspinal commands that control activity in spinal circuits and regulated by sensory feedback being an important mechanism to refine the pattern of locomotor output (Grillner & Jessell, 2009). As such, muscle synergies are commonly associated with central pattern generators (CPG), ensembles of oscillatory neurons that produce rhythmic motor patterns (Zehr, 2005). These modules remain similar in frogs during swimming and jumping before and after deafferentation, altering, however, the amplitude and temporal patterns of muscle synergies and suggesting that sensory feedback regarding the specificity of the task may modulate the activation of centrally organized synergies (D'Avella & Bizzi, 2005). The absence of sensory and/or descending modulation during fictive locomotion in neonates results in lack of specific activation pattern on foot contact (Dominici et al., 2011). In adult humans, some studies suggest the conclusions enumerated before. For instance, the composition of synergies of the unaffected and affected arm of mildly to-moderately impaired stroke survivors with lesions in motor cortical areas were similar, despite differences in motor output, which can be due faulty activation of spinal modules by altered descending commands (Cheung et al., 2009), and merging of unaffected arm muscle synergies correlated with the severity of motor impairment (Cheung et al., 2012).

The main approach to study muscle synergies suggesting indirectly evidence of neural control in humans is to measure EMG from a large number of muscles and to apply statistical analyses to group the activation of muscles (Tresch & Jarc, 2009). This topic will be detailed later in this document. However, not all studies suggested muscle synergies as having a neural origin, proposing in contrast that muscle synergies appear to reflect task-related biomechanical constraints, and a model predicting musculotendon length changes on estimating muscle activity (through EMG records) could control feedback-related synergies, even though this model in not currently feasible yet (Kutch & Valero-Cuevas, 2012). For example, these authors attribute the results reported by Cheung and colleagues (2009) as being consequent of similar task constraints and upper-limbs biomechanical structure (Kutch & Valero-Cuevas, 2012). Furthermore, addition of new muscle patterns of activation from neonates to toddlers reveals the importance of neural adaptation to biomechanical changes, incorporating information about biomechanical properties in the characteristics of motor modules activation and imposing specific highly calibrated motor performance (Dominici et al., 2011; Bizzi & Cheung, 2013). Thus, origin of muscle synergies remains a controversial topic. Nevertheless, the concept of a neural origin of muscle synergies is not incompatible with the idea that biomechanical properties of the limb are incorporated in their structure (Bizzi & Cheng, 2013).

3.3. *Electromyography (EMG) and Nonnegative matrix factorization (NMF)*

Muscle coordination can be studied from electromyography and force patterns of muscles. Although resultant joint torques can be reliably estimated through inverse dynamics analysis, there are not valid experimental methods that allow to estimate individualized muscle forces. As such, and considering its inability to measure deep muscles, the main methodology used to study muscle coordination is surface electromyography (Erdemir, McLean, Herzog, & van den Bogert, 2007). Considering the study of muscle synergies and knowing that it is not certain that EMG can provide information about neural strategies for movement control (namely regarding to drawbacks in EMG technique – amplitude cancellation, crosstalk or spatial variability of muscle activity – and processing methods – smoothing or amplitude normalization), we will assume that surface EMG reflects the muscle coordination (Hug, 2011).

For the study of muscle coordination, we can process the EMG signals in three ways (Hug, 2011): 1) defining the EMG profile in a certain task, performing a rectification, smoothing and amplitude normalization. To get information about muscle function, we should consider the onset and offset of muscle activation during the recorded period, and then average the linear envelopes. When studying muscle coordination in movements with consecutive repetitions, it is required a time normalization that allows locating the EMG patterns along the cycles. Between 20 and 40 cycles are usually used (Hug, 2011); 2) extracting muscle synergies, allowing us to understand the behavior of a combination of muscles that present common activity in the movement (muscles with similar EMG profiles that are activated in synchrony). The muscle synergies extraction reveals two components: muscle synergy vectors (fixed component) and synergy activation coefficients (time-varying component); 3) processing the signal in the frequency domain, discussed elsewhere.

The computational procedure utilized to extract muscle synergies from multiple EMG signals is the nonnegative matrix factorization (NMF), proposed by Lee & Seung (1999, 2001). NMF is a method that allows to decompose a principal matrix into a product of two smaller matrices, extracting time-invariant synergies, i.e., synergies whose muscles are activated synchronously reflecting spatially fixed regularities while using multiplicative update rules that allow to converge to a locally optimal matrix factorization (Lee & Seung, 1999, 2001; Bizzi & Cheung, 2013; Hirashima & Oya, 2016). The particularity of this method is the use of nonnegativity constraints that will lead to a parts-based analysis only with addictive combinations (Lee & Seung, 1999). Besides muscle synergy extraction, NMF is used in other biological data, like gene expression (Devarajan, 2008).

Besides NMF, there are other types of matrix decomposition, like Vector Quantization (VQ), Principal Component Analysis (PCA) or Independent Component Analysis (ICA). From the referenced algorithms, NMF responds to the nonnegative values of muscle activation measured by processed EMG. NMF allows to each muscle to be part of various synergies and to coactivate synergies, in contrast with VQ, that allows only one synergy at a time, and PCA, where all muscles are part of all synergies assuming sometimes negative values and hampering interpretation (Lee & Seung, 1999). As result, one cannot compare studies with synergies extracted by PCA and studies with synergies extracted by NMF (Lambert-Shirzad & Van der Loos, 2017). However, NMF makes no further assumptions about the statistical dependencies of synergies (Lee & Seung, 1999). When comparing these algorithms, NMF appeared to perform better than PCA in identifying muscle synergies (Tresch, Cheung, & d'Avella, 2006), and outperformed ICA (Lambert-Shirzad & Van der Loos, 2017). The procedures of NMF are schematized in Figure 6.

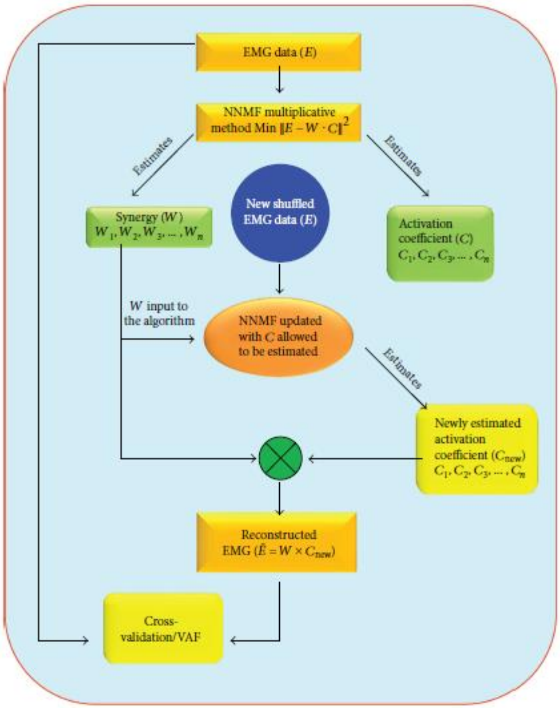

Figure 6 - Procedure to extract muscle synergies from the NMF multiplicative method. Muscle vectors (W) are extracted from EMG data and then fixed in the algorithm while activation coefficients (C) are estimated and newly estimated though an iterative process that allow to converge to a locally optimal matrix factorization (Cnew) (reprinted from Singh, Iqbal, White, & Hutchinson, 2018).

For the extraction of muscle synergies, Steele and colleagues (2013) recommended to select dominant muscles in the movement (identified from musculoskeletal simulation). They selected a subset of 5 to 29 muscles and compared the similarity of the synergies calculated from each subset to a master set of synergies calculated from all muscles. The choice of dominant muscles or muscles with the largest isometric force appeared to better represent the master set with all muscles, and more than 10 muscles improved similarity above 0.8 (Steele, Tresch, & Perreault, 2013).

3.4. *Muscle synergies in sports-related tasks*

Muscle synergies have shown to be related to neurophysiological interpretations in the construction of movements. The promising results of the reliability of muscle synergy extraction may allow this statistical procedure to be seen as an useful tool concerning the representation of low-level control of muscles. In daily life activities, namely walking, stepping, running, ascending and descending stairs, the EMG reconstruction was found to be excellently reliable, although some individual muscles just presented a fair local reconstruction (Taborri, Palermo, Del Prete, & Rossi, 2018). Walking was the least reliable motor tasks. The authors justified with the less variability of the other tasks, caused by external constraints. In another study regarding the bench press reliability of muscle synergies, between-day analysis showed that general structure of muscle coordination was present across days (Kristiansen, Samani, Madeleine, & Hansen, 2016b). Additionally, those two studies similarly concluded that although muscle synergy vectors and synergy activation coefficients are both reliable, the muscle vectors representing the weightings of each muscle in the synergies are more variable than the timings of activation of synergies (Kristiansen et al., 2016b; Taborri, Palermo, et al., 2018).

Recent reviews have emphasized muscle synergy theory outcomes in clinics, robotics, and sports (Singh et al., 2018; Taborri, Agostini, et al., 2018). Table 1, 2 and 3 show sports- and exercise-related studies with extraction of muscle synergies. Those tables comprise adapted information provided by Taborri and colleagues (Taborri, Agostini, et al., 2018) and incorporate other relevant studies in the field.

Some studies have characterized muscle synergies during human postural responses to unexpected perturbations. EMG variability in tasks where platforms move in an unexpected direction may be explained by spatial fixed muscle synergies (Safavynia &

Ting, 2012), being the spatial and temporal components similar among subjects (Torres-Oviedo & Ting, 2007). A study focusing in the comparison of highly trained female ice hockey players with non-athletes concluded that, during this kind of tasks, hockey players have shorter recovery periods in the center of mass stabilization and present less coactivation of muscle synergies (Kim, Kim, Kim, & Yoon, 2018).

Regarding locomotion tasks, various studies verified the displacement speed during walking and running. Motor modules have been identified during walking at different speeds (Gui & Zhang, 2016) and recording of surface and intramuscular EMG had no significant differences on PCA waveforms, in spite of the presence of some different components in intramuscular EMG of *sartorius* and *tensor fascia latae* (Ivanenko, Poppele, & Lacquaniti, 2004). Moreover, high similarity of muscle synergies was obtained while walking at different speeds and slopes, despite the existence of differences in kinematics in children (Rozumalski, Steele, & Schwartz, 2017). In adults, the same results were found in another study (Saito, Tomita, Ando, Watanabe, & Akima, 2018) that comprised a higher number of muscles in synergy extraction (Steele et al., 2013), showing, however, a specific adaptation of the synergy that included mainly *rectus femoris* activation. Muscle synergies were also shared across linear and curvilinear trajectories of walking, being those synergies associated to biomechanical walking phases and adapting its timings of activation to the type of trajectory (Chia Bejarano et al., 2017). Muscle patterns were also shared between walking and running, being the transition in the two locomotion paths defined by timing activation of muscle synergies (Cappellini, Ivanenko, Poppele, & Lacquaniti, 2006). However, after 10 minutes of running, one muscle synergy that had been activated during stance and comprised trunk muscles, engaged muscles around the pelvis, being activated after landing, showing that after a relatively low level of fatigue induction, the muscle recruitment in posture control changes from the trunk muscles to lower-limb muscles (Matsunaga, Imai, & Kaneoka, 2017). During hands- and knees- crawling, synergies showed to be stable in intralimb coordination and to be consistent during speeds, despite some timing adjustments (Chen, Niu, Wu, Yu, & Zhang, 2017).

Table 1 – Posture and locomotion studies using muscle synergy analysis

Reference	Exercise	Aim	Subjects	Tasks	Muscles	LPF	Synergies
Torres-Oviedo & Ting, 2007	Posture tasks	Characterize human postural responses	9 subjects	Maintain posture during platform perturbations	16 (trunk and lower limb)	40Hz, 3rd order	<6
Safavynia & Ting, 2012	Posture tasks	Characterize human postural responses	8 subjects	Maintain posture during platform perturbations	16 (trunk and lower limb)	40Hz	<7
Kim et al., 2018	Ice Hockey	Compare postural responses in trained and untrained subjects	7 hockey players; 7 non-athletes	Maintain posture during platform perturbations	16 (trunk and lower limb)	40Hz, 3rd order	5-6 initial phase; 6-7 reversal phase
Ivanenko et al., 2004	Walking	Characterize human locomotion during walking at different speeds	6 subjects	Walking at different speeds with external loads	12-16 (trunk and lower limb)	15Hz	5
Cappellini et al., 2006	Walking and running	Characterize human locomotion during walking at different speeds	8 subjects	Walking at different speeds	32 (both sides)	10Hz	5
Rozumalski et al., 2017	Walking	Characterize children locomotion during walking at different speeds	16 children	Walking at different speeds and slopes	5 (lower limb)	10Hz	3
Chia Bejarano et al., 2017	Walking	Compare walking in rectilinear and curvilinear trajectories	13 subjects	Walking in different directions	13 (back and lower limb)	5Hz, 3rd order	4

Table 1 – Continued

Reference	Exercise	Aim	Subjects	Tasks	Muscles	LPF	Synergies
Saito et al., 2018	Walking	Compare human locomotion during walking at different speeds and slopes	12 subjects	Walking at different speeds and slopes	10 (lower limb)	9Hz, 4th order	<4
Gui & Zhang, 2016	Walking	Characterize muscle synergies during walking at different speeds	8 subjects	Walking at different speeds	8 (lower limb)	5th, 2nd order	4
Chen et al., 2017	Hands- and Knee-crawling	Assess intra- and inter-limb coordination in crawling	20 adults	Crawling at different speeds	32 (both sides)	15Hz	2
Matsunaga et al., 2017	Running	Compare muscle synergies before and after running	8 subjects	10-min running at 70%VO2max	15 (trunk and lower limb)	-	4

In what concerns specific sports, some cyclic tasks (cycling, rowing and breaststroke swimming) and some specific techniques of certain sports (gymnastics, athletics, badminton, american football and golf) have been studied through extraction of muscle synergies. The study of different biomechanical constraints and expertise effect have been the two main topics in the research about muscle synergies in sports.

While the number of synergies remained similar, interindividual variability in highly trained cyclists showed to be linked to muscle synergy vectors rather than activation coefficients, that is, between subjects the main differences were associated with muscle weightings in each synergy more than temporal patterns of synergies (Hug, Turpin, Guével, & Dorel, 2010). However, between untrained subjects, the muscle vectors during cycling remained highly similar, while most of the variability in force profile and EMG patterns was found in variability of activation coefficients. In other words, the main difference was verified in temporal patterns of synergies (De Marchis, Schmid, Bibbo, Bernabucci, & Conforto, 2013). Muscle synergies in cycling were also studied regarding different biomechanical constraints, namely, consistency in muscle synergies between tasks differing in speed or power output and position (seated or standing) has been verified (Hug, Turpin, Couturier, & Dorel, 2011; Turpin, Costes, Moretto, & Watier, 2017). To maintain cadence while incrementing power output, no different timings of muscle activation were verified, although different timings of knee and ankle extensors between seated and standing position were found (Turpin et al, 2017). In what concerns to speed changes in isokinetic cycling, muscle vectors remained the same between conditions and activation coefficients across torques and postures showed timing adaptations (Hug et al., 2011). This study had an interesting particularity related with the smoothing of the EMG: for different speeds, different low-pass filters (LPF) have been used, namely, with speed increment higher cut-off values of LPF were applied (Hug, 2011; Hug, Turpin, Dorel, & Guével, 2012).

In rowing, similar muscle synergies were extracted, implying that training does not promote a different dimension of movement control in tasks regarding mean power of a 2000m test and an incremental VO2max test (Turpin, Guével, Durand, & Hug, 2011c; Shaharudin & Agrawal, 2016). Muscle synergies and individual muscle patterns remained stable across different power outputs, being the performance differences explained by increases in EMG activity levels (Turpin, Guével, Durand, & Hug, 2011a). When a fatigue protocol was applied, muscle synergies remained the same, and EMG profiles, vectors and activation coefficients suffered only slight modifications. However, increased muscle activity was verified in some muscles (*biceps femoris, gluteus maximus, semitendinosus, trapezius medius* and *vastus medialis*) and decreased muscle activity was shown to one muscle: *longissimus* (Turpin, Guével, Durand, & Hug, 2011b). Comparing different rowing ergometers, the modular organization remained the same, being the slide ergometer more solicitor of biarticular muscles (Shaharudin, Zanotto, & Agrawal, 2014).

In breaststroke swimming, a more complex task than rowing, muscle synergies were not profoundly affected when comparing experts and novices, although differences in timing of activation of a synergy encompassing upper-limb muscles and individual EMG profiles of *biceps brachii, pectoralis major, rectus femoris* and *tibialis anterior* were found (Vaz et al., 2016). Between highly trained gymnasts, muscle synergy structure was not profoundly altered, despite some variability in the muscle synergy related with grip and hip extension has been verified (Frère & Hug, 2012). In highly trained pole vaulters, some variability in EMG profiles has been found, but two modules shared time characteristics, even though muscle vectors of each module were also different between-subjects (Frère, Göpfert, Hug, Slawinski, & Tourny-Chollet, 2012). However, some accentuated differences between-subjects and between differently leveled groups have been found: one of the synergies defined by VAF showed extreme intragroup differences in novice and advanced badminton players, that is, this synergy was a neural strategy of each individual in a smash shot task; while one synergy between the advanced and novice players remained consistent between groups (regarding trunk rotation), other synergy (comprising forearm flexor muscles at impact) was found just in advanced players, revealing that enhanced performance in badminton smash shots may be related with neural strategies developed by training (Matsunaga & Kaneoka, 2018).

Table 2 – Sports studies using muscle synergy analysis

Reference	Sport	Aim	Subjects	Tasks	Muscles	LPF	Synergies
Turpin et al., 2017	Cycling	Compare standing vs seated position	17 untrained	Cycling at different power-outputs in standing and seated position	9 (lower limb)	9Hz, 2nd	4
Hug et al., 2010	Cycling	Assess inter-individual variability	9 cyclists	Pedaling at 80% maximal power in incremental test	10 (lower limb)	5Hz	3
Hug et al., 2011	Cycling	Verify consistency of muscle synergies at different power-outputs	11 cyclists	Pedaling at different isokinetic velocities seated and standing	11 (lower limb)	Adapted to pedaling rate	3
De Marchis et al., 2013	Cycling	Assess inter-individual variability	9 untrained	2min of submaximal pedaling	8 (lower limb)	4Hz, 3rd	4
Turpin et al., 2011a	Rowing	Verify the power-output effect in muscle synergies	7 rowers; 8 untrained	Rowing at different power-outputs	23 (full-body)	8Hz	3
Turpin et al., 2011b	Rowing	Verify the fatigue effect in muscle synergies	9 subjects	Rowing at 2000m test mean power until fatigue	23 (full-body)	9Hz	3
Turpin et al., 2011c	Rowing	Verify the expertise effect in muscle synergies	7 rowers; 8 untrained	Rowing at 2000m test mean power	23 (full-body)	8Hz	3
Shaharudin et al., 2014	Rowing	Verify ergometer differences in muscle synergies	9 physically active	6-min test in two in slides and in fixed ergometer	16 (both sides)	8Hz	3
Shaharudin & Agrawal, 2016	Rowing	Verify the expertise effect in muscle synergies	10 rowers; 10 untrained	Incremental VO2max test	16 (full-body)	9Hz	3

Table 2 – Continued

Reference	Sport	Aim	Subjects	Tasks	Muscles	LPF	Synergies
Vaz et al., 2016	Breaststroke swimming	Verify the expertise effect in muscle synergies	8 swimmers; 8 beginners	25m maximal effort	8 (upper and lower limb)	12Hz, 4th order	3
Frère & Hug, 2012	Gymnastic	Assess between-subject variability	9 gymnasts	2x11 backward giant swings on the high bar	12 (full-body)	9Hz, 2nd order	3
Frère et al., 2012	Athletics	Characterize coordination in pole vaulting catapult effect	7 athletes	5-10 jumps at 90% of personal record	10 (upper limb)	5Hz, 4th order	3
Matsunaga & Kaneoka, 2018	Badminton	Verify the expertise effect in muscle synergies	7 advanced; 6 novices	3 successful smash shots	8 (trunk both sides); 5 (upper limb)	-	2 in beginners; 3 in advanced
Cruz Ruiz, Pontonnier, Sorel, & Dumont, 2015	American Football	Characterize muscular activity	1 footballer	8 hand throws to a 4m target	16 (right arm and trunk)	6Hz, 4th order	3

Recently, muscle synergy extraction regarding strength training tasks has been performed. A study evaluating muscle synergies in a drop-landing task showed that similar muscle synergies explain variance in boys and girls (Kipp et al., 2014). However, weightings of muscles in each synergy are different, namely girls present greater medial hamstring activation in pre-landing and touchdown associated muscle synergies, while boys showed greater activity of *vastus medialis* in post-landing associated synergy. Still concerning drop-landing, a recent longitudinal study encompassing 4 weeks of wobble board sensorimotor training concluded that, after training, the experimental group presented modified modular organization in the early landing phase, with separation of the synergy that comprised plantar flexors and ankle evertors, which was accompanied with a reduction in secondary muscle activation (Silva, Oliveira, Mrachacz-Kersting, & Kersting, 2018).

Considering loaded exercises, the effect of fatigue in muscle synergies in one-legged and two-legged squat was observed. Three synergies were extracted for two-legged squat, while four synergies were extracted for single-legged squat. Two-legged squats did not suffer significant differences with fatigue, whereas in single-legged squat one synergy with general coactivation became a predominantly knee extensor synergy after fatigue (Smale, Shourijeh, & Benoit, 2016). In bench press at different velocities, trained subjects showed similar temporal patterns of muscle activation, although individual weightings of each muscle in synergies have been shown (Samani & Kristiansen, 2018). Across conditions, the synergy associated to eccentric phase showed a muscle vector with more intra-subject than inter-subject similarity for slow velocity, being more individualized across conditions than shared across subjects when performed slowly. However, regarding concentric phase synergy, the activation coefficient presented more inter-subject similarity at fast velocity than intra-subject similarity across conditions, i.e., synergy timing varied more between conditions than between subjects when performed quickly (Samani & Kristiansen, 2018). Between powerlifters and untrained subjects, the powerlifters showed larger inter-subject variability in concentric phase activation coefficient, while the weightings of each muscle within the synergies were less variable in powerlifters (Kristiansen, Madeleine, Hansen, & Samani, 2015). Applying a five-week bench press training to untrained subjects, it was demonstrated that post-training muscle synergy vectors were significantly different from pre-training, corroborating the results from the previous study (Kristiansen, Samani, Madeleine, & Hansen, 2016a).

