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Similarity of different lifting techniques in trunk muscular synergies

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Lifting is known to be a major reason for musculoskeletal injuries. In this way, lifting has a crucial effect on human musculoskeletal system and intensity of this impact depends slightly on the selection of techniques. Underlying mechanisms by which trunk muscles are executed during performing lifting are central to biomechanical study of lifting techniques. In the current study, the trunk muscular control mechanisms of lifting are investigated using the synergetic control analysis. Non-negative matrix factorization has been used to extract trunk muscles synergies from their activities – which are computed by a previously validated musculoskeletal model – during different lifting techniques aimed to investigate motor control strategies. Three lifting techniques are considered; stoop, squat and semi-squat. Three synergies account for variety among muscle activation of trunk muscles with related VAF (Variability Account For) of over 95%. Trunk muscle synergy weightings and related time-varying coefficients are calculated for each kind of lifting techniques considering three synergies. Paired correlation coefficients between muscle synergies are all greater than 0.91 ($P < 0.05$) suggesting that trunk muscle synergies are similar for examined techniques in spite of their kinematic diversity. This similarity can be a result of their common ultimate goal. The acquired results also elucidate the mechanisms of muscle activation patterns that can be exploited in future studies and ergonomic interventions.

Key words: *trunk muscle synergies, lifting techniques, optimization and inverse dynamics*

1. Introduction

Manual material handling is a major cause of Low Back Disorder (LBD), Low Back Pain (LBP) and other musculoskeletal injuries particularly in workplaces [1]. The problems mentioned have become an epidemic to society and have high direct and indirect costs [2].

Lifting techniques have a great impact on mechanical spinal loading [18]. The lifting effects on musculoskeletal health are widely discussed and it is shown that a biomechanically appropriate lifting technique can reduce the risk factors [23]. Lifting techniques are biomechanically evaluated mostly considering mechanical loads (Net, Extensor or Bending moment and Compression or shear forces) or direct measurement such as Intra-Discal Pressure (IDP), Intra-Abdominal Pressure (IAP), spinal shrinkage and EMG (electromyography). Other researchers have focused on postural responses during various kinds of lifting techniques in order to assess key strategies of each one [23]. In addition to prior studies, neuro-mechanical investigation on motor control mechanisms of lifting techniques could link the above-mentioned approaches and explain how CNS (central nervous system) coordinates muscles to perform a specified kind of lifting.

As it is impractical to take direct measurements of the muscle forces, the laboratory methods such as biomechanical models are exploited to measure muscles activity indirectly [3], [10].

Biomechanical musculoskeletal models are categorized based on their approach for prediction of forces. EMG-based models use muscle electromyograms and a system of simulated muscles and joints to compute forces. Some models use inverse dynamics and an objective function that optimizes a specific parameter, for instance, muscles tensions, to analyze forces. The current study uses a fully validated whole-body model, which combines optimization and inverse dynamics, and allows

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the calculation of muscle activities. AnyBody modeling system is software for development and analysis of multibody dynamics of musculoskeletal system. This software was used for musculoskeletal simulation and successfully validated in various applications. It should be noted that these kinds of models need input kinematic data to be derived (required data for current study obtained from previous studies of Lee et al. [23], Hwang et al. [9] and Xiang et al. [26]).

Highly complex and multidimensional environment of muscles has been considered as a major problem for the nervous system [11]. Theory of synergies was introduced by Bernstein [4] as a method for grouping variables which facilitates understanding of their control mechanism. The synergetic approach towards muscle redundancy can explain how recruitment of muscles for production of movements is simplified [5].

Latash et al. [11] describes synergies as an organization of a multi-element system which firstly organizes sharing of a task among a set of variables and secondly provides co-variation among variables for stabilizing their performances. Muscle synergy refers to limited organizations that share a natural behavior among a set of muscles activity and can be identified by decomposition algorithms. In this approach, muscle activity patterns consist of two components: a *fixed* component and a *task-varying* component.

