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Lower Limb Muscle Co-Activation Maps in Single and Team Lifting at Different Risk Levels

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Abstract: The central nervous system uses muscle co-activation for body coordination, effector movement control, and joint stabilization. However, co-activation increases compression and shear stresses on the joints. Lifting activity is one of the leading causes of work-related musculoskeletal problems worldwide, and it has been shown that when the risk level rises, lifting enhances trunk muscle co-activation at the L5/S1 level. This study aims to investigate the co-activation of lower limb muscles during liftings at various risk levels and lifting types (one-person and vs. two-person team lifting), to understand how the central nervous system governs lower limb rigidity during these tasks. The surface electromyographic signal of thirteen healthy volunteers (seven males and six females, age range: 29–48 years) was obtained over the trunk and right lower limb muscles while lifting in the sagittal plane. Then co-activation was computed according to different approaches: global, full leg, flexor, extensor, and rostro-caudal. The statistical analysis revealed a significant increase in the risk level and a decrease in the two-person on the mean and/or maximum of the co-activation in almost all the approaches. Overall, our findings imply that the central nervous system streamlines the motor regulation of lifting by increasing or reducing whole-limb rigidity within a distinct global, extensor, and rostro-caudal co-activation scheme, depending on the risk level/lifting type.

Keywords: two-person team lifting; bipolar sEMG; co-contraction; manual material handling; lower limb; spinal output

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1. Introduction

Lifting is one of the primary causes of work-related musculoskeletal diseases globally, affecting a considerable number of industrial workers and manual material handlers [1–4].

To prevent work-related musculoskeletal diseases, it is crucial to adopt effective ergonomic interventions designed on an accurate and precise estimate of the biomechanical risk level also by using approaches based on wearable sensor networks and specific algorithms and indexes [5]. These approaches allow us to estimate the risk levels during the execution, among the other manual material handling activities, of lifting tasks performed in the team by more than one person or performed with the aid of exoskeletons and collaborative robots [5–9]. The latter would not be assessable with methods listed within the international ergonomic standards [10–12].

Since during lifting heavy loads, the spine is the most affected body district, the scientific literature shows that the mainly used indexes are based on the trunk behavior in terms of kinematics [13–16], forces at the L5/S1 level [17–19] and surface electromyography [6,20–22].

On the other hand, although a correct execution of the lifting by the lower limbs can allow the trunk to stoop less reducing net moments, muscle forces, and internal spinal load [23], lower limbs have received little consideration to date and few studies are available in the literature [24–28]. Furthermore, lower limb work-related musculoskeletal diseases

are still present and widespread [29], (e.g., it is possible to see the incidence and prevalence of work-related musculoskeletal diseases in Italy at the link https://bancadaticsa.inail.it, accessed on 8 April 2024). Finally, analyzing the behavior of some indices associated with the lower limbs would be relevant to enrich the instrumental approaches with the further chance to train high-performance artificial neural networks [30,31].

Moreover, with this goal, it would be useful to investigate the behavior of lower limb muscle co-activation to understand how the central nervous system (CNS) modulates joint stiffness by regulating the duration and intensity of concurrent activity of a pair or group of muscles [22,32–34].

Muscle co-activation is thought to maintain effector-level control (low dimensional), removing the need for individual muscle coordination control (high dimensional) [32]. However, it can be counterproductive, as it generates additional compression and shear forces on the joint, that may lead to injury [19,22,35–37]. Lifting has been demonstrated to enhance the co-activation of the trunk muscles, causing moments that do not add to the required net trunk moment [6,22,31].

Lower limb co-activations could be calculated globally by considering all the muscles, but also at the level of different spinal segments by mapping the simultaneous activity of various muscles during lifting onto the anatomical rostro-caudal position of motor neuron populations in the human spinal cord-derived from previously published studies during walking [38–43]. Furthermore, co-activation could be calculated by considering either flexor or extensor muscles separately [43]. Lifting usually requires the need to extend ankles, knees, and hips through the action of the muscles that generate internal extensor moments. On the contrary, it is functionally important that the flexor muscles do not generate an opposing moment and this, among others, can occur when the motor task becomes more demanding. Hence, both extensors and flexors approaches would allow us to consider indices for biomechanical risk assessment starting from a simplified sensors setup.

For all these reasons, there is a need to better study the behavior of the lower limbs during the execution of heavy lifting activities in an occupational context. Indeed, a correct motor execution of the lower limbs during lifting allows for less overload of the spine [44–46]. Furthermore, global co-activation of lower limb muscles could be used as an index in instrumental risk assessment methods and to train machine learning algorithms for automated risk level estimation. The two "rostro-caudal" and "flexor-extensor" approaches, in addition to representing an in-depth analysis of the mechanisms adopted by the CNS, would allow the calculation of the co-activation index starting from a simplified sensor setup, which is always desirable in the workplace.

