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Review

A review of methods to assess coactivation in the spine

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ABSTRACT

Coactivation is an important component for understanding the physiological cost of muscular and spinal loads and their associations with spinal pathology and potentially myofascial pain. However, due to the complex and dynamic nature of most activities of daily living, it can be difficult to capture a quantifiable measure of coactivation. Many methods exist to assess coactivation, but most are limited to two-muscle systems, isometric/complex analyses, or dynamic/uniplanar analyses. Hence, a void exists in that coactivation has not been documented or assessed as a multiple-muscle system under realistic complex dynamic loading. Overall, no coactivation index has been capable of assessing coactivation during complex dynamic exertions. The aim of this review is to provide an understanding of the factors that may influence coactivation, document the metrics used to assess coactivity, assess the feasibility of those metrics, and define the necessary variables for a coactivation index that can be used for a variety of tasks. It may also be clinically and practically relevant in the understanding of rehabilitation effectiveness, efficiency during task performance, human-task interactions, and possibly the etiology for a multitude of musculoskeletal conditions.

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1. Introduction

Lumbar and cervical spinal disorders have been a source of direct and indirect costs for both the individual and the workplace (Andersson and Watkins-Castillo, 2008; Cote et al., 2008; Davis

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Table 1
Calculations of coactivation in the literature. The interpretation is based on the assumption that antagonists have either less or equal contribution to the agonists, otherwise they would be deemed agonists.

Reference	Body region	Inputs	# Muscles considered	Definition of muscle contribution	Antagonist continuously defined	Isometric/dynamic	Calculation of CI	CI range and interpretation
Bautmans et al. (2011)	Upper extremity	Normalized EMG	2	Predefined	No	Dynamic	Ratio	0–100%, low to high coactivation
Brookham et al. (2011)	Upper extremity	Normalized EMG	5	Predefined	No	Isometric	Ratio/Area under curve	0% = flexors not active 50% full coactivation, 100% – extensors not active
Crenna et al. (1992)	Lower extremity	Normalized EMG	2	Undefined	No	Dynamic	Area under curve (overlap)	0–100%, low to high coactivation
Granata et al. (2000)	Lower extremity	Normalized EMG	2	Most active (agonist) vs. Least active (antagonist)	Yes	Dynamic	Scaled ratio	0–∞, low to high coactivation
Lamontagne et al. (2000)	Lower extremity	EMG	2	Undefined	No	Dynamic	Area under curve (overlap)	0–100%, low to high coactivation
Rudolph et al. (2000)	Lower extremity	Normalized EMG	2	Most active (agonist) vs. Least active (antagonist)	Yes	Dynamic	Scaled ratio normalized by time	0–200%, low to high coactivation
Don et al. (2007)	Lower extremity	Normalized EMG	2	Most active (agonist) vs. Least active (antagonist)	Yes	Dynamic	Scaled ratio normalized by time	0–100%, low to high coactivation
Falconer and Winter (1984)	Lower extremity	EMG	2	Most active (agonist) vs. Least active (antagonist)	Yes	Dynamic	Area under curve	0–100%, low to high coactivation
Kellis et al. (2003)	Lower extremity	Normalized EMG	2	Predefined	No	Dynamic	Ratio of area under curve	0% = flexors not active 50% full coactivation, 100% – extensors not active
Unnithan et al. (1996)	Lower extremity	Normalized EMG	2	Most active (agonist) vs. Least active (antagonist)	Yes	Dynamic	Area under curve	0–100%, low to high coactivation
Choi (2003)	Neck	Force, Optimization	28 muscles in model, 8 electrode sites	Muscle forces at zero net moment	No	Isometric	Ratio	0–100%, low to high coactivation
Cheng et al. (2008, 2014)	Neck	Normalized EMG	6	Predefined	No	Isometric and Dynamic	Ratio	0–100%, low to high coactivation
Fathallah et al. (1997)	Trunk	Normalized EMG	10	Predefined	No	Dynamic	Ratio	0–100% low to high coactivation
Hughes (1991) and Hughes et al. (2001)	Trunk	Normalized EMG	10	Predefined	No	Isometric	Marginal Cost	0–∞, low to high coactivation
Ranavolo et al. (2015)	Trunk	Normalized EMG	6	Undefined	No	Dynamic	Sigmoid-Weighted, Statistical approach	0–100%, low to high coactivation
Lavender et al. (1992a,b)	Trunk	Normalized EMG	8	Undefined	No	Isometric	Individual muscle comparison to total active muscles	0–100%, low to high coactivation
Thelen et al. (1995)	Trunk	Muscle Force, Optimization	12	Muscle forces at zero net moment	No	Isometric	Ratio	0–100%, low to high coactivation
Sparto et al. (1997)	Trunk	Muscle Moment	10	Predefined	No	Isometric	Ratio	1 = no coactivation of flexors, 2 = much coactivation of flexors and extensors
Song and Chung (2004, 2007)	Trunk	Muscle Moment	10	Predefined	No	Isometric	Ratio	0–50%, low to high coactivation
van Dieen et al. (2004)	Trunk	Normalized EMG and Muscle Moment	12	Predefined	No	Dynamic	Ratio	0–∞, low to high coactivation

