



Development and testing of a moment-based coactivation index to assess complex dynamic tasks for the lumbar spine

Peter Le^a, Alexander Aurand^a, Jonathan S. Dufour^a, Gregory G. Knapik^a, Thomas M. Best^b, Safdar N. Khan^c, Ehud Mendel^d, William S. Marras^{a,*}

^a Spine Research Institute – Biodynamics Laboratory, Department of Integrated Systems Engineering, The Ohio State University, 210 Baker Systems Engineering, 1971 Neil Avenue, Columbus, OH 43210, USA

^b Department of Family Medicine, The Ohio State University, Columbus, OH 43210, USA

^c Department of Orthopaedics, The Ohio State University, Columbus, OH 43210, USA

^d Department of Neurological Surgery, The Ohio State University, Columbus, OH 43210, USA

ARTICLE INFO

Keywords:

Co-contraction
Lumbar spine
Trunk muscles
Neuromuscular

ABSTRACT

Background: Many methods exist to describe coactivation between muscles. However, most methods have limited capability in the assessment of coactivation during complex dynamic tasks for multi-muscle systems such as the lumbar spine. The ability to assess coactivation is important for the understanding of neuromuscular inefficiency. In the context of this manuscript, inefficiency is defined as the effort or level of coactivation beyond what may be necessary to accomplish a task (e.g., muscle guarding during postural stabilization). The objectives of this study were to describe the development of an index to assess coactivity for the lumbar spine and test its ability to differentiate between various complex dynamic tasks.

Methods: The development of the coactivation index involved the continuous agonist/antagonist classification of moment contributions for the power-producing muscles of the torso. Different tasks were employed to test the range of the index including lifting, pushing, and Valsalva.

Findings: The index appeared to be sensitive to conditions where higher coactivation would be expected. These conditions of higher coactivation included tasks involving higher degrees of control. Precision placement tasks required about 20% more coactivation than tasks not requiring precision, lifting at chest height required approximately twice the coactivation as mid-thigh height, and pushing fast speeds with turning also required at least twice the level of coactivity as slow or preferred speeds.

Interpretation: Overall, this novel coactivation index could be utilized to describe the neuromuscular effort in the lumbar spine for tasks requiring different degrees of postural control.

1. Introduction

One of the possible causal pathways for low back disorders (LBD) has been linked to the neuromuscular patterns needed to stabilize the trunk and/or external load (Granata and Marras, 2000). These patterns typically involve the concurrent activation of agonist and antagonist muscles, also known as coactivation (Lavender et al., 1992a). Through the understanding of coactivation, it is possible to explore the neuromuscular effort of an exertion. Tasks requiring more control as well as inefficient coordination patterns in people with low back pain (LBP) or inexperienced workers would incur higher neuromuscular efforts. These efforts may stem from higher muscular activations to guard from

pain (LBP patients) (Marras et al., 2004) or during higher task frequency for inexperienced workers (Marras et al., 2006). Depending on the contributing muscles during coactivation as well as their respective magnitudes and time-dependence, coactivation can affect the directionality and magnitude of spinal loads (Granata and Marras, 1995b) or influence myofascial pain (Ge and Arendt-Nielsen, 2011). The interaction of these effects on the neuromuscular system warrants the exploration of coactivation.

Several methods that exist to describe coactivation in the lumbar spine are dependent on processed surface electromyography (EMG) techniques. These include normalized EMG, muscle forces, and moment contributions relative to the joint of interest. In a multiple-muscle

* Corresponding author at: Spine Research Institute, The Ohio State University, Department of Integrated Systems Engineering, 1971 Neil Avenue, 210 Baker Systems Engineering, Columbus 43210, OH, USA.

E-mail addresses: Le.105@osu.edu (P. Le), Aurand.20@osu.edu (A. Aurand), Dufour.8@osu.edu (J.S. Dufour), Knapik.1@osu.edu (G.G. Knapik), Tom.Best@osumc.edu (T.M. Best), Safdar.Khan@osumc.edu (S.N. Khan), Ehud.Mendel@osumc.edu (E. Mendel), Marras.1@osu.edu, Marras.1@osu.edu (W.S. Marras).

system, the outputs from the different methods were typically clustered into predefined categories of agonists and antagonists depending on the task (Le et al., 2017). The clustering of agonist/antagonist behavior provides context on the system of muscles opposing or supporting the primary motion. Assessments of coactivation using this approach typically involve ratios between the antagonist and agonist groups (Fathallah et al., 1997; Song and Chung, 2004; Song and Chung, 2007; Song et al., 2004; Sparto et al., 1997). Ratios were commonly chosen to describe neuromuscular effort due to antagonist opposition relative to the agonist system. Other approaches that do not rely on a priori definitions of agonist or antagonist behavior include: a sigmoid-weighting factor dependent on relative differences between muscles (Ranavolo et al., 2015), individual muscle contribution to the system (Lavender et al., 1992a; Lavender et al., 1992b), or stability equations (Granata and Orishimo, 2001; Thelen et al., 1995).

Each of these approaches has their respective merits. However, they are also limited in their functions. First, muscles change their contribution to the internal moment relative to postural changes needed to support an external load. Predefining muscle behavior as agonist or antagonist limits the analysis to uniplanar motion. Evidence has shown that muscles switch their roles depending on the directionality of the external moment (Lavender et al., 1992b). It is during these complex exertions that the understanding of coactivation is critical in regards to neuromuscular effort. As previously described, this effort is commonly defined as a ratio between antagonist and agonist behavior. Throughout a complex motion, muscles either oppose or support the movement depending on the posture required. Misclassification of the muscles would lead to misinterpretation of the ratio describing neuromuscular effort. Hence, a methodology is necessary to properly classify muscles throughout a motion. Prior techniques have not been resilient enough to assess coactivity across a spectrum of complex tasks due to their inability to continuously capture changes in agonist and antagonist behavior. Understanding the switching of muscle behavior would provide a better understanding of the role of muscle opposition in maintaining postural stabilization throughout a task. Secondly, the nature of work and activities of daily living are complex (multi-planar) and dynamic. From postural stabilization during sedentary work to the generation of momentum to execute a task, or general activities of daily living, coactivation represents differing levels of neuromuscular effort to the musculoskeletal system. The methods discussed have either assessed complex postures with isometric loads or uniplanar postures with dynamic movements. Hence, a void exists in which a coactivation index that accounts for complex dynamic tasks has not been developed. Overall, coactivation is not necessarily a negative response. It is the amount of excess coactivation beyond what may be necessary to accomplish a task that may be deemed harmful and influence spinal loads. This excess coactivation or neuromuscular effort may be represented in the form of an index to describe the differing degrees of postural control needed to accomplish a task.