We proposed a novel approach to studying time-varying multi-muscle co-activation function (*TMCf*), which is a good indicator of the CNS's overall strategy for modulating the muscle co-activation during locomotion [43] and lifting [6,22]. This approach gives an alternative viewpoint on the spatiotemporal motor control of the trunk and/or lower limbs, highlighting how trunk and/or lower limb muscles are concurrently co-activated to increase whole-limb stiffness, regardless of single-joint antagonist muscles or modular activation of a group of muscles [47].

We hypothesized that the lower limb muscle co-activation increases when lifting with a higher LI is performed and decreases in team lifting compared to that of one-person lifting. Furthermore, we hypothesize that, due to the nature of the motor task, the co-activation of the extensor muscles increases with the level of risk and that it varies across the rostro-caudal recruitment map.

The current study aimed to investigate the concurrent contractions of multiple lower limb muscles during liftings at various risk levels and lifting types (one-person vs. two-person team lifting) to gain insight into how the CNS manages lower limb rigidity and to include muscle co-coactivation indexes within instrumental-based tool risk assessment.

2. Materials and Methods

In this work, the experimental approach mentioned in ref. [6] and briefly summarized below was used.

2.1. Experimental Procedures

Each subject lifted a crate in the sagittal plane (without trunk rotation) with both hands at three different risk levels determined according to the NIOSH method alone and in team with another subject, as detailed in ref. [6], Figure 1.

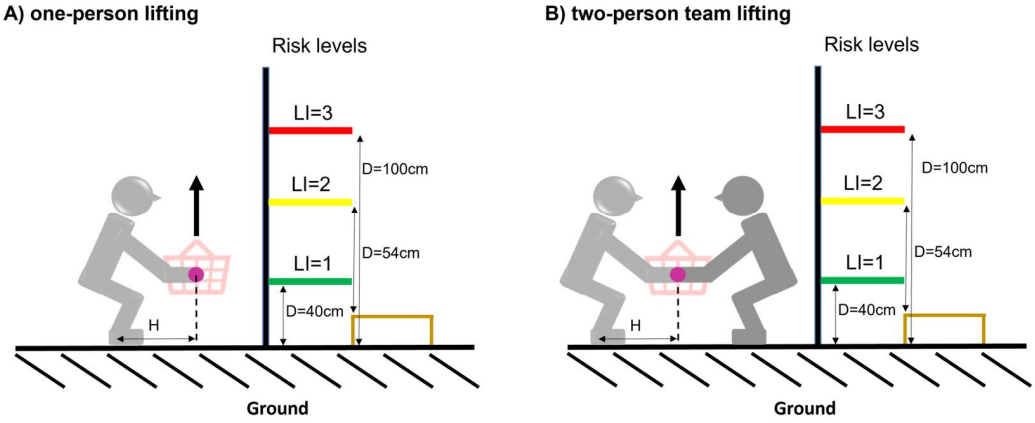

Figure 1. This figure displays the experimental setup: (**A**) one-person and (**B**) two-person-team lifting. The picture depicts how the load's horizontal distance (H), and vertical displacement (D) were controlled to meet the risk levels identified according to the NIOSH method, (lifting index, LI).

Table 1 shows the values of the experimental setup parameters that contribute to determining the risk level given by the NIOSH lifting index (LI) both in one- and two-person team lifting.

Table 1. This table reports for each lifting task the values of the load weight (L), the horizontal (H) and vertical (V) locations, the vertical travel distance (D), the asymmetry angle (A), the lifting frequency (F) and the hand-to-object coupling (C) and the corresponding values of the multipliers and recommended weight limit (RWL) for one-person and two-person team lifting (RWL and RWLT, respectively). LC was defined as 23 kg in RNLE. The value of LI for one-person lifting (LI) and for two-person team lifting (LI_T) were also reported.

Task	LC (kg)	H (cm)	HM	V (cm)	VM	D (cm)	DM	A (°)	AM	F (lift/min)	FM	C	CM	L (kg)	RWL	RWL_T	LI	LI_T
A	23	63	~0.40	10	~0.81	40	~0.93	0	1	≤2	1	good	1	7	6.85	4.59	1.02	0.51
B	23	60	~0.42	31	~0.868	54	~0.90	0	1	≤2	1	good	1	15	7.51	5.03	2.00	0.99
C	23	60	~0.42	10	~0.805	100	~0.87	0	1	≤2	1	good	1	20	6.67	4.47	3.00	1.49

To ensure that all NIOSH parameters were effectively controlled, and risk levels were correct, the positions of the feet for the various tasks, as well as the positioning of the box, were marked on the ground with tape so that the horizontal distance (H) between the center of the malleoli and the center of the load was actually (and for all subjects) 60 and 63 cm, for tasks A, B, and C, respectively. Furthermore, the maximum height to which the weight had to be lifted was indicated with a three-level rod, resulting in vertical displacements (D) of 40, 54, and 100 cm for jobs A, B, and C, respectively. Finally, the initial height of the load center (V) from the ground was controlled using a support surface to ensure that it was exactly 10 cm for tasks A and C and 31 cm for task B.