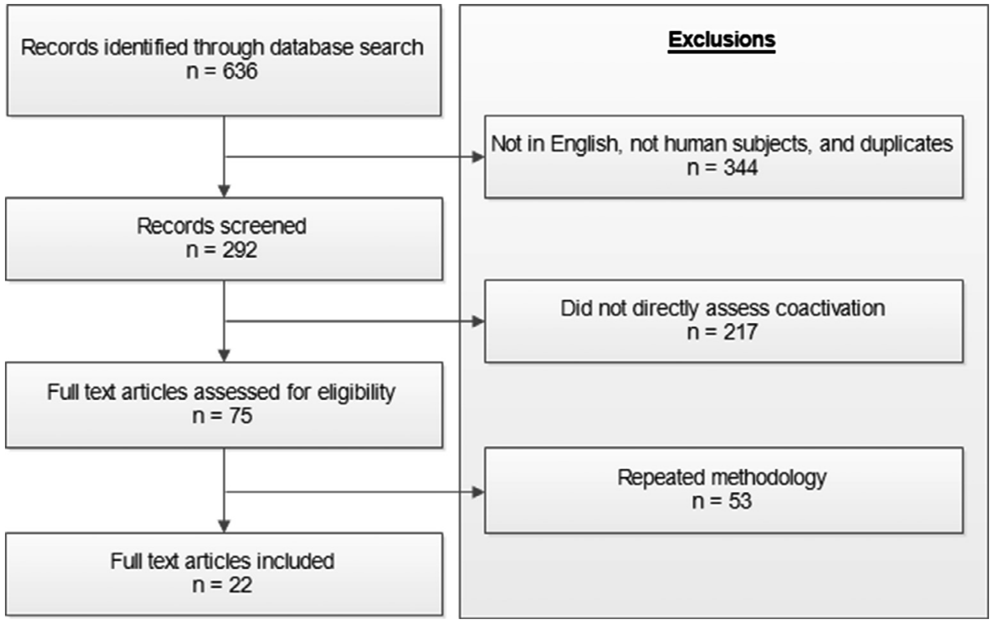

Fig. 1. Screening for coactivation assessment methods.

et al., 2014). Although some research sheds light on the causal pathways, the etiology of these disorders remain complex due to the multifaceted interactions of the human with the work environment (Marras, 2012). These etiologies appear to have a strong biomechanical influence via the neuromuscular drivers required to accomplish the task.

A commonly discussed component of this causal pathway involves muscular activation thought to be important for joint stabilization and motor control (De Luca and Mambrito, 1987; Smith, 1981); also known as coactivation or co-contraction (Hogan, 1984; Kellis, 1998; Lavender et al., 1992b; Levine and Kabat, 1952). Generally understood as the synergy of antagonist and agonist activations, coactivation represents the physiological/metabolic cost of inefficient muscular loading patterns onto a joint. Although coactivation indicates the "cost" to the system, it also provides neuromuscular stabilization to protect the spine (Davis and Marras, 2000) and satisfies the intent of the neuromuscular recruitment effort (Erlandson and Fleming, 1974). The key to interpretation is to understand when the cost may be deemed necessary or excessive. Relative to the level of physical demand, increases in antagonist activations may reflect system inefficiency if it impedes task performance. Low-level physical work (i.e. sedentary office work) may require intermittent periods of increased coactivation in order to encourage blood flow and muscular substitution to mitigate myalgia or myofascial pain from prolonged loading (Bathaii and Tabaddor, 2006; Eriksen, 2004; Hayden et al., 2006; Sjøgaard et al., 2000; Sjøgaard and Søgaard, 1998). On the other hand, coactivation during manual materials handling may reduce task performance and impose higher loads onto the spine (Marras and Mirka, 1990). In addition, individual perceptions due to fear-avoidance behavior (Thomas et al., 2008), inexperience (Marras et al., 2006), precision-dependent tasks (Beach et al., 2006; Collier et al., 2014; Joseph et al., 2014), or the interaction of precision and psychosocial influences (Marras et al., 2000), may also interact with the biomechanical loads to influence the level of coactivation. The interaction of these factors may increase antagonist activity, thus shifting the directionality of the internal moment and increase the magnitude of the spinal loads, which, in turn, may result in vertebral/disc pathology over time (Granata and Marras, 1995b). This increase in antagonistic activity, particularly in the internal/external obliques also impose higher shear and axial torsional loads onto the spine (Marras and Granata, 1995). Nevertheless, activities of daily living and tasks in the work environment are dynamic and complex in nature. Rarely are they static and/or in one plane. Picking up groceries, climbing stairs, and reaching/moving items all involve complex movements for motor control stabilization. Even standing tasks endure a natural postural sway (Kim et al., 2010; Madigan et al., 2006; Winter et al., 1998). Lifting, pushing, pulling, and bracing also occur in various postures and include asymmetry in their execution (Granata and Marras, 1993; Jones et al., 2013; Knapik and Marras, 2009; Lavender et al., 1992a). Within these tasks, sudden unexpected loading may also occur, thereby requiring coactivation to stabilize the posture and load (Marras et al., 1987). Therefore, in order to realistically understand coactivation, dynamics and task complexity must be taken into account. In this paper, dynamics refers to the various motions, velocities, and accelerations to accomplish a task. Complexity is operationally defined as the motions occurring in all three anatomical planes (sagittal, lateral, and axial) simultaneously.