Table 3 – Strength training related tasks studies using muscle synergy analysis

Reference	Exercise	Aim	Subjects	Tasks	Muscles	LPF	Synergies
Smale et al., 2016	Squat	Verify the fatigue effect in muscle synergies	9 subjects	Double-legged squats until exhaustion	12 (lower limb)	5Hz, 4^{th} order	3 in double-legged; 4 in one-legged
Kipp et al., 2014	Landing	Assess sexual dimorphism in single-leg drop-landing	11 boys; 16 girls	5 trials of jump landing	6 (lower limb)	6Hz, 4^{th} order	3
Silva et al., 2018	Landing	Verify the training effect in muscle synergies	9 control; 11 training	4 weeks of wobble board training	12 (lower limb)	20Hz	6-7
Kristiansen et al., 2015	Bench Press	Verify the expertise effect in muscle synergies	10 powerlifters; 9 untrained	3x8 repetitions with 60% 3RM	9 (full-body)	5Hz, 4^{th} order	2
Samani & Kristiansen, 2018	Bench Press	Verify the speed effect in muscle synergies	13 trained	Bench pressing at two different speeds	13 (full-body)	5Hz, 4^{th} order	2
Kristiansen et al., 2016a	Bench Press	Verify the training effect in muscle synergies	13 control; 17 training	5 weeks of bench press training	13 (full-body)	5Hz, 4^{th} order	2

C – Objectives

The general purpose of this thesis is to characterize motor control in human movement regarding strength training tasks. We generally aimed to understand if muscle coordination through extraction of muscle synergies is a reliable measure and if there are different neuromuscular strategies of motor control in a complex strength training task between populations with different levels of expertise. The chosen exercise, the power clean, is a variation of OWL exercises and the high barbell velocities and loads, concerning to great power outputs, demand a coordinative strategy well defined by the practitioners.

Thus, we intend to answer the following questions: which are the characteristics of power clean exercise in unexperienced and experienced subjects, considering EMG profiles?; is there reliability of muscle synergies extracted by NMF within and between sessions in unexperienced subjects in a complex motor task associated to strength training?; what is the role of expertise in EMG profiles, muscle synergy vectors and synergy activation coefficients while executing an exercise with high number of DOF?; are neural adaptations in intermuscular coordination task-specific or does each subject adapt through subject-specific neural strategies?

Study 1 – Within and between day reliability of muscle synergies in power clean

It is intended to determine if EMG reconstruction is reliable between sets of the exercise and between days. We hypothesize that EMG profiles, muscle synergy vectors and synergy activation coefficients are reliable, assuming that muscle coordination and the consequently extracted muscle synergies are not significantly modified across sets and days.

Study 2 – Muscle synergies during power clean in Olympic weightlifters and untrained individuals: assessment of intra and intergroup variability

Our aim is to compare muscle coordination strategies in untrained subjects and weightlifters. We hypothesize that EMG profiles present some time-shifts, and that synergistic organization may present slight differences when comparing the two groups. We also pretend to verify if weightlifters present variability regarding subject-specific adaptations.

D – General Methodology

This chapter will provide general information about the adopted methods in Study 1 and 2. Information regarding participants, experimental setup and common data processing will be presented.

1. PARTICIPANTS

Unexperienced participants (UNE) and experienced weightlifters (EXP) relevant information of Study 1 and Study 2 is overviewed in Tables 1 and 2, respectively. Specific information is provided in chapters E and F of this document.

	N	Age (years)	Height (cm)	Weight (kg)	5RM (kg)
Day 1	12	24.5 ± 2.3	171.4 ± 4.4	68.2 ± 6.5	53.3 ± 9.8
Day 2	11				53.2 ± 11.5

Table 1 – Study 1 participants information

	N	Age (years)	Height (cm)	Weight (kg)	5RM (kg)
UNE	10	24.8 ± 2.0	173.0 ± 4.3	68.0 ± 5.5	53.0 ± 8.4
EXP	7	30.7 ± 9.3	177.6 ± 6.0	85.9 ± 9.0	102.1 ± 9.6

Table 2 – Study 2 participants information

2. TEST SESSION DATA COLLECTION AND MATERIALS

After the warm-up, participants were tested in 5RM power clean. The lifted load in each set was increased by 2.5-5kg until the 5RM load was determined. The participants had four minutes rest between sets, and after the 5RM was found, they had approximately one hour to recover while we placed the electrodes and reflexive markers.

An eight-camera system (Qualisys, Gothenburg, Sweden) was used and placed around the space where the exercise was performed. Three markers were attached to each side of the barbell to measure its displacement. Movement data were sampled at 200 samples/s.

The data collection of myoelectrical signals was recorded on sixteen muscles of the right side of the body (Figure 1): *upper trapezius* (TS), *pectoralis major* (PM), *biceps brachii* (BB), *triceps brachii lateral head* (TB), *flexor digitorum superficialis* (FDS), *extensor digitorum communis* (EDC), *latissimus dorsi* (LD), *erector spinae* (ES), *rectus abdominis* (RA), *external oblique* (OE), *gluteus maximus* (Gmax), *vastus lateralis of quadriceps* (VL), *biceps femoris long head* (BF), *semitendinosus* (ST), *lateral gastrocnemius* (GL) and *tibialis anterior* (TA). The muscles were selected so we could assess to trunk, lower and upper limb agonist-antagonist muscles. Due to the exercise limitations, we were not able to place electrodes on *anterior deltoideus* and *rectus femoris of quadriceps*. The electrodes were placed according to SENIAM (Surface EMG for Non-Invasive Assessment of Muscles), with exception of FDS, EDC, LD, PM, RA and OE: FDS and EDC were placed as recommended by Zipp (1982); LD was positioned according to de Sèze and Cazalets (2008); PM was placed medially to the anterior axillary border; RA and OE were located 3 and 15cm laterally from the umbilicus, respectively. Before the placement of the electrodes, the skin was shaved and cleaned with alcohol to minimize skin impedance.

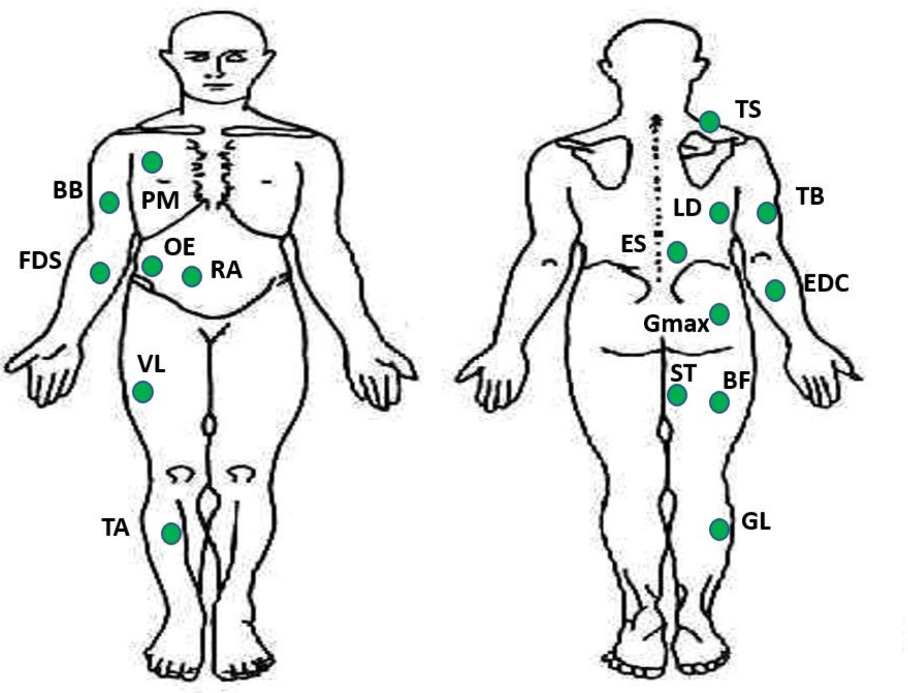

Figure 1 - Electrodes placement

Surface EMG was acquired using sixteen bipolar surface electrodes (EMG Delsys, TrignoTM), fixed with specially designed adhesive interface, aligned with the muscle fibers (Hermens et al., 2000), and then additionally fixed with tape to avoid movement artefacts. EMG signals were preamplified and band-pass filtered between 20 and 450Hz, while digitized at 1000 samples/s.

Participants performed one set of three repetitions with 90% of the 5RM. Since the amplitude normalization procedure in studies with extraction of muscle synergies is still debatable, we used this set for task-specific submaximal dynamic normalization (Kristiansen et al., 2015). Then, we instructed the participants to perform four sets of eight repetitions with 70% of the 5RM. In these sets they should do *touch-and-go* on the floor between repetitions, performing the ascendant phase in the most explosive way possible and the descendant phase in a controlled way. The beginning of the ascendant phase was defined at the lowest position of the barbell (when the discs are in contact with the ground) and the end in the highest position of the barbell. The beginning and the ending of the descendant phase were defined in the opposite way. Each phase was time normalized to 100%, since different individuals may not have the same relative time phases, and the bar displacement was smoothed with a low-pass filter (8Hz, 4^{th} order Butterworth). The first and last repetitions of all sets were excluded.

3. DATA PROCESSING

Raw EMG signals were band-pass filtered (20-490Hz), rectified, smoothed with a low-pass filter (12Hz, 4^{th} order Butterworth) and normalized to the average value of the 100ms across the EMG peak of the set of 3 repetition with 90% of the 5RM. After a visual inspection of the EMG signals, some repetitions and some individual muscles were excluded due to signal artefacts. For each set, at least 4 repetitions were considered (mean: 5.9 ± 0.6, range: 4-8), and the number of muscles used for extracting muscle synergies was 15.7 ± 0.6 (range: 13-16). The linear envelopes of each phase were interpolated to 100 points, since it was not our aim to analyze the degree of muscle activation (Hug, 2011).

Extraction of muscle synergies has been done through NMF, implementing the algorithm proposed by Lee and Seung (2001). Matrix factorization minimizes the residual Frobenius norm between the initial matrix and its decomposition, given as:

$$E = WC + e$$

$$W \geq 0 \ ^{min} \ ||E - WC||_{FRO}$$
$$C \geq 0$$

where E is a p-by-n matrix (p = number of muscles; n = number of time points), W is a p-by-s (s = number of synergies), C is an s-by-n matrix and e is a p-by-n matrix. $|| \, ||_{FRO}$ establishes the Frobenius norm and e is the residual error matrix. Therefore, the two multiplication matrices in which the initial matrix is decomposed, represent two components: the muscle synergy vectors (W), regarding the relative weighting of each muscle within each synergy and, the synergy activation coefficient (C), regarding the relative activation time of the muscle synergies during the power clean. The algorithm was repeated 100 times.

Each set consisted in 4 to 8 repetitions. Thus, E was a 16 row by 800 to 1600 columns matrix. The analysis was iterated by varying the number of synergies between 1 and 16. The number of muscle synergies selected was dependent on variance accounted for (VAF). Therefore, the number of muscle synergies was the smallest number that defined 90% of VAF, considering that each synergy should represent at least 5% of VAF. The application of the NMF does not sort the muscle synergies in the same way for all sets of the participants which required that the muscle synergies had been previously sorted.

Specific statistical analysis of each study will be detailed later, in methods of chapters E and F of this document.

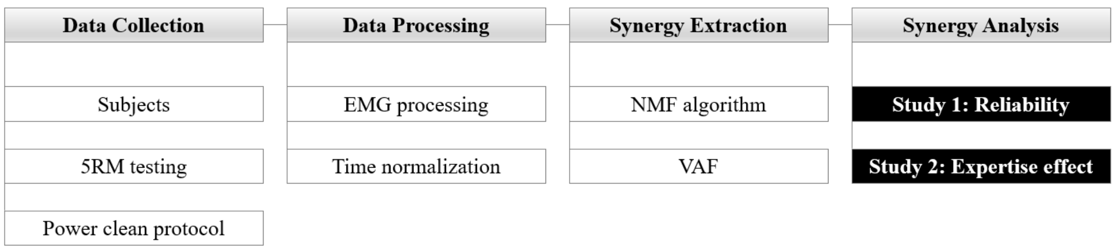

Figure 2 - Research route of the thesis (adapted from Chen et al., 2017)

E – Study 1

WITHIN AND BETWEEN DAY RELIABILITY OF MUSCLE SYNERGIES IN POWER CLEAN

Authors: Paulo Guia dos Santos, João Rocha Vaz, Paulo Freitas Correia, Maria João Valamatos, António Prieto Veloso, Pedro Pezarat-Correia

1.INTRODUCTION

When performing a motor task, the Central Nervous System (CNS) has to control the biomechanical redundancy established by infinite neuromuscular interactions, in a way that all muscles involved can lead to the desired joint moments and assure that the task is successfully performed (Bernstein, 1967). The complexity of the CNS control of all the involved elements is not completely understood yet. It has been suggested that there might be a mechanism that deals with the many degrees of freedom available in the neuromusculoskeletal system. Such mechanism would consist in a low-dimensional elements that decrease the computational burden and, hence, would allow a more efficient control from the CNS (Hirashima and Oya, 2016). Thus, these low-dimensional elements, also known as muscle synergies, allow the CNS to control smaller number of variables, simplifying the construction of motor behaviors (Tresch and Jarc, 2009; Safavynia et al., 2011; d'Avella et al., 2003). Recent research in this field suggest that muscle synergies represent motor modules controlled by motor cortical areas and integrating sensory information that activate groups of muscles to generate a specific motor output (Bizzi and Cheung, 2013; Bruton and O'Dwyer 2018). Despite the origin of muscle synergies is still a debatable issue, considering that studies suggest that muscle synergies reflect biomechanical constraints (Kutch & Valero-Cuevas, 2012), other studies defend that these coordinative primitives have a neural origin and are structured in the brainstem or spinal cord (Bizzi and Cheung, 2013; Hart and Giszter 2010; Takei et al. 2017).

Muscle synergies are extracted from surface electromyographic signals (EMG) of multiple muscles and, ultimately, reflect muscle coordination strategies (Hug, 2011). The study of muscle synergies has shown to be relevant in neurorehabilitation (Safavynia et al., 2011), robotics and sports (Singh et al. 2018; Taborri et al. 2018). In neurorehabilitation, muscle synergy extraction has provided an improving neuromuscular diagnosis and rehabilitation assessment on poststroke patients, spinal cord injuries, Parkinson's disease and cerebral palsy. In robotics the utilization of Muscle Synergy hypothesis has been used in the construction of artificial limbs, mainly robotic arms. In sports field, the low-level control of complex movements has provided useful information to improve athlete performance and training. Generally, the extraction of muscle synergies may provide information about how the CNS recruits muscles during motor tasks, reducing the dimensionality of muscle control (Taborri et al., 2018).

The production of voluntary movement in humans has been studied regarding this procedure in crawling (Chen et al. 2017) walking and running (Cappellini et al. 2006), postural control tasks in response to unexpected external perturbations (Kim et al. 2018), pedaling (Hug et al., 2010, 2011), rowing (Turpin et al. 2011), backward giant swing (Frère and Hug 2012), breaststroke swimming (Vaz et al., 2016) and bench press (Kristiansen et al. 2015).

A necessary next step in this field of research is the deeper understanding of the effect of training in these muscle coordination strategies assessed through muscle synergy analysis. Recently, Kristiansen et al. (2015) showed that experienced powerlifters exhibited larger inter-subject variability in the muscle vectors (i.e. individual contribution of each muscle to each synergy) compared to untrained individuals. Interestingly, a follow-up study from this group revealed that after a 5-week training protocol, the training group exhibited a larger inter-subject variability compared to baseline regarding the observed decreases in intra-group correlation-values (Kristiansen et al., 2016a). Furthermore, a recent study found that individuals that participated in a 4-weeks proprioceptive training (wobble board) altered the modular organization of the synergies in the early phase of a single-leg drop-landing task (Silva et al., 2018). The authors propose that this change was caused by the emerging of a new synergy composed by the plantarflexors and ankle evertors muscles. The findings from the Kristiansen et al.'s studies are not very surprising because the mechanical degrees of freedom of a bench press task is small. Therefore, a crucial step in the study of the effect of strength training in muscle synergies requires a whole-body task that involves more joints from both the upper and lower limb muscles.

The power clean exercise, for example, is a derivative exercise of the full clean (first movement of the Clean & Jerk lift) and one of the most utilized exercises in strength and power training in sports. This exercise encompasses movement at high angular velocities in upper- and lower-limb joints, while the trunk stabilization is a key point to the task success. Thereby, the exercise complexity demands a more accurate motor control of broader degrees of freedom than bench press that promotes movement on only two joints.

Thus, before conducting an intervention study to explore the effect of strength training in this complex task, a reliability study is required to better interpret possible results from a training protocol. Therefore, the aim of the present study was to investigate the intra- and inter-day reliability of the muscle synergies and the individual EMG signals during the power clean exercise in untrained individuals. Based on previous research (Taborri, Palermo, Del Prete, & Rossi, 2018; Kristiansen et al., 2016b), we hypothesized that the synergistic organization of motor control would remain the same, while muscle synergies components and individual EMG would exhibit moderate-to-high values of intra- and inter-day reliability.

2.METHODS

Participants

Twelve male subjects (age 24.5 ± 2.3 years, height 171.4 ± 4.4 cm, body mass 68.2 ± 6.5 kg) with five repetition maximum (5RM) in power clean of 53.3 ± 9.8 kg and 53.2 ± 11.5 kg at first and second session, respectively, participated in this study. The inclusion criterion encompassed healthy subjects (Physical Education students) without prior knowledge about the critical points of the exercise. Two subjects were excluded by failing to meet the critical points of the exercise, which could compromise their physical safety. The subjects were informed to abstain from any physical activity in the day before the evaluation sessions. All participants provided informed written consent. This study was approved by the Faculty's Ethics Committee (CEFMH 4/2018) and all procedures adhered to the Declaration of Helsinki.

Experimental Approach

Aiming to assess the reliability of extracted muscle synergies in a complex strength training task in unexperienced subjects, the participants performed the power clean. This exercise is commonly used for training and assessment of physical capacities and it has been previously shown to be a reliable indicator of performance in experienced (Comfort, 2013), unexperienced (Comfort & McMahon, 2015) and adolescent athletes (Faigenbaum et al., 2012). Each participant performed three sessions, with exception of one participant that did not realize the last one. The first session had the purpose of familiarize the participants with the task and with the laboratory equipment. In this familiarization all participants had one-hour session of technical learning of the movement, with video demonstration and a first experience performing the exercise. The two subsequent sessions, approximately one week after the familiarization, were performed to investigate the within and between session reliability of muscle synergies in power clean. These two sessions were separated by three to seven days.

Test session data collection and materials

After the warm-up, participants were tested in power clean 5RM. The lifted load in each set was increased by 2.5-5kg until the 5RM load was determined. The participants had four minutes rest between sets, and after the 5RM was found, they had approximately one hour to recover while we placed the electrodes.

An eight-camera system (Qualisys, Gothenburg, Sweden) was used and placed around the space where the exercise was performed. Three markers were attached to each side of the barbell to measure its displacement. Movement data were sampled at 200 samples/s. The data collection of myoelectrical signals was recorded on sixteen muscles of the right side of the body: *upper trapezius* (TS), *pectoralis major* (PM), *biceps brachii* (BB), *triceps brachii lateral head* (TB), *flexor digitorum superficialis* (FDS), *extensor digitorum communis* (EDC), *latissimus dorsi* (LD), *erector spinae* (ES), *rectus abdominis* (RA), *external oblique* (OE), *gluteus maximus* (Gmax), *vastus lateralis of quadriceps* (VL), *biceps femoris long head* (BF), *semitendinosus* (ST), *lateral gastrocnemius* (GL) and *tibialis anterior* (TA). The muscles were selected so we could assess to trunk, lower and upper limb agonist-antagonist muscles. Due to the exercise limitations we were not able to place electrodes on *anterior deltoideus* and *rectus femoris of quadriceps*. The electrodes were placed according to SENIAM (Surface EMG for Non-Invasive Assessment of Muscles), with exception of FDS, EDC, LD, PM, RA and OE: FDS and EDC were placed as recommended by Zipp (1982); LD was positioned according to de Sèze and Cazalets (2008); PM was placed medially to the anterior axillary border; RA and OE were located 3 and 15cm laterally from the umbilicus, respectively. Before the placement of the electrodes, the skin was shaved and cleaned with alcohol to minimize impedance. Surface EMG was acquired using sixteen bipolar surface electrodes (EMG Delsys, TrignoTM), fixed with specially designed adhesive interface, aligned with the muscle fibers (Hermens et al., 2000) and then additionally fixed with tape to avoid movement artefacts. EMG signals were preamplified and band-pass filtered between 20 and 450Hz, while digitized at 1000 samples/s.

Participants performed one set of three repetitions with 90% of the 5RM. Since the amplitude normalization procedure in studies with extraction of muscle synergies is still debatable, we used this set for task-specific submaximal dynamic normalization (Kristiansen et al., 2015). Then, we instructed the participants to perform four sets of eight repetitions with 70% of the 5RM. In these sets they should do *touch-and-go* on the floor between repetitions, performing the ascendant phase the most explosive way possible and the descendant phase in a controlled way. The beginning of the ascendant phase was defined in the lowest position of the barbell (when the discs are in contact with the ground) and the end in the highest position of the barbell. The beginning and ending of the descendant phase were defined in the opposite way (Figure 1). Each phase was time normalized to 100%, since different individual may not have the same relative time phases, and the barbell displacement was smoothed with a low-pass filter (8Hz, 4th order Butterworth). The first and last repetitions of all sets were excluded.

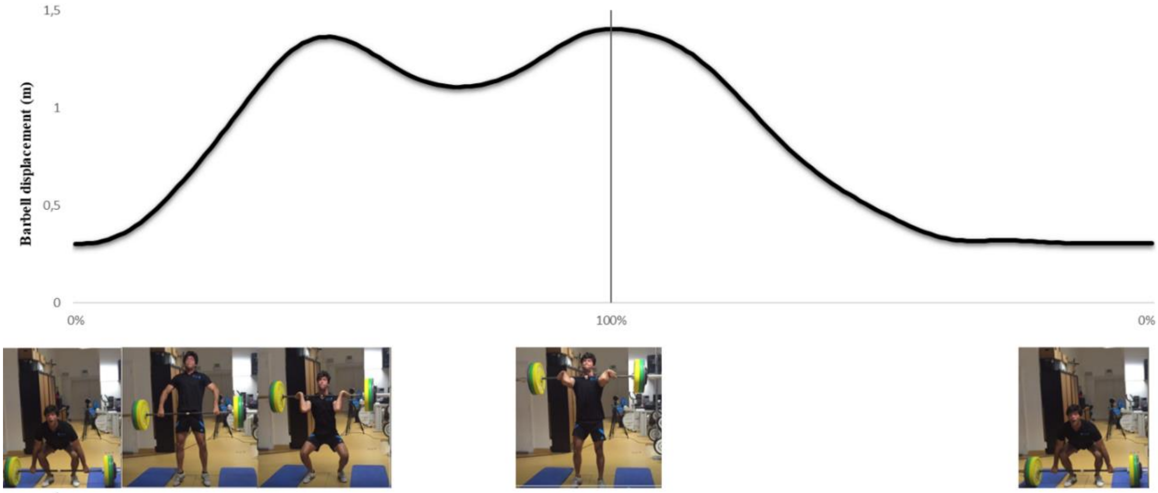

Figure 1 - Cycle segmentation in ascendant (0→100%) and descendant phases (100→0%). The thick black line represents the bar displacement along the cycle and the vertical black line represents the highest height attained by the barbell. The figures are illustrating the movement progression.