Each participant performed 3 repetitions of each risk condition for both one- and two-person team lifting, so to have a total of 18 trials. The different liftings were executed at random across the three risk conditions and one- and two-person team lifting to avoid bias.

Before starting the measurements, a global reference system was defined by executing a calibration procedure according to [48] with a mean spatial accuracy of 0.2 mm. The movement of one spherical marker covered with aluminum powder reflective material was detected at a sampling frequency of 340 Hz by using an optoelectronic motion analysis system (SMART-DX 6000 System, BTS, Milan, Italy) with eight infrared cameras. The marker was placed over the right anterior vertex of the load (a plastic crate).

Surface electromyography (sEMG) has been recorded with a 16-channel Wi-Fi transmission surface electromyograph (Mini Wave Infinity, Cometa, Milan, Italy) with a 2000 Hz sampling frequency. After skin preparation, bipolar electrodes were placed according to the Atlas of Muscle Innervation Zones [49] and the European Recommendations for Surface Electro-myography [50], bilaterally over the rectus abdominis superior and erector spinae longissimus muscles and over the following right lower limb's muscles: peroneus longus, soleus, gastrocnemius medialis and lateralis, tibialis anterior, biceps femoris, semitendinosus, tensor fascia latae, vastus medialis and lateralis, rectus femoris, and gluteus medius [51,52]. Kinematic, and sEMG data were recorded simultaneously.

2.2. Data Analysis

The raw sEMG data have been processed as in [6] with a with a self-written Matalb (version 2018b 9.5.0.1178774, MathWorks, Natick, 193 MA, USA) script. Briefly, the raw sEMG signals has been filtered and we determined the envelope. Then, for each muscle, the sEMG envelope was amplitude-normalized to the maximum of each corresponding muscle among all the trials [50,53,54].

2.3. Cycle Definition and Time Normalization

We determined the start and stop of each lifting with the same procedure already detailed in ref. [22] by analyzing the vertical displacement and velocity of one of the four markers placed on the load. Then, to be able to compare different lifting cycles, we time-normalized all the liftings with a polynomial procedure to the same number of samples (201 samples), as in ref. [22].

2.4. Global, Full Leg, Flexor, Extensor, and Rostro-Caudal Co-Activation

The time-varying multi-muscle co-activation function (*TMCf*) was used to calculate the simultaneous activation of the trunk and lower limb muscles [6,22,43] according to the following formula:

$$TMCf(d(i),i) = \left(1 - \frac{1}{1+e^{-12(d(i)-0.5)}}\right).\frac{\left(\sum_{m=1}^{M} EMG_m(i)/M\right)^2}{max_{m=1\ldots M}[EMG_m(i)]}$$

where M is the number of muscles considered, $EMG_m(i)$ is the sEMG sample value of the m-th muscle at instant i, and $d(i)$ is the mean of the differences between each pair of sEMG values at instant i:

$$d(i) = \left(\frac{\sum_{m=1}^{M-1}\sum_{n=m+1}^{M}|EMG_m(i) - EMG_n(i)|}{Lx(M!/(2!(M-2)!))}\right)$$

L is the length of the sEMG signal (201 samples in this case), $M!/(2!(M-2)!)$ is the total number of possible differences between each pair of $EMG_m(i)$. This function's values ranged from 0 to 100%.

All the sixteen acquired muscles were inserted in the calculation of the *TMCf* to assess global co-activation ($TMCf_{glob}$). Moreover, the co-activation of all the lower limb muscles ($TMCf_{full_leg}$), extensor ($TMCf_{ext}$), flexor ($TMCf_{flex}$) muscles separately, and according to the rostro-caudal organization ($TMCf_{L3}$; $TMCf_{L4}$; $TMCf_{L5}$; $TMCf_{S1}$; $TMCf_{S2}$) [40,42,43,47,55,56] was assessed using subgroups of muscles (see Table 2). Muscles were considered as flexors or extensors based on their concentric function in the sagittal plane [55]. The biarticular muscles were considered as flexors or extensors based on their proximal function [57].

Table 2. Each dot in the table indicates muscles included in the time-varying co-activation (*TMCf*) function for each muscle co-activation investigated: global, full leg, extensor, flexor, and rostro-caudal organization. The smallest dots indicate a halved weight (amplitude of muscle activity multiplied by 0.5) for that specific muscle in the *TMCf* function.