Previously, several methods have been developed in order to assess coactivation in the trunk, upper extremities, and lower extremities. These methods include indices evaluating coactivation as a function of electromyography (EMG), muscle force, and muscle moments. However, a void currently exists in which coactivation has not been assessed as a multiple muscle system in the trunk and neck under complex and dynamic loading paradigms. Currently, there is no universally accepted metric or index to describe this physiological cost to the system. Thus, the objective is to review coactivation indices used in the literature, consider their respective merits and potential issues, and discuss the need for the development of a concise, understandable metric of coactivation.

2. Search methods

A systematic literature review of published articles and conference proceedings was conducted using Google Scholar, PubMed, and Web of Science. Specific search criteria were chosen in order for a relevant paper to be selected. These included the keywords: (1) 'muscle' and 'coactivation ratio' or 'coactivation index', and (2) 'muscle' or 'muscular' and 'coactivation' or 'cocontraction'. In addition, the language criterion was set to 'English' and study population was 'human'. Citations within the articles retrieved were also assessed as additional sources.

Studies were then screened based upon the title, abstract, and full text to meet more specific criteria for this review. In order to pass the first screening, a study needed to contain a description and method to assess coactivation or contain a reference citing the methodology. Studies that alluded to coactivation, but did not describe an index, ratio, or direct assessment of coactivation were excluded.

Selected studies were then categorized into specific body regions of: (1) 'lower-extremity' (hip, knee, and ankle), (2) 'upper-extremity' (shoulder, elbow, wrist), and (3) 'trunk and neck' (lumbar and cervical spine). Methodological approaches were then categorized relative to (1) inputs to assess coactivation and (2) type of experimental task. The inputs to assess coactivation were: (1) 'electromyography', (2) 'force', and (3) 'moment'. The experimental tasks involved: (1) complex motion and (2) static/dynamic loading.

2.1. Search results

The initial search of PubMed resulted in 137 hits, Google Scholar search resulted in 193 hits, and ISI Web of Science search resulted in 306 hits. Further screening of the title, abstract, and full texts were conducted to exclude irrelevant or duplicate studies. Studies that referred to similar methods were tracked to the original source. Only the original method was reported. This resulted in the final selection of 22 studies which included methodology employing EMG, muscle force, and muscle moment techniques. Fig. 1 describes the search criteria for paper selection. Tables 1 and 2 describe the overall methods found (including lower and upper extremity) and spine-specific approaches, respectively.

3. Methods used to assess coactivation

Coactivation is typically measured via surface electromyography (EMG) and is analyzed and interpreted differently depending on the method employed. Several methods exist in order to explain coactivity to understand the progression of movement, asymptomatic vs. symptomatic subjects, and complex loading. These methods have been found in studies for the lower extremity (Crenna et al., 1992; Don et al., 2007; Falconer and Winter, 1984; Frost et al., 1997; Granata et al., 2000; Karakostas et al., 2003; Kellis, 1998; Kellis et al., 2003; Lamontagne et al., 2000; Peterson and Martin, 2010; Rudolph et al., 2000; Unnithan et al., 1996), upper extremity (Bautmans et al., 2011; Brookham et al., 2011; Meinck et al., 1984), neck (Cheng et al., 2014, 2008; Choi, 2003), and trunk (Fathallah et al., 1997; Hughes, 1991; Hughes et al., 1995, 2001; Lavender et al., 1992a,b; Mirka and Marras, 1993; Ranavolo et al., 2015; Song and Chung, 2004, 2007; Thelen et al., 1995; van Dieen et al., 2004). An exhaustive search of methods used to assess coactivation in the literature is presented in Table 1.

3.1. EMG-based methods

EMG inputs into the proposed coactivation measures were dependent upon normalization techniques either through maximum voluntary contraction or reference contraction to reduce the amount of variability from differences between and within individuals (Lehman and McGill, 1999). These signals may be used as a possible indicator of muscle moment based upon EMG/muscle tension relationships (Bigland and Lippold, 1954; Inman et al., 1952; Milner-Brown and Stein, 1975). Therefore, it may be assumed that a higher EMG activity contributes to a higher force, thus higher moment and may be denoted as the prime mover or agonist of the joint. In the cases of lower extremity and upper extremity analyses, it was much simpler to define agonist and antagonist activity when assessing two-muscle systems. The muscle with higher activity would be deemed agonist and the lower activity antagonist. As the number of muscles increases, the agonist/antagonist classification becomes more complex due to the difficulty of showing which muscle serves more as an agonist when looking at several signals overlapping each other. Hence, in some of the studies presented in Table 1, muscles were either predefined as summed clusters of agonists and clusters of antagonists in relation to the task. In some cases, the muscle contributions were not given a definition. Rather, they were described as how they coordinate with each other in general. The problem in regards to predefined clusters of antagonist/agonist behavior is that it would not allow the understanding of changes in muscle contribution continuously throughout a complex task. Neuromuscular control has been postulated as a series of three dynamic mechanisms involving (1) a feed-forward process in which the an internal process estimates the interaction with the environment, (2) a feedback process in which the body compensates for misrepresentation of the environment or unexpected loads, and (3) musculoskeletal impedance from passive stiffness (Stroeve, 1998). These mechanisms infer that muscles can change their contribution based upon the task at hand (i.e. postural control). Hence, it is imperative to understand which muscles are antagonists and which are agonist when assessing coactivation.

EMG-based calculations in the neck and trunk (Table 2) shed light onto the complexity of having a multiple muscle system to describe coactivity. Complexity is conveyed through the anatomical structures surrounding both the cervical and lumbar spine, which involves an intricate network of muscles with multiple layers and lines of action wrapping in opposing directions. This imposes difficulty in the understanding of complex motions such as axial rotation or other combinations of movements.