- a *fixed component*, named "*synergy*", is an indication of relative weighting of each muscle within each synergy [21].
- a *task-varying component* named "*activation coefficient*" indicates the relative contribution of the muscle synergy to the original muscle activation [21].

According to muscle synergy theory – or modular organization as referred to in literature [16] – the muscle activation patterns during performing a specific task may in fact be organized in a set of limited groups (time-varying synergies) [8], [19]. Synergy activation coefficients are considered to be related to movement organization [14], [19]. Ting et al. [19] assessed the hypothesis and provided evidence that biomechanical behavior corresponds to limited muscle synergies by investigating muscles EMGs and reaction forces in cats. Neptune et al. [16] also demonstrate that synergies obtained during walking can perform basic neural control elements and provide evidence for each synergy's contribution to the biomechanical control strategy.

One of the most efficient methods, which were used to compute synergies, is Non-Negative Matrix Factorization (NNMF). This algorithm has been developed to compute synergies and identify muscle-sharing patterns [19], [20]. It is shown by Trsech et al. [22] that NNMF is an operative method to identify muscle synergies. This method has been developed for extracting muscle synergies and is based on two assumptions: any muscle can belong to more than one synergy and the relative weighting of muscles within each synergy has a constant level of activation [19].

Control mechanisms of body movements are investigated in different ways [10], [17], [24], [25]. In terms of postural control, for instance, Kollmitzer et al. [10] contrasted stance conditions during lifting showing complex control for step stance as compared to parallel stance. In terms of muscle control, muscle synergies have the capacity to provide knowledge on CNS strategies [24], [25] which can be used to assess each individual muscle group contribution to adjust and maintain the whole-body balance while subjects are standing. Muscles grouping or synergetic control of trunk muscles can lead to a further insight to motor control of lifting.

In the current study, muscle synergies of different lifting techniques are extracted in order to assess their mechanisms of execution. The present musculoskeletal model of lifting is validated for three kinds of lifting techniques; stoop, squat and semi-squat. The trunk muscles timing and composition of the synergies are extracted by computed muscle activities patterns using NNMF algorithm.

2. Methods

2.1. Lifting model simulation

A musculoskeletal model is developed in order to compute trunk muscle activities during lifting. This comprehensive model of whole body has been created in AnyBody^{TM} modeling system (version 5.0, AnyBody Technology, Aalborg, Denmark) and is driven dynamically [7].

In the current study, lifting was simulated based on the standing model repository that is in three main parts: the arms, trunk and leg. The arm part or shoulder area had two sides with each side including 118 muscles that are made based on a shoulder Dutch design. The trunk part consists of seven areas including pelvic, lumbar and five thoracic vertebras and chest. AnyBody^{TM} uses inverse dynamic to balance external loads in order to compute muscle activities. Related equilibrium equation for a musculoskeletal system takes the following form

$$[C]_{i\times m}[f]_{m\times 1} = [r]_{i\times 1} \tag{1}$$

where f is a vector of muscle and joint forces, r is a vector representing the external forces and inertia forces and C is a matrix of equation coefficients. For solving redundancy of the muscle recruitment problem, optimization problem is formulated as follows

$$\text{Minimize } G(\mathbf{f}^{(\mathrm{m})}) \quad \mathbf{f}^{(\mathrm{m})} > 0, \quad i = 1, ..., n^{(\mathrm{m})}, \tag{2a}$$

$$\text{Subject to } \mathbf{Cf} = \mathbf{r}, \tag{2b}$$

where G is an objective function and is aimed at distributing external forces within muscles. Two kinds of objective functions are used in the current study: min/max and polynomial. Min/max optimizer minimized the maximum muscle forces trying to balance the external load with a positive distribution in a way that each muscle has a minimal max activity. Polynomial muscle recruitment is a high order objective function for distributing load equally between muscles.

2.2. Boundary conditions of lifting

Lifting model has been driven by defined input trajectories. To determine the lifting motion, the required input data are: elbow, ankle, knee, hip and shoulder flexion and the trunk extension. Lee et al. [13] captured these joint trajectories for finding postural reaction of body during stable and unstable load lifting. Xiang et al. [26] simulated human motion during various lifting techniques. The position data recorded by Lee et al. [13] and Xiang et al. [26] are used for diving lifting model.