It was hypothesized that the proposed moment-based coactivation index would be able to differentiate between a range of dynamic complex loading tasks. The objectives of this study were to 1) develop a coactivation index for the lumbar spine and 2) test the index's ability to distinguish between exertions requiring higher coactivation through a variety of complex dynamic tasks. Overall, the purpose of the index is to describe the neuromuscular efforts associated with varying degrees of postural control. Its practical utility may reside in the assessment of ergonomic or rehabilitation/treatment effectiveness when comparing to a control population. A series of index thresholds in future studies may be defined using larger datasets. The purpose of this study is to provide the means to measure an index.

2. Coactivation index structure

The coactivation index developed in this work was dependent on the calculation of moments imposed by the active force components

relative to the total (active) internal moment. An extensively validated, multi-level, dynamic EMG-driven lumbar spine model was used to predict the moments from the 10 power-producing muscles of the trunk (Dufour et al., 2013; Granata and Marras, 1993, 1995a; Hwang et al., 2016; Jorgensen et al., 2001; Knapik and Marras, 2009; Marras and Granata, 1997; Marras and Sommerich, 1991a, 1991b; Marras et al., 2001; Theado et al., 2007). Further details of the model can be found from Hwang et al. (2016).

In general, force calculations from the model consist of both active and passive force components. For the purposes of understanding coactivation, only the active component (F_{Active}) of each muscle was extracted (Eq. 1) which was calculated as the product of the Gain Ratio (GR), EMG activity, cross-sectional area, as well as force-length ($f[L]$) and force-velocity ($f[V]$) modulation factors. The active moments (M_{Active}) were determined as the cross-product of the moment arms relative to the active forces (F_{Active}) (Eq. 2). The summation of the active moments (M_{Active}) resulted in the total moment contribution (Eq. 3).

$$F_{Active_i}(t) = (GR_i) \cdot EMG_i(t) \cdot Area_i \cdot f_{active}[L_i(t)] \quad (1)$$

$$\vec{m}_{Active_i} = \vec{r}_i \times \vec{F}_{Active_i} \quad (2)$$

$$\vec{M}_{Active} = \sum_{i=1}^{10} \vec{m}_{Active_i} \quad (3)$$

The moment contribution of each muscle was then compared to the direction of the total internal moment contribution through a dot-product definition from Andrews and Hay (1983) and scaled by the resultant magnitude of the total moment (Eq. 4). The resulting scalar projection data for each muscle were classified as agonist (positive scalar) or antagonist (negative scalar) (Eq. 5–6). At each time point, the summation of antagonist (Eq. 7) and agonist (Eq. 8) contributions represented their respective system outputs. The ratio of the antagonist system to the agonist system was defined as the balance factor (Eq. 9). The total moment activation from the agonist and antagonist systems provided the magnitude of the input into the system (Eq. 10). The coactivation index was then described as the balance factor multiplied by the total moment activation normalized by the maximum total moment activation (655 Nm) was operationally defined using the peak total activation of the entire dataset from this study (all subject data) (Eq. 12). The intent of the anchor was to allow for utility across a variety of studies.

$$Proj_i = \frac{\vec{m}_{Active_i} \cdot \vec{M}_{Active}}{\| \vec{M}_{Active} \|} \quad (4)$$

$$antagonist_i = \begin{cases} 0, & Proj_i > 0 \\ |Proj_i|, & Proj_i \leq 0 \end{cases} \quad (5)$$

$$agonist_i = \begin{cases} Proj_i, & Proj_i > 0 \\ 0, & Proj_i \leq 0 \end{cases} \quad (6)$$

$$antagonist_{Total} = \sum_{i=1}^{10} antagonist_i \quad (7)$$

$$agonist_{Total} = \sum_{i=1}^{10} agonist_i \quad (8)$$

$$b(t) = \frac{antagonist_{Total}(t)}{agonist_{Total}(t)} \quad (9)$$

$$activation_{Total}(t) = Antagonist_{Total}(t) + Agonist_{Total}(t) \quad (10)$$

$$CI(t) = b(t) \left(\frac{activation_{Total}(t)}{\max(activation_{Total})} \right) \quad (11)$$

$$CI(t) = b(t) \left(\frac{\text{Antagonist}(t) + \text{Agonist}(t)}{655Nm} \right) \quad (12)$$

3. Methods

3.1. Approach

A study was conducted to test the moment-based coactivation index developed to assess neuromuscular effort across different complex dynamic conditions.

3.2. Subjects

Seventeen subjects (7 males and 10 females) were recruited for this study (age 26.7 (5.8) years, mass 73.6 (17.1) kg, and height 172.4 (7.1) cm). All subjects reported no LBP in the past 6 months. Subjects provided informed consent prior to participating and the study was approved by the University Institutional Review Board.

3.3. Experimental design

Three different tasks were tested to assess the range of the index. Tasks were grouped and counterbalanced as lifting/lowering, pushing, and Valsalva maneuvers. Within the grouped tasks, a separate set of independent variables were tested, except for the Valsalva, which was executed while standing upright and repeated 4 times. Lifting/lowering and pushing tasks were chosen to test the index under complex dynamic conditions. The Valsalva was chosen to test higher levels of coactivation which was expected during non-complex, static exertions. In particular, strenuous and reflexive activities involving increases in intra-abdominal pressure (IAP) have been correlated with increases in EMG from the abdominal muscles (Cresswell et al., 1992). Hence, one approach towards increasing IAP is through the application of a Valsalva maneuver. Ideally, static Valsalva maneuvers would increase antagonist activity. The agonist system would increase to maintain the upright posture, thereby increasing the balance factor. The balance factor would describe the proportion of the total activity due to coactivation.

3.3.1. Independent measures for lifting/lowering

Lifting/lowering tasks consisted of a $3 \times 2 \times 2 \times 2$ design with 4 independent variables: lift asymmetry (clockwise (CW) 90°, CW 45°, and mid-sagittal 0°), handle height (chest and mid-thigh), precision placement (constrained and no constraint), and weight (4.5 kg and 11.3 kg). Tasks were counterbalanced by height, randomized by the other three variables, and repeated twice for a total of 48 trials. Precision placement was defined as a 29.2 cm \times 29.2 cm area in which a box of 28 cm \times 28 cm area needed to be placed.