In the neck, studies by Cheng and colleagues (Cheng et al., 2014, 2008) evaluated coactivation dynamically in various planes (sagittal and lateral) and included a system of 6 different muscles. Their studies assessed coactivation at different speeds of head motion for asymptomatic individuals and patients with neck pain. However, analyses of coactivity were limited to predefined groupings relative to the assigned movement. In the trunk, three methods were applied to assess coactivation (Table 2). The first method for discussion was from Fathallah and colleagues (1997), in which complex dynamic lifting was employed to understand EMG-based coactivation for a 10 muscle system. Complex dynamic lifting and lowering included both sagittal and asymmetric exertions. However, muscles were clustered into preset groupings of flexors and extensors with the assumption of flexor contribution as antagonistic behavior. This poses a problem during asymmetric lifts and lowers as the external oblique contribution may be misrepresented as being antagonist, thereby inflating its contribution. Although this study provided insight on muscular activations for complex dynamic lifts, the calculated coactivation through predefining muscle contribution does not afford the ability to understand agonist versus antagonist behavior, thus limiting it to sagittally-symmetric lifts.

Another method to assess coactivation in the trunk was produced by Lavender et al. (1992a,b) was used to evaluate the effect of asymmetric isometric loads and directionality of the externally applied moment. Agonist and antagonist muscles contributions were not defined in these studies. Instead, each of the experimental conditions were assessed as an individual muscle's contribution relative to the total of the statistically significant EMG values. This limits the understanding of muscle activity to individual muscle activations relative to a grouping of activations. However, it does not give an indication of a muscle's contribution as an antagonist or agonist in the system. Therefore, this method presents difficulty in understanding the balance between agonist and antagonist behavior during different loading paradigms.

The third approach to assess coactivation was from Ranavolo and colleagues (2015). This method defined a sigmoid-weighted, time-dependent function for the inclusion of multiple muscles during a sagittal lifting task. The result was a temporal mean of a sigmoid-weighted function multiplied by the ratio of the summation of all normalized muscle EMGs. The end value was the average coactivation for the task taking into account the differences of each possible combination of muscles in order to determine the influence of the sigmoid-weighted function. If the differences between muscles were large, then the sigmoid aspect of the function would approach 0 (less coactivation between muscles). If the differences between muscles were small, the sigmoid-weight of the function would approach 1 (more coactivation between muscles). This method provided a general understanding of the overall muscle activations relative to each other throughout a sagittal task. However, the separation between agonists and antagonists were not understood. Relative to the operationally defined meaning behind coactivation (simultaneous activation of agonist and antagonist muscles), sigmoid-weighted coactivity may inflate coactivation as a function of posterior muscular contributions (i.e. erector spinae and latissimus dorsi) rather than assess the balance between the erector spinae and rectus abdominis as agonist and antagonist, for the tasks employed in this study respectively.

Overall, the EMG-based methods utilized to assess coactivation have been limited in their utility due to *a priori* defined muscular contributions relative to the task at hand (controlled dynamic or complex isometric). Another limiting factor was the assessment of muscle coactivation as an overall system or as individual muscles which does not provide an understanding of agonist and antagonist behavior and the balance between the two systems. Predefined muscle contributions or no classification was primarily due to the difficulty in classifying agonist and antagonist musculature within a multiple muscle system. It is possible that understanding the muscles' force and moment contribution may provide better insight into coactivity between muscles. Further processing through the utilization of biomechanical models afford the understanding of muscle force and moment generation during tasks.

3.2. Biomechanical model dependent methods (Force and Moment)

Biomechanical models are necessary in order to assess coactivation as a function of muscle force and moment. In the methods found in Tables 1 and 2, mathematical optimization methods were typically applied to calculate the coactivation as the forces necessary to balance the net joint moment (Choi, 2003; Granata et al., 2005; Hughes, 1991; Thelen et al., 1995). This methodology presumes that the motor control system optimizes its activation arrangement to minimize joint loading. A study from Callaghan and McGill (1995) found through the evaluation of different

Table 2
List of coactivation indices used in the spine and their abilities to accommodate dynamic and complex tasks. Dynamic, complex tasks are operationally defined as tasks enduring motions in all three anatomical planes (sagittal, lateral, and axial). A void exists in which a coactivation metric capable of being sensitive to various complex dynamic tasks has not been developed and applied.