Toes and heels are fixed to the ground and non-rigid elements are used between them and the ground in order to create non-sticking boundary conditions. Weight of the lifted load was simulated with creating forces concentrated in the center of the left and right hand (palm joint) using 44 N for each hand.

2.3. Validation of lifting simulation

Four muscles electromyography (EMG) during both squat and stoop lifting were recorded simultaneously; Biceps (Bi-E), Brachioradialis (Br-E), Erector Spine (Es-E) and Hamstring (Ha-E) muscles [13]. Muscle activities, which were computed by software, are statistically compared with the four muscles electromyography (EMG) calculating Pearson's correlation coefficients. These coefficients among EMGs and muscle activities were computed using two recruitment functions (polynomial and Min/Max) during stoop and squat lifting. Further details were provided in our earlier study [15].

2.4. Computing muscle synergies and identifying their sharing patterns at lifting techniques

NNMF algorithm is used to identify muscle activation synergies in which each muscle can be activated by multiple synergies. Muscle activation synergies (W) and coefficients (C) are predicted by the following equation

$$m_{ACT} \approx m_{PRE} = \sum_{i=1}^{N} C_i W_{ij} \tag{3}$$

where j and i indices indicate the muscles and synergies, respectively, m_{ACT} is a matrix including muscle activities, and N is the number of synergies. If N synergies are able to reconstruct muscle activities, W_{ij} is the proportion of synergy, i, for muscle j and C_i represents the coefficient. In equation (3), m_{PRE} stands for the predicted muscle activities constructed by synergies.

C and W matrices are considered to be non-negative (as muscle activation could not be negative) and they are calculated using alternating least-squares algorithm formed in equations (4) and (5). This method was used for the first time by Lee and Sueng [12]. For a given number of synergies, the initial values of C and W matrices are selected randomly and are updated using the following equations

$$C_{ij\_new} = C_{ij} \frac{(W^T m)_{ij}}{(W^T W C)_{ij}}, \tag{4}$$

$$W_{ij\_new} = W_{ij} \frac{(m C^T)_{ij}}{(W C C^T)_{ij}}. \tag{5}$$

The Variability Accounted For (VAF) the muscle reconstruction is calculated to compare the pattern and the absolute value of the reconstructed activates and muscle activities. VAF is defined as the ratio of the sum of squared errors to the sum of squared original data

$$VAF_o = \left[1 - \frac{\mathrm{var}(m_{obs} - m_{pre})}{\mathrm{var}(m_{obs})}\right] \times 100. \tag{6}$$

Three lifting techniques have been considered in this model: stoop, semi-squat and squat. Lifting duration for all techniques is the same, 1.5 second. The amount of force applied to each hand is 44 N. The number of trunk muscles is enormous (148) in human body model repository of AnyBody^{TM} and it is not feasible to take them all into account. Nine muscles have been selected for being imported to synergy input matrix (m_{ACT}). All of these muscles are selected in one specific level except for multifidi and erector spine muscles that were chosen in 2 and 4 levels, respectively. Table 1 contains an inclusive list of all the selected muscles and their levels. In order to achieve summarized figures, related abbreviations are used instead of full name.

Table 1. Selected muscles and their levels label and associated number (L = Lumbar hvirvel, T = Thoracic hvirvel, C = Costae)

Muscle	Label	Muscle	Label
Multifidi	MF L1	Obliquus externus	OE C10
Multifidi	MF L5	Obliquus internus	OI C12
Erector spine	ES L1	Semispinalis	SE L1
Erector spine	ES L4	Thoracic multifidi	TMF L1
Erector spine	ES C9	Spinalis	SP L1
Erector spine	ES T9	Transversus	Ts L1
Quadratus Lumborum	QL C12		