3.3.2. Independent measures for pushing

Pushing tasks consisted of a $3 \times 2 \times 2 \times 2$ design with 4 independent variables: subjective speed (slow, preferred, and fast/hurried), weight ('light' 54.4 kg and 'heavy' 145.2 kg), push type (straight and turn), and precision placement (constrained and no constraint). Tasks were counterbalanced by weight, randomized by the three other variables and repeated twice for a total of 48 trials. Pushing tasks were performed on a hard cement surface with a cart measuring 57 cm wide \times 122 cm long \times 118 cm tall with 15 cm diameter \times 5 cm wide hard rubber wheels. Weights, speeds, and width of precision placement were chosen based on the pushing study from Marras et al. (2009a). Preliminary findings showed that movement of the 'light' and 'heavy' cart weights required approximately 205 N and 278 N of resultant hand force to initiate the push, respectively. The width of precision placement was 30% larger than the width of the cart (74.1 cm).

3.3.3. Dependent measure

Only one dependent measure, the coactivation index was reported. Based on the understanding of the influence of coactivity on spinal loads (Granata and Marras, 1995b), the index was extracted at the peak resultant spinal loads for each endplate level from T12/L1 to L5/S1.

3.4. Apparatus

EMG data were collected with a 16-channel MA400–28 EMG system (Motion Lab Systems, Inc., Baton Rouge, LA, USA) and sampled at a rate of 1000 Hz. Signals were high-pass filtered at 30 Hz, low-pass filtered at 450 Hz, and notch filtered at 60 Hz as well as its aliases. Signals were rectified and smoothed using a zero-phase moving average filter. Kinematic data was collected using the 24 infrared camera OptiTrack Flex 3 motion capture system (NaturalPoint, Corvallis, OR, USA). Kinetic data was collected from a Bertec 4060A force plate (Bertec, Worthington, OH, USA).

3.5. Procedure

After briefing the subject about the experiment and receiving informed consent, subject anthropometry was collected. Surface EMG electrodes were placed bilaterally on the latissimus dorsi, erector spinae, rectus abdominis, external obliques, and internal obliques (Mirka and Marras, 1993). Reflective markers were placed on 41 landmarks for whole body motion capture. Subjects were then asked to complete a series of calibration exertions using a 9.07 kg medicine ball (Dufour et al., 2013). The subjects were then instructed on the tasks assigned and allowed to practice the tasks in order to mitigate any learning effects.

3.5.1. Valsalva/abdominal bracing

The basic instruction for bracing to the subject was to stand in an upright position and gently swell the waist without drawing in the abdomen or moving the back or pelvis and maximally exert the abdominals (Urquhart et al., 2005). The exertion was held for approximately 2–3 s.

3.5.2. Lifting/lowering

Lifts and lowers occurred at chest height and mid-thigh height for different clockwise asymmetries, weights, and precision placements (Fig. 1). Distance was measured from the right acromion to the center of the box handles. Chest height was defined as the location of the xiphoid process. Mid-thigh height was defined as the midpoint between the knee and hip joint. The horizontal distances were set to 75% of arm length. For each trial, the destination (lower) was assigned as the same location as the origin (lift). During the lowering of the box for precision placement, the subject was instructed to align the box within a designated zone before releasing the box. If the subject missed the placement, a buzzer would sound and the trial would have to be repeated.

3.5.3. Pushing

Pushing tasks were assigned as different combinations of push type, weight, speeds, and precision placement. Wheels were aligned parallel to the cart at the initiation of the push. Push type was assigned as either a straight push or a push with turns defined by a taped pathway (fig. 2). If precision placement was involved, the perimeter was bounded by barriers. If the subject were to strike one of the barriers the trial was repeated.

3.6. Data reduction and analysis

3.6.1. Data processing and extraction

The coactivation index was assessed at different phases of the lift/lower and push, except for the Valsalva. The lift was assessed from the

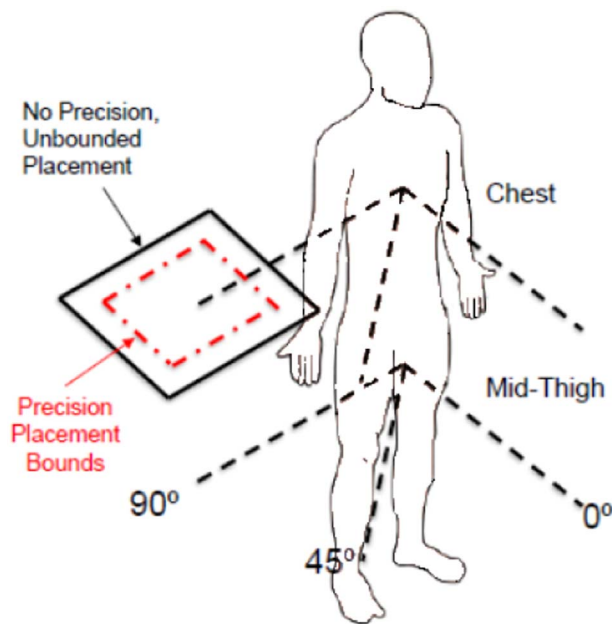


Fig. 1. Diagram of experimental design for lifting/lowering tasks. The destination (lower) was the same as the origin (lift) depending on the combination assigned.

origin to the upright position and lower from the upright position to the destination. Pushing task was separated into 2 phases (initial and placement push) marked by optical motion capture of a cart relative to a rigid body along the path of the push. The location of the centroid of the cart relative to the centroid of the rigid body determined which phase the exertion was occurring. Within each phase, the data were further reduced through the assessment of the resultant peak spinal load at L3/L4.

3.6.2. Statistical analysis

A within subjects, split plot ANOVA (SAS 9.2, SAS Institute, Cary, NC, USA) was used to evaluate the dependent variables relative to the main effects and their interactions at $\alpha = 0.05$. Post-hoc Tukey tests were performed to assess the differences between tasks. This method

was utilized to assess the tasks relative to one another (Valsalva, pushing, and lifting) as well as subtasks within the sets of pushing and lifting. The lifting/lowering trials were combined to represent the lifting global task and all pushing trials were combined to represent the pushing global task.