Data processing

Raw EMG signals were band-pass filtered (20-490Hz), rectified, smoothed with a low-pass filter (12Hz, 4th order Butterworth) and normalized to the average value of the 100ms across the EMG peak of the set of 3 repetition with 90% of the 5RM. After a visual inspection of the EMG signals, some repetitions and some individual muscles were excluded due to movement artefacts. For each set at least 4 repetitions were considered (mean: 5.9 ± 0.6, range: 4-8), and the number of muscles used for extracting muscle synergies was 15.7 ± 0.6 (range: 13-16). The linear envelopes of each phase were interpolated to 100 points, since it is not our aim to analyze the degree of muscle activation (Hug, 2011).

Extraction of muscle synergies has been done through NMF, implementing the algorithm proposed by Lee and Seung (2001). Matrix factorization minimizes the residual Frobenius norm between the initial matrix and its decomposition, given as:

$$E = WC + e$$

$$W \geq 0 \; ^{min} \; ||E - WC||_{FRO}$$
$$C \geq 0$$

where E is a p-by-n matrix (p = number of muscles; n = number of time points), W is a p-by-s (s = number of synergies), C is an s-by-n matrix and e is a p-by-n matrix. $|| \; ||_{FRO}$ establishes the Frobenius norm and e is the residual error matrix. Therefore, the two multiplication matrices in which the initial matrix is decomposed, represent two components: the muscle synergy vectors (W), regarding the relative weighting of each muscle within each synergy, considering that a 0.3 threshold defined if muscles were considered active in the synergy (Xiong et al., 2018), and the synergy activation coefficient (C), regarding the relative activation time of the muscle synergies across the power clean. The algorithm was repeated 100 times.

Each set consisted in 4 to 8 repetitions. Thus, E was a 16 row by 800 to 1600 columns matrix. The analysis was iterated by varying the number of synergies between 1 and 16. The number of muscle synergies selected was dependent on variance accounted for (VAF). Therefore, the number of muscle synergies was the smaller number that defined 90% of VAF if each synergy represented at least 5% of VAF. Also, VAF for each muscle (VAFmuscle) was calculated, guarantying that the extracted muscle synergies accounted their activity pattern. A VAFmuscle higher than 75% was considered satisfying (Frère & Hug, 2012). The application of the NMF does not sort the muscle synergies in the same way for all sets of the participants which required that the muscle synergies had been previously sorted.

Statistical analysis

To assess the intraday reliability of muscle synergies, we used a two-way mixed-effects intraclass correlation, ICC (3,4), with 95% confidence interval (CI), measuring the relative reliability of VAF and VAFmuscle. The mean value of the four sets is considered when applying average ICC. Values of ICC were categorized as follows: 0.9 - 1.00, excellent; 0.75 - 0.9, high; 0.5 - 0.75, moderate; < 0.5, poor (Koo & Li, 2016). Standard error of measurement (SEM) was calculated to measure absolute reliability of VAF and VAFmuscle (Weir, 2005).

To compare the muscle synergy vectors across the four sets Pearson's correlation coefficient (*r*) were calculated. Thus, the *r* of each muscle synergy vector represents the average of the correlation coefficients between each pair of sets (6 values). The synergy activation coefficients and individual EMG patterns were assessed through the maximum cross-correlation function (*rmax*), being an indicator of the waveform similarity, and the lag time, obtained using the Matlab 2015a (Mathworks Inc., Natick MA, USA) *xcorr* function for centered data (option "*coeff*"). The lag time is determined at the maximum cross correlation function and enables the assessment of differences in timing of activation. This analysis was made in two dimensions: first, by averaging the *rmax* and lag time-values of each pair of repetitions (i.e., for each set); second, by averaging the *rmax* and lag time-values of each pair of sets (i.e., for each day). *R*-values were categorized as follows: 0.7 - 1.0, strong correlation; 0.3 - 0.7, moderate correlation; < 0.3, weak correlation (Sheskin, 2011).

The differences in the lag time between repetitions and sets were evaluated performing a sample Student's t-test with zero as reference value and the Cohen's d as measure of effect size. We verified normality through the Shapiro-Wilk test (SPSS version 25.0, SPSS Inc., Chicago, IL, USA) using a significance level of $p < 0.05$. If normality was not assumed, one-sample Wilcoxon signed rank test was used.

Interday reliability of VAF and VAFmuscle was assessed by using single measure ICC (3,1) for the average of the four sets of each day. ICC (3,1) was also used to measure interday reliability of the 5RM power clean test. Regarding muscle synergy vectors and synergy activation coefficients we compared each set of the first day with each set of the second day. Then, the reliability analysis was similar to the described for intraclass analysis. We calculated for each subject the average of the sixteen values of *r* for each muscle synergy vector and the average of the sixteen values of *rmax* for each synergy activation coefficient and individual EMG patterns (*rmax* and lag times). The differences in the lag time between days were evaluated performing a sample Student's t-test with zero as reference value or one-sample Wilcoxon signed rank test when normality was not assumed. To justify possible weaker correlations of muscle vectors between days, we realized a posterior cluster analysis dividing the subjects in two groups: one with anterior background in general strength training (CST) and the other without that experience (CUE). Normality was tested and t-test for independent samples was performed to assess significative differences in *r*-values.

3.RESULTS

Using the described criteria to identify the number of muscle synergies, three muscle synergies were identified in the first day for all subjects. In the second day for one subject, the third muscle synergy did not account 5% of VAF, while the other subjects presented three muscle synergies too. Three muscle synergies were extracted for all subjects to facilitate the comparison. The muscle synergy #1 mainly represented the back and hip extension (LD, ES, Gmax, BF, ST) and the plantarflexion (GL), presenting two peaks, one in the ascendant and other in the descendant phase. The muscle synergy #2 involved the upper-limb muscles (TS, BB, TB, FDS, EDC) and the muscle synergy #3 represented the final of the ascendant phase and mainly involved the core muscles (RA, OE, ES) the PM, VL and TA.

Intra-day reliability

The three muscle synergies represented 86.6 ± 1.6% and 87.3 ± 1.8% of VAF in first and second day, respectively (Figure 2 and 3). An excellent reliability was shown for the three extracted synergies in both days (ICC (3,4)-values ranging from 0.92 to 0.98) and a high to excellent reliability was shown for VAFmuscle (0.80 - 0.98) with exception of OE in day 1 that presented only moderate values of ICC (0.65). The reliability-values are presented in Table 1.

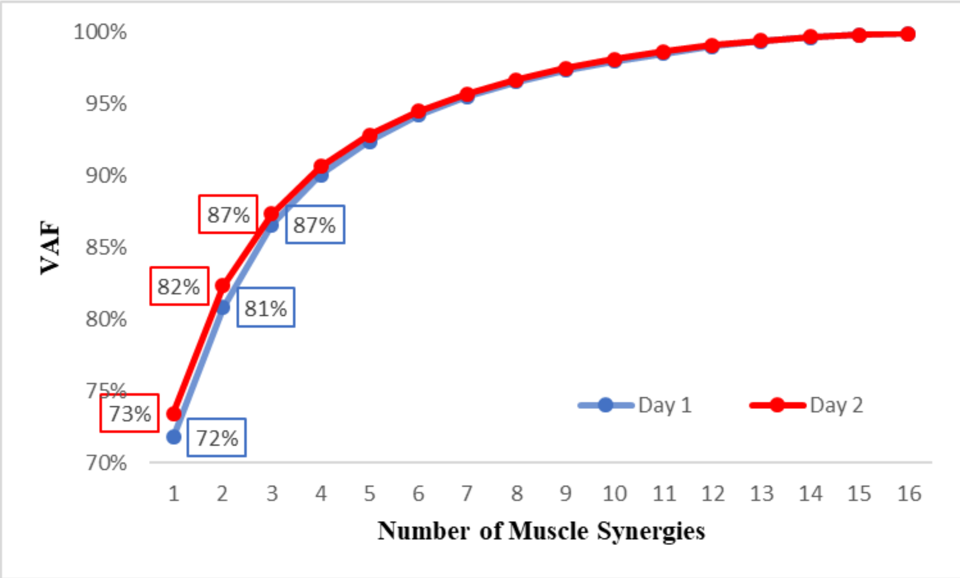

Figure 2 - Mean values of variance accounted for (VAF) relatively to the original extraction iteration of sixteen muscle synergies for day one and two.

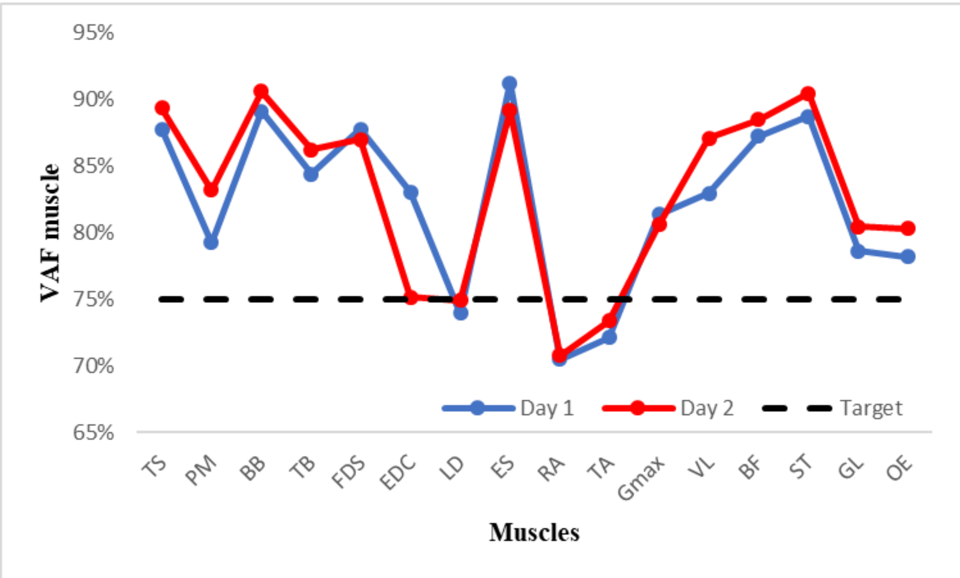

Figure 3 - Mean values of variance accounted for each muscle (VAFmuscle) regarding a three synergy-model for day one and two. The dashed black line represents 75% defined threshold (Torres-Oviedo & Ting, 2007).

Table 1 – ICC, SEM and Confidence Interval (CI(95%)) for of intra (day 1 and 2) and interday reliability analysis of VAF and VAFmuscle

		VAF			**VAF muscle**															
		#1	**#2**	**#3**	**TS**	**PM**	**BB**	**TB**	**FDS**	**EDC**	**LD**	**ES**	**RA**	**TA**	**Gmax**	**VL**	**BF**	**ST**	**GL**	**OE**
Intra-day 1	ICC (3,4)	0.95	0.94	0.92	0.92	0.91	0.82	0.89	0.91	0.97	0.94	0.80	0.89	0.84	0.97	0.84	0.94	0.89	0.92	0.65
	SEM	0.02	0.01	0.01	0.03	0.08	0.03	0.05	0.05	0.03	0.07	0.06	0.14	0.09	0.03	0.10	0.03	0.04	0.05	0.10
	CI (95%)	0.87 0.98	0.84 0.98	0.81 0.97	0.82 0.98	0.78 0.97	0.56 0.94	0.74 0.97	0.77 0.97	0.91 0.99	0.87 0.98	0.52 0.94	0.70 0.97	0.60 0.95	0.92 0.99	0.60 0.95	0.85 0.98	0.72 0.97	0.82 0.98	0.13 0.90
Intra-day 2	ICC (3,4)	0.98	0.97	0.92	0.98	0.97	0.94	0.97	0.95	0.97	0.95	0.94	0.92	0.93	0.95	0.88	0.88	0.81	0.95	0.89
	SEM	0.01	0.01	0.00	0.02	0.03	0.02	0.03	0.03	0.05	0.06	0.03	0.07	0.07	0.03	0.04	0.02	0.05	0.04	0.05
	CI (95%)	0.95 0.99	0.93 0.99	0.81 0.98	0.95 0.99	0.91 0.99	0.84 0.94	0.92 0.99	0.88 0.99	0.91 0.99	0.87 0.99	0.84 0.98	0.76 0.98	0.81 0.98	0.87 0.98	0.70 0.96	0.69 0.96	0.52 0.94	0.87 0.99	0.70 0.97
Inter-day	ICC (3,1)	0.66	0.62	0.54	0.09	0.43	0.48	0.83	0.24	0.13	0*	0.09	0.42	0.30	0.63	0.29	0*	0.26	0.38	0.19
	SEM	0.03	0.02	0.01	0.07	0.10	0.03	0.04	0.09	0.15	0.20	0.08	0.18	0.11	0.06	0.08	0.07	0.07	0.09	0.09
	CI (95%)	0.14 0.90	0.07 0.88	0.06 0.85	-0.52 0.63	-0.19 0.81	-0.13 0.83	0.49 0.95	-0.39 0.72	-0.51 0.68	-0.69 0.44	-0.51 0.64	-0.24 0.82	-0.34 0.75	0.08 0.88	-0.34 0.74	-0.72 0.38	-0.37 0.73	-0.25 0.79	-0.43 0.69

(*) Negative-values of ICC are usually taken to be zero reliability (Bartko, 1976)

Regarding muscle synergy vectors in the first day, we verified strong correlations (0.84, 0.85 and 0.74 for vector 1, 2 and 3, respectively). Also, in second day, all muscle synergy vectors have shown strong correlations (0.83, 0.87 and 0.86 for vectors 1, 2 and 3, respectively). Synergy activation coefficients showed strong correlations between sets of day 1 and day 2 (0.93 - 0.97). However, lag time showed to be significantly different of 0 between sets for synergy #2 in day 1. Vectors and coefficients are depicted in Figure 4 and 5, and the correlation-values are presented in Table 2 and 4. The individual EMG profiles showed a very strong correlation across sets in both days, presenting *rmax*-values ranging from 0.89 to 0.99 (Table 2). However, significant lag times were verified for TS, PM, BF and ST in both days, for GL in day 1 and for BB in day two.

Considering the inter-repetition analysis, synergy activation coefficients were strongly correlated (0.89 – 0.92) in both days, with relative time shifts for synergy #2. For individual EMG patterns the correlations were strong in both days, ranging between 0.86 and 0.95, and slight shifts were found in particular sets (Day1 → Set 3: GL; Set 4: BB, TB, FDS, LD, ES, Gmax, VL, BF, OE; Day 2 → Set 1: RA; Set 3: PM, EDC, LD, RA; Set 4: EDC).

Inter-day reliability

Between days, the 5RM power clean test used to determine the lifted weight by each participant showed an excellent reliability (0.97), and the SEM was 2.82.

VAF for the three synergies had moderate ICC (3,1)-values (0.66, 0,62 and 0,54 for synergy #1, #2 and #3, respectively). For VAFmuscle, ICC assumed generally poor-values, excepting Gmax and TB that had moderate (0.63) and high (0.83) reliability values, respectively.

Synergy activation coefficients showed no differences in lag time and appeared to be strongly correlated (0.87 - 0.90) across days. However, muscle synergy vectors presented moderate-values of correlation (0.56, 0.59 and 0.50 for synergy #1, #2 and #3, respectively). Correlation-values are presented in Table 3 and 4. The cluster analysis showed significantly higher values of correlation in synergy #2 for the CST (Figure 6).

Individual EMG profiles presented strong correlation-values (0.89 – 0.97) and did not present any time shifts between days.

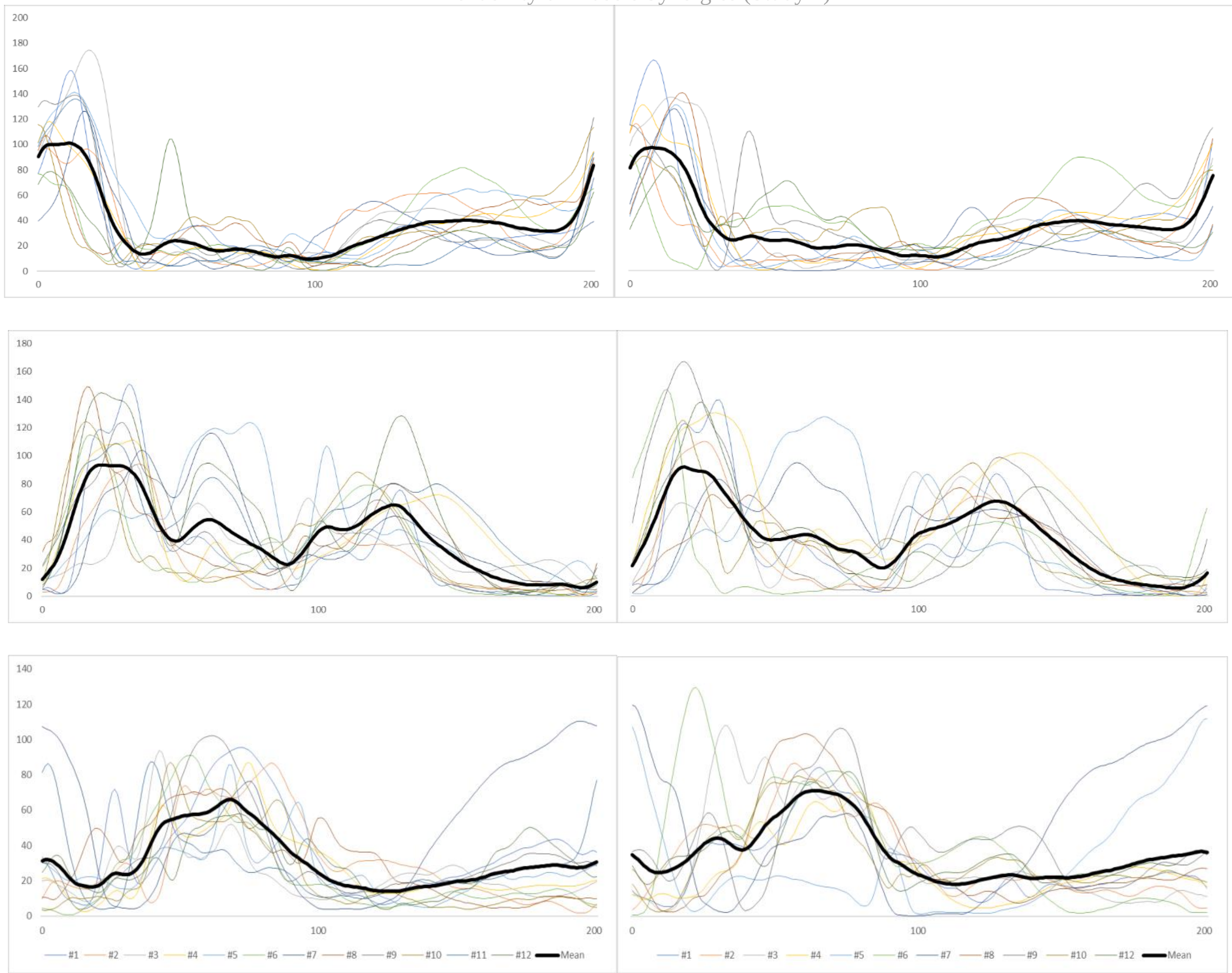

Figure 4 - Synergy activation coefficients (UA) across subjects in each day. Day 1 is represented in left side plots, while day 2 plots are in right side. Top panel regards to synergy #1, central panel to synergy #2 and bottom panel to synergy #3. The thick black line represents the group mean, while the thin colored lines represent individual synergy activation coefficients.

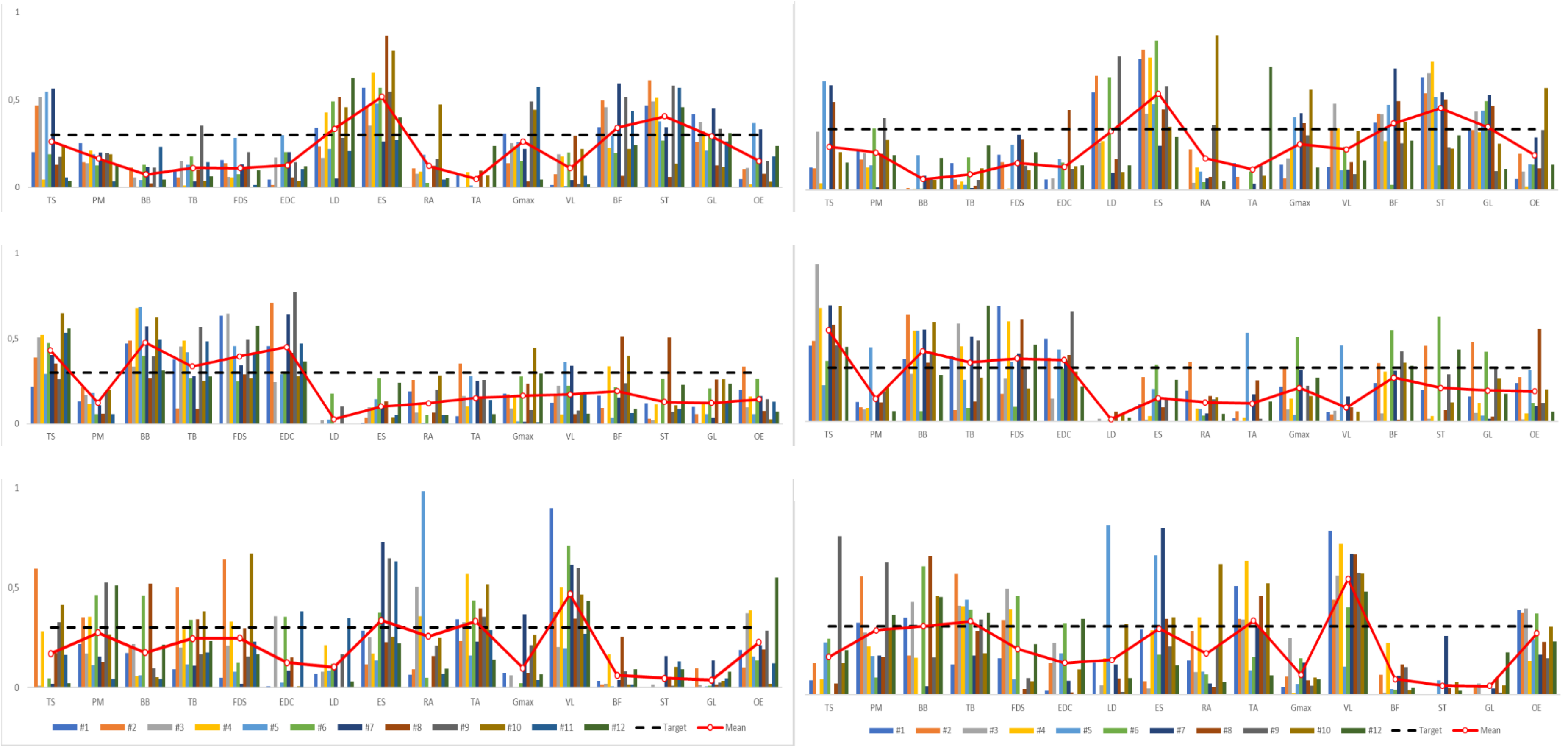

Figure 5 – Muscle synergy vectors (UA) across subjects in each day. Day 1 is represented in left side plots, while day 2 plots are in right side. Top panel regards to synergy #1, central panel to synergy #2 and bottom panel to synergy #3. The dashed black line represents the 0.3, which defines if muscles are considered active in the synergy (Xiong et al., 2018), the red line represents the group mean for each muscle, and the colored bars represent individual muscle synergy vectors.