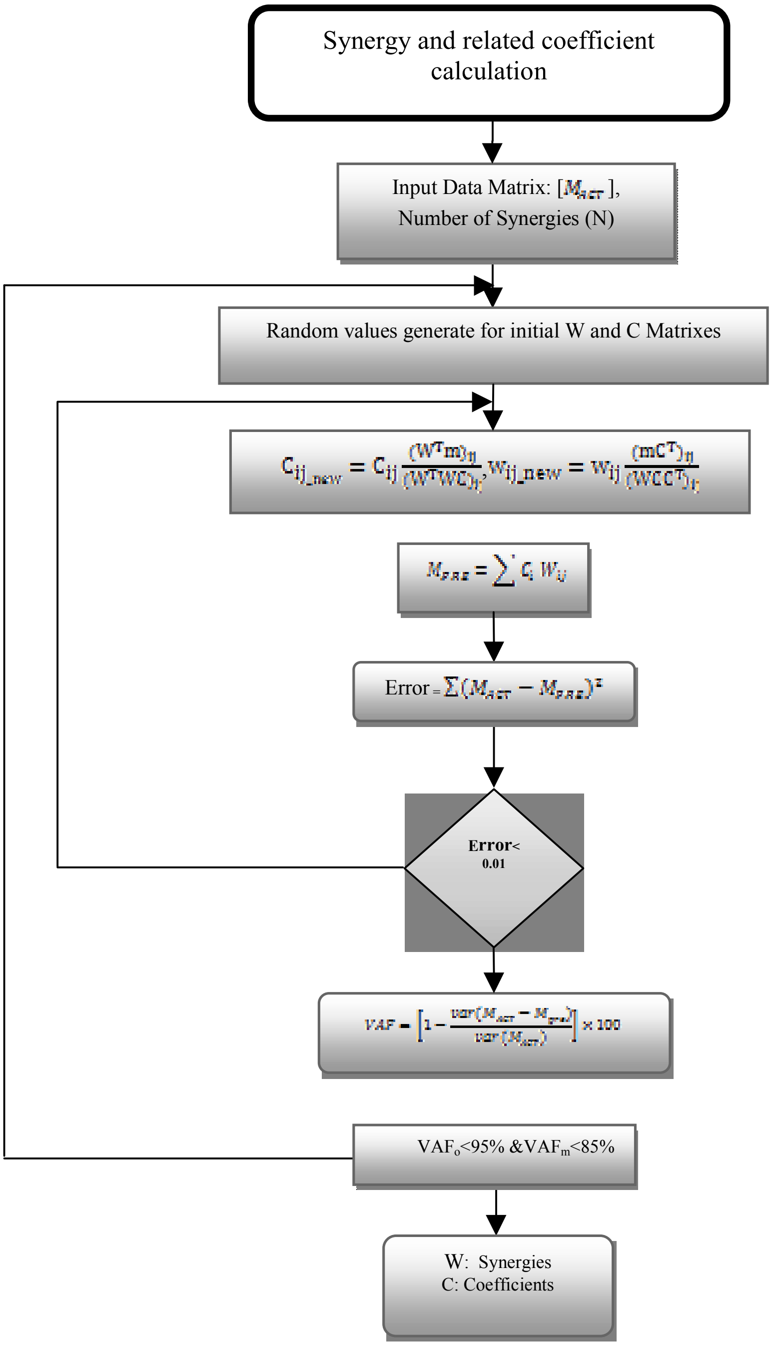

Fig. 1. The procedure of computing muscle synergies and their related activation coefficients using developed method of Bizzi et al., given the muscle activities as a function of time incorporated in the Data Matrix (M_{ACT}) and the number of synergies

The algorithm, which is depicted in Fig. 1, starts with generating random values and incorporating them into the matrix structures. In each iteration, the total squared error between the reconstructed data and activities is calculated. This process ends when the total squared errors become less than 0.01. In order to extract trunk muscle synergies during lifting, each time-varying muscle activity is located in a row of m_{ACT} that is a 13 × 15 matrix containing 13 trunk muscles in 15 time steps of lifting.