Once the global assessment of coactivation between tasks was completed, subsets within each task were assessed. Lifting was compared to lowering and the initial push was compared to the placement. After the between subset analysis, a within subset analysis was completed. Lifting was analyzed relative to the main effects and interactions of asymmetry, height, and weight. Lowering had the same main effects and interactions, and included precision. Both initial and placement pushing subsets were assessed relative to the main effects and interactions of speed, weight, push type, and precision placement.

4. Results

The summary of statistically significant differences for the main effects and interactions can be found in Table 1 ($\alpha = 0.05$). Examples of scalar projection classifications at peak spinal load can be found in Fig. 3. Relative to the current dataset, the maximum total system activation (655 Nm) was operationally designated as the normalization factor in the coactivation index equation (Eq. 12). The maximum total system activation was determined by solving for the peak summation of agonist and antagonist system activity across all trials.

To place emphasis on the coactivation index at the peak spinal load, the results were presented in the following series of figures based on the decision parameter of the bivariate statistical significance. Both spinal load data and coactivation data had to be statistically significant for both independent variables listed to be considered for inclusion in the results and discussion (Table 1). Since the focus of this paper was on the coactivation index, only the results from the index will be presented. Discussion of the results represented in the Figs. 4–6 can be found in Section 5.2.

5. Discussion

The purposes of this paper were two-fold: 1) develop a coactivation index for a multiple-muscle system and 2) test it across a series of complex dynamic tasks to describe the coordination and magnitude

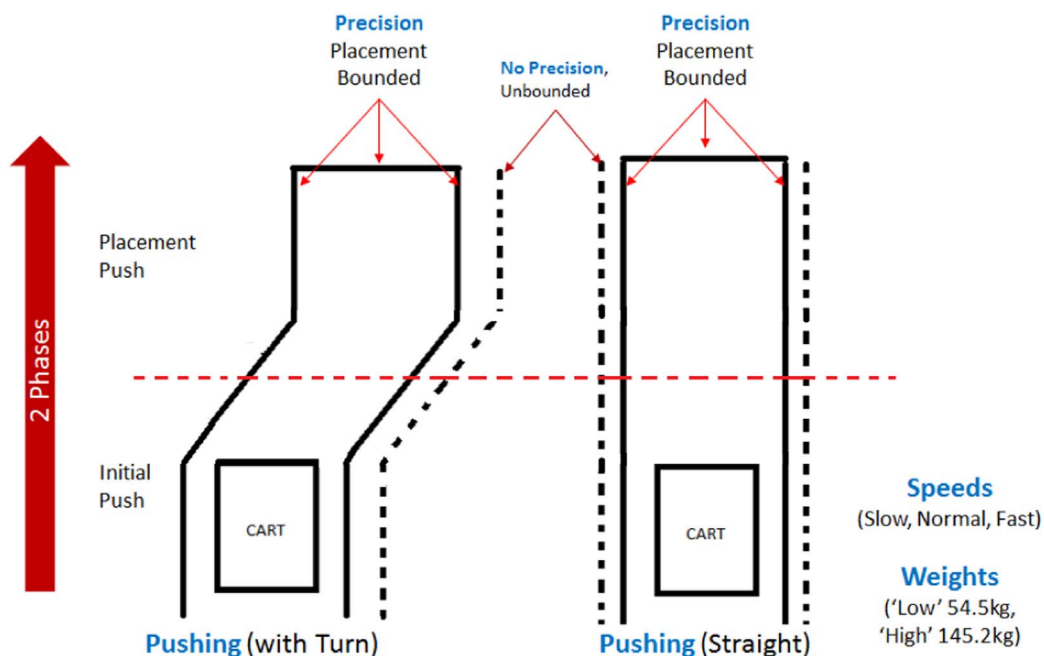


Fig. 2. Diagram of experimental design for pushing tasks.

Table 1

Summary of the statistically significant main effects and interactions for the dependent measures of coactivation index, L3/L4 peak resultant spinal load at $\alpha = 0.05$ (** $p < 0.001$, ** $0.001 < p < 0.01$, * $0.01 < p < 0.05$), and inclusion based upon bivariate statistical significance.

P-values at $\alpha = 0.05$: *** $p < 0.001$, $0.001 < p < 0.01$, * $0.01 < p < 0.05$		Coactivation index	Resultant spinal loads	Inclusion
Global	Across exertions	***	***	X
	Lift vs. lower	**	*	X
	Initial push vs. placement push	**	**	X
Lifting	Height	***	***	X
	Asymmetry		***	
	Weight	***	***	X
	Asymmetry * height			
	Weight * height	***	**	X
	Weight * asymmetry	**		
Lowering	Weight * asymmetry * height			
	Height	***	***	X
	Asymmetry	*		
	Weight	***	***	X
	Precision	**	***	X
	Asymmetry * height			
	Weight * height	***	*	X
	Height * precision	*	*	X
	Weight * asymmetry			
	Asymmetry * precision			
	Weight * precision	***	***	X
	Weight * asymmetry * height			
	Asymmetry * height * precision			
	Weight * height * precision	*		
	Weight * asymmetry * precision			
Weight * asymmetry * height * precision				
P-values at $\alpha = 0.05$: *** $p < 0.001$, $0.001 < p < 0.01$, * $0.01 < p < 0.05$		Coactivation index	Resultant spinal loads	Inclusion
Initial push	Speed	***	***	X
	Type	**	***	X
	Weight		*	
	Precision			
	Type * Speed	**	*	X
	No other statistically significant 2-way, 3-way, or 4-way interactions			
Placement push	Speed	***	***	X
	Type		***	
	Weight		*	
	Precision		*	
	Type * speed	***	**	X
	Weight * speed			
	Speed * precision			
	Weight * type			
	Type * precision			
	Weight * precision		*	
	Weight * type * speed		*	
	Type * speed * precision			
	Weight * speed * precision		*	
	Weight * type * precision			
Weight * type * speed * precision				

between antagonists and agonists as a system. The intent of the index was to provide a meaningful, concise way to describe overall coactivity within a range from 0 to 1 with extreme cases possibly exceeding 1. The first objective was achieved through the continuous classification of active muscle moments as agonists and antagonists. The second objective was achieved by testing the index across a series of lifting and pushing tasks at the peak resultant spinal load. In general, the index developed was able to differentiate between the complex dynamic tasks. The logic behind the design, interpretation, and application of the coactivation index is discussed here.