Muscles	Global	Full Leg	Extensor	Flexor	L3	L4	L5	S1	S2
Rectus Abdominis Superior	•								
Erector Spinae Longissimus	•								
Glutes Medius	•	•	•			•	•	•	
Rectus Femoris	•	•		•	•	•			
Vastus Lateralis	•	•	•			•			
Vastus Medialis	•	•	•		•	•			
Tensor Fasciae Late	•	•		•	•	•	•	•	
Semitendinosus	•	•	•			•	•	•	•
Biceps Femoris	•	•	•				•	•	•
Tibialis Anterior	•	•		•		•	•	•	
Gastrocnemio Medialis	•	•	•					•	•
Gastrocnemio Lateralis	•	•	•					•	•
Soleus	•	•					•	•	•
Peroneus	•	•				•	•	•	

2.5. Co-Activation Parameters

Within each lifting, the following parameters were calculated for each *TMCf*: (i) the synthetic co-activation index (CI_{glob}; CI_{full_leg}; CI_{ext}; CI_{flex}; CI_{L3}; CI_{L4}; CI_{L5}; CI_{S1}; CI_{S2}), which is computed as the mean value of each *TMCf* curve, representing the average of the co-activation level over the lifting cycle, [% co-activation]; (ii) the maximum value of each *TMCf* curve (Max_{glob}; Max_{full_leg}; Max_{ext}; Max_{flex}; Max_{L3}; Max_{L4}; Max_{L5}; Max_{S1}; Max_{S2}), as a punctual index, that returns instantaneous information about the peak at which each co-activation arrives within each lifting cycle [% co-activation].

2.6. Statistical Analysis

Statistical analyses have been performed using SPSS 20.0 (IBM SPSS) software. For each subject, we averaged the data from all the trials at the same risk level and lifting type (i.e., one-person or two-person team lifting). Firstly, we checked if the data were normally distributed with the Shapiro–Wilk normality test, then we investigated if there was effect of the risk level (low, Task A, medium, Task B, or high, Task C, determined according to the NIOSH method) or of the lifting type by executing a two-way repeated measure ANOVA. Finally, we performed a post hoc analysis with Bonferroni's correction, if the repeated measure ANOVA test revealed a main effect. In all the cases, if the p values were lower than 0.05, the difference was considered statistically significant.

3. Results

3.1. Subjects

The study included thirteen participants (seven males, age range: 29–43 years, mean age = 40.29 $\pm$ 5.09 years, height = 1.71 $\pm$ 0.06 m, weight = 68.93 $\pm$ 6.35 kg, body mass index [BMI] = 23.41 $\pm$ 0.91 kg/m^2; and six females, age range: 29–48 years, mean age mean age = 32.83 $\pm$ 8.40 years, height = 1.61 $\pm$ 0.04 m, weight = 55.83 $\pm$ 9.20 kg, body mass index [BMI] = 21.38 $\pm$ 2.76 kg/m^2). During the current study, all the enrolled subjects were not taking part in any clinical drug trials and had no history of upper and lower limb and trunk surgery, orthopedic or neurological diseases, vestibular system disorders, or back pain. Other exclusion criteria included inability to give informed written consent, orthopedic diseases, metabolic or inflammatory conditions, visual impairments or back pain, current pregnancy, current pharmacological treatment and/or infections that may influence the functional status during working posture and movement assessment, and obesity or overweight. Participants provided written informed consent after receiving a thorough explanation of the experimental procedure and prior to participating in the study, which adhered to the Helsinki Declaration and was approved by the local ethics committee

(N. 0078009/2021). To prevent bias, neither any information about the expected outcomes was given.

3.2. TMCf Maps

As in [43], we reconstructed the spinal maps of the co-activation in the lumbosacral enlargement by mapping the *TMCf* profiles onto the rostro-caudal location of the motoneuron pools. Figure 2 shows the mean of the segmental *TMCf* at three risk levels for each spinal segment over the lifting cycles performed by a one-person team and Figure 3 illustrates it over the lifting cycles executed by a two-person team. The maps show different co-activation loci at each lumbar segment (especially at the L3 level) at the beginning of the lifting both in one-person and two-person team lifting at all three risk levels (Figures 2 and 3) and by an increased co-activation from the beginning to 80% of the lifting cycle at the S2 sacral segment both in one-person and two-person team lifting (Figures 2 and 3). Figures 2 and 3 show that under medium risk conditions (LI = 2), the *TMCf* at level S2 is around 15% from the beginning to 80% of the cycle in one-person team lifting, whereas it only remains at this level at the very beginning of the cycle (from 0% to 10% of the lifting cycle) in two-person team lifting. Under high-risk conditions (LI = 3), the effect is even more pronounced; in Figure 2 in one-person liftings, the *TMCf* at segment S2 is between 20 and 30%, whereas in two-person liftings, it is around 17% from the beginning to 80% of the cycle.