The synergetic control analysis has been done using one to five synergies for each lifting technique. Local (for each muscle) and overall (for all muscles) VAF are determined in each case. For a given number of synergies, if the overall VAF and the local VAF exceed a large predefined percentage (95% and 85%, respectively) it would be assumed that the synergies are able to account for muscle pattern.

3. Results

3.1. Validation

Appropriate consistency – presented by relatively high values of Pearson reported in our previous study [15] – was among the muscle activities of the model and their related EMGs. However, this consistency varies depending on the recruitment function. Our results (Table 2) indicated that utilizing polynomial recruitment function generally results in higher levels of PCCs in comparison with the Min/Max method.

Table 2. Pearson's coefficient between Lee study muscle EMG and muscular activities of the model

Recruit Function	Muscles			
	Bicep	Brach	ES L3	Hams
Squat				
Poly	0.72	0.83	0.92	0.78
Min/Max	0.42	0.87	0.90	0.28
Stoop				
Poly	0.87	0.30	0.60	0.78
Min/Max	0.10	0.15	0.90	0.76
Semi-squat				
Poly	0.64	0.40	0.81	0.62
Min/Max	0.31	0.32	0.78	0.68

3.2. Muscle activity of lifting techniques

Lifting is simulated in AnyBody modeling system and trunk muscle activity patterns are computed during stoop, semi-squat, and squat techniques. The simulation results are shown in Fig. 3 and Fig. 4. During each lifting technique, some muscle activities demonstrate similar pattern, for instance, ES T9 and TS L1 at squat (Fig. 2), SP l1 and OI C12 at stoop lifting (Fig. 3a) or SP L1 and SE L1 at semi squat lifting (Fig. 3b) but most of the muscle activities have different trend and their patterns are very complex.

Each individual muscle is activated with a different trend during each lifting technique. For instance, SP L1 muscle activity decreases sharply over the first one second and remains almost constant over the last 0.5 second at stoop technique, however, it reflects a different trend with two local peaks at squat lifting.

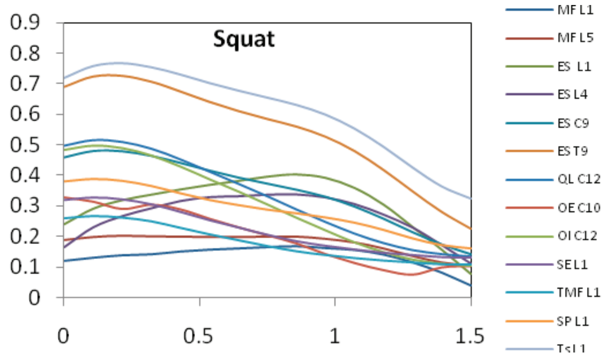

Fig. 2. Squat muscular activities over lifting time period

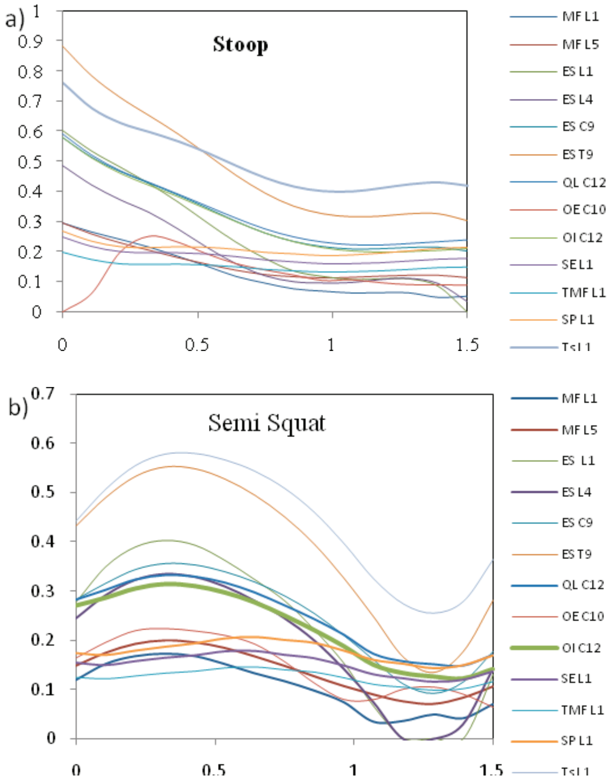

Fig. 3. Stoop and semi-squat muscular activities over lifting time period

3.3. Muscle activity decomposition

As shown in Table 3, three synergies are able to reconstruct muscle activities during stoop lifting (VAF > 0.95). For two synergies, overall VAF is 84% and muscles VAF are more than 38% beside OE muscle. For three muscle synergies, all muscles VAF and overall VAF are greater than 95%.