5.1. Coactivation index logic and development

Muscles change their contribution depending on the posture, external moment, and dynamics of the task. To accommodate these factors, the key to the index lies in its ability to continuously classify muscles as agonist or antagonist through the active component of the

muscle force. The active component was chosen based on the operational definition of coactivation: the synergistic activation of antagonist and agonist muscles (Lavender et al., 1992a), which is dependent on the contractile element from Hill's elastic muscle force model (Hill, 1938). The myoelectric excitation of the active, contractile component contributes to the mechanical stiffness of the muscles, thereby affecting coactivity between the muscles (Morgan, 1977). Negating the passive component affects the muscle force during lengthening, particularly during stooping postures when the active components of the erector spinae may silence as the load is transferred to the passive components. However, for individuals with low back pain, the erectors are typically active as a protective response (Colloca and Hinrichs, 2005). This may affect the calculation of the overall force, but would not affect the coactivation index because of its dependence on the myoelectric, contractile contributions. Understanding agonist and antagonist contributions allows for the knowledge of the muscles that are primarily moving the load relative to those opposing the movement and their

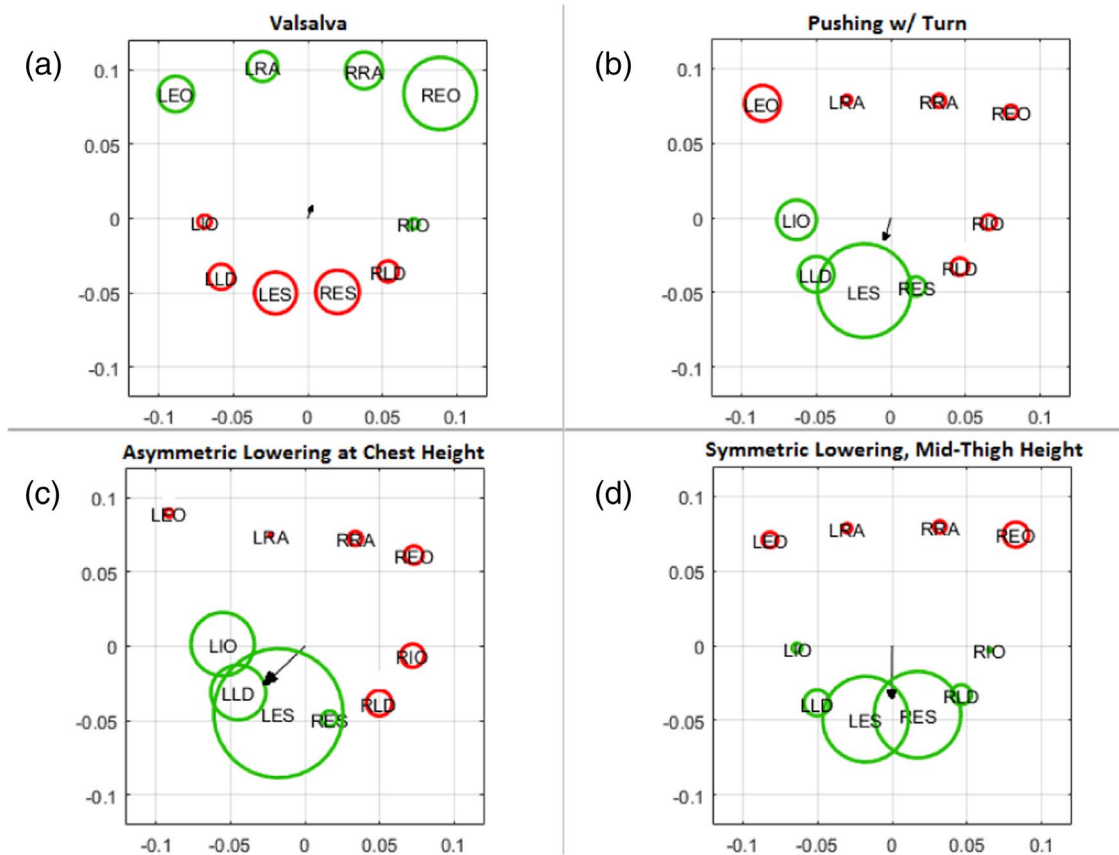


Fig. 3. Example scalar projections at peak spinal load for (a) Valsalva, (b) pushing with a turn, (c) 90-degree asymmetric lowering at chest height with precision placement, and (d) sagittal lowering at mid-thigh height. For visualization purposes, only the sagittal and lateral moment dimensions were displayed. However, classifications were based upon all three dimensions. Agonists are displayed as green and antagonists are displayed as red. The size of the circle depicts the relative contribution of each muscle to the total internal moment. The arrow represents the direction of the total internal moment. Muscles are listed bilaterally (L – Left and R – Right) as: ES (erector spinae), LD (latissimus dorsi), IO (internal obliques, EO (external obliques), and RA (rectus abdominis). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

respective magnitudes to understand the neuromuscular effort of an exertion. Song and Chung (2007) have assessed the antagonist contribution using a similar dot-product method under static loading conditions. However, the measures were limited to static upright postures in which joint-angle relationships were not accounted for, thus active force potentials could not be modulated for varying postures. Moment-arm relations are affected by the joint-angle relationships, thereby affecting the force potential of the muscle (Rassier et al., 1999). In the erector spinae, the moment-arm lengths change relative to the changes in spinal curvature (Tveit et al., 1994). The current biologically-assisted muscle wrapping model for the lumbar spine accounts for changes in the moment-arms during spine motion which modulates the force-length relations (Hwang et al., 2016). After individual muscle classification of agonist/antagonist activity, the summations of the classified components represent a systems view of agonist coactivity and antagonist coactivity. The ratio of the antagonist to the agonist describes the balance of the two systems during an exertion. If the system is in ‘pure’ balance ($b = 1$), the antagonist contribution would be equal to the agonist contribution and the total internal moment would be equal to zero. No antagonist contribution would result in a balance factor of zero, indicating that the system is agonist driven. However, under realistic circumstances, the balance factor may approach 0 or 1, but unlikely to result at those bounds. This is due to the load distribution to the passive tissues, structural loading components of the spine, and the external load. The index or neuromuscular effort due to coactivation is then described as the product of the balance factor and total moment activation. This provides an understanding of which proportion of the total activation is due to coactivation. To provide a range for occupational tasks and activities of

daily living from 0 to 1 (extreme cases may exceed 1), the total moment activation for each task was normalized to the maximum total activation (655 Nm) from this study. The normalization factor corresponded with high spinal loads of 8468 N for compression and 1001 N for A/P shear, which were beyond the NIOSH ‘maximal permissible limit’ of 6400 N for compression (Waters et al., 1993) and occasional exposure limit of 1000 N for A/P shear (Gallagher and Marras, 2012), respectively. The purpose of normalization was to provide a high upper bound to allow for extreme cases of occupational loading to be assessed outside of this study.