Reference	Body region	Method of calculation	Agonist/antagonist definitions	Coactivation definition	Anatomical planes assessed	Task	Antagonist continuously defined	Dynamic?	Complex?
Choi (2003)	Neck	Force, Optimization	Muscle forces at zero net moment	Ratio of muscles at equilibrium to overall force	Sagittal, Lateral, Axial	Isometric quasi-static exertions		No	Yes
Cheng et al. (2008, 2014)	Neck	Normalized EMG	Predefined	Ratio of antagonist to total EMG	Sagittal, Lateral	Voluntary motions at different speeds		Yes	No
Fathallah et al. (1997)	Trunk	Normalized EMG	Predefined	Ratio of flexors to summation of flexors and extensors	Sagittal, Lateral, Axial	Free-Dynamic Lifting		Yes	Yes
Ranavolo et al. (2015)	Trunk	Normalized EMG	Undefined	Average of sigmoid-weighted function	Sagittal	Free-Dynamic Lifting		Yes	No
Lavender et al. (1992a,b)	Trunk	Normalized EMG	Undefined	Individual muscles relative to total of statistically significant muscles	Sagittal, Lateral, Axial	Isometric loading		No	Yes
Granata et al. (2005) and Thelen et al. (1995)	Trunk	Force, Optimization	Muscle forces at zero net moment	Ratio of muscles at equilibrium to overall force	Sagittal, Lateral, Axial	Isometric loading		No	Yes
Hughes (1991) and Hughes et al. (2001)	Trunk	Force, Optimization	Predefined	Marginal cost exceeding minimum force necessary to accomplish task	Sagittal, Lateral	Isometric loading		No	Yes
Sparto et al. (1997)	Trunk	Moment	Predefined	Ratio of flexor and extensor torques	Sagittal, Lateral, Axial	Isometric loading		No	Yes
Song and Chung (2004, 2007)	Trunk	Force and Moment	Predefined	Sum of Antagonist Force, Ratio of antagonist to total muscle force, Antagonist Moment, Ratio or antagonists to L5/S1 compression	Sagittal, Lateral, Axial	Isometric loading		No	Yes
van Dieen et al. (2004)	Trunk	Normalized EMG, Moment	Predefined	Average abdominal contribution	Sagittal	Lifting unstable loads		Yes	No

applied shear/compressive loading patterns, muscle activation patterns showed that it was unlikely that an individual minimizes and optimizes their muscle force distribution during loading. A rise in abdominal and extensor activity during increased compressive loading suggested that a different mechanical requirement was necessary for coordination of the posture. Therefore, the evaluation of coactivation using the optimization methodology may not appropriately assess individual muscle activation strategies. Secondly, the optimization methods did not assess coactivity as a balance between agonist and antagonist activations. Instead, the individual muscle forces of coactivity were assessed as a summation of all the forces. This poses the issue of misunderstanding where the coactive forces originate. Coactivation exists in various forms between agonists and other agonists, antagonists and other antagonists, and relative to the context of this review, antagonist relative to agonist coactivity. In essence, if the bilateral erector spinae increased in activation during a lifting exertion (agonist-agonist coactivity), but not the abdominals (antagonist), the summation of coactivation forces would be essentially driven by the erectors/agonist activity.

The assessment of coactivation necessitates the use of a biomechanical model that allows for individual muscle activation strategies. Such an approach has been applied by Song and Chung (2004, 2007), Sparto et al. (1997) and van Dieen et al. (2003, 2004) in the form of electromyography-assisted models involving multiple trunk muscles (Table 1). Force contributions were calculated as a function of maximum muscle stress or optimized gain, normalized EMG, cross-sectional area of the individual muscles with the exception of van Dieen and colleagues, which also considered the changes in force–length and force–velocity components of the muscles. These factors are vital components in properly assessing loads onto the spine during dynamic tasks. Modulation of the muscle force through force–length changes allow for the understanding of active and passive contributions during lengthening and shortening of the muscle (Maganaris, 2001). Force-velocity allows for the understanding of the speed of eccentric or concentric contraction and how that influences the muscle force output (Bigland and Lippold, 1954). These forces would then be further assessed as moments imposed upon the spine. The predefined antagonistic force/moment contribution would be related to the level of coactivation in the system. The limitation that exists within the Song and Chung works (Song and Chung, 2004, 2007) as well as the coactivation method calculated from Sparto et al. (1997) was the assumption where both force–length and force–velocity components were constant (equal to 1) because the exertions were isometric, thereby limiting its utility to isometric loads and *a priori* assignment of muscle antagonism. Although the coactivation method assessed from van Dieen et al. (2003) included changes in force–length and force–velocity components of muscle, the approach was limited to sagittally-symmetric lifts due to the *a priori* assignment of antagonistic musculature specific to the lift. Overall, although biomechanical models have been employed to calculate muscle forces and muscle moments, many have been limited in their ability to assess coactivation between agonist and antagonist musculature continuously during dynamic tasks. A void exists in which continuous classification of agonist and antagonist systems of muscles have not been employed to assess coactivation. Neuromuscular recruitment feedback and feed-forward processes necessitate changes in the individual muscle contributions relative to dynamics and the level of complexity the task may entail.

3.3. Tasks used to test coactivation indices for the spine

The utility of the coactivation indices were limited to the task descriptions presented (Table 2). These limitations involved isometric tasks or controlled dynamic tasks (uniplanar). As previously stated, many tasks involved isometric exertions (Choi, 2003; Granata et al., 2005; Hughes et al., 2001; Lavender et al., 1992a,b; Song and Chung, 2004, 2007; Sparto et al., 1997; Thelen et al., 1995). Although these studies provide insight on different static loading paradigms, biomechanical predictions based upon these paradigms may overestimate the muscle force production/contribution. A study by Marras et al. (1984) showed that increases in trunk velocity were associated with lower muscle activations in the erector spinae during maximal trunk extension exertions. Therefore, static loading paradigms utilized to estimate coactivation for dynamic tasks may be misrepresentative of loading onto the spine.