The trunk muscle synergetic control analysis during squat using two groups of muscles (synergies) leads to an overall VAF of above 90%, while the least muscles VAF is about 93%. As the number of muscle synergies increased to 3, the overall VAF becomes about 99% (Fig. 4). The least semi-squat trunk muscles VAF is about 86% for two muscle synergies. This value increased by 13% for three synergies.

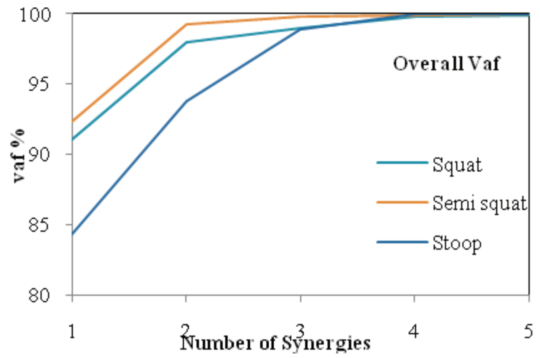

Fig. 4. Overall variability accounting for trunk muscle activities using different number of modulus during squat, stoop and semi-squat

Trunk muscle synergy weightings (W1, W2 and W3) and their related timing (time-varying) coefficients (C1, C2 and C3) are demonstrated in Fig. 5.