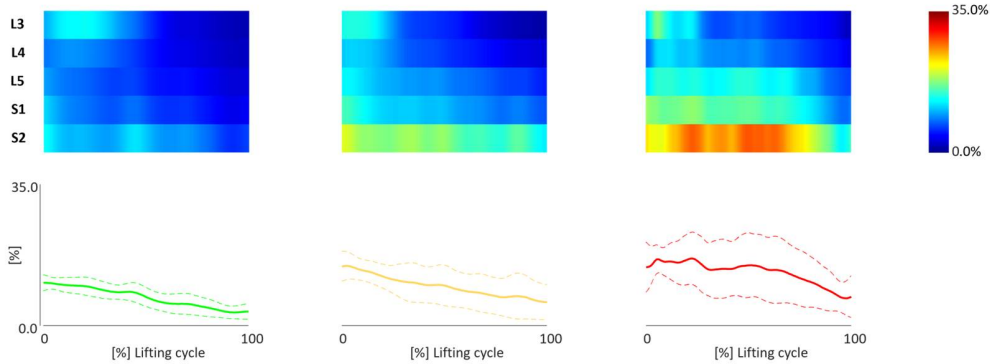

Figure 2. Spatiotemporal maps of the co-activation of the muscles innervated by the lumbosacral enlargement in one-person team lifting at low (LI = 1, green), medium (LI = 2, yellow), and high (LI = 3, red) risk levels. The top panels show the output pattern of each segment (mean ± SD) in a color scale. The lowest plots show the co-activation (*TMCf* averaged across participants, mean ± SD) as a function of the lifting cycle and spinal segment level (L3–S2).

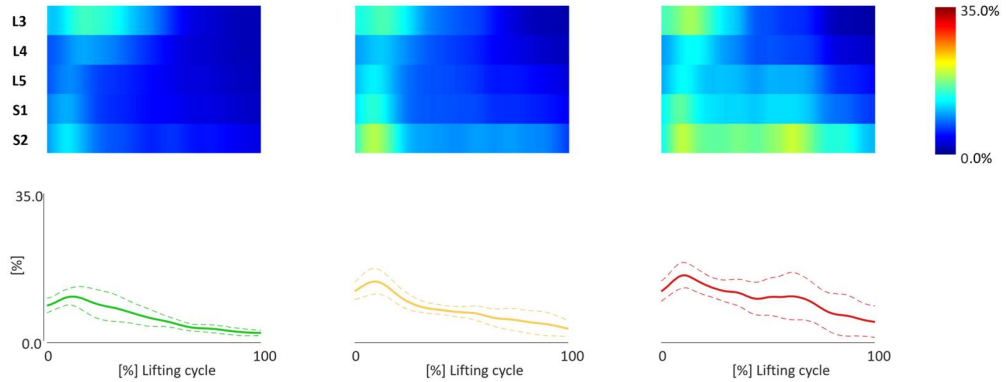

Figure 3. Spatiotemporal maps of the co-activation of the muscles innervated by the lumbosacral enlargement in two-person team lifting at low (LI = 1, green), medium (LI = 2, yellow), and high (LI = 3, red) risk levels. The top panels show the output pattern of each segment (mean ± SD) in a color scale. The lowest plots show the co-activation (*TMCf* averaged across participants, mean ± SD) as a function of the lifting cycle and spinal segment level (L3–S2).

3.3. TMCf Indices

The two-way repeated measures ANOVA showed a significant main effect of the lifting type on CI_{glob}, CI_{full_leg}, CI_{ext}, CI_{L3}, CI_{L4}, CI_{L5}, CI_{S1}, CI_{S2} (Table 3), Max_{glob}, Max_{full_leg}, Max_{ext}, Max_{L3}, Max_{L4}, Max_{L5}, Max_{S1}, Max_{S2} (Table 4) and of the LI on CI_{glob}, CI_{full_leg}, CI_{ext}, CI_{L4}, CI_{L5}, CI_{S1}, CI_{S2} (Table 3), Max_{glob}, Max_{full_leg}, Max_{ext}, Max_{L3}, Max_{L4}, Max_{L5}, Max_{S1}, Max_{S2} (Table 4).

Table 3. The table shows the results of the two-way repeated measures ANOVA (F, dF, and *p* values) on the co-activation index (CI) calculated for each *TMCf*. Bold indicates significant differences.