It was suspected that higher degrees of control would require increases in antagonist activity for postural stabilization which may be seen in LBP patients (Marras et al., 2004) or inexperienced workers (Marras et al., 2006). As a response, agonist activity may increase in order accommodate task demands, thereby increasing the neuromuscular effort of exertion. Under ideal, more ‘efficient’ conditions, the index would be driven by the agonists with small contributions from the antagonists. Hence, much of the effort may be attributed to antagonist coactivation as described by the proposed index.

5.2. Application of the coactivation index

The coactivation index was tested across a series of complex dynamic exertions from lifting and lowering to pushing to Valsalva maneuvers. The global tasks were distinguishable from one another with the Valsalva maneuvers incurring the highest coactivation, followed by pushing and lifting as the lowest. Interestingly, the index was also able to distinguish differences between conditions within the global tasks. The general findings from the index were expected in

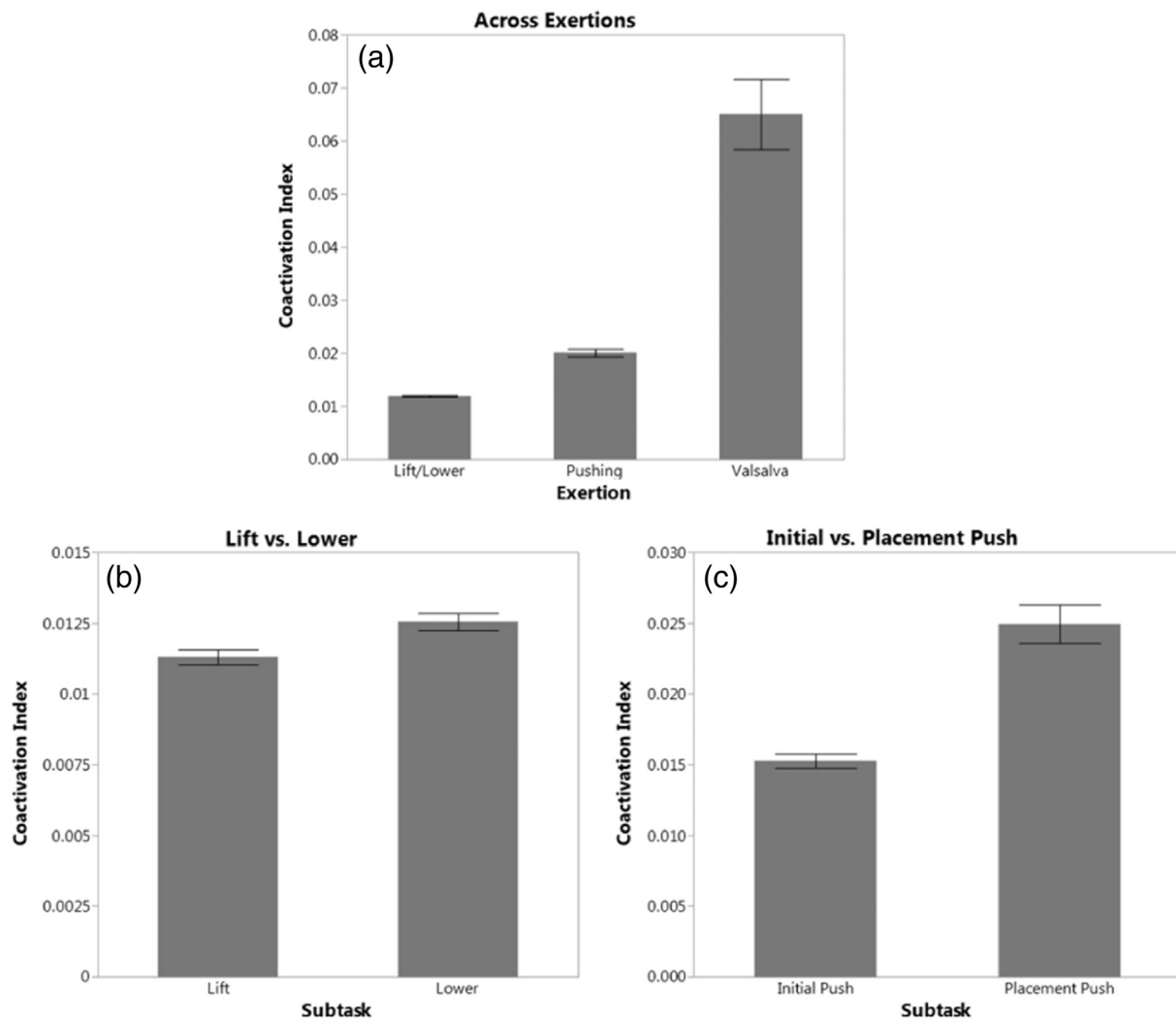


Fig. 4. Main effect plot of coactivation index across (a) exertions, (b) lifting vs. lowering, and (c) initial vs. placement push (mean SE).

regards to previous studies.