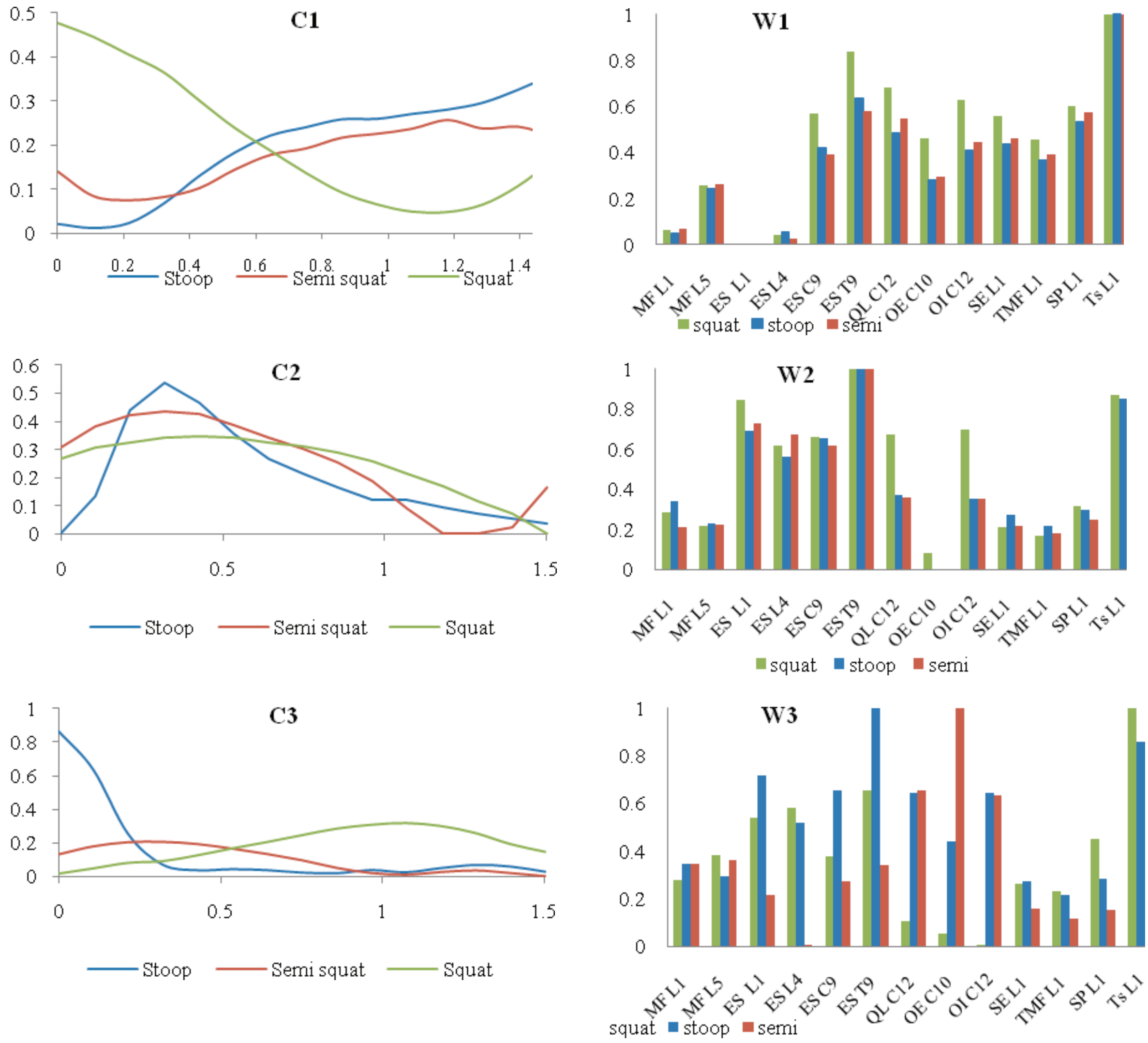

Fig. 5. Muscle synergies (W) and their related coefficient (C) for three kinds of lifting techniques; stoop (blue) squat (grey) and semi squat (red). Bar chart (right side) demonstrates three relative synergies (W1, W2 and W3) of muscles accounting for trunk muscle activities

Some muscles are activated mainly by one synergy and other synergies make a relatively small contribution to their activation, i.e., ES muscle at some levels (ES L1&L4) are activated by W2 synergy composition and exhibit very low weights in the W1 weightings during all lifting techniques. On the other hand, activity of some muscles such as MF L5 and TS L1 is constructed by sharing evenly among these three synergies.

C1 coefficient timing trends related to stoop and semi-squat increase gradually over lifting time period, however, this coefficient decreases during squat lifting. C2 coefficient grows up at the beginning of the lifting span and then falls down. C3 declines sharply over initial 0.5 second and stays almost zero over the rest of the stoop lifting time period while it levels off during the squat and semi-squat.

3.4. Similarity of lifting synergies

Similar activation patterns have been seen over trunk muscle synergy vectors across all lifting techniques, as indicated by relatively high figures of Pearson's correlation coefficients in each paired lifting trunk muscle synergy (Table 3).

Table 3. Paired Samples Correlations between synergies related to stoop (st), squat (sq) and semi-squat (se) lifting

		N	Correlation	Sig.
Pair 1	W1 $_{Sq\,\&St}$	13	.952	.000
Pair 2	W1 $_{St\,\&Se}$	13	.987	.000
Pair 3	W2 $_{Sq\,\&St}$	13	.913	.000
Pair 4	W2 $_{St\,\&Se}$	13	.911	.000

During squat and semi-squat lifting, two synergies account for more than 90% of the activities variance for all trunk muscles. Just like the three synergy decompositions, there are strong consistencies in the composition of the synergies across squat and semi-squat synergies and two of the stoop lifting synergies.

4. Discussion

Techniques used for lifting are of great importance as it is proved that lifting has a significant role in causing musculoskeletal injuries [2]. These techniques including squat and stoop are different in biomechanical terms; for instance, shear forces are greater in stoop lifting in comparison with squat lifting [1]. Shear forces during stoop and squat related to our previous study are summarized in Table 4, reporting a significant increase of approximately 60 percent in the shear force of L5S1 in both studies. The importance of adopting appropriate techniques is clear as it has a central impact particularly on force acting on the spine. It should also be noted that trunk muscle forces make a considerable contribution to forces on lumbar spine [23].