A few studies assessing coactivation indices during dynamic tasks (Table 2) have involved direction-defined voluntary motions of the neck at different speeds (Cheng et al., 2014, 2008), free-dynamic sagittal lifts (Ranavolo et al., 2015; van Dieen et al., 2003), as well as free-dynamic complex lifting and lowering (Fathallah et al., 1997). The dynamic study for the neck allowed movements limited to the sagittal plane and lateral plane. Sagittally-symmetric movements (flexion and extension) as well as lateral bend tests (right and left) during this study started from neutral head posture. Due to the complex dynamic motions typically endured by the neck, this methodology was limited in its assessment for only the planes starting from a neutral position. For the trunk, the sagittally-symmetric lifts endured by subjects in the work of van Dieen et al. (2003) only assessed *a priori* defined antagonistic muscles in the sagittal plane. Although this study provided insight into coactivation relative to unstable loads, coactivation was only quantifiable for the predefined musculature in the predefined lift direction, thereby limiting its utility for multi-planar analyses. The study by Ranavolo and colleagues (2015) also assessed sagittal lifts. Aside from the previously mentioned limitation of uniplanar lift direction, the electrode placement also limited their assumptions to one plane. EMG was only placed on the right side of the body which creates assumptions of symmetry in which the bilateral musculature would ideally be equal when assessing coactivation. This assumption cannot be justified as studies have shown that side dominance plays a role in differing magnitudes in activation patterns between bilateral sets of muscles (Farina et al., 2003; Sung et al., 2004). Non-dominant muscles tend to fatigue faster and respond slower than their dominant counterparts (Farina et al., 2003). Hence, it is important to take into account the bilateral set of muscles in the spine when assessing exertions, even if the tasks are sagittally-symmetric. Lastly, a study by Fathallah et al. (1997) assessed coactivation as a function of predefined flexor activity (antagonist) versus extensor activity (agonist) for a series of lifting and lowering tasks in different planes. Although this study provided an understanding of muscle activity changes relative to lift asymmetries and dynamics, the *a priori* definitions limited the interpretations of coactivation. Asymmetric lifts necessitate changes in muscle classifications between agonistic and antagonistic contributions (i.e. external obliques may switch to agonist during twist). Overall, tasks used to assess coactivation indices have been limited to either isometric tasks with complex loading or dynamic tasks with uniplanar loading. A full scope of tasks has not been assessed requiring high coactivation to low coactivation. It is postulated that tasks requiring higher stabilization such as precision placement, unstable loads, or higher levels of controlled movements would require higher coactivation. However, these tasks have not been tested relative to indices presented. Also as seen in Table 2, none of the studies found were able to define the antagonistic nature continuously across tasks. A gap in the literature exists in which a coactivation index has not been tested across a wide range of complex dynamic tasks such as precision control, asymmetric lifting, and pushing/pulling.

3.4. Outputs for the interpretation and definition of coactivation

The definitions of coactivation vary in their assessment and interpretation between the different methods presented (Table 2). Variation propagates from the system inputs (EMG or biomechanical model outputs) through the tasks employed to the final calculation of the coactivation index. As stated previously, the *a priori* definition of agonist/antagonist behavior limits the interpretations to specific motions (i.e. sagittal plane) and force/moment calculations are highly dependent on the biomechanical model utilized and the assumptions that are associated with them. The normalized EMG, forces, and moments were inputs into the calculations of coactivation (Table 2) which were typically represented as ratios between antagonist behavior to a total muscle contribution, individual muscles relative to total contribution, or as a function of marginal cost. Overall, variability between methods creates difficulty when trying to compare between different tasks across the literature due to their vast differences in their methodological approaches. There is no clear, concise 'gold standard' for understanding coactivation of a multiple muscle system. A gap in the literature has been identified in which a continuously-defined, coactivation index applicable for the testing of different complex dynamic tasks has not been developed.

4. Discussion

The purpose of the coactivation index is to provide a measure of physiological 'cost' and 'efficiency' for a multiple set of muscles surrounding a joint during a realistic task. Based upon the previous discussions of the indices available to assess coactivation for a multiple muscle system (Table 2), all have been limited in their scope of analyses to a specific set of tasks. Hence, before developing an index capable of assessing various complex dynamic tasks, we must seek to understand what factors may affect coactivation so that we could assure that any index developed is sensitive and specific to activities of daily living. These involve the interaction of biomechanical, psychosocial, and individual factors in relation to a task (Marras, 2008). Biomechanical factors involve the stabilization of the load weight, velocity of the exertion, frequency, as well as the origin and destination. Psychosocial and individual factors often serve more as modifiers of coactivation depending on factors such as environmental stressors, job demands, personality, fitness and strength, and anthropometry. Each of the factors have varying influence on the activations of the musculature, and depending on the task, one may be more of a driving factor than the other. For example, during low-level physical exertions, psychosocial factors may have more of an influence on coactivation than external biomechanical factors, whereas during higher physical exertions, coactivation is more biomechanically driven (Marras, 2008). Individual differences from anthropometry to gender to pain-related behavior can also affect the levels of coactivation due to muscle size/strength capabilities and fear. Hence, an ineffective match between the task and these factors may induce inefficient motor patterns resulting in increased risk for musculoskeletal disorders. In this section, a discussion is presented to consider the features and factors needed in order to develop a useful and robust coactivation index.

4.1. General coactivation

As we can recall from the operationally defined meaning of coactivation (simultaneous activation of antagonist and agonist musculature), depending on the task, as one system increases, the other will adjust accordingly to counterbalance the system. In some cases, both may be unnecessarily high for the task, thereby imposing an undue physiological 'cost' to the system. These 'costs' impose increased loading onto the spine, faster time to fatigue, and neuromuscular inefficiency. A robust index would need to capture these 'costs' across a wide variety of tasks from complex dynamic loading, muscular guarding, and learning/anticipation.