	Lifting Type		Risk Level		Lifting Type Risk Level	
	F	***p***	**F**	***p***	**F**	***p***
CI_{glob}	$F_{(1,12)} = 60.402$	**<0.001**	$F_{(2,24)} = 71.477$	**<0.001**	$F_{(2,24)} = 0.752$	0.482
CI_{full_leg}	$F_{(1,12)} = 58.307$	**<0.001**	$F_{(2,24)} = 72.454$	**<0.001**	$F_{(2,24)} = 1.138$	0.337
CI_{ext}	$F_{(1,12)} = 82.544$	**<0.001**	$F_{(2,24)} = 75.031$	**<0.001**	$F_{(2,24)} = 3.975$	**0.032**
CI_{flex}	$F_{(1,12)} = 2.491$	0.141	$F_{(2,24)} = 0.847$	0.441	$F_{(2,24)} = 0.328$	0.723
CI_{L3}	$F_{(1,12)} = 5.310$	**0.040**	$F_{(2,24)} = 2.404$	0.112	$F_{(2,24)} = 0.082$	0.921
CI_{L4}	$F_{(1,12)} = 7.219$	**0.020**	$F_{(2,24)} = 24.425$	**<0.001**	$F_{(2,24)} = 0.311$	0.735
CI_{L5}	$F_{(1,12)} = 58.770$	**<0.001**	$F_{(2,24)} = 109.746$	**<0.001**	$F_{(2,24)} = 1.938$	0.166
CI_{S1}	$F_{(1,12)} = 83.003$	**<0.001**	$F_{(2,24)} = 112.766$	**<0.001**	$F_{(2,24)} = 2.105$	0.144
CI_{S2}	$F_{(1,12)} = 106.360$	**<0.001**	$F_{(1.322,15.861)} = 103.238$	**<0.001**	$F_{(2,24)} = 3.558$	**0.044**

Table 4. This table shows the results of the two-way repeated measures ANOVA (F, df, and *p* values) on the maximum value (Max) calculated for each *TMCf*. Bold indicates significant differences.

	Lifting Type		Risk Level		Lifting Type Risk Level	
	F	***p***	**F**	***p***	**F**	***p***
Max_{glob}	$F_{(1,12)} = 14.974$	**0.002**	$F_{(2,24)} = 22.637$	**<0.001**	$F_{(2,24)} = 0.456$	0.639
Max_{full_leg}	$F_{(1,12)} = 6.737$	**0.023**	$F_{(2,24)} = 30.956$	**<0.001**	$F_{(1.253,15.034)} = 0.781$	0.469
Max_{ext}	$F_{(1,12)} = 17.749$	**0.001**	$F_{(2,24)} = 63.992$	**<0.001**	$F_{(2,24)} = 2.906$	0.074
Max_{flex}	$F_{(1,12)} = 0.643$	0.438	$F_{(2,24)} = 1.925$	0.168	$F_{(1.316,15.794)} = 1.344$	0.276
Max_{L3}	$F_{(1,12)} = 9.122$	**0.011**	$F_{(2,24)} = 4.840$	**0.017**	$F_{(1.302,15.624)} = 1.719$	0.212
Max_{L4}	$F_{(1,12)} = 24.425$	**<0.001**	$F_{(2,24)} = 10.115$	**0.001**	$F_{(1.324,15.890)} = 0.536$	0.523
Max_{L5}	$F_{(1,12)} = 8.044$	**0.015**	$F_{(2,24)} = 30.870$	**<0.001**	$F_{(1.232,14.780)} = 0.032$	0.903
Max_{S1}	$F_{(1,12)} = 40.144$	**<0.001**	$F_{(2,24)} = 44.657$	**<0.001**	$F_{(1.347,16.164)} = 2.340$	0.140
Max_{S2}	$F_{(1,12)} = 39.398$	**<0.001**	$F_{(2,24)} = 54.751$	**<0.001**	$F_{(2,24)} = 1.621$	0.219

Figures 4 and 5 show the results of pairwise comparisons of risk levels and lifting styles for *CI* and *Max* of *TMCf*. For brevity and conciseness, only the approaches that resulted in statistically significant differences are shown.

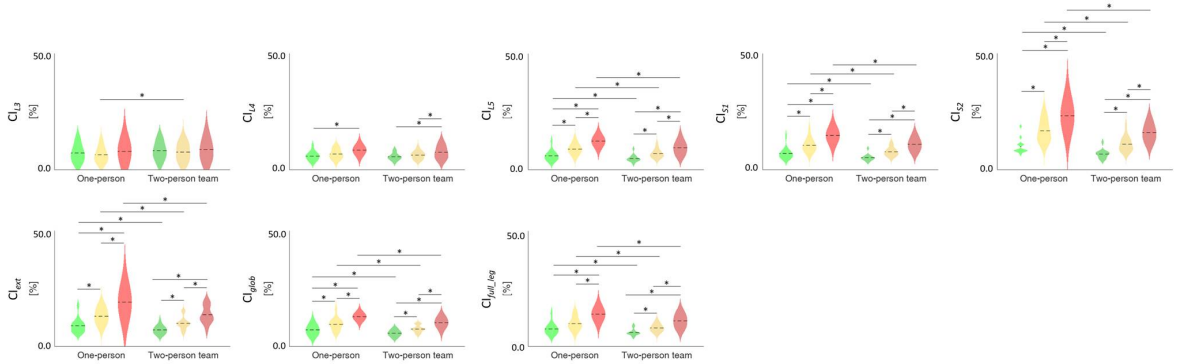

Figure 4. Violin plots of the mean of the *TMCf* function over the lifting cycle (CI) over all the subjects for each risk level (LI = 1 green, LI = 2 yellow, LI = 3 red) in one-person and two-person team lifting for each muscle co-activation investigated: global (CI_{glob}), full leg (CI_{full_leg}), extensor (CI_{ext}), flexor (CI_{flex}), and rostro-caudal organization (from L3 to S2: CI_{L3}, CI_{L4}, CI_{L5}, CI_{S1} and CI_{S2}). The dotted black lines correspond to the mean of each CI value over all the subjects. An asterisk (*) indicates significant differences.