Table 2 – Between repetition and between set similarity values (*rmax*) and lag times (% of the power clean cycle) of synergy activation coefficients and individual EMG profiles. Bold values represent significantly differences from zero and Cohen's *d* above 0.8.

	Inter-repetition				Inter-set							
	Day 1		Day 2		Day 1				Day 2			
	lag (%)	*rmax*	lag (%)	*rmax*	lag %	lag *p*	lag *d*	*rmax*	lag %	lag *p*	lag *d*	*rmax*
Individual EMG Profiles												
TS	-0.08 ± 0.75	0.93 ± 0.02	-0.16 ± 0.77	0.94 ± 0.02	-0.22 ± 0.46	**0.05**	-0.58	0.98 ± 0.01	-0.33 ± 0.47	**0.04**	-0.61	0.98 ± 0.01
PM	-0.10 ± 1.61	0.88 ± 0.05	-0.25 ± 0.56	0.90 ± 0.03	-0.19 ± 0.33	**0.03**	-0.63	0.96 ± 0.03	-0.21 ± 0.30	**0.04**	-0.61	0.98 ± 0.01
BB	-0.01 ± 1.03	0.94 ± 0.02	-0.11 ± 0.81	0.95 ± 0.02	-0.30 ± 0.45	0.05	-0.63	0.98 ± 0.00	-0.37 ± 0.40	**0.02**	**-0.88**	0.99 ± 0.01
TB	-0.43 ± 0.77	0.92 ± 0.04	-0.40 ± 1.05	0.93 ± 0.03	-0.18 ± 0.48	0.24	-0.36	0.98 ± 0.01	-0.22 ± 0.42	0.13	-0.50	0.98 ± 0.01
FDS	-0.31 ± 1.02	0.93 ± 0.03	-0.39 ± 1.04	0.92 ± 0.03	-0.18 ± 0.45	0.21	-0.39	0.98 ± 0.01	-0.33 ± 0.60	0.12	-0.52	0.98 ± 0.02
EDC	-0.29 ± 0.83	0.94 ± 0.03	-0.42 ± 0.72	0.94 ± 0.03	-0.19 ± 0.38	0.21	-0.40	0.98 ± 0.01	-0.07 ± 0.30	0.53	-0.20	0.97 ± 0.02
LD	-0.15 ± 1.42	0.88 ± 0.05	-0.34 ± 1.47	0.88 ± 0.06	-0.01 ± 0.02	0.32	-0.29	0.96 ± 0.02	-0.06 ± 0.15	0.18	-0.40	0.96 ± 0.02
ES	-0.07 ± 0.53	0.93 ± 0.03	-0.07 ± 0.46	0.93 ± 0.03	0.00 ± 0.00	1.00	0.00	0.98 ± 0.01	0.00 ± 0.00	1.00	0.00	0.98 ± 0.01
RA	-0.08 ± 2.29	0.86 ± 0.06	-0.82 ± 1.81	0.88 ± 0.05	-0.30 ± 0.53	0.13	-0.49	0.95 ± 0.02	-0.02 ± 0.23	0.84	-0.06	0.96 ± 0.02
TA	-0.10 ± 1.72	0.87 ± 0.04	-0.94 ± 2.18	0.87 ± 0.03	-0.15 ± 0.76	0.54	-0.18	0.97 ± 0.01	-0.20 ± 040	0.15	-0.47	0.96 ± 0.01
Gmax	-0.14 ± 0.91	0.93 ± 0.02	0.00 ± 0.84	0.93 ± 0.02	-0.06 ± 0.35	0.56	-0.17	0.98 ± 0.01	-0.08 ± 0.29	0.67	-0.13	0.98 ± 0.01
VL	-0.18 ± 0.58	0.94 ± 0.02	-0.13 ± 0.55	0.94 ± 0.02	-0.03 ± 0.17	0.71	-0.11	0.99 ± 0.00	-0.07 ± 0.13	0.11	-0.48	0.99 ± 0.00
BF	-0.04 ± 0.93	0.92 ± 0.04	-0.12 ± 0.64	0.94 ± 0.02	-6.87 ± 3.27	**<0.001**	**-2.01**	0.92 ± 0.03	-8.80 ± 3.48	**<0.001**	**-0.86**	0.93 ± 0.02
ST	-0.11 ± 0.53	0.93 ± 0.04	-0.08 ± 0.60	0.93 ± 0.04	-0.77 ± 0.94	**0.03**	-0.75	0.94 ± 0.02	-0.62 ± 0.71	**0.02**	**-0.83**	0.94 ± 0.03
GL	0.26 ± 1.62	0.88 ± 0.04	-0.03 ± 1.30	0.89 ± 0.05	-6.45 ± 8.81	**0.03**	-0.61	0.89 ± 0.01	-5.16 ± 8.01	0.07	-0.61	0.89 ± 0.02
OE	-0.66 ± 2.04	0.87 ± 0.05	-0.11 ± 1.39	0.88 ± 0.04	-0.15 ± 0.43	0.29	-0.32	0.97 ± 0.01	-0.06 ± 0.21	0.42	-0.26	0.97 ± 0.01
Synergy Activation Coefficients												
#1	-2.40 ± 8.06	0.89 ± 0.04	-0.15 ± 4.75	0.91 ± 0.04	-0.30 ± 0.85	0.11	-0.46	0.97 ± 0.03	0.28 ± 1.45	0.71	-0.11	0.95 ± 0.05
#2	-4.27 ± 3.07	0.91 ± 0.04	-0.86 ± 2.68	0.92 ± 0.03	0.74 ± 4.35	**0.05**	-0.58	0.97 ± 0.02	-0.37 ± 0.78	0.17	-0.45	0.97 ± 0.02
#3	2.29 ± 6.48	0.89 ± 0.06	1.59 ± 7.30	0.91 ± 0.04	-1.53 ± 4.76	0.37	-0.26	0.93 ± 0.05	-1.56 ± 3.26	0.08	-0.54	0.96 ± 0.04

Table 3 – Between day similarity values (*rmax*) and lag times (%) of synergy activation coefficients and individual EMG profiles. Bold values represent significantly differences from zero and Cohen's *d* above 0.8.

	Inter-day			
	lag			*rmax*
	%	*p*	*d*	
Individual EMG Profiles				
TS	-0.22 ± 0.64	0.30	-0.33	0.94 ± 0.02
PM	-0.21 ± 0.63	0.21	-0.38	0.90 ± 0.08
BB	0.09 ± 0.61	0.65	0.14	0.95 ± 0.04
TB	0.29 ± 0.76	0.26	0.36	0.95 ± 0.02
FDS	-0.59 ± 1.65	0.44	-0.23	0.93 ± 0.05
EDC	4.43 ± 9.05	0.05	0.58	0.92 ± 0.04
LD	1.86 ± 5.05	0.14	0.45	0.89 ± 0.08
ES	5.43 ± 17.16	0.32	0.30	0.96 ± 0.03
RA	7.30 ± 17.72	0.11	0.48	0.92 ± 0.04
TA	0.88 ± 1.74	0.14	0.48	0.93 ± 0.03
Gmax	0.05 ± 0.83	0.84	0.06	0.94 ± 0.05
VL	2.63 ± 8.67	0.89	-0.04	0.97 ± 0.01
BF	-0.12 ± 0.48	0.44	-0.24	0.96 ± 0.02
ST	1.87 ± 5.74	0.80	0.08	0.95 ± 0.04
GL	1.22 ± 2.80	0.20	0.39	0.93 ± 0.05
OE	4.82 ± 14.15	0.12	0.47	0.93 ± 0.04
Synergy Activation Coefficients				
#1	0.07 ± 1.12	0.69	-0.12	0.87 ± 0.08
#2	-0.92 ± 2.26	0.07	-0.54	0.90 ± 0.06
#3	-1.32 ± 16.92	0.14	-0.45	0.87 ± 0.08

Table 4 – Between set and between day similarity values (*r*) of muscle synergy vectors.

	Inter-set		**Inter-day**
	Day 1	**Day 2**	
Muscle Synergy Vectors			
#1	0.84 ± 0.19	0.83 ± 0.24	0.56 ± 0.27
#2	0.85 ± 0.20	0.87 ± 0.13	0.59 ± 0.25
#3	0.74 ± 0.24	0.86 ± 0.20	0.50 ± 0.27

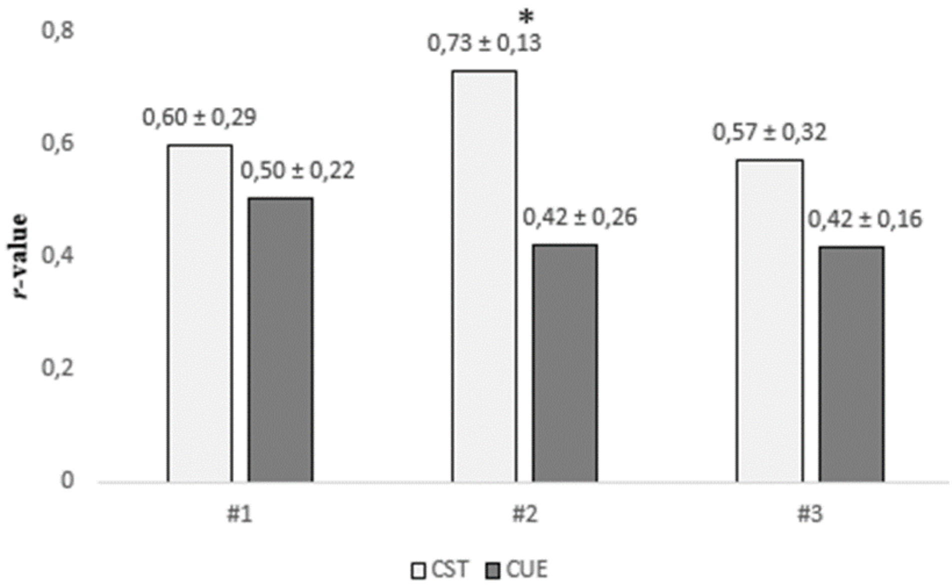

Figure 6 - Muscle synergy vectors comparison between CST and CUE clusters. (*) represents significative differences between the two clusters

4.DISCUSSION

The aim of this study was to evaluate within- and between-day reliability of muscle synergies extracted by NMF algorithm to sixteen EMG signals collected in whole-body muscles in a complex task regarding strength training, namely the power clean exercise. We hypothesized that muscle synergies would be reliable within- and between-days. Despite some minor differences in the timing of activation of some muscles in muscle synergy components, our hypothesis was globally verified.

First and foremost, we ensured the reliability of the test used to prescribe the loads defined in the protocol and individualized to each subject. The 5RM test showed an excellent reliability with a near 1 ICC-value and a low SEM-value. This result is in line with previous studies that reported that multiple repetition maximum tests of traditional strength training exercises are reliable in recreational athletes (Gail & Künzell, 2014; Taylor & Fletcher, 2011).

VAF and VAFmuscle

Although three synergies justified less than the 90% target defined for synergy extraction, a three-synergy model was chosen because the fourth synergy explained less than 5% of variance across sets. The total VAF-values defined for the chosen synergy model explaining less than the 90% target may be related with the complexity of motor control when performing the exercise, considering the variability between individuals that showed slight differences in the variance explained by each synergy (Frère & Hug, 2012). The same number of synergies defined with the same criteria was extracted in other complex tasks like rowing (Turpin et al., 2011), breaststroke swimming (Vaz et al., 2016) or backward giant swing (Frère & Hug, 2012). However, regarding strength training, the bench press synergy analysis showed that just two synergies related with the concentric and eccentric phases, respectively, explained >90% of total VAF, given that for some subjects just one synergy was sufficient to represent this target value (Kristiansen et al., 2015; Kristiansen et al., 2016b). This difference can be explained by the number of degrees of freedom available at a certain task (Frère & Hug, 2012). However, it is important to note that this comparison should be carefully made due to the potential effect of different filtering techniques prior to the extraction of muscle synergies (Hug, Turpin, Dorel & Guével, 2012).

The intra-day reliability of total VAF, using ICC (3,4), was excellent for the three extracted muscle synergies in both days, revealing that across sets subjects utilized the same synergistic organization while performing power clean. VAFmuscle ICC-values were high to excellent between sets, with exception of OE in first day, meaning that a three synergy-model just explained moderately the variance of the muscle. This may be related with the complex anatomy of the abdominal region and adipose tissue around the abdominal muscles that would affect signal integrity (Marshall & Murphy, 2003). However, in second day all muscles showed high to excellent VAFmuscle ICC-values.

Between-days the reliability of the three muscle synergies was moderate, using ICC (3,1), although slight differences in the values of the VAF were observed. The SEM-value ranged between 0.01 and 0.03 when comparing both days, similarly to the comparison made between sets where SEM varied between 0.01 and 0.02. Thus, although ICC-values for inter-day reliability analysis are just moderate, the low SEM-values associated with absolute reliability represent a 0.01-0.03 of scatter in VAF-values around the actual score (Weir, 2005). Also between days, besides TB and Gmax, all muscles presented poor-values of VAFmuscle ICC. Although the mean values of the sets for each day were quite similar for all muscles and with exception of EDC, LD, RA and TA, SEM values were low (Crouzier et al., 2018), ranging between 0.03 and 0.10. RA presents the same limitations of OE, mainly regarding the adipose tissue of the abdominal region (Marshall & Murphy, 2003). The other three muscles lack of reliability may be associated with EMG technique limitations in dynamic tasks, namely crosstalk with other muscles. LD EMG signal may be overestimated, reflecting crosstalk of the ES (Ginn & Halaki, 2015), EDC EMG signal may vary regarding the crosstalk with other forearm muscles (Leijnse, Carter, Gupta, & McCabe, 2008), and TA may reflect crosstalk with gastrocnemius muscles (De Luca, Kuznetsov, Gilmore, & Roy, 2012). However, for both days, almost every muscle accounted for >75% of VAFmuscle (Torres-Oviedo & Ting, 2007), with exception of RA and TA that showed low-values of VAFmuscle, meaning that three synergies did not account the defined 75% threshold and the variability in the dataset is not accounted adequately by the two muscles. The lower reliability-values of VAFmuscle compared with total VAF are in line with the results of Kristiansen et al. (2016b) and Taborri, Palermo et al. (2018).

Individual EMG patterns

Individual EMG patterns for untrained individual were highly correlated across sets and days (0.89<rmax<0.99), revealing similar patterns for all muscles, with some shifts that may be associated with the low proficiency of the subjects in the task. Namely, shifts in upper-limb muscles (TS, PM and BB) and lower-limb extensors (BF, ST and GL) were observed between-sets, reflecting for untrained subjects an inter-set variability in the activation of muscles during the pull, looking for better strategies to perform the lift. Although shifts in the main upper-limb muscles do not present real differences in activation timings (shifts < 1%), in the BF and in the GL larger adjustments are presented, probably related with variations of the lower-limbs joint angles in the starting position of the ascendant phase. Interestingly, between-days no shifts were found, and this may be caused by the averaging of the paired sets correlations that canceled eventually the higher and lower-values of between-day sets comparison.

The slight shifts observed between repetitions may be difficult to interpret due to the randomness of the muscles presenting timing differences. Muscles that encompass, mainly, each of the three extracted synergies presented some time shifts. However, with exception of RA in second day, all the shifts were observed in the last two sets. This may be associated with some induced fatigue of the evaluation protocol that may have caused a more varied activation of some muscles to eventually compensate other muscles reduced capacity to maintain performance. However, fatigue was not measured in this study. Despite this, it should be noted that although variability of muscle patterns between repetitions has existed, all these significative shifts represented less than 2% of time variation for each set.

Synergy activation coefficients and muscle synergy vectors

The muscle synergy vectors and the synergy activation coefficients had strong correlation between-sets. Synergy activation coefficients had rmax values above 0.93 and 0.89, for inter-set and inter-repetition analysis, respectively, suggesting that basic temporal activations are consistent within-day. However, for synergy #2 in day one, a significant shift was found in inter-repetition and inter-set analysis, maybe revealing that untrained participants with low refinement in the task may look for different adjustments in muscle activation when performing the power clean. However, we should note that the shift represents a small variation and the statistical differences between set are due to one particular subject that presented a considerable shift. This statistical difference in time shift was not observed in day two, which suggest that the referred subject stabilized the movement technique in what concerns to the upper-limb synergy.

Muscle synergy vectors had strong correlation across sets, presenting however slightly lower values of *r* between sets than synergy activation coefficients, revealing that the weighting of muscles in synergies, mainly in synergy #3 in day one, may suffer small variations across the sets. Synergy 3# regards to the final of the ascendant phase, involving the core muscles stabilizing the trunk, the PM, the TA and the VL near the higher position of the bar. The vectors of this synergy had higher values of correlation in the second day, in line with the presented information regarding VAFmuscle intra-day reliability.

Between-days, synergy activation coefficients were strongly correlated and did not present any significative shift in time, i.e., subjects presented generally the same synergy activation timings across days. However, muscle synergy vectors just had moderate correlation between first and second session, which may reflect variations of the relative weighting of each muscle within each synergy. These findings are in line with the results presented by Kristiansen and colleagues (2016b) regarding reliability of muscle synergies in bench press. The first obvious explanation may be related with EMG electrodes placements across sessions, considering that slight deviations in position and orientation to the muscle fibers may cause modifications of the EMG signal. Also, as suggested by Kristiansen and colleagues (2016b), the lower correlation of muscle vectors may be due to the number of points utilized in the compared time series (equal to the number of muscles = 16) that are considerably less than the 200 time points utilized in activation coefficients comparison. Besides, a learning effect may be present from the first to the second session, in which the redundancy of the musculoskeletal system and the optimization process minimizing motor effort cost may cause one altered recruitment option (Hirashima & Oya, 2016; Latash, Scholz & Schöner, 2007). Considering that muscle synergies can be recruited by single neural commands, representing just one variable that may be controlled (Bizzi & Cheung, 2013; Latash et al., 2007), the temporal activation of those commands will be consistent when performing a task (Taborri, Palermo et al., 2018), and consequently the synergy activation coefficients reliability will be stronger than the reliability of muscle synergy vectors (Kristiansen et al., 2016b). The moderate reliability of muscle vectors in a complex task may also be associated to the different levels of learning of the individuals and with the training background of each one. Namely, with a cluster analysis dividing the untrained subjects in groups with anterior background in general strength training and without that experience, we observed that generally the muscle vectors of the CST were more reliable than the muscle vectors of the other group for the three synergies, even having the muscle vector #2 of CST passed from moderate to strong correlation. Thus, we expect that strength training may create adaptations that provide a greater capacity to adapt and to stabilize quickly in different demanding tasks for the neuromusculoskeletal system. This 'transfer of learning' may occur in a positive way when training of one task, or in this case a number of various strength training traditional exercises, contribute to an increase in motor performance during a subsequent task, the power clean (Carroll, Riek & Carson, 2001). This suggests that previous developed coordination strategies shared with other acquired tasks may ensure that muscle synergies composition be flexibly exploited by individuals during skill acquisition (Carson & Riek, 2001).

Limitations

As suggested by Kristiansen and colleagues (2016b), bilateral recording of EMG could support the study conclusions. Moreover, kinematic data could provide information regarding the muscle activation and the contribute of each muscle synergy during the movement, which could possibly relate the contribute of muscles along time and their impact in changes of kinematic variables, like joint angles and velocities. It is important to understand that although support of muscle synergies as neural low-dimensional modules exists and the applied methodology and its theoretical background is well-founded (d'Avella & Bizzi, 2005; Bizzi & Cheung, 2013), there is evidence that task constraints may influence the extracted muscle synergies by mathematic procedures (Hirashima & Oya, 2016; Kutch & Valero-Cuevas, 2012). When comparing with other studies caution should be taken because it may differ the synergy extraction methodology (Lambert-Shirzad & Van der Loos, 2017), VAF definition criteria (Frère & Hug, 2012), low-pass filtering (Hug et al., 2012) and chosen muscles (Steele, Tresch & Perreault, 2013).

Conclusion and Perspective

This study provided information about muscle synergy extraction with NMF within- and between-day reliability during power clean, a strength training complex exercise. Although the subjects presented low-level of expertise in the movement, the synergistic organization of movement remained the same between sets and days. Also, the synergy components revealed to have strong correlation-values between sets, although a slight lag times may have been observed. Between days, the synergy activation coefficients were strongly correlated without significative lag times. The vectors were moderately correlated between-days, which may suggest small variations in the relative weighting of each muscle in the synergies (Kristiansen et al., 2016b). The general structure of muscle coordination was maintained between repetitions, sets and days, which was reflected by regular number of extracted synergies and similar muscle synergy components and EMG profiles. This information may reveal the robustness of muscle synergy extraction procedure, establishing relation between the mathematical output with the neurophysiological organization and adaptation of motor control. Thus, further investigation regarding strength and power training whole-body exercises, namely the power clean, should be done providing information about untrained individuals and weightlifters in order to compare coordination strategies inherent to highly trained subjects, and if these subjects present individual neural strategies of motor control.

5.REFERENCES

Bartko, J. J. (1976). On various intraclass correlation reliability coefficients. Psychological Bulletin, 83(5), 762–765.

Bernstein, N. (1967). The co-ordination and regulation of movements.

Bizzi, E., & Cheung, V. C. K. (2013). The neural origin of muscle synergies. Frontiers in Computational Neuroscience, 7, 51.

Bruton, M., & O'Dwyer, N. (2018). Synergies in coordination: a comprehensive overview of neural, computational, and behavioral approaches. Journal of Neurophysiology, 120(6), 2761–2774.

Cappellini, G., Ivanenko, Y. P., Poppele, R. E., & Lacquaniti, F. (2006). Motor patterns in human walking and running. Journal of Neurophysiology, 95(6), 3426–3437.

Carson, R. G., & Riek, S. (2001). Changes in muscle recruitment patterns during skill acquisition. Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale, 138(1), 71–87.

Carroll, T. J., Riek, S., & Carson, R. G. (2001). Neural adaptations to resistance training: implications for movement control. Sports Medicine , 31(12), 829–840.

Chen, X., Niu, X., Wu, D., Yu, Y., & Zhang, X. (2017). Investigation of the Intra- and Inter-Limb Muscle Coordination of Hands-and-Knees Crawling in Human Adults by Means of Muscle Synergy Analysis. Entropy , 19(5), 229.

Comfort, P. (2013). Within- and Between-Session Reliability of Power, Force, and Rate of Force Development During the Power Clean. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 27(5), 1210–1214.

Comfort, P., & McMahon, J. J. (2015). Reliability of Maximal Back Squat and Power Clean Performances in Inexperienced Athletes. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 29(11), 3089–3096.