4.2. Complex postures and dynamic loading

Complex loading involves varying postures throughout the three anatomical planes. Muscles have differing moment contributions onto joints in different planes depending on the task (Granata and Marras, 1995a). Hence, their contribution may differ due to the rotation of the head or trunk and exertion applied. During a rotation such as required for asymmetric tasks, the muscles' lines of action also rotate, thus changing their individual contributions to the internal moment. Depending on the location and magnitude of the external load, a robust CI would be able to classify agonist and antagonist muscles accordingly. For example, if the external load is anterior to the body such as during a lift or lower, then the CI should be able to classify the posterior muscles as agonist. If the load is asymmetric, unilateral external oblique contributions may change to agonist behavior, but change back to antagonist once the load has been brought back to the sagittal plane. In essence, depending on the moment arms relative to the joint of interest, agonist/antagonist classifications from the CI should be captured with respect to the direction of exertion. Tasks such as pushing, pulling, lifting/lowering, and sitting/standing/leaning all require different postures and magnitudes of loading that a CI should be able to account for. Methods found in Table 2 do not adjust for different postural needs throughout an exertion. Hence, the missing component is a method for adaptable classification of muscular contributions to accommodate postural changes for complex loading.

Pushing/pulling and lifting/lowering endure different postures throughout an exertion and are thereby dynamic in nature. Depending on the kinematics associated with the task, trunk velocity affects the contractile velocity of the muscles and force outputs as well as the stabilizing contribution from coactivation (Bigland and Lippold, 1954). Methods used to assess coactivation would need to take into account postural muscle changes across time in order to account for neuromuscular coordination throughout and exertion. The dynamic methods utilized from Table 2 for the spine are limited in scope in that only average coactivity was assessed across tasks. This approach does not allow for the understanding of intermittent changes in coactivity across time, local minima and maxima, coactivation relative to spinal loads, as well as cumulative responses. These perspectives would allow for an understanding of neuromuscular shifting between musculature to mitigate constant static loading of the low threshold type I motor units (Cinderella fibers) (Hägg, 1991) as well as coactivation effects on spinal loads (Granata and Marras, 1995b). Overall, due to the complex and dynamic nature of many tasks, all of the systemic factors noted present a challenge in defining a CI that would incorporate task variability. A robust CI should be able to incorporate both time-dependence and complex postures.

4.3. Guarding and muscle loading

Another influencer of muscle loading magnitude and coactivation is guarding due pain/discomfort. Pain is a perception influenced by the interaction of thought processes, emotional states, and behavior as a reaction to tissue loading and/or sensitization (Marras, 2008). Discomfort, pain, or fear of pain elicits muscular contractions as a CNS response (Stokes et al., 2006). A robust CI would be able to detect the system of muscular activations due to pain responses through an increase in agonist and antagonist activity. These responses may be more apparent during lower physical loads, in particular, during prolonged static contractions, myalgia, and myofascial trigger points, thereby affecting the magnitude of the force output from the muscles. Over time the muscles would fatigue which may result in inefficient muscle recruitment. Compensation may occur from the surrounding musculature to support the load, thus changing the posture and moment contribution from muscle loading (Parnianpour et al., 1988). It is postulated that these responses would display an increase in coactivity from increases in agonist and antagonist responses. However, coactivation from periods of constant loading may only be detected if evaluated continuously across time. The methods in Table 2 are limited in their ability to assess coactivation continuously as they only provide averages from the task exposures. Overall, a continuous CI would allow for the assessment of periods of time in which guarding may be occurring, cumulative exposures, as well as intermittent periods of muscular rest.

4.4. Anticipation and learning

Sudden loads experienced during manual materials handling tasks have shown higher muscle forces in comparison to static loading scenarios and were even higher during unexpected loading (Marras et al., 1987). This suggests that anticipation plays a role in muscle response (Lavender, 1990). Relative to the anticipated load, it has been suggested that the brain may preset the muscles to prepare for the load (Patterson et al., 1986). The preset has a strong association with the amount of warning time and muscle responses during sudden loading (Lavender et al., 1989). As the warning time prior to loading increased, the onset time of muscle force activation also increased. A continuously-defined CI would allow for the understanding of muscular preset and the cumulative exposure to the preset. With the introduction of unexpected loads, Marras et al. (1987) found that unexpected loading produced as much as 2.5 times the amount of muscle force and muscles were loaded longer. The unexpected load may also increase joint velocity and thereby increase reflexive coactivation in order to stabilize the load (Hagood et al., 1990). Through the understanding of the load to be acquired as well as expectation of load dynamics, the index should be able to respond subsequently through an increase in the index. Overall, anticipation plays a role in determining the onset of muscle activation, force-feedback characteristics, and cumulative load response. It is postulated that load anticipation would increase coactivity prior to the initiation of movement as well as during the response to a sudden load. During this preset and response, the CI would ideally be higher than a CI in a relaxed state.