5.2.1. Lifting/lowering

Height was the primary driver of coactivity during lifting and lowering (Fig. 4). During tasks requiring more torso flexion, the imposed moment of the torso and the external load resulted in increases in agonist activity in order to achieve the lift. At chest height, more antagonistic activity occurred during the lift potentially due to the need to stabilize the torso to keep it upright, particularly with heavier weight (Fig. 5a). However, less agonist activity was necessary since the torso was more upright during the lift at chest height resulting in a smaller effective load moment arm. This shift from agonist to antagonist contribution thereby increased the balance factor or ratio between the contributions, thereby attributing a higher proportion of the total activation due to coactivation. Based upon the magnitude of the activation required to stabilize the load, the result is a higher index. This does not always carry a negative connotation, as the balance factor just represents the ratio of coactivity (antagonist/agonist). The problem exists when the magnitude of the total activation needed to maintain the balance factor exceeds the necessary amount for postural stabilization (i.e., guarding), thus resulting in a higher index. This finding can be supported by Granata and Orishimo (2001) which showed increases in antagonist flexor activity at higher heights. The interesting finding in regards to height was that lowering the weight required more coactivity than lifting to control the load (Fig. 4b). This finding was dependent on height and level of precision in the task (Fig. 5c). At chest height,

subjects tended to raise the load slightly higher than the shoulders during the lowering of the weight in order to visually target the placement region. This required increases in antagonist-defined flexor activity for postural control. With little to no difference in the agonist activity between lifting and lowering, the index became more antagonist driven, thereby increasing the index when compared to the lift. At mid-thigh height, precision placement of the weight was associated with posterior translation of the hips and increased torso flexion in order to see the target. This required increases in arm extension, thereby increasing the external moment and the resulting coactivity to stabilize the load. The precision placement findings can be supported by Davis et al. (2002) which showed increases in activations across multiple muscles in the trunk during tasks requiring precision placement and increased mental processing. Overall, lowering the weight required more control than lifting, especially when precision placement was involved. The result was a higher index compared to lifting or lowering at the same height without precision placement.

5.2.2. Pushing

Pushing tasks incurred higher levels of coactivation than lifting (Fig. 4a). This was marked by higher antagonistic coactivation which has been found to be more pronounced during torso flexion compared to extension as typically seen during pushing tasks (Granata et al., 2005). In our study, the primary driver of coactivity during pushing was the interaction of speed and the type of push (straight or turn). Higher coactivity was seen during the turn (Fig. 6), which agrees with findings

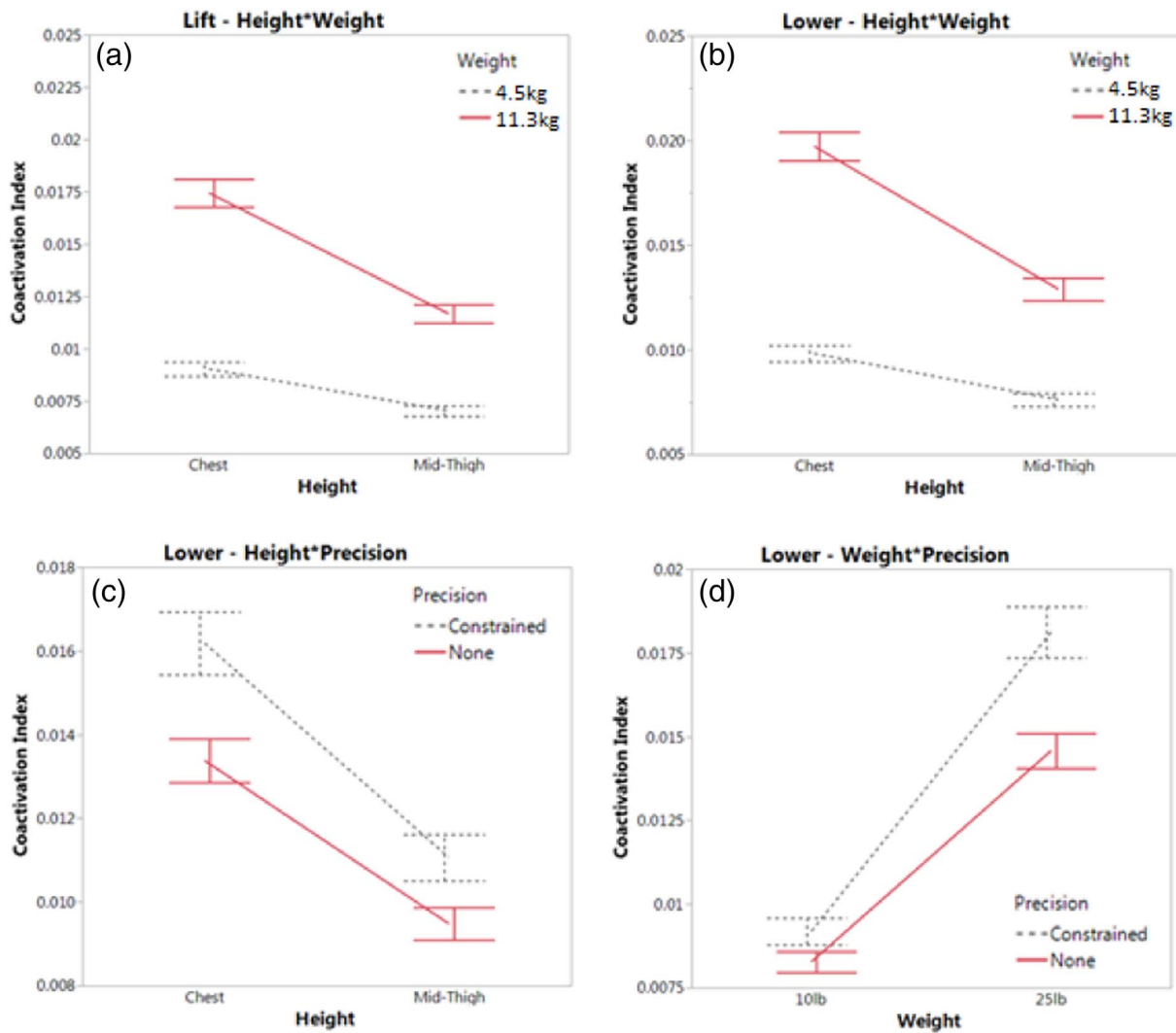


Fig. 5. Interaction plots of the coactivation index for (a) height and weight for lifting, (b) height and weight for lowering, (c) height and precision for lowering, and (d) weight and precision for lowering (mean SE).