Crouzier, M., Hug, F., Dorel, S., Deschamps, T., Tucker, K., & Lacourpaille, L. (2018). Do individual differences in the distribution of activation between synergist muscles reflect individual strategies? Experimental Brain Research. Experimentelle Hirnforschung. Experimentation Cerebrale. https://doi.org/10.1007/s00221-018-5445-6

d'Avella, A., & Bizzi, E. (2005). Shared and specific muscle synergies in natural motor behaviors. Proceedings of the National Academy of Sciences, 102(8), 3076–3081.

d'Avella, A., Saltiel, P., & Bizzi, E. (2003). Combinations of muscle synergies in the construction of a natural motor behavior. Nature Neuroscience, 6(3), 300–308.

De Luca, C. J., Kuznetsov, M., Gilmore, L. D., & Roy, S. H. (2012). Inter-electrode spacing of surface EMG sensors: reduction of crosstalk contamination during voluntary contractions. Journal of Biomechanics, 45(3), 555–561.

de Sèze, M. P., & Cazalets, J.-R. (2008). Anatomical optimization of skin electrode placement to record electromyographic activity of erector spinae muscles. Surgical and Radiologic Anatomy: SRA, 30(2), 137–143.

Faigenbaum, A. D., McFarland, J. E., Herman, R. E., Naclerio, F., Ratamess, N. A., Kang, J., & Myer, G. D. (2012). Reliability of the one-repetition-maximum power clean test in adolescent athletes. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 26(2), 432–437.

Frère, J., & Hug, F. (2012). Between-subject variability of muscle synergies during a complex motor skill. Frontiers in Computational Neuroscience, 6, 99.

Gail, S., & Künzell, S. (2014). Reliability of a 5-Repetition Maximum Strength Test in Recreational Athletes. Deutsche Zeitschrift Fur Sportmedizin, 2014(11), 314–317.

Ginn, K. A., & Halaki, M. (2015). Do surface electrode recordings validly represent latissimus dorsi activation patterns during shoulder tasks? Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 25(1), 8–13.

Hart, C. B., & Giszter, S. F. (2010). A neural basis for motor primitives in the spinal cord. The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 30(4), 1322–1336.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 10(5), 361–374.

Hirashima, M., & Oya, T. (2016). How does the brain solve muscle redundancy? Filling the gap between optimization and muscle synergy hypotheses. Neuroscience Research, 104, 80–87.

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography? Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 21(1), 1–12.

Hug, F., Turpin, N. A., Couturier, A., & Dorel, S. (2011). Consistency of muscle synergies during pedaling across different mechanical constraints. Journal of Neurophysiology, 106(1), 91–103.

Hug, F., Turpin, N. A., Dorel, S., & Guével, A. (2012). Smoothing of electromyographic signals can influence the number of extracted muscle synergies. Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 123(9), 1895–1896.

Hug, F., Turpin, N. A., Guével, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? Journal of Applied Physiology, 108(6), 1727–1736.

Kim, M., Kim, Y., Kim, H., & Yoon, B. (2018). Specific muscle synergies in national elite female ice hockey players in response to unexpected external perturbation. Journal of Sports Sciences, 36(3), 319–325.

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. Journal of Chiropractic Medicine, 15(2), 155–163.

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 & Science in Sports, 25(1), 89–97.

Kristiansen, M., Samani, A., Madeleine, P., & Hansen, E. A. (2016a). Effects of 5 Weeks of Bench Press Training on Muscle Synergies. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 30(7), 1948–1959.

Kristiansen, M., Samani, A., Madeleine, P., & Hansen, E. A. (2016b). Muscle synergies during bench press are reliable across days. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 30, 81–88.

Kutch, J. J., & Valero-Cuevas, F. J. (2012). Challenges and new approaches to proving the existence of muscle synergies of neural origin. PLoS Computational Biology, 8(5), e1002434.

Lambert-Shirzad, N., & Van der Loos, H. F. M. (2017). On identifying kinematic and muscle synergies: a comparison of matrix factorization methods using experimental data from the healthy population. Journal of Neurophysiology, 117(1), 290–302.

Latash, M. L., Scholz, J. P., & Schöner, G. (2007). Toward a New Theory of Motor Synergies. Motor Control, 11(3), 276–308.

Lee, D. D., & Seung, H. S. (2001). Algorithms for non-negative matrix factorization. In T. K. Leen, T. G. Dietterich, & V. Tresp (Eds.), Advances in neural information processing systems 13 (pp. 556–562). Cambridge, MA: MIT Press.

Leijnse, J. N. A. L., Carter, S., Gupta, A., & McCabe, S. (2008). Anatomic basis for individuated surface EMG and homogeneous electrostimulation with neuroprostheses of the extensor digitorum communis. Journal of Neurophysiology, 100(1), 64–75.

Marshall, P., & Murphy, B. (2003). The validity and reliability of surface EMG to assess the neuromuscular response of the abdominal muscles to rapid limb movement. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 13(5), 477–489.

Safavynia, S. A., Torres-Oviedo, G., & Ting, L. H. (2011). Muscle Synergies: Implications for Clinical Evaluation and Rehabilitation of Movement. Topics in Spinal Cord Injury Rehabilitation, 17(1), 16–24.

Sheskin, D. J. (2003). Handbook of Parametric and Nonparametric Statistical Procedures: Third Edition. CRC Press.

Silva, P. B., Oliveira, A. S., Mrachacz-Kersting, N., & Kersting, U. G. (2018). Effects of wobble board training on single-leg landing neuromechanics. Scandinavian Journal of Medicine & Science in Sports, 28(3), 972–982.

Singh, R. E., Iqbal, K., White, G., & Hutchinson, T. E. (2018). A Systematic Review on Muscle Synergies: From Building Blocks of Motor Behavior to a Neurorehabilitation Tool. Applied Bionics and Biomechanics, 2018, 1–15.

Steele, K. M., Tresch, M. C., & Perreault, E. J. (2013). The number and choice of muscles impact the results of muscle synergy analyses. Frontiers in Computational Neuroscience, 7, 105.

Taborri, J., Agostini, V., Artemiadis, P. K., Ghislieri, M., Jacobs, D. A., Roh, J., & Rossi, S. (2018). Feasibility of Muscle Synergy Outcomes in Clinics, Robotics, and Sports: A Systematic Review. Applied Bionics and Biomechanics, 2018, 1–19.

Taborri, J., Palermo, E., Del Prete, Z., & Rossi, S. (2018). On the Reliability and Repeatability of Surface Electromyography Factorization by Muscle Synergies in Daily Life Activities. Applied Bionics and Biomechanics, 2018, 5852307.

Takei, T., Confais, J., Tomatsu, S., Oya, T., & Seki, K. (2017). Neural basis for hand muscle synergies in the primate spinal cord. Proceedings of the National Academy of Sciences of the United States of America, 114(32), 8643–8648.

Taylor, J. D., & Fletcher, J. P. (2012). Reliability of the 8-repetition maximum test in men and women. Journal of Science and Medicine in Sport / Sports Medicine Australia, 15(1), 69–73.

Tresch, M. C., & Jarc, A. (2009). The case for and against muscle synergies. Current Opinion in Neurobiology, 19(6), 601–607.

Turpin, N. A., Guével, A., Durand, S., & Hug, F. (2011). No evidence of expertise-related changes in muscle synergies during rowing. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 21(6), 1030–1040.

Vaz, J. R., Olstad, B. H., Cabri, J., Kjendlie, P.-L., Pezarat-Correia, P., & Hug, F. (2016). Muscle coordination during breaststroke swimming: Comparison between elite swimmers and beginners. Journal of Sports Sciences, 34(20), 1941–1948.

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 19(1), 231–240.

Xiong, Q. L., Wu, X. Y., Yao, J., Sukal-Moulton, T., Xiao, N., Chen, L., … Hou, W. S. (2018). Inter-Limb Muscle Synergies and Kinematic Analysis of Hands-and-Knees Crawling in Typically Developing Infants and Infants With Developmental Delay. Frontiers in Neurology, 9, 869.

Zipp, P. (1982). Recommendations for the standardization of lead positions in surface electromyography. European Journal of Applied Physiology and Occupational Physiology, 50(1), 41–54.

F – Study 2

MUSCLE SYNERGIES DURING POWER CLEAN IN OLYMPIC WEIGHTLIFTERS AND UNTRAINED INDIVIDUALS: ASSESSEMENT OF INTRA AND INTERGROUP VARIABILITY

Authors: Paulo Guia dos Santos, João Rocha Vaz, Paulo Freitas Correia, Maria João Valamatos, António Prieto Veloso, Pedro Pezarat-Correia

1.INTRODUCTION

Regular practice of strength training is associated to increases in maximal strength, changes in neuromuscular function and muscle morphology. Neural adaptations to strength training occur earlier than muscle adaptations and the initial gains in strength are not accompanied by increase in muscle size. Furthermore, changes in neural drive to the muscle have been inferred from surface electromyography (EMG) studies that show increases in EMG of the agonist muscle during first weeks of training (Folland & Williams, 2007; Sale, 1988; Sale, 2003; Moritani & DeVries, 1979; Duchateau, Semmler & Enoka, 2006). This increase in EMG reflects increases in fiber recruitment or firing frequency, being also sensitive to changes in synchronization (Folland & Williams, 2007). Additionally, motor unit recruitment thresholds are reduced in response to training (Griffin and Cafarelli, 2005; Folland & Williams, 2007; Sale, 2003). Regarding neural adaptations in intermuscular coordination, three mechanisms are described to promote gains in strength performance: increased activation of agonists, decreased activation of antagonists and activation of synergists. Thus, the coordination of all muscles would allow to produce the required joint moments in the intended direction to perform specific movements (Häkkinen et al., 1998; Sale, 2003; Folland & Williams, 2007; Duchateau et al., 2006; Griffin & Cafarelli, 2005).

During whole-body and power movements, like in Olympic Weightlifting (OWL) the level of activation of antagonists may be greater as compared with less complex movements, and it is essential that the nervous system can control unwarranted co-contraction of the antagonists, which may possibly result in a reduced power output (Arabatzi & Kellis, 2012; Folland & Williams, 2007). However, after training, a reduced antagonist/agonist ratio of the knee was observed in subjects submitted to an OWL protocol, when compared to traditional resistance training, possibly indicating increases in knee extension torque at propulsion in vertical jumps, in contrast to the traditional resistance training group that exhibited a higher ratio of activation (Arabatzi & Kellis, 2012).

The coordination of muscles has been studied through the decomposition of surface EMG recordings into muscle synergies. Each synergy integrates the combination of multiple muscles, and the combination of recruitment of multiple synergies will result in the production of a wide range of possible complex movements. Thus, specific tasks can be achieved by modulating neural commands that specify patterns of muscle activation, resulting in the production of natural motor behaviors (Safavynia, Torres-Oviedo, & Ting, 2011; Ting & McKay, 2007). The synergies are extracted through Nonnegative Matrix Factorization (NMF) and two components are provided, setting information about timing of activation and the weight of each muscle in each synergy during movements (Hug, 2011; Bizzi and Cheung, 2013). When applied to sports-related tasks, muscle synergies have been studied in walking and running (Cappellini et al. 2006), postural control tasks in response to unexpected external perturbations (Kim et al. 2018), pedaling (Hug et al., 2010, 2011), rowing (Turpin et al. 2011), backward giant swing (Frère and Hug 2012), breaststroke swimming (Vaz et al., 2016) and bench press (Kristiansen et al. 2015). Particularly, Kristiansen and colleagues (2015) have investigated muscle coordination in power lifters and untrained subjects, showing that powerlifters exhibited larger inter-subject variability in muscle vectors of concentric phase of bench press when compared to untrained subjects, corroborating these results with a five-week training protocol of untrained individuals (Kristiansen et al., 2016). Also, four weeks of wobble board training appeared to modify modular organization in the early landing phase of a single-leg drop-landing with separation of the synergy comprising plantar flexors and ankle evertors while the activation of secondary muscles was reduced (Silva et al., 2018).

Strength gains in advanced training stages are associated to continued muscle adaptations. However, regarding to complex movements expertise, the role of training in the refinement of these tasks and the possible timings of skill acquisition are issues that remain unexplored (Sale, 1988). Considering that Kristiansen and colleagues (2015, 2016) provided the only study associating the extraction of muscle synergies and the neural strategies developed in a strength training process, our aim is to study a more complex task with more degrees of freedom regarding strength training, the power clean exercise. We intend to identify differences in neural strategies between populations with different levels of expertise, and this information may provide an important contribution to research in neuromuscular adaptations to strength training. The power clean is a variation of OWL exercises and the high barbell velocities and loads, concerning to great power outputs, demand a coordinative strategy well defined by the practitioners. We hypothesize that EMG profiles present some time-shifts, and that synergistic organization may present slight differences when comparing the two groups. We also pretend to verify if weightlifters present variability regarding subject-specific adaptations.

2.METHODS

Participants

Seventeen male subjects, 10 unexperienced (UNE, age 24.8 ± 2.0 years, height 173.2 ± 4.3 cm, body mass 68.6 ± 6.3 kg) and 7 weightlifters (EXP, age 30.7 ± 9.3 years, height 177.6 ± 6.0 cm, body mass 85.9 ± 9.0 kg) with five repetition maximum (5RM) in power clean of 53.3 ± 9.8 kg and 102.1 ± 9.6 kg, respectively, participated in this study. Untrained subjects were healthy Physical Education students without prior knowledge about the critical points of the exercise, while weightlifters were practitioners with at least two years of experience and training at least 4 times per week. All participants provided informed written consent. This study was approved by the Faculty's Ethics Committee (CEFMH 4/2018) and all procedures adhered to the Declaration of Helsinki.

Experimental Approach

Aiming to assess the differences between groups in the extracted muscle synergies in a complex task regarding strength training, participants performed the power clean. This exercise is commonly used for training and assessment of physical capacities and it has been previously shown to be a reliable indicator of performance in experienced (Comfort, 2013), inexperienced (Comfort and McMahon, 2015) and adolescent athletes (Faigenbaum, 2012). Each untrained participant performed two sessions. The first session had the purpose of familiarize the participants with the task and with the laboratory equipment. In this familiarization all untrained participants had one-hour session of technical learning of the movement, with video demonstration and a first experience performing the exercise. The subsequent session for untrained participants (approximately one week after the familiarization), and the only one performed by weightlifters, was performed to evaluate the neural strategies associated to a complex strength training exercise and to assess intra and intergroup variability of muscle synergies in untrained and trained subjects.

Test session data collection and materials

After the warm-up, participants were tested in 5RM power clean. The lifted load in each set was increased by 2.5-5kg until the 5RM load was determined. The participants had four minutes rest between sets, and after the 5RM was found, they had approximately one hour to recover while we placed the electrodes and reflexive markers.

An eight-camera system (Qualisys, Gothenburg, Sweden) was used and placed around the space where the exercise was performed. Three markers were attached to each side of the barbell to measure its displacement. Movement data were sampled at 200 samples/s. The data collection of myoelectrical signals was recorded on sixteen muscles of the right side of the body: *upper trapezius* (TS), *pectoralis major* (PM), *biceps brachii* (BB), *triceps brachii lateral head* (TB), *flexor digitorum superficialis* (FDS), *extensor digitorum communis* (EDC), *latissimus dorsi* (LD), *erector spinae* (ES), *rectus abdominis* (RA), *external oblique* (OE), *gluteus maximus* (Gmax), *vastus lateralis of quadriceps* (VL), *biceps femoris long head* (BF), *semitendinosus* (ST), *lateral gastrocnemius* (GL) and *tibialis anterior* (TA). The muscles were selected so we could assess to trunk, lower and upper limb agonist-antagonist muscles. Due to the exercise limitations, we were not able to place electrodes on *anterior deltoideus* and *rectus femoris of quadriceps*. The electrodes were placed according to SENIAM (Surface EMG for Non-Invasive Assessment of Muscles), with exception of FDS, EDC, LD, PM, RA and OE: FDS and EDC were placed as recommended by Zipp (1982); LD was positioned according to de Sèze and Cazalets (2008); PM was placed medially to the anterior axillary border; RA and OE were located 3 and 15cm laterally from the umbilicus, respectively. Before the placement of the electrodes, the skin was shaved and cleaned with alcohol to minimize skin impedance. Surface EMG was acquired using sixteen bipolar surface electrodes (EMG Delsys, TrignoTM), fixed with specially designed adhesive interface, aligned with the muscle fibers (Hermens et al., 2000) and then additionally fixed with tape to avoid movement artefacts. EMG signals were preamplified and band-pass filtered between 20 and 450Hz, while digitized at 1000 samples/s.

Participants performed one set of three repetitions with 90% of the 5RM. Since the amplitude normalization procedure in studies with extraction of muscle synergies debatable, we used this set for task-specific submaximal dynamic normalization (Kristiansen et al., 2015). Then, we instructed the participants to perform four sets of eight repetitions with 70% of the 5RM. In these sets they should do *touch-and-go* on the floor between repetitions, performing the ascendant phase in the most explosive way possible and the descendant phase in a controlled way. The beginning of the ascendant phase was defined at the lowest position of the bar (when the discs are in contact with the ground) and the end at the highest position of the bar. The beginning and the ending of the descendant phase were defined in the opposite way. Each phase was time normalized to

100%, since different individuals may not have the same relative time phases, and the bar displacement was smoothed with a low-pass filter (8Hz, 4th order Butterworth). The first and last repetitions of all sets were excluded.

Data processing

Raw EMG signals were band-pass filtered (20-490Hz), rectified, smoothed with a low-pass filter (12Hz, 4th order Butterworth) and normalized to the average value of the 100ms across the EMG peak of the set of 3 repetition with 90% of the 5RM. The linear envelopes of each phase were interpolated to 100 points, since it was not our aim to analyze the degree of muscle activation (Hug, 2011).

Extraction of muscle synergies has been done through NMF, implementing the algorithm proposed by Lee and Seung (2001). Matrix factorization minimizes the residual Frobenius norm between the initial matrix and its decomposition, given as:

$$E = WC + e$$

$$W \geq 0 \ ^{min} ||E - WC||_{FRO}$$
$$C \geq 0$$

where E is a p-by-n matrix (p = number of muscles; n = number of time points), W is a p-by-s (s = number of synergies), C is an s-by-n matrix and e is a p-by-n matrix. $|| \ ||_{FRO}$ establishes the Frobenius norm and e is the residual error matrix. Therefore, the two multiplication matrices in which the initial matrix is decomposed, represent two components: the muscle synergy vectors (W), regarding the relative weighting of each muscle within each synergy and, the synergy activation coefficient (C), regarding the relative activation time of the muscle synergies across the power clean. The algorithm was repeated 100 times.

Three sets of each subject were analyzed, and each set consisted in 4 to 8 repetitions. Thus, E was a 16 row by 800 to 1600 columns matrix. The analysis was iterated by varying the number of synergies between 1 and 16. The number of muscle synergies selected was dependent on variance accounted for (VAF). Therefore, the number of muscle synergies was the smallest number that defined 90% of VAF, considering that each synergy should represent at least 5% of VAF. Also, VAF for each muscle (VAFmuscle) was calculated, guarantying that the extracted muscle synergies accounted their activity pattern. A VAFmuscle higher than 75% was considered satisfying (Frère &

Hug, 2012). The application of the NMF does not sort the muscle synergies in the same way for all sets of the participants which required that the muscle synergies had been previously sorted.

Assessment of within- and between-group similarity

Differences in synergy activation coefficients and individual EMG patterns were assessed through the maximum cross-correlation function (*rmax*), being an indicator of the waveform similarity, and the lag time, obtained using the Matlab 2015a (Mathworks Inc., Natick MA, USA) *xcorr* function for centered data (option "*coeff*"). The lag time is determined at the maximum cross correlation function and enables the assessment of differences in timing of activation. The lag time and *rmax* were calculated for each pair of subjects, as well as the *r*-values of the muscle synergy vectors.

The indexes of intra and intergroup variability were assessed by averaging the *rmax*-values of all the intra and intergroups pairwise (70 untrained-weightlifters pairs [7 weightlifters x 10 untrained], 45 untrained pairs [each of the 10 subjects compared with each of the other 9] and 21 weightlifters pairs [each of the 7 subjects compared with each of the other 6]). These indexes are indicators of the waveform consistency within and between populations (Turpin et al., 2011; Vaz et al., 2016). Similarly, also muscle synergy vectors were compared across subjects (*r*-values).

Statistical analysis

We verified normality through the Shapiro-Wilk test (SPSS version 25.0, SPSS Inc., Chicago, IL, USA) using a significance level of $p < 0.05$. The differences in the lag time within and between groups were evaluated performing a sample Student's t-test with zero as reference value. When normality was not assumed, one-sample Wilcoxon signed rank test was used. VAF, VAFmuscle, *r*- and *rmax*-values were compared between groups using a sample Student's t-test. The Cohen's *d* was reported as measure of effect size. When normality was not assumed, a Mann-Whitney U-test was used.

3.RESULTS

Regarding the participants characteristics, no significative differences were shown between groups for age ($p = 0.173$) and height ($p = 0.120$), although significative differences were found for weight ($p = 0.001$) and 5RM load ($p < 0.001$).

Muscle Synergies

Using the described criteria to identify the number of muscle synergies, three muscle synergies were identified for all subjects of UNE and EXP groups. The three-extracted muscle synergies accounted for a similar VAF between weightlifters (85.5 ± 0.7%) and unexperienced subjects (86.6 ± 1.5%). No statistical differences were found for the three extracted muscle synergies between groups ($p = 0.133$; $d = 0.01$). For both groups, TA accounted for less than 75% of VAFmuscle, as well as PM, FDS, RA and OE for EXP and LD for UNE. Significant differences in VAFmuscle of BB ($p = 0.011$; $d = 0.30$) and FDS ($p = 0.014$; $d = 0.244$) were found between groups. VAF and VAFmuscle are depicted in Figure 1 and 2.

For UNE group muscle synergy #1 mainly represented the back and hip extension (TS, LD, ES, Gmax, BF, ST) and the plantarflexion (GL). The muscle synergy #2 mainly involved the upper-limb muscles (TS, BB, TB, FDS, EDC) and the muscle synergy #3 represented the final of the ascendant phase and involved mainly the core muscles (RA, OE, ES) the PM, VL and TA. For the EXP group, although the general composition of each synergy was similar, some differences were found. In synergy #1 the LD and ES presented a lower weighting than for UNE, while VL was encompassed mainly in this synergy. Synergy #2 showed to be composed by the same group of muscles in both groups. Finally, in synergy #3, the main muscles were ES and LD, while TA and VL did not present such relevance.

For each group, inter-subject variability was assessed. Regarding the synergy's synchrony, i.e. the lag time, no significative shifts were found in both groups, and all *rmax*-values had a strong correlation (range: 0.77 - 0.87) showing higher similarity indexes. However, for muscle synergy vectors just moderate values of correlation were found in both groups (range: 0.34 – 0.52).