As a person learns to do a task, coactivation patterns change to adapt to the task. The level of experience is associated with perception which influences the level of coactivation (Marras et al., 2006). Inexperienced people tend to be more rigid during task execution, which impedes upon the functional synergy needed for fluidic motion (Bernstein, 1967). Whereas, for experienced workers, motor patterns cooperate more optimally to execute the task (Magill, 2004). As evidenced by Marras and colleagues (2006), inexperienced workers may ineffectively coactivate their muscles to accomplish complex higher speed tasks, thereby exposing them to a higher risk for musculoskeletal pain and eventually pathology of the lumbar spine. Relative to the theoretical findings stated, levels of agonist and antagonist activity from an assessment of coactivity would both be higher for inexperienced workers during a task. As experience is acquired, learning over time may provide a basis for the modification of central control to optimize task execution by minimizing the coactivation necessary (Schmidt and Wrisberg, 2000), thereby making the task more efficient. Overall, coactivation is influenced by the level of experience. Ideally, learning over time would allow for more effective motor coordination and thus reduce the CI when compared to the initial exposure for a task.

5. Conclusions

In order to develop a biologically plausible and interpretable coactivation index, several factors need to be considered. These include tasks that are to be analyzed, their complex and dynamic nature, the interaction within the human (biomechanical, psychosocial, and individual), and their meaning between different tasks. Since the nature of tasks are time-dependent, coactivation also needs to be assessed continuously. Relative to the discussion of complex postures, dynamics, anticipation, guarding, and learning, understanding continuous behavior is necessary to understand preparatory responses prior to task initiation, acquisition of the load at its origin, stabilization of the load towards its destination as well as unexpected perturbations along the way. The assessment of average coactivation responses alone would wash out interesting aspects of neuromuscular change. Coactivity for dynamic tasks necessitates the understanding of local maxima and minima, different phases of loading, its effect on peak spinal loads, and cumulative responses. In addition, the problem lies in the cost of coactivation due to the excess needed to accomplish the task at hand. Currently, an index does not exist for the assessment of complex, dynamic tasks under different work conditions. Given the spectrum of possible interactions from physical loading and modifiers from psychosocial and individual factors, it is postulated that a mind–body interaction exists which warrants a continuously defined agonist/antagonist coactivation index sensitive enough to detect those differences.

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Ehud Mendel, MD, FACS currently holds the Justine Skestos Endowed Chair and is the Director of the Neurosurgical Spine Program, Spine Oncology Program, Director of Fellowship Program and the Medical Director of the Spine Research Institute at The Ohio State University. In addition, he is a Professor in the Departments of Neurosurgery, Oncology, Orthopaedics, and Integrated Systems Engineering. Dr. Mendel is The Current President Elect for the Ohio State Neurosurgical Society, Fellow of the American College of Surgeons (F.A.C.S.) and a Fellow of the American Association for the Advancement of Science (AAAS). He is a member of the Academy of Neurological Surgeons and is well known nationally and internationally for his experience in the treatment of spine tumors and has been identified as one of "America's leading experts on spine cancer". Dr. Mendel is also a member of numerous professional societies (AANS-American Association of Neurological Surgeons, CNS- Congress of Neurological Surgeons, NASS- North American Spine Society, AO North America, AANS/CNS Joint Spine and Trauma Sections) and honor societies including Alpha Omega Alpha. He has been voted to *Best Doctors in America* since 2005 and *Top Surgeon in America*. In 2008, Dr. Mendel received the Columbus Business First's Health Care Heroes Award and was voted as "One of the 100 Best Spine surgeons and Specialists to Know". He is a delegate to the council of State Neurological Surgeons (CSNS) as a representative of the Ohio State Neurosurgical Society (OHSNS).

William S. Marras, PhD is the Executive Director & Scientific Director of the Spine Research Institute, the Executive Director of the Center for Occupational Health in Automotive Manufacturing (COHAM), and the Executive Director of the Institute for Ergonomics. He is the Honda Chair Professor in the Department of Integrated Systems Engineering at The Ohio State University, and holds joint appointments in the Departments of Orthopaedic Surgery, Department of Physical Medicine, and the Department of Neurosurgery. His research is centered on understanding the role of biomechanics in spine disorder causation and its role in the prevention, evaluation, and treatment of spine disorders. His research includes epidemiologic studies, laboratory biomechanics studies, mathematical modeling, and clinical studies. His findings have been published in over 200 peer-reviewed journal articles, and have been cited over 11,000 times. He also has written numerous books and book chapters including his most recent book entitled "The Working Back: A Systems View." He has appeared on Good Morning America, CNN, and NPR and has a TEDx talk entitled "Back Pain and your Brain." Professor Marras' work has attracted national as well as international recognition. He is a two-time winner (1993 and 2002) of the prestigious Swedish Volvo Award for Low Back Pain Research, has won Austria's Vienna Award for Physical Medicine, the Liberty Mutual Prize for Injury Prevention Research, and was awarded an Honorary Doctor of Science degree from the University of Waterloo for his work on the biomechanics of low back disorders. He has been elected fellow in six professional societies including the American Association for the Advancement of Science (AAAS), American Institute of Medical and Biological Engineers, the American Industrial Hygiene Association, the Human Factors and Ergonomics Society, the Ergonomics Society (UK), and the International Ergonomics Association. Professor Marras has served as Chair for numerous National Research Council committees and boards including The Committee on Human Factors, the Committee on Human Systems Integration, and the Board on Human Systems Integration. Dr. Marras currently serves as Deputy Editor of Spine and was the previous Editor-in-Chief of Human Factors. He is the current president of the Human Factors & Ergonomics Society (HFES). In 2009 Dr. Marras was elected to the National Academy of Engineering (the National Academies).