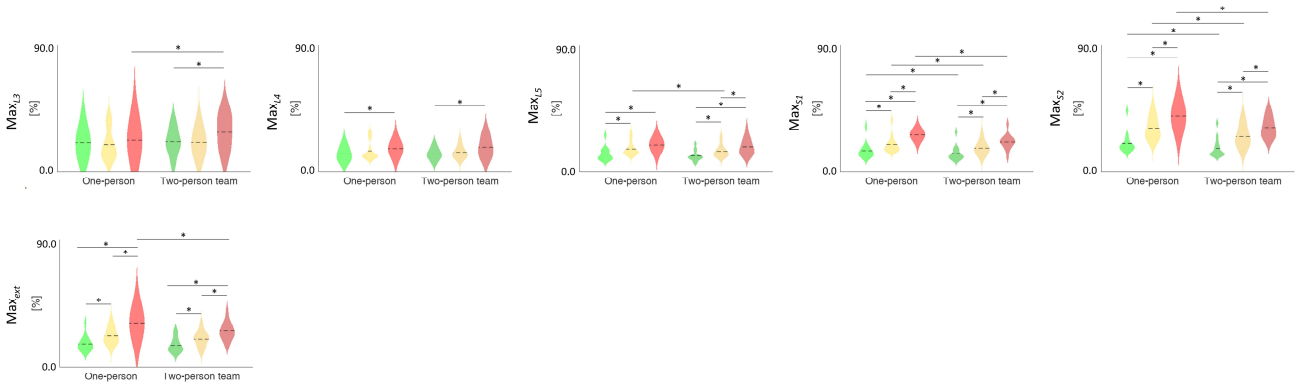

Figure 5. Violin plots of the maximum of the *TMCf* function over the lifting cycle (Max) over all the subjects for each risk level (LI = 1 green, LI = 2 yellow, LI = 3 red) in one-person and two-person team lifting for each muscle co-activation investigated: global (Max_{glob}), full leg (Max_{full_leg}), extensor (Max_{ext}), flexor (Max_{flex}), and rostro-caudal organization (from L3 to S2: Max_{L3}, Max_{L4}, Max_{L5}, Max_{S1} and Max_{S2}). The dotted black lines correspond to the mean of each Max value over all the subjects. An asterisk (*) indicates significant differences.

4. Discussion

With this work, we investigated the behavior of global muscle co-activation, the one calculated with the rostro-caudal approach and then separating flexors and extensors, during lifting activities under different risk conditions and performed by a single person and in a team. Team lifting is one of the ergonomic strategies suggested in ISO 11228-1 [12] to decrease the exposure of workers to biomechanical risk and could influence lower limb co-activation.

As already carried out for the analysis of the trunk [6], to better understand how a two-person team lifting strategy might influence the biomechanical risk, intended as a mechanical risk due to ergonomic risk factors, such as aspects of the job that post a mechanical stress to the employee (i.e., forceful exertion, repetition, awkward or static postures...) and that can cause ergonomic injuries and/or illnesses (e.g., injuries and illnesses of the muscles, nerves, tendons, ligaments, joints, cartilage and spinal discs), we evaluated the effect of two factors: the lifting type (i.e., one- vs. two-person team lifting) and risk level (low LI = 1, medium LI = 2, and high LI = 3). Moreover, we decided to investigate the *TMCf*, because it is already known for the trunk that it is related to the force acting at the lumbosacral level and is sensitive enough to be able to discriminate between the different levels of risk [6,22,30].

More in detail, regarding the *TMCf* maps we found that the activity profiles of the co-activation of the muscles innervated at the level of the sacral segments widens considerably as the risk level increases in one-person lifting, while in team lifting it remains contained. In single lifting, spinal maps demonstrated a propensity toward a greater spread level of the *TMCf* during most parts of the lifting cycle, initially affecting the sacrum and lower lumbar regions while the risk level increases, while this does not happen in team lifting. Such a pattern highlights how team lifting is an ergonomic tool also effective in reducing co-activation of the lower limb and how this tool contributes to reducing the concurrent activation of the muscles innervated by the distinct spinal levels, both lumbar and sacral.