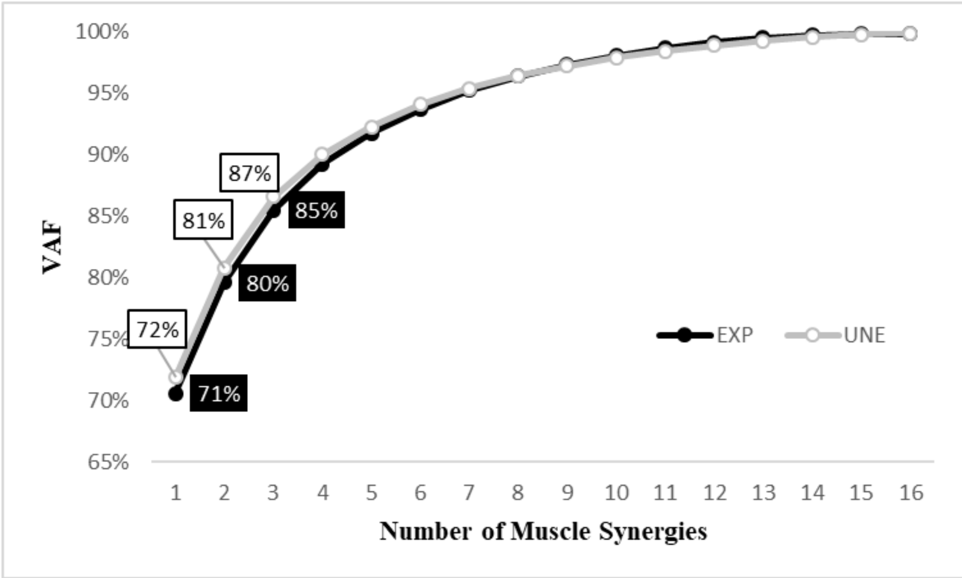

Figure 1 - Mean values of variance accounted for (VAF) relatively to the original extraction iteration of sixteen muscle synergies for UNE and EXP.

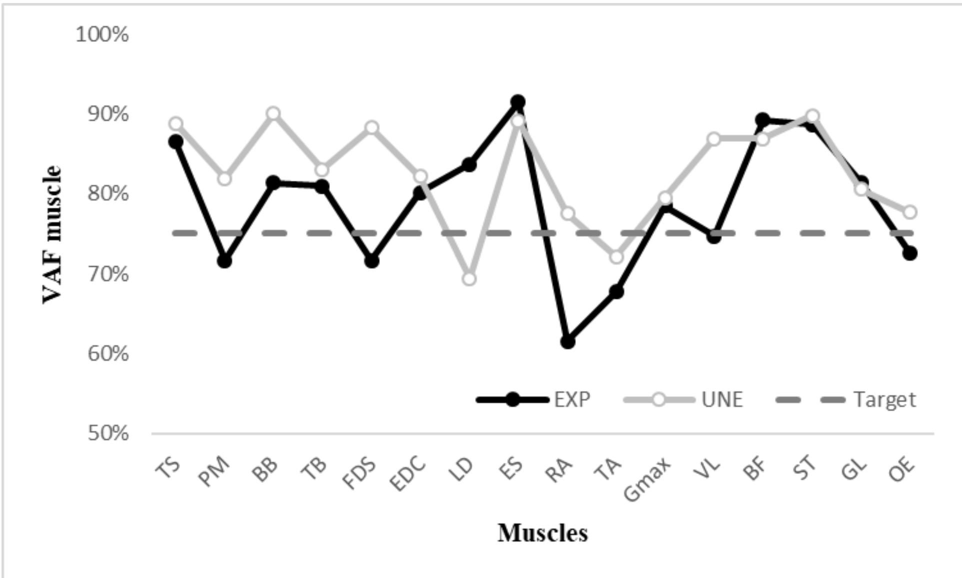

Figure 2 - Mean values of variance accounted for each muscle (VAFmuscle) regarding a three synergy-model for day one and two. The dashed line represents the 75% defined threshold.

Comparing both groups inter-subject variability, in synergy #1 and #2 no differences were found in *r* and *rmax*-values corresponding to muscle synergy vectors and synergy activation coefficients, respectively. However, for synergy #3 a significant difference in *rmax*-values was found (p = 0.001; d = 1.36), presenting the UNE group a higher correlation value. The inter-subject variability of this synergy is depicted in Figure 3. Regarding the intergroup analysis, significant shifts were found in the three extracted synergies, with synergy #1 (p < 0.001; d = -0.55) and #2 (p < 0.001; d = -0.66) activating earlier for UNE, and synergy #3 (p = 0.005; d = 0.34) activating earlier for EXP (Figure 4). The similarity indexes of the synergy activation coefficients were high, presenting strong correlations (0.78, 0.88 and 0.76 for synergy #1, #2 and #3, respectively). However, muscle synergy vectors presented weak to moderate correlations (0.31, 0.53 and 0.10 for synergy #1, #2 and #3, respectively). The correlation-values are presented in Table 1 and 2, while Figure 3 and 4 represent the averaged values for each group.

Individual EMG

For each group, individual EMG patterns were strongly correlated (0.73 < rmax < 0.92). However, for UNE, shifts were found in PM (p = 0.03; d = -0.32) and TA (p = 0.01; d = 0.39), and for EXP, shifts were found also in PM (p = 0.01; d =-0.31), EDC (p = 0.01; d = 0.39) and VL (p = 0.02; d = -0.28).

Between groups, despite the correlation-values were still strong (0.82 < rmax < 0.91), more temporal adjustments were found. TS (p < 0.001; d = -0.95), BB (p < 0.001; d = -0.52), EDC (p < 0.001; d = -0.74), Gmax (p < 0.001; d = -0.82), BF (p < 0.001; d = -0.72), ST (p < 0.001; d = -0.74), GL (p < 0.001; d = -0.77) and OE (p < 0.001; d = -0.54) presented significant backward shifts for the UNE. However, VL shift was statistically significant (p = 0.01; d = 0.30), presenting a delayed activation for the UNE. Individual EMG are depicted in Figure 6, and correlation and shift-values are presented in Table 2.

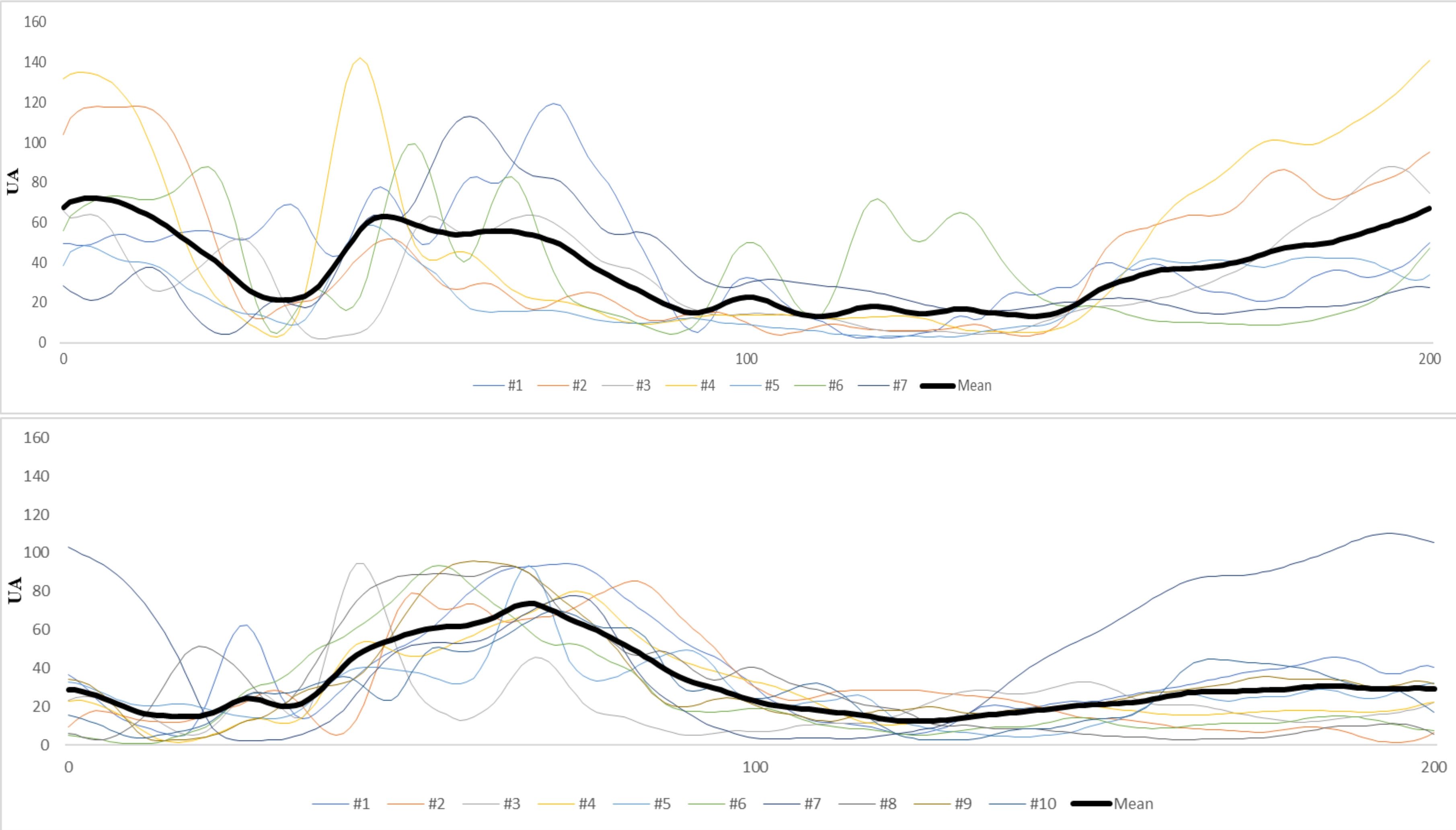

Figure 3 – Inter-individual variability of Synergy #3 activation coefficients. Top panel corresponds to EXP while bottom panel regards to UNE. The thick black line represents the group mean, while the thin colored lines represent individual synergy activation coefficients.

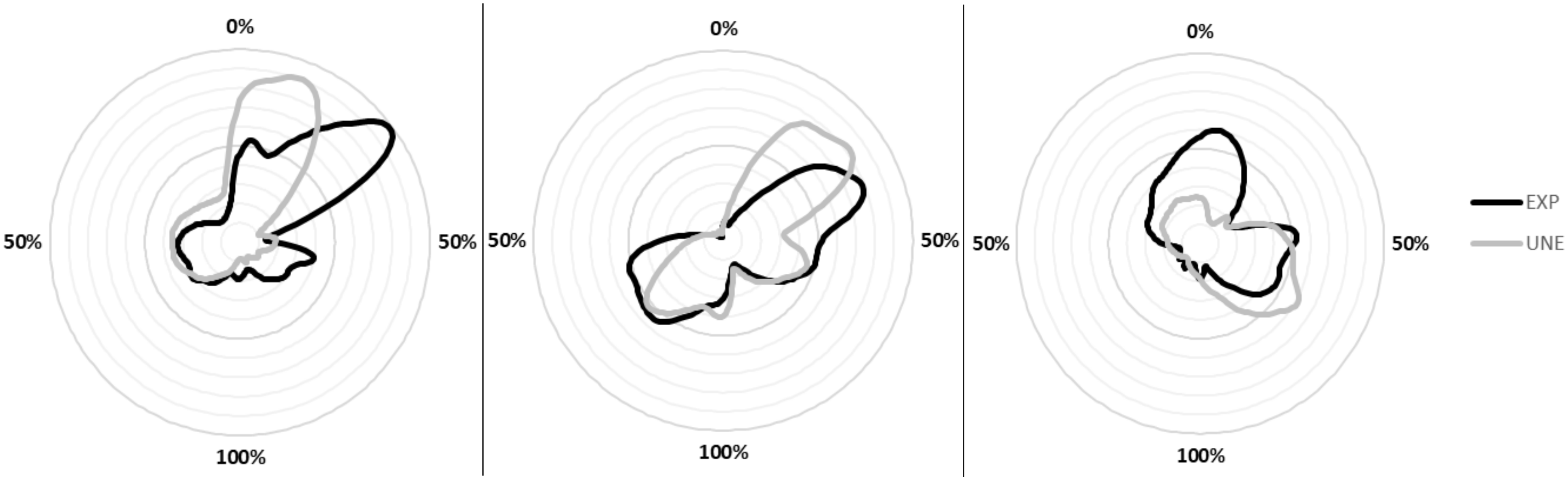

Figure 4 – Averaged synergy activation coefficients of EXP and UNE. Left panel regards to Synergy #1, central panel to Synergy #2 and right panel to Synergy #3. The right hemisphere of the graphs corresponds to the ascendant phase (0-100% of the power clean cycle), while the left hemisphere corresponds to descendant phase (100-0% of the power clean cycle).

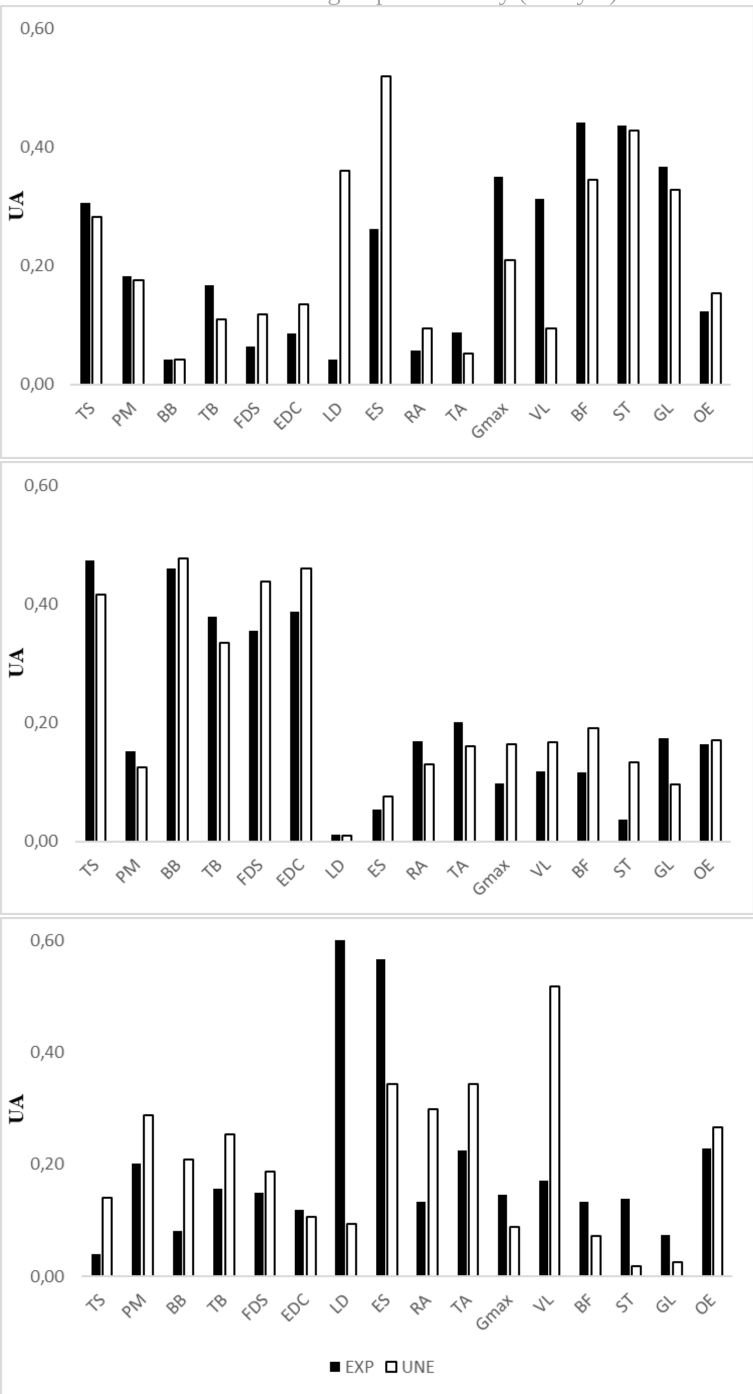

Figure 5 – Averaged muscle synergy vectors of EXP and UNE. Top panel regards to Synergy #1, central panel to Synergy #2 and bottom panel to Synergy #3.

Table 1 – Intra-group and inter-group similarity values (r) of muscle synergy vectors.

	Intra-group		**Inter-group**
	UNE	**EXP**	
Muscle Synergy Vectors			
#1	0.52 ± 0.22	0.40 ± 0.27	0.31 ± 0.30
#2	0.51 ± 0.23	0.52 ± 0.13	0.53 ± 0.18
#3	0.34 ± 0.23	0.47 ± 0.34	0.10 ± 0.26

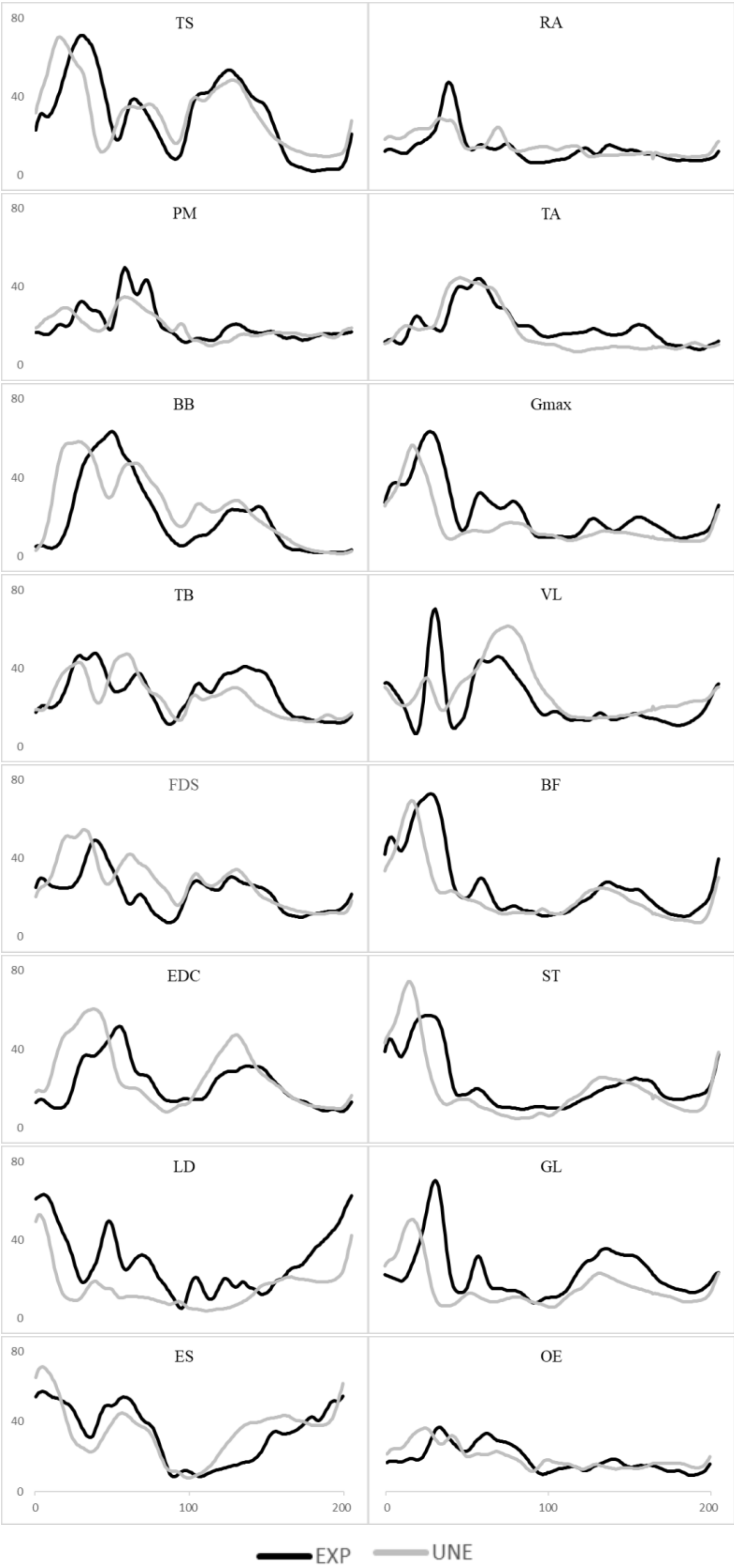

Figure 6 – Averaged EMG envelopes (UA) from 16 muscles obtained in 7 EXP and 10 UNE during power clean cycle (200 time points).

Table 2 – Intra-group and inter-group similarity values (rmax) and lag times (%) of synergy activation coefficients and individual EMG profiles. Bold values represent statistical differences from zero and Cohen's *d* above 0.8.