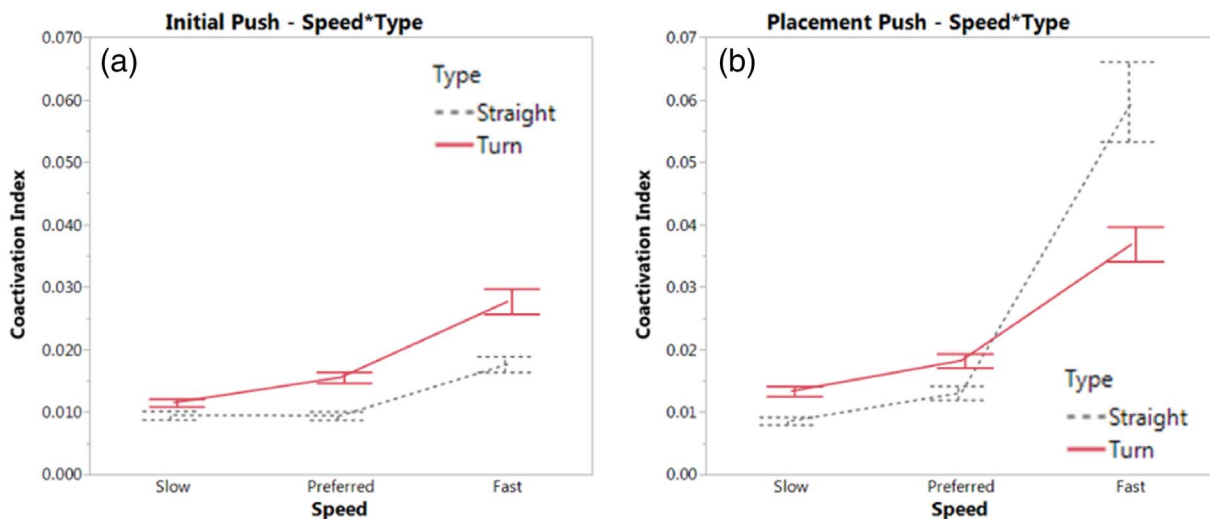


Fig. 6. Interaction plots of coactivation for the speed and type of push (straight vs turn) during the (a) initial push (left) and (b) placement push (right) (mean SE).

from Marras et al. (2009b) in which higher coactivity was also observed during the turn. During the straight push, most of the contribution of coactivity resided in the sagittal moments from the active musculature. However, during the turn, individual muscle lateral and axial moments increased in order to generate the torque necessary to turn the cart. As the speed increased, the effect was magnified to generate the force needed to increase cart momentum, thereby requiring higher coactivity. The rise in coactivation has been associated with increased A/P shear loading, particularly from muscles with more of a horizontal orientation (Marras et al., 2009a).

Interestingly, the interactions of speed and push type were also dependent on the phase of the push (initial vs. placement). Placement of the cart resulted in higher coactivation, particularly during the fast speed condition (Fig. 6). The straight push had ample space to accelerate during the initial push (0.80 m/s^2) compared to the push with a turn (0.07 m/s^2). In order to stop the cart at a fast speed, higher coactivation was necessary for the straight push, which resulted in a cart deceleration of (-1.1 m/s^2) compared to (-0.21 m/s^2) during placement after a turn. Hence, the level of control to navigate through confined spaces and/or at a hurried pace incites an inefficient neuromuscular effort to the system which increases loading onto the spine and risk for LBD.

5.2.3. Valsalva

Maximal effort Valsalva maneuvers were employed to test the sensitivity of the balance factor (0 to 1, where the upper bound is 1) or ratio between the antagonist and agonist systems. This ratio provides an understanding of how much of the magnitude (total activation) is due to antagonist/agonist system opposition. The results showed that the Valsalva maneuvers were the highest of the three global tasks (Fig. 4a). However, full balance between antagonist and agonist systems was not often seen as Valsalva strategies differed from subject to subject, even with practice and instruction. This resulted in variability in the data and values lower than expected. It was likely that full balance was not experienced due to the distribution of the load to the passive tissues, facet joints, and bone. Nevertheless, the Valsalva maneuver still displayed the highest coactivity among the three global tasks.

5.3. Limitations

A few potential limitations need to be considered in the use and interpretation of the developed index. First, although the dataset incorporated a wide range of tasks, the subtasks were limited in scope. Lifting was limited to right-sided asymmetry and two heights, which assumed symmetry between the sides. A study from Marras and Davis (1998) showed that lifts originating left of the sagittal plane (counterclockwise) had higher contralateral muscle activity than lifts originating to the right of the sagittal plane. Pushing was limited to one type of cart with the same handle height for all subjects. However, the general aim was to control the tasks for external validity with the purpose to evaluate the sensitivity of the index in separating tasks. Secondly, the coactivation measures were model-dependent. The use of a different model with different moment-arms and modulation factors could affect the findings and result in misclassification of muscle contribution. Third, although the subjects were provided ample time to practice the task, there was still variability in how each individual accomplished the task due to a variety of factors from anthropometry, strength, and fear of task failure. For example, during precision-constrained pushing tasks, some subjects had slower ‘fast’ pushes than others because of the fear of having to redo the task. Hence, the ‘fast’ speed push contributed to some of the variability in the data. Fourth, coactivation was only assessed at the peak spinal load. It is understood that many other points of interest may exist, such as the points of peak coactivity, peak antagonist behavior, preparatory responses, etc. However, based upon much discussion in the literature of coactivity and spinal loads, this

study was limited to investigating the effect of coactivation on spinal loading at a single point in time. The index is still unique in its ability to assess coactivation continuously during a dynamic task. Future studies would further test the sensitivity of the index across other combinations of tasks as well as points of interest. In light of the limitations, the current study still provides insight into the sensitivity of the coactivation index developed to assess complex dynamic tasks.

6. Conclusions

This study provided a description of a coactivation index developed to assess the neuromuscular effort of various complex dynamic tasks. The effort was operationally defined as the amount of coactivation needed to accomplish a task. Tasks requiring higher degrees of postural control would ideally require higher neuromuscular effort and consequently, a higher coactivation index. Although all tasks incur some form of neuromuscular effort, it is the amount beyond what may be necessary to accomplish a task that may impose risk of LBD. Using a biologically-assisted lumbar spine model, moment contributions from the active components of the muscle force were classified with respect to the total internal moment to understand agonist/antagonist behavior. This classification provided the basis for understanding the neuromuscular effort from opposition between the two systems. Experimental testing of the index and coactivation components demonstrated its effectiveness in distinguishing the varying efforts associated with neuromuscular control during lifting/lowering and pushing tasks. These efforts were reflected as higher index values for tasks requiring higher degrees of postural control. Overall, the coactivation index developed may be applicable in assessing muscular inefficiency between tasks, and effectiveness of rehabilitation or surgical interventions. Its utility provides a systems-level understanding of neuromuscular effort within complex, multi-muscle systems.

Conflict of interest

There are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements

The authors would like to thank Jon Simmel for his assistance in data collection.

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