Interestingly, our results are in accordance with what has already been published on myotomal charts [55,58], which showed that muscles with larger activations include tibialis anterior, peroneus longus, soleus, gastrocnemius medialis and lateralis, biceps femoris and semitendinosus. They are innervated from the spinal cord's more distal segments (L4–S2) and have a greater range of activity, mostly involving the sacral segments and then, in more severe neurological patients, the lumbar segments. This type of behavior can be explained in two ways. Voluntary control is pyramidal and is therefore significantly expressed in distal districts. Furthermore, in heavy lifting activities, the kinematic chain remains open for the upper limbs and is closed for the lower limbs. This indicates the necessity to control

the ground reaction force that acts distally on the lower limbs. For the reasons listed above, co-activation increases mainly distally due to the need to stabilize the entire system by responding to the stresses determined by the reaction force. We observed enhanced *TMCf* of these muscles with the risk level in the one-person team lifting and a strong mitigation of this effect in the two-person team lifting.

Co-activation widening may potentially be a compensatory technique, as prolonging co-contractions has been shown to stabilize joints [6,22,32,33].

Regarding synthetic indexes computed over the co-activation maps, we considered the mean and the maximum value of the lifting cycles. The *CI* is the mean of the co-activation function over the lifting cycle, and it has been chosen because it is connected with the average level of *TMCf* during the lifting cycle, hence it provides information about the overall task execution. The Max over the lifting cycle is a timely index that indicates the maximum value of antagonist muscle activation while lifting. It has been proven that, in terms of the trunk, it relates to peak loads that can produce severe spinal injuries, resulting in degeneration and pain [59]. In the obtained results we can observe that, in the global full leg and extensors approach there is a significant increase in *CI*s as risk levels increase in both one-person and two-person team lifting. Regarding the *Max*, the same results emerge in the approach that takes into consideration only the extensor muscles. Considering the flexors there are no statistically significant differences in terms of *CI* and *Max*. This is understandable, as the flexor muscles play a less significant role within the task under consideration, unlike the role of the extensor muscles which generate the necessary moment concentrically in lifting and counteract the external moment of lowering by contracting eccentrically.

In fact, the full leg and extensor approach shows a significant reduction of *CI* at all risk levels and of *Max* at LI = 3 for the Max in two-person compared to the one-person team lifting.

Moving on to the rostro-caudal approach, results between LI pairs are observed in muscles innervated at the L3 level, while the co-activation increases significantly again proceeding towards L4 At L5 co-activation is significantly reduced in two-person compared to the one-person team lifting, up to levels S1 and S2 in which there is a similar behavior to that observed in co-activation with a global approach.

These results are in relation to what we have already found for the trunk both in the case of lifting performed individually and in teams [6,22,31].

Furthermore, our findings are consistent with the necessity for the CNS for greater co-activation, and therefore the rigidity of the lower limb, to cope with greater efforts and gain stability.

Finally, the fact that in teams the co-activation at the same level of risk is almost always lower than that which occurs in single lifts, shows that the need to coordinate between subjects does not affect the ability of individual coordination.

Our findings indicate that the CNS streamlines motor regulation of lifting by adjusting whole-limb stiffness based on risk level and lifting type.

Our findings indicate that the CNS reduces motor control of lifting by adjusting whole-limb stiffness based on risk level and lifting type. The first limitation of this study is that the electromyographic activity of only one of the two subjects of the team was investigated and, in the future, it will be necessary to investigate both the involved subjects; then, the study is still based on a small number of participants, so another need is to increase the sample size; together with the expansion of the examined sample, it will be possible to analyze the data differently by gender, as in this case, for the few subjects available, we have mixed males and females with different anthropometric characteristics, as well as leg extensor muscle and back extensor muscle strength levels, which is an additional limitation of the study. Furthermore, it will also be necessary to evaluate the case of asymmetric lifting in which the rotation of the trunk must be taken into consideration.

Another limitation is related to the absence of information about the habitual physical activity of the participants so the results obtained should be interpreted with caution.

Furthermore, for the biomechanical characterization of the lower limb, it is necessary to expand the study by also considering other factors such as the analysis of kinematics, and the evaluation of any compensation and stability [14,15,60–62].

Lastly, considering the diffusion and popularity that wearable robotic technologies are acquiring, another future development to take could be to assess the effects of wearable technologies on the lower limb while performing single vs. team lifting tasks.

5. Conclusions

In conclusion, this study highlights that the global lower limb muscle co-activation indexes can be associated with different levels of risk in both one-person and two-person lifting. Furthermore, muscles innervated by more distal spinal segments, or the extensors alone may be included in simplified co-activation indexes to be used in instrumental approaches for biomechanical risk assessment. Lastly, this study adds credence to the idea that team lifting is an effective ergonomic intervention that can be used to reduce biomechanical risk.

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