	Intra-group								Inter-group			
	UNE				EXP							
	lag			*rmax*	lag			*rmax*	lag			*rmax*
	%	*p*	*d*		%	*p*	*d*		%	*p*	*d*	
Individual EMG Profiles												
TS	-0.03 ± 1.60	0.53	-0.09	0.88 ± 0.05	1.26 ± 3.15	0.17	0.17	0.89 ± 0.05	-2.60 ± 2.73	**<0.001**	**-0.95**	0.86 ± 0.06
PM	-2.63 ± 7.73	**0.03**	-0.32	0.86 ± 0.06	2.29 ± 3.26	**0.01**	0.31	0.87 ± 0.04	0.79 ± 7.13	0.88	0.02	0.85 ± 0.06
BB	0.29 ± 5.56	0.29	0.16	0.89 ± 0.07	1.62 ± 3.63	0.06	0.25	0.92 ± 0.04	-3.94 ± 6.49	**<0.001**	-0.52	0.86 ± 0.04
TB	-0.49 ± 8.87	0.68	-0.06	0.89 ± 0.04	0.69 ± 2.20	0.26	0.14	0.91 ± 0.04	0.20 ± 6.94	0.36	-0.11	0.88 ± 0.05
FDS	0.86 ± 8.26	0.24	0.18	0.86 ± 0.05	-0.95± 2.08	0.06	-0.23	0.82 ± 0.07	0.08 ± 9.35	0.72	-0.04	0.84 ± 0.06
EDC	-0.19 ± 2.96	0.70	-0.06	0.88 ± 0.04	3.74 ± 5.24	**0.01**	0.39	0.85 ± 0.06	-6.47 ± 6.57	**<0.001**	-0.74	0.86 ± 0.06
LD	0.00 ± 0.00	1.00	0.00	0.82 ± 0.08	-4.03 ± 15.1	0.47	-0.09	0.73 ± 0.12	0.27 ± 11.43	0.38	-0.10	0.76 ± 0.09
ES	0.00 ± 0.00	1.00	0.00	0.91 ± 0.03	0.13 ± 0.50	0.32	0.12	0.91 ± 0.03	-0.16 ± 1.51	0.66	-0.05	0.89 ± 0.05
RA	-4.07 ± 10.2	0.26	-0.33	0.84 ± 0.07	-2.57 ± 4.49	0.05	-0.26	0.83 ± 0.09	3.39 ± 11.51	0.28	0.13	0.84 ± 0.08
TA	1.41 ± 3.57	**0.01**	0.39	0.89 ± 0.05	1.21 ± 4.00	0.19	0.17	0.89 ± 0.05	-0.77 ± 3.79	0.09	-0.20	0.87 ± 0.07
Gmax	0.29 ± 3.22	0.55	0.09	0.88 ± 0.06	-5.10 ± 14.5	0.14	-0.18	0.83 ± 0.11	-8.83 ± 13.8	**<0.001**	**-0.82**	0.83 ± 0.08
VL	-0.40 ± 5.06	0.25	0.17	0.91 ± 0.05	-0.36 ± 0.64	**0.02**	-0.28	0.89 ± 0.04	2.29 ± 6.16	**0.01**	0.30	0.84 ± 0.07
BF	0.11 ± 0.87	0.31	0.15	0.89 ± 0.04	-0.21 ± 1.15	0.48	-0.09	0.89 ± 0.04	-3.01 ± 2.86	**<0.001**	-0.72	0.87 ± 0.05
ST	-0.09 ± 0.83	0.33	-0.15	0.90 ± 0.05	0.24 ± 1.82	1.00	0.00	0.86 ± 0.06	-3.31 ± 2.73	**<0.001**	-0.74	0.83 ± 0.05
GL	-0.49 ± 11.2	0.14	-0.22	0.83 ± 0.08	-0.12 ± 2.56	0.08	-0.22	0.88 ± 0.05	-5.74 ± 3.57	**<0.001**	-0.77	0.82 ± 0.06
OE	0.28 ± 5.13	0.72	0.05	0.85 ± 0.05	-4.67 ± 12.8	0.31	-0.13	0.86 ± 0.06	-6.94 ± 10.9	**<0.001**	-0.54	0.85 ± 0.06
Synergy Activation Coefficients												
#1	0.06 ± 0.91	0.72	0.05	0.86 ± 0.07	3.21 ± 8.09	0.11	0.35	0.86 ± 0.06	-2.46 ± 18.7	**<0.001**	-0.55	0.78 ± 0.08
#2	0.79 ± 7.87	0.29	0.16	0.87 ± 0.06	0.57 ± 3.56	0.48	0.16	0.89 ±0.06	-4.60 ± 5.71	**<0.001**	-0.66	0.88 ± 0.07
#3	-2.51 ± 17.2	0.68	-0.06	0.86 ± 0.08	0.45 ± 14.25	0.55	-0.13	0.77 ± 0.10	1.86 ± 17.39	**0.01**	0.34	0.76 ± 0.11

4.DISCUSSION

The aim of this study was to evaluate inter-subject variability in muscle coordination during power clean, in EXP and UNE, and to assess muscle coordination differences between both groups. While the shape of activation patterns of synergies presented strong correlations across subjects of each group, the weightings of each muscle within the synergies were more variable. Comparing groups, the synergistic organization of muscle coordination was not profoundly affected by expertise. However, the three extracted synergies were shifted in time, with the UNE group anticipating synergy #1 and #2 and delaying synergy #3. Even so, the synergies presented similar shapes between groups, unlike muscle synergy vectors that were rather more variable, even existing changes in composition of synergy #1 and #3.

EXP and UNE were generally similar in age. This is an important methodological consideration because an eventually different age group could compromise the data. For instance, junior and master weightlifters demonstrate a smaller ability to tolerate higher volumes of high-intensity loading when compared to seniors, which could possibly compromise weightlifting performance (Storey & Smith, 2012). Differences in group weights regard to the heavy weight classes of EXP participating in the study when compared with the UNE. Also, differences in the lifted load during the 5RM test were expected since the EXP were specialized in the task and currently training.

Muscle Synergies

For both groups, three muscle synergies were enough to accomplish the defined criteria for VAF. The synergistic organization of movement was the same and the three extracted synergies explained VAF similarly. Supporting these results, other studies showed that muscle synergies are consistent across expert cyclists (Hug et al., 2010), rowers (Turpin et al., 2011), gymnasts (Frère & Hug, 2012) and powerlifters (Kristiansen et al., 2015) as well as untrained subjects during rowing (Turpin et al., 2011), pedaling (De Marchis, Schmid, Bibbo, Bernabucci, & Conforto, 2013) and bench pressing (Kristiansen et al., 2015). As mentioned in **study 1**, and considering the potential effect of different filtering techniques prior to the extraction of muscle synergies utilized across the studies (Hug, Turpin, Dorel & Guével, 2012), the same number of muscle synergies was defined in other complex motor tasks like rowing (Turpin et al., 2011), breaststroke swimming (Vaz et al., 2016) or backward giant swing (Frère & Hug, 2012). However, the only two extracted muscle synergies in bench press (Kristiansen et al., 2015) may be viewed as result of the less complexity of the exercise (Frère & Hug, 2012).

It is interesting to note that differences in VAFmuscle were found in two upper-limb muscles, the BB and the FDS. We may justify this mismatch of the variance explained by the BB, with the pull of the barbell by UNE that showed to present some variability in **study 1**. This may influence percentage of VAFmuscle defined by a three-synergy model. However, the mismatch in FDS VAFmuscle regards to lower-values of EXP group. Despite it may be an unexpected result, we can relate it with the unusual grip situation for the EXP. In normal training situation, EXP use lifting straps that allow them to concern only about the pull. To standardize the evaluation situation of both groups, all participants performed the power clean without lifting straps. This fact may be related with some variability at the grip level in EXP, which could possibly influence the VAFmuscle.

Intra-group variability

For each group we found generally similar values of correlation for the synergy temporal component. For UNE and EXP, the pairwise analysis did not reveal significantly different timing characteristics of the synergies. This means that between subjects of each group the three extracted synergies presented consistent activation timings during the task. Also, for each group, the shape of the synergies was generally similar, exhibiting little inter-subject variability. However, significant differences between correlation values of synergy #3 were found between groups, revealing that UNE were less variable. This is in line with previous study of inter-individual variability in muscle synergies in bench press, having shown that powerlifters utilized specific motor strategies well adapted to individual anthropometry and muscle architecture, thereby promoting a better performance in the task (Kristiansen et al., 2015). Additionally, another study regarding rowing showed that although activation coefficients of two of the three extracted synergies in rowers were less variable than in untrained subjects, the third synergy of rowers presented great variability (Turpin et al., 2011). This may suggest that, in power clean, experts modulate and adapt the synergy #3 to their specific characteristics through training. It is also possible that the training method may influence this modulation.

Regarding the spatial component of synergies, the muscle synergy vectors, more variability was found within each group. This supports the existing data of other tasks showing that muscle vectors are more variable than activation coefficients for EXP in backward giant swing (Frère & Hug, 2012) and pole vaulting (Frère, Göpfert, Hug, Slawinski, & Tourny-Chollet, 2012), and for EXP and UNE in bench press (Kristiansen et al., 2015) and in rowing (Turpin et al., 2011). In both groups the correlation between muscle vectors was moderate for the three extracted synergies. This may represent the musculoskeletal redundancy of motor behavior, which allows the CNS to adopt infinite solutions to perform a task (Latash, Scholz, & Schöner, 2007), meaning that although the activation of the synergies is consistent in time, the muscle weightings may vary. The differences in correlations of both groups did not have statistical significance. However, muscle vector #1, regarding back and hip extension, was more variable in EXP. This may be justified by individualized positions to start the ascendant phase of the movement by the EXP, regarding knee and hip angular positions. Furthermore, this synergy in EXP incorporates VL, which may add some inter-subject variability adapted to individual characteristics, regarding the knee displacement during the pull. Additionally, and in contrast to synergy activation coefficients, the muscle vectors for synergy #3 varied more in UNE than in EXP. In EXP this synergy encompassed mainly LD and ES muscles. The LD in EXP presented more peak activation timings along the cycle, and the muscle pattern shows that EXP activate the muscle during the ascendant phase in contrast to UNE. The incorporation of core muscles (RA and OE) and TA in this synergy by the UNE may be associated with some variability, namely because the VAFmuscle for these muscles presents low-values regarding the defined threshold of 75%. In synergy #3, the higher correlation of the muscle vector when compared to activation coefficient for EXP means that although temporal pattern of synergy #3 may vary between EXP subjects more than for UNE, the UNE, on the other hand, present more variability in the muscle weightings of the synergy. Thus, although UNE are relying on intrinsic synergies used in similar motor tasks in what concerns to temporal parameters, they use a vaster number of strategies to control the DOF, considering the musculoskeletal redundancy whereby task performance may be achieved using multiple biomechanical solutions.

Inter-group variability

We observed that during power clean, the synergy #3 of EXP, subjects had two peaks, contrary to UNE's synergy #3 that had only one peak. This difference may be related with the integration of synergy #1 and #3 of EXP in the final of descendant phase and in the beginning of ascendant phase. While in UNE, the synergy #3 probably regards only to the knee extension to the stand position, in EXP the third synergy pattern shows a second increasing moment whose peak coincide with the beginning of activation of the first synergy. With the existence of this peak, synergies #1 and #3 for EXP present some level of coactivation, which is not observed for UNE. With this coactivation, the synergy #1 of UNE seems to be divided into the synergy #1 and the first peak of synergy #3 of EXP. This fractionation results into an incorporation of the VL for the EXP in synergy #1, while the ES and the LD compose mainly synergy #3. The fractionation of muscle synergies has been observed in stroke chronically-affected patients (Cheung et al., 2012). In this study, patients presented fractionations of some muscle synergies when comparing the affected with the unaffected-arm, and the fractionation was more evident in patients with longer post-stroke duration, which may have been an adaptive process triggered in response to the poststroke impairment. In our case, the fractionation observed in EXP when compared with UNE, may be related with an adaptation in intermuscular coordination developed through training. This adaptation may have provided a more flexible control, mainly, of the lower-limb and back muscles while preparing and starting the execution of the movement.

As expected, muscle vectors presented low-values of correlation. With exception of synergy #2 that showed to be less variable in composition, synergy #1 and #3 presented weaker correlations. Regarding synergy #2, this possibly means that UNE are relying on intrinsic synergies already used in similar motor tasks, since the variation within both groups was approximately the same as between-groups. For synergy #1 and #3, the weaker correlations may be associated to modulation of muscle synergies by the EXP. This is in line with previous studies finding that specific strategies in response to unexpected external perturbations were developed by elite hockey players (Kim, Kim, Kim & Yoon, 2018), and that a new synergy was incorporated in elite badminton players during the smash shot (Matsunaga & Kaneoka, 2018). Also, after four weeks of sensorimotor training, untrained individuals modified modular organization during landing (Silva et al., 2018), while five weeks of bench press training provided a more individualized motor strategy to the individuals (Kristiansen et al., 2016).

Regarding temporal parameters, the three extracted synergies revealed time shifts between both groups. Despite a strong correlation in activation coefficients observed between the two groups, synergy #1 and #2 exhibited a significant backward time shift in UNE. This result is accordance with previous study referring to breaststroke swimming, showing that one of the extracted synergies was anticipated in novices when compared to experts (Vaz et al., 2016). The backward shift observed for synergy #1 is mainly related with the lower-limb muscles. The UNE showed to present some variability between sets in temporal parameters of the BF and GL. These muscles are represented in this synergy, and the time adjustments may be related with variations of the knee angle in the starting position of the ascendant phase, as suggested in **study 1**. Additionally, significant shifts were found for individual EMG patterns, which means that all the muscles that contribute to lower-limb triple extension (with exception of the VL) present a backward shift for UNE. Thus, UNE may anticipate the activation of the synergy to compensate the initial angular position of the hip, eventually more closed than for EXP (with less deeper squat position and with great trunk forward inclination for UNE). For synergy #2, it is observed the greater shift. UNE present an activation of synergy involving the upper-limb muscles anticipated in relation to EXP. These muscles present, generally, an earlier activation along the cycle for UNE, and it may be related with the early flexion of the upper-limbs when compared to EXP. Namely for the UNE, the scapular elevation and the forearm flexion, by TS and BB, respectively, while the lower-limbs are not completely extended may justify the anticipation of synergy #2. Nevertheless, it is interesting to note that this synergy presented the higher correlation value. This means that despite a considerable shift in time, the shape of the activation pattern does not vary between groups. Thus, previous coordination strategies utilized in other tasks may be shared between different behaviors (d'Avella & Bizzi, 2005), and this contribute may increase motor performance during a subsequent task, in this case the power clean. Relatively to synergy #3, the UNE delayed its activation. Despite the composition of this synergy between EXP and UNE be slightly different, UNE presented a forward shift regarding the final of the ascendant phase. This may be explained by the pattern of VL, that during triple extension of lower-limbs presented a delayed activation.

Limitations

The main limitation of this study was the lack of kinematic data corroborating the EMG-related results. Kinematic data would provide information about the muscle activation during the movement, relating some group-specific characteristics in EMG patterns with mechanical events. Other possible limitation is the different level of training background of the UNE. Despite they were not familiarized with the exercise, some of them referred an anterior practice of strength training, and this suggest that they may be able to adapt more easily to a new task, performed with external load.

Conclusion and Perspective

In conclusion, the present study showed that the same number of muscle synergies was extracted for both groups during the power clean. Within-groups the components of muscle synergies just presented small variation between-subjects. However, when comparing both groups, synergy #1 of the UNE showed to be fractionated into synergy #1 and #3 of the EXP. Additionally, all synergies presented slight time shifts between groups, which was explained by adjustments in individual EMG patterns. Also, muscle weightings within each synergy were highly variable. A possible suggestion is that athletes in an initial phase of training should attempt to delay the hip extension, as well as the upper-limbs flexion.

We verified some between-group differences in this study, and a randomized controlled study regarding strength training, including OWL exercises, would possibly assess how unexperienced subjects could modify coordination over time. Thus, submit subjects to a training protocol should demonstrate how these adaptations of neural strategies to perform complex movements tend to evolve, and what are the phases of the training process that should be considered when the objective is to promote intermuscular adaptations.

5.REFERENCES

Arabatzi, F., & Kellis, E. (2012). Olympic weightlifting training causes different knee muscle-coactivation adaptations compared with traditional weight training. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 26(8), 2192–2201.

Bizzi, E., & Cheung, V. C. K. (2013). The neural origin of muscle synergies. Frontiers in Computational Neuroscience, 7, 51.

Cappellini, G., Ivanenko, Y. P., Poppele, R. E., & Lacquaniti, F. (2006). Motor Patterns in Human Walking and Running. Journal of Neurophysiology, 95(6), 3426–3437.

Cheung, V. C. K., Turolla, A., Agostini, M., Silvoni, S., Bennis, C., Kasi, P., … Bizzi, E. (2012). Muscle synergy patterns as physiological markers of motor cortical damage. Proceedings of the National Academy of Sciences of the United States of America, 109(36), 14652–14656.

Comfort, P. (2013). Within- and Between-Session Reliability of Power, Force, and Rate of Force Development During the Power Clean. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 27(5), 1210–1214.

Comfort, P., & McMahon, J. J. (2015). Reliability of Maximal Back Squat and Power Clean Performances in Inexperienced Athletes. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 29(11), 3089–3096.

De Marchis, C., Schmid, M., Bibbo, D., Bernabucci, I., & Conforto, S. (2013). Inter-individual variability of forces and modular muscle coordination in cycling: a study on untrained subjects. Human Movement Science, 32(6), 1480–1494.

de Sèze, M. P., & Cazalets, J.-R. (2008). Anatomical optimization of skin electrode placement to record electromyographic activity of erector spinae muscles. Surgical and Radiologic Anatomy: SRA, 30(2), 137–143.

Duchateau, J., Semmler, J. G., & Enoka, R. M. (2006). Training adaptations in the behavior of human motor units. Journal of Applied Physiology, 101(6), 1766–1775.

Faigenbaum, A. D., McFarland, J. E., Herman, R. E., Naclerio, F., Ratamess, N. A., Kang, J., & Myer, G. D. (2012). Reliability of the one-repetition-maximum power clean test in adolescent athletes. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 26(2), 432–437.

Folland, J. P., & Williams, A. G. (2007). The adaptations to strength training: morphological and neurological contributions to increased strength. Sports Medicine, 37(2), 145–168.

Frère, J., Göpfert, B., Hug, F., Slawinski, J., & Tourny-Chollet, C. (2012). Catapult effect in pole vaulting: is muscle coordination determinant? Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 22(1), 145–152.

Frère, J., & Hug, F. (2012). Between-subject variability of muscle synergies during a complex motor skill. Frontiers in Computational Neuroscience, 6, 99.

Griffin, L., & Cafarelli, E. (2005). Resistance training: cortical, spinal, and motor unit adaptations. Canadian Journal of Applied Physiology = Revue Canadienne de Physiologie Appliquee, 30(3), 328–340.

Häkkinen, K., Kallinen, M., Izquierdo, M., Jokelainen, K., Lassila, H., Mälkiä, E., … Alen, M. (1998). Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. Journal of Applied Physiology, 84(4), 1341–1349.

Hermens, H. J., Freriks, B., Disselhorst-Klug, C., & Rau, G. (2000). Development of recommendations for SEMG sensors and sensor placement procedures. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 10(5), 361–374.

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography? Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 21(1), 1–12.

Hug, F., Turpin, N. A., Couturier, A., & Dorel, S. (2011). Consistency of muscle synergies during pedaling across different mechanical constraints. Journal of Neurophysiology, 106(1), 91–103.

Hug, F., Turpin, N. A., Dorel, S., & Guével, A. (2012). Smoothing of electromyographic signals can influence the number of extracted muscle synergies. Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 123(9), 1895–1896.

Hug, F., Turpin, N. A., Guével, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? Journal of Applied Physiology, 108(6), 1727–1736.

Kim, M., Kim, Y., Kim, H., & Yoon, B. (2018). Specific muscle synergies in national elite female ice hockey players in response to unexpected external perturbation. Journal of Sports Sciences, 36(3), 319–325.

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 & Science in Sports, 25(1), 89–97.

Kristiansen, M., Samani, A., Madeleine, P., & Hansen, E. A. (2016). Effects of 5 Weeks of Bench Press Training on Muscle Synergies. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 30(7), 1948–1959.

Latash, M. L., Scholz, J. P., & Schöner, G. (2007). Toward a New Theory of Motor Synergies. Motor Control, 11(3), 276–308.

Lee, D. D., & Seung, H. S. (2001). Algorithms for non-negative matrix factorization. In T. K. Leen, T. G. Dietterich, & V. Tresp (Eds.), Advances in neural information processing systems 13 (pp. 556–562). Cambridge, MA: MIT Press.

Matsunaga, N., & Kaneoka, K. (2018). Comparison of Modular Control during Smash Shot between Advanced and Beginner Badminton Players. Applied Bionics and Biomechanics, 2018, 6592357.

Moritani, T., & deVries, H. A. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. American Journal of Physical Medicine, 58(3), 115–130.

Safavynia, S. A., Torres-Oviedo, G., & Ting, L. H. (2011). Muscle Synergies: Implications for Clinical Evaluation and Rehabilitation of Movement. Topics in Spinal Cord Injury Rehabilitation, 17(1), 16–24.

Sale, D. G. (1988). Neural adaptation to resistance training. Medicine and Science in Sports and Exercise, 20(5 Suppl), S135–S145.

Sale, D. G. (2003). Neural Adaptation to Strength Training. In Strength and Power in Sport (pp. 281–314).

Silva, P. B., Oliveira, A. S., Mrachacz-Kersting, N., & Kersting, U. G. (2018). Effects of wobble board training on single-leg landing neuromechanics. Scandinavian Journal of Medicine & Science in Sports, 28(3), 972–982.

Storey, A., & Smith, H. K. (2012). Unique aspects of competitive weightlifting: performance, training and physiology. Sports Medicine , 42(9), 769–790.

Ting, L. H., & McKay, J. L. (2007). Neuromechanics of muscle synergies for posture and movement. Current Opinion in Neurobiology, 17(6), 622–628.

Turpin, N. A., Guével, A., Durand, S., & Hug, F. (2011). No evidence of expertise-related changes in muscle synergies during rowing. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 21(6), 1030–1040.

Vaz, J. R., Olstad, B. H., Cabri, J., Kjendlie, P. L., Pezarat-Correia, P., & Hug, F. (2016). Muscle coordination during breaststroke swimming: Comparison between elite swimmers and beginners. Journal of Sports Sciences, 34(20), 1941–1948.

Zipp, P. (1982). Recommendations for the standardization of lead positions in surface electromyography. European Journal of Applied Physiology and Occupational Physiology, 50(1), 41–54.

G – General Considerations

1.LIMITATIONS

Although specific limitations of each study are presented in the corresponding chapter, below we discuss the general limitations of the topic.

Regarding data collection, we did not collect all the muscles initially proposed. Namely *rectus femoris* and *anterior deltoideus* electromyographic information was not assessed due to the exercise limitations. For experienced subjects, there was some physical limitations that possibly constrained the movement ecology, namely the non-utilization of lift straps, and it would be relevant to perform a first session to familiarize them with the laboratory equipment. For untrained subjects, the major limitation corresponded to different training backgrounds of other sport activities, and different learning capacity that dictated a worse or better performance of the task. Also, bilateral recording of EMG and the utilization of force platforms could support the study conclusions, helping to understand if each limb has a symmetric behavior in the different populations. This could possibly suggest an eventual risk of injury related with asymmetry for either group. Additionally, kinematic data could add an important contribution. Despite it was collected, we did not analyze it in this study. A future approach should be done regarding the analysis of this data and relating the kinematic variables with EMG and muscle synergies analysis.

Regarding the data processing it is important to understand that although support of muscle synergies as neural low-dimensional modules exists and the applied methodology and its theoretical background is well-founded (d'Avella & Bizzi, 2005; Bizzi & Cheung, 2013), there is evidence that task constraints may influence the extracted muscle synergies by mathematical procedures (Hirashima & Oya, 2016; Kutch & Valero-Cuevas, 2012). When comparing with other studies caution should be taken because it may differ the synergy extraction methodology (Lambert-Shirzad & Van der Loos, 2017), VAF definition criteria (Frère & Hug, 2012), low-pass filtering (Hug et al., 2012) and chosen muscles (Steele, Tresch & Perreault, 2013).

2.GENERAL CONCLUSION AND PERSPECTIVE

We assessed within and between-day reliability of muscle synergies. We concluded that synergistic organization of movement remained the same across repetitions, sets and days. Slight adjustments in time were done within-day, while the spatial component of muscle synergies varied more between-day, which may suggest small variations in the relative weighting of each muscle in the synergies (Kristiansen et al., 2016b). The general structure of muscle coordination was maintained between repetitions, sets and days, and this information supports the robustness of muscle synergy extraction procedure, establishing relation between the mathematical output with the neurophysiological organization of motor control.

Synergistic organization was also maintained across populations. Small variations were presented within groups, regarding temporal aspects of motor control. However, when comparing both groups, some synergies presented a different composition and significant shifts of the three synergies were found. This may indicate an adaptation in intermuscular coordination with training. A possible practical application of these results is that athletes in an initial phase of training should attempt to delay the hip extension, as well as the upper-limbs flexion.