Table 4. L5S1 shear forces during stoop and squat lifting

Study	Method	Load	Stoop	Squat	Diff % stoop
Potvin et al. (1991)	Dynamic LSM +EMG	15	450	156	65
Mirakhorlo, Azghani et al. (2013)	Inverse Dynamic	18	876	360	58

The muscle synergy organization is developed for reducing muscle activation complexities and finding simpler motor pattern used by central nervous system (CNS) [14]. It is speculated that CNS uses such synergies to recruit muscles instead of controlling each muscle activity individually to provide a practical manner of control for redundant variables [5].

It is demonstrated that a limited number of independently activated synergies account for the complexity variability of their activities over a simulated lifting time period using NNMF processing algorithm. Three synergies are identified by this approach for each lifting technique (Fig. 2). Synergy number 1, as shown in its timing profile, has a dominant effect in muscles activities pattern construction at the half of stoop and semi-squat lifting period in contrast to squat lifting which is co-activated by this synergy mostly in the first half. This synergy mostly activates abdominal muscles such as OI C12, TS L1, while the weightings related to back muscles that extend the vertebral column (ES MF), are very low in this synergy. In contrast to the first synergy, in the synergy no 2 back muscles such as ES and MF exhibit higher weighting values and abdominal internal oblique OI C12 are activated weakly.

As shown in Fig. 2 and Fig. 3, muscle activities for stoop, semi-squat and squat lifting have different patterns demonstrating high inter-technique variability. However, comparing squat, stoop, and semi-squat lifting muscular synergies, it is shown that two of the three synergies of squat, stoop and semi-squat lifting trunk muscle activities are similar in weighting combinations (Table 4). In synergetic control analysis for squat and semi-squat lifting, even two synergies could reconstruct muscle activities (VAF > 90%). In this case, two synergies of squat and semi-squat trunk muscles and two of the three stoop synergies are correlated with each other, which implies that the trunk muscles are activated in three synergies vectors during lifting. Two of these synergies are shared among all lifting techniques and one of them is specific to stoop lifting.

Two characters of synergies described by Latash [11] are referred to organizing a shared task among a set of variables; and providing co-variation among variables. Considering all kinds of lifting techniques as a purposeful movement task aimed at elevating a load and muscle activities as variables, a common organization of muscle activation synergies is observed for different lifting techniques. Not only does it imply a shared coordination control mechanism between the trunk muscles during each individual lifting technique, but it also shows that CNS uses similar synergies to activate muscles by sharing organization of trunk muscles during lifting.

Motor redundancy suggests that the nervous system is capable of producing different muscle activity patterns for a given movement and also this capability is observed for various types of tasks with common goal. In the case of inter-individual variability for a given task, similar muscular synergies across the participants are observed as they are performing the task, i.e., Hug et al. [8] claimed that muscle synergies are similar across trained cyclists in spite of the variability of individual EMG patterns. In another study that examined gait cycle over a wide range of walking speeds, Clark et al. [6] provide evidence that muscle patterns decompositions are similar in the timing and the composition of the synergies across subjects. Their following study emphasizes former evidence of similar co-activity of muscles during walking [16]. Shared trunk muscle synergies for different lifting techniques such as stoop, squat or semi-squat, in spite of their dissimilar kinematics, impress a similar muscular control mechanism for lifting task. This finding indicates that similarity across muscle synergies in a task – shown by previous studies – could also be among various types of a task.

5. Conclusion

All kinds of lifting indicate the same coordination control manner as they are in accordance with their goal (elevating the load to specific position). Previous research findings indicated that there is not any significant inter-individual variation of muscle synergies during a specific movement (walking, rowing, cycling, etc.), so CNS uses a simple modular organization to recruit muscles for that specific task. The similarity across trunk muscle synergies during various types of lifting could generalize this inference not even for a given movement but also for different kinds of given tasks that are similar in purpose.

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