Thus, these two studies suggest, for one hand, the robustness of muscle synergies, and for the other hand, some differences in muscle coordination between groups of different levels of expertise. When combined, the results point to the realization of two different future studies:

1) Comparison of the muscle synergies extracted from the ascendant phase of various exercises: i) for experienced subjects, comparing muscle synergies from power clean with another complex weightlifting task, the snatch. This would possibly reveal some shared patterns of muscle synergy activation between complex tasks, establishing relations between the two tasks in some basic aspects of motor control, and possibly providing basic aspects of intermuscular coordination, shared between movements, that could help trainers to optimize the training strategies; ii) for unexperienced subjects, comparing muscle synergies from vertical jumps and power clean. This would possibly help to justify if muscle synergies engaging lower-limbs in power clean are intrinsic and adapted from a natural motor behavior, the jump.

2) Realization of a randomized controlled study regarding strength training, including OWL exercises. This would possibly assess how unexperienced subjects could modify coordination over time. Knowing that there are differences between untrained subjects and weightlifters, it would be important to understand how these adaptations of neural strategies to perform complex movements tend to evolve, and what are the phases of the training process that should be considered when the objective is to promote intermuscular adaptations. Thus, a training intervention with at least 8-12 weeks of training, with multiple test sessions during the period, should be done to assess the timeframes of neural adaptations in intermuscular coordination and to relate the evolution with other specific adaptations, namely in muscle morphology, strength and movement quality. Additionally, it would be interesting to assess if specific training of one particular movement, for instance the power clean, could cause changes in the muscle synergies of other related task, such as snatch, and therefore evaluate how muscle synergies may possibly be easily modulated with training or if neural adaptations in intermuscular coordination are specific to the exercise.

H – References

Ahtiainen, J. (2006). Neuromuscular, Hormonal and Molecular Responses to Heavy Resistance Training in Strength Trained Men (Doctoral Dissertation). Jyväskylä, Finland.

Aoi, S., & Funato, T. (2016). Neuromusculoskeletal models based on the muscle synergy hypothesis for the investigation of adaptive motor control in locomotion via sensory-motor coordination. Neuroscience Research, 104, 88–95.

Arabatzi, F., & Kellis, E. (2012). Olympic weightlifting training causes different knee muscle-coactivation adaptations compared with traditional weight training. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 26(8), 2192–2201.

Bernstein, N. (1967). The co-ordination and regulation of movements. Oxford: Pergamon.

Berton, R., Lixandrão, M. E., Pinto, C., & Tricoli, V. (2018). Effects of weightlifting exercise, traditional resistance and plyometric training on countermovement jump performance: a meta-analysis. Journal of Sports Sciences, 36(18), 2038–2044.

Bizzi, E., & Cheung, V. C. K. (2013). The neural origin of muscle synergies. Frontiers in Computational Neuroscience, 7, 51.

Bruton, M., & O'Dwyer, N. (2018). Synergies in coordination: a comprehensive overview of neural, computational, and behavioral approaches. Journal of Neurophysiology, 120(6), 2761–2774.

Caldwell, J. T. (2015). Biomechanical comparisons of the power clean and power hang clean exercises at different relative intensities (Master's Theses and Doctoral Dissertations). Eastern Michigan University, USA.

Cappellini, G., Ivanenko, Y. P., Poppele, R. E., & Lacquaniti, F. (2006). Motor Patterns in Human Walking and Running. Journal of Neurophysiology, 95(6), 3426–3437.

Carroll, T. J., Riek, S., & Carson, R. G. (2001). Neural adaptations to resistance training: implications for movement control. Sports Medicine , 31(12), 829–840.

Carson, R. G. (2006). Changes in muscle coordination with training. Journal of Applied Physiology, 101(5), 1506–1513.

Channell, B. T., & Barfield, J. P. (2008). Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 22(5), 1522–1527.

Chaouachi, A., Hammami, R., Kaabi, S., Chamari, K., Drinkwater, E. J., & Behm, D. G. (2014). Olympic Weightlifting and Plyometric Training With Children Provides Similar or Greater Performance Improvements Than Traditional Resistance Training. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 28(6), 1483–1496.

Chen, X., Niu, X., Wu, D., Yu, Y., & Zhang, X. (2017). Investigation of the Intra- and Inter-Limb Muscle Coordination of Hands-and-Knees Crawling in Human Adults by Means of Muscle Synergy Analysis. Entropy , 19(5), 229.

Cheung, V. C. K., Piron, L., Agostini, M., Silvoni, S., Turolla, A., & Bizzi, E. (2009). Stability of muscle synergies for voluntary actions after cortical stroke in humans. Proceedings of the National Academy of Sciences of the United States of America, 106(46), 19563–19568.

Cheung, V. C. K., Turolla, A., Agostini, M., Silvoni, S., Bennis, C., Kasi, P., … Bizzi, E. (2012). Muscle synergy patterns as physiological markers of motor cortical damage. Proceedings of the National Academy of Sciences of the United States of America, 109(36), 14652–14656.

Chia Bejarano, N., Pedrocchi, A., Nardone, A., Schieppati, M., Baccinelli, W., Monticone, M., … Ferrante, S. (2017). Tuning of Muscle Synergies During Walking Along Rectilinear and Curvilinear Trajectories in Humans. Annals of Biomedical Engineering, 45(5), 1204–1218.

Cruz Ruiz, A. L., Pontonnier, C., Sorel, A., & Dumont, G. (2015). Identifying representative muscle synergies in overhead football throws. Computer Methods in Biomechanics and Biomedical Engineering, 18 Suppl 1, 1918–1919.

d'Avella, A., & Bizzi, E. (2005). Shared and specific muscle synergies in natural motor behaviors. Proceedings of the National Academy of Sciences of the United States of America, 102(8), 3076–3081.

d'Avella, A., Saltiel, P., & Bizzi, E. (2003). Combinations of muscle synergies in the construction of a natural motor behavior. Nature Neuroscience, 6(3), 300–308.

Delis, I., Hilt, P. M., Pozzo, T., Panzeri, S., & Berret, B. (2018). Deciphering the functional role of spatial and temporal muscle synergies in whole-body movements. Scientific Reports, 8(1), 8391.

De Marchis, C., Schmid, M., Bibbo, D., Bernabucci, I., & Conforto, S. (2013). Inter-individual variability of forces and modular muscle coordination in cycling: a study on untrained subjects. Human Movement Science, 32(6), 1480–1494.

Desrochers, E., Harnie, J., Doelman, A., Hurteau, M.-F., & Frigon, A. (2019). Spinal control of muscle synergies for adult mammalian locomotion. The Journal of Physiology, 597(1), 333–350.

Devarajan, K. (2008). Nonnegative matrix factorization: an analytical and interpretive tool in computational biology. PLoS Computational Biology, 4(7), e1000029.

Dominici, N., Ivanenko, Y. P., Cappellini, G., d'Avella, A., Mondì, V., Cicchese, M., … Lacquaniti, F. (2011). Locomotor primitives in newborn babies and their development. Science, 334(6058), 997–999.

Duchateau, J., Semmler, J. G., & Enoka, R. M. (2006). Training adaptations in the behavior of human motor units. Journal of Applied Physiology, 101(6), 1766–1775.

Erdemir, A., McLean, S., Herzog, W., & van den Bogert, A. J. (2007). Model-based estimation of muscle forces exerted during movements. Clinical Biomechanics, 22(2), 131–154.

Eriksson Crommert, M., Ekblom, M. M., & Thorstensson, A. (2014). Motor control of the trunk during a modified clean and jerk lift. Scandinavian Journal of Medicine & Science in Sports, 24(5), 758–763.

Folland, J. P., & Williams, A. G. (2007). The adaptations to strength training: morphological and neurological contributions to increased strength. Sports Medicine, 37(2), 145–168.

Frère, J., Göpfert, B., Hug, F., Slawinski, J., & Tourny-Chollet, C. (2012). Catapult effect in pole vaulting: is muscle coordination determinant? Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 22(1), 145–152.

Frère, J., & Hug, F. (2012). Between-subject variability of muscle synergies during a complex motor skill. Frontiers in Computational Neuroscience, 6, 99.

Fry, A. C., Schilling, B. K., Staron, R. S., Hagerman, F. C., Hikida, R. S., & Thrush, J. T. (2003). Muscle fiber characteristics and performance correlates of male Olympic-style weightlifters. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 17(4), 746–754.

Griffin, L., & Cafarelli, E. (2005). Resistance training: cortical, spinal, and motor unit adaptations. Canadian Journal of Applied Physiology = Revue Canadienne de Physiologie Appliquee, 30(3), 328–340.

Grillner, S., & Jessell, T. M. (2009). Measured motion: searching for simplicity in spinal locomotor networks. Current Opinion in Neurobiology, 19(6), 572–586.

Gui, K., & Zhang, D. (2016). Influence of locomotion speed on biomechanical subtask and muscle synergy. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 30, 209–215.

Hackett, D., Davies, T., Soomro, N., & Halaki, M. (2016). Olympic weightlifting training improves vertical jump height in sportspeople: a systematic review with meta-analysis. British Journal of Sports Medicine, 50(14), 865–872.

Häkkinen, K., Kallinen, M., Izquierdo, M., Jokelainen, K., Lassila, H., Mälkiä, E., … Alen, M. (1998). Changes in agonist-antagonist EMG, muscle CSA, and force during strength training in middle-aged and older people. Journal of Applied Physiology, 84(4), 1341–1349.

Hao, Y., Zhang, S., Zhang, Q., Li, G., Chen, W., & Zheng, X. (2017). Neural synergies for controlling reach and grasp movement in macaques. Neuroscience, 357, 372–383.

Hart, C. B., & Giszter, S. F. (2010). A neural basis for motor primitives in the spinal cord. The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 30(4), 1322–1336.

Helland, C., Hole, E., Iversen, E., Olsson, M. C., Seynnes, O., Solberg, P. A., & Paulsen, G. (2017). Training Strategies to Improve Muscle Power: Is Olympic-style Weightlifting Relevant? Medicine and Science in Sports and Exercise, 49(4), 736–745.

Hirashima, M., & Oya, T. (2016). How does the brain solve muscle redundancy? Filling the gap between optimization and muscle synergy hypotheses. Neuroscience Research, 104, 80–87.

Hoffman, J. R., Cooper, J., Wendell, M., & Kang, J. (2004). Comparison of Olympic vs. traditional power lifting training programs in football players. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 18(1), 129–135.

Hug, F. (2011). Can muscle coordination be precisely studied by surface electromyography? Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 21(1), 1–12.

Hug, F., Turpin, N. A., Couturier, A., & Dorel, S. (2011). Consistency of muscle synergies during pedaling across different mechanical constraints. Journal of Neurophysiology, 106(1), 91–103.

Hug, F., Turpin, N. A., Dorel, S., & Guével, A. (2012). Smoothing of electromyographic signals can influence the number of extracted muscle synergies. Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, 123(9), 1895–1896.

Hug, F., Turpin, N. A., Guével, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? Journal of Applied Physiology, 108(6), 1727–1736.

Ivanenko, Y. P., Poppele, R. E., & Lacquaniti, F. (2004). Five basic muscle activation patterns account for muscle activity during human locomotion. The Journal of Physiology, 556(Pt 1), 267–282.

James, L. P., Gregory Haff, G., Kelly, V. G., Connick, M. J., Hoffman, B. W., & Beckman, E. M. (2018). The impact of strength level on adaptations to combined weightlifting, plyometric, and ballistic training. Scandinavian Journal of Medicine & Science in Sports, 28(5), 1494–1505.

Kim, M., Kim, Y., Kim, H., & Yoon, B. (2018). Specific muscle synergies in national elite female ice hockey players in response to unexpected external perturbation. Journal of Sports Sciences, 36(3), 319–325.

Kipp, K., & Meinerz, C. (2017). A biomechanical comparison of successful and unsuccessful power clean attempts. Sports Biomechanics / International Society of Biomechanics in Sports, 16(2), 272–282.

Kipp, K., Pfeiffer, R., Sabick, M., Harris, C., Sutter, J., Kuhlman, S., & Shea, K. (2014). Muscle synergies during a single-leg drop-landing in boys and girls. Journal of Applied Biomechanics, 30(2), 262–268.

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 & Science in Sports, 25(1), 89–97.

Kristiansen, M., Samani, A., Madeleine, P., & Hansen, E. A. (2016a). Effects of 5 Weeks of Bench Press Training on Muscle Synergies. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 30(7), 1948–1959.

Kristiansen, M., Samani, A., Madeleine, P., & Hansen, E. A. (2016b). Muscle synergies during bench press are reliable across days. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 30, 81–88.

Kutch, J. J., & Valero-Cuevas, F. J. (2012). Challenges and new approaches to proving the existence of muscle synergies of neural origin. PLoS Computational Biology, 8(5), e1002434.

Lambert-Shirzad, N., & Van der Loos, H. F. M. (2017). On identifying kinematic and muscle synergies: a comparison of matrix factorization methods using experimental data from the healthy population. Journal of Neurophysiology, 117(1), 290–302.

Latash, M. L. (2008). Synergy. In M. L. Latash (Ed.). Oxford: Oxford University Press.

Latash, M. L. (2015). Bernstein's "Desired Future" and Physics of Human Movement. Cognitive Systems Monographs, 25, 287–299.

Latash, M. L., Krishnamoorthy, V., Scholz, J. P., & Zatsiorsky, V. M. (2005). Postural synergies and their development. Neural Plasticity, 12(2-3), 119–130; discussion 263–272.

Latash, M. L., Scholz, J. P., & Schöner, G. (2007). Toward a New Theory of Motor Synergies. Motor Control, 11(3), 276–308.

Lee, D. D., & Seung, H. S. (1999). Learning the parts of objects by non-negative matrix factorization. Nature, 401(6755), 788–791.

Lee, D. D., & Seung, H. S. (2001). Algorithms for non-negative matrix factorization. Advances in Neural Information Processing Systems, 13, 556–562.

MacKenzie, S. J., Lavers, R. J., & Wallace, B. B. (2014). A biomechanical comparison of the vertical jump, power clean, and jump squat. Journal of Sports Sciences, 32(16), 1576–1585.

Matsunaga, N., Imai, A., & Kaneoka, K. (2017). Comparison of muscle synergies before and after 10 minutes of running. Journal of Physical Therapy Science, 29(7), 1242–1246.

Matsunaga, N., & Kaneoka, K. (2018). Comparison of Modular Control during Smash Shot between Advanced and Beginner Badminton Players. Applied Bionics and Biomechanics, 2018, 6592357.

Mcbride, J. M., Triplett-Mcbride, T., Davie, A., & Newton, R. U. (1999). A Comparison of Strength and Power Characteristics Between Power Lifters, Olympic Lifters, and Sprinters. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 13(1), 58–66.

Moritani, T., & deVries, H. A. (1979). Neural factors versus hypertrophy in the time course of muscle strength gain. American Journal of Physical Medicine, 58(3), 115–130.

Mussa-Ivaldi, F. A., Giszter, S. F., & Bizzi, E. (1994). Linear combinations of primitives in vertebrate motor control. Proceedings of the National Academy of Sciences of the United States of America, 91(16), 7534–7538.

Oliveira, M. A. & Shim, J. K. (2008). Redundância motora: o problema de graus de liberdade na ciência do movimento humano. Revista Brasileira de Ciências do Esporte, 29(2), 9-25.

Overduin, S. A., d'Avella, A., Carmena, J. M., & Bizzi, E. (2012). Microstimulation activates a handful of muscle synergies. Neuron, 76(6), 1071–1077.

Passos, P. & Barreiros, J. (2013). A variabilidade e o problema dos Graus de Liberdade: o contributo de Nikolai Bernstein. In P. Passos (Ed.), Comportamento motor, controlo e aprendizagem (pp. 115-136). Cruz Quebrada: Edições FMH.

Pezarat-Correia, P. (2012). Adaptações do Aparelho Locomotor à Atividade Física e à Inatividade. In P. Pezarat-Correia (Ed.), Aparelho Locomotor Vol.2 (pp. 183-271). Cruz Quebrada: Edições FMH.

Pires, R. & Mendonça, G. V. (2015). Halterofilismo. In P. Mil-Homens, P. Pezarat-Correia & G. V. Mendonça (Ed.), Treino da Força, Princípios Biológicos e Métodos de Treino (pp. 249-269). Cruz Quebrada: Edições FMH.

Prevete, R., Donnarumma, F., d'Avella, A., & Pezzulo, G. (2018). Evidence for sparse synergies in grasping actions. Scientific Reports, 8(1), 616.

Rozumalski, A., Steele, K. M., & Schwartz, M. H. (2017). Muscle synergies are similar when typically developing children walk on a treadmill at different speeds and slopes. Journal of Biomechanics, 64, 112–119.

Rutherford, O. M., & Jones, D. A. (1986). The role of learning and coordination in strength training. European Journal of Applied Physiology and Occupational Physiology, 55(1), 100–105.

Safavynia, S. A., & Ting, L. H. (2012). Task-level feedback can explain temporal recruitment of spatially fixed muscle synergies throughout postural perturbations. Journal of Neurophysiology, 107(1), 159–177.

Safavynia, S. A., Torres-Oviedo, G., & Ting, L. H. (2011). Muscle Synergies: Implications for Clinical Evaluation and Rehabilitation of Movement. Topics in Spinal Cord Injury Rehabilitation, 17(1), 16–24.

Saito, A., Tomita, A., Ando, R., Watanabe, K., & Akima, H. (2018). Similarity of muscle synergies extracted from the lower limb including the deep muscles between level and uphill treadmill walking. Gait & Posture, 59, 134–139.

Sale, D. G. (1988). Neural adaptation to resistance training. Medicine and Science in Sports and Exercise, 20(5 Suppl), S135–S145.

Sale, D. G. (2003). Neural Adaptation to Strength Training. In Strength and Power in Sport (pp. 281–314).

Saltiel, P., Wyler-Duda, K., D'Avella, A., Tresch, M. C., & Bizzi, E. (2001). Muscle synergies encoded within the spinal cord: evidence from focal intraspinal NMDA iontophoresis in the frog. Journal of Neurophysiology, 85(2), 605–619.

Samani, A., & Kristiansen, M. (2018). Inter- and Intrasubject Similarity of Muscle Synergies During Bench Press With Slow and Fast Velocity. Motor Control, 22(1), 100–115.

Shaharudin, S., & Agrawal, S. (2016). Muscle synergies during incremental rowing VO2max test of collegiate rowers and untrained subjects. The Journal of Sports Medicine and Physical Fitness, 56(9), 980–989.

Shaharudin, S., Zanotto, D., & Agrawal, S. (2014). Muscle Synergies of Untrained Subjects during 6 min Maximal Rowing on Slides and Fixed Ergometer. Journal of Sports Science & Medicine, 13(4), 793–800.

Shim, J. K., Hsu, J., Karol, S., & Hurley, B. F. (2008). Strength training increases training-specific multifinger coordination in humans. Motor Control, 12(4), 311–329.

Silva, P. B., Oliveira, A. S., Mrachacz-Kersting, N., & Kersting, U. G. (2018). Effects of wobble board training on single-leg landing neuromechanics. Scandinavian Journal of Medicine & Science in Sports, 28(3), 972–982.

Singh, R. E., Iqbal, K., White, G., & Hutchinson, T. E. (2018). A Systematic Review on Muscle Synergies: From Building Blocks of Motor Behavior to a Neurorehabilitation Tool. Applied Bionics and Biomechanics, 2018, 3615368.

Smale, K. B., Shourijeh, M. S., & Benoit, D. L. (2016). Use of muscle synergies and wavelet transforms to identify fatigue during squatting. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 28, 158–166.

Steele, K. M., Tresch, M. C., & Perreault, E. J. (2013). The number and choice of muscles impact the results of muscle synergy analyses. Frontiers in Computational Neuroscience, 7, 105.

Storey, A., & Smith, H. K. (2012). Unique aspects of competitive weightlifting: performance, training and physiology. Sports Medicine , 42(9), 769–790.

Storey, A., Wong, S., Smith, H. K., & Marshall, P. (2012). Divergent muscle functional and architectural responses to two successive high intensity resistance exercise sessions in competitive weightlifters and resistance trained adults. European Journal of Applied Physiology, 112(10), 3629–3639.

Taborri, J., Agostini, V., Artemiadis, P. K., Ghislieri, M., Jacobs, D. A., Roh, J., & Rossi, S. (2018). Feasibility of Muscle Synergy Outcomes in Clinics, Robotics, and Sports: A Systematic Review. Applied Bionics and Biomechanics, 2018, 3934698.

Taborri, J., Palermo, E., Del Prete, Z., & Rossi, S. (2018). On the Reliability and Repeatability of Surface Electromyography Factorization by Muscle Synergies in Daily Life Activities. Applied Bionics and Biomechanics, 2018, 5852307.

Takei, T., Confais, J., Tomatsu, S., Oya, T., & Seki, K. (2017). Neural basis for hand muscle synergies in the primate spinal cord. Proceedings of the National Academy of Sciences of the United States of America, 114(32), 8643–8648.

Teo, S. Y. M., Newton, M. J., Newton, R. U., Dempsey, A. R., & Fairchild, T. J. (2016). Comparing the Effectiveness of a Short-Term Vertical Jump vs. Weightlifting Program on Athletic Power Development. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 30(10), 2741–2748.

Ting, L. H., & McKay, J. L. (2007). Neuromechanics of muscle synergies for posture and movement. Current Opinion in Neurobiology, 17(6), 622–628.

Torres-Oviedo, G., & Ting, L. H. (2007). Muscle synergies characterizing human postural responses. Journal of Neurophysiology, 98(4), 2144–2156.

Tresch, M. C., Cheung, V. C. K., & d'Avella, A. (2006). Matrix factorization algorithms for the identification of muscle synergies: evaluation on simulated and experimental data sets. Journal of Neurophysiology, 95(4), 2199–2212.

Tresch, M. C., & Jarc, A. (2009). The case for and against muscle synergies. Current Opinion in Neurobiology, 19(6), 601–607.

Turpin, N. A., Costes, A., Moretto, P., & Watier, B. (2017). Can muscle coordination explain the advantage of using the standing position during intense cycling? Journal of Science and Medicine in Sport / Sports Medicine Australia, 20(6), 611–616.

Turpin, N. A., Guével, A., Durand, S., & Hug, F. (2011a). Effect of power output on muscle coordination during rowing. European Journal of Applied Physiology, 111(12), 3017–3029.

Turpin, N. A., Guével, A., Durand, S., & Hug, F. (2011b). Fatigue-related adaptations in muscle coordination during a cyclic exercise in humans. The Journal of Experimental Biology, 214(Pt 19), 3305–3314.

Turpin, N. A., Guével, A., Durand, S., & Hug, F. (2011c). No evidence of expertise-related changes in muscle synergies during rowing. Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology, 21(6), 1030–1040.

Vaz, J. R., Olstad, B. H., Cabri, J., Kjendlie, P.-L., Pezarat-Correia, P., & Hug, F. (2016). Muscle coordination during breaststroke swimming: Comparison between elite swimmers and beginners. Journal of Sports Sciences, 34(20), 1941–1948.

Winchester, J. B., Erickson, T. M., Blaak, J. B., & McBride, J. M. (2005). Changes in bar-path kinematics and kinetics after power-clean training. Journal of Strength and Conditioning Research / National Strength & Conditioning Association, 19(1), 177–183.

Zehr, E. P. (2005). Neural control of rhythmic human movement: the common core hypothesis. Exercise and Sport Sciences Reviews, 33(1), 54–60.