

BIOMECHANICAL RISK IN FATIGUING FREQUENCY-DEPENDENT LIFTING ACTIVITIES: MUSCLE COACTIVATION IN PEOPLE WITH AND WITHOUT LOW BACK PAIN

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ABSTRACT

Musculoskeletal diseases and disorders from biomechanical overload are very common among workers. In Italy in 2019, occupational diseases of the osteomuscular system and connective tissue accounted for 66% of the total number of diseases reported to INAIL. Many factors can contribute to the establishment of a condition of biomechanical overload and therefore to the onset of work-related musculoskeletal disorders (WMSDs). Among these, work-related low-back disorders (WLBDs), caused mainly by handling heavy loads, are very common.

In recent years, several methods have been developed to assess the risk of biomechanical overload, included in several international standards (ISO-11228, ISO-11226, ISO/TR 12295 and 12296) aimed at identifying high-risk work activities and assessing the effectiveness of ergonomic interventions. Among the best known, with regard to the manual lifting of heavy loads, there is the Revised NIOSH Lifting Equation that, while presenting many advantages (cost-effectiveness, non-invasiveness, speed of application ...) at the same time also has limitations concerning mainly the high subjectivity (subject of scientific debate) and the impossibility of these methods to assess all work tasks.

From these premises, it is clear the usefulness of being able to use new quantitative risk assessment methodologies, objectifiable and repeatable, which provide for the possibility of assessing the risk from biomechanical overload even in modern working scenarios where the use of exoskeletons by workers and the sharing of working space with cobots is becoming increasingly widespread. In fact, the methods currently used are incomplete and ineffective in assessing the real impact that these technologies have on the health and safety of workers in Industry 4.0.

Recent studies (some of which we were involved in) have introduced the possibilities offered by optoelectronic systems, inertial sensors (IMUs) and surface electromyography (sEMG), to integrate the most widely used observational methodologies. These modern technologies, evaluating how a subject moves his joints and uses his muscles during the execution of a work task, can integrate the observational methods, quantify the elements that characterize the risk minimizing the evaluation errors caused by individual subjectivity and allow to carry out the assessment of biomechanical risk even in those areas where the currently most widespread methodologies are not able to give exhaustive answers. In particular, the innovative methodologies based on IMUs and sEMG, allow the instrumental quantitative assessment of biomechanical risk directly in the field thanks to the fact that the sensors are miniaturized, wearable, easily transportable and based on "wireless" transmission of data acquired on the worker who performs the task. These aspects facilitate data recording, allowing accurate signal acquisition even in unfavorable environments and in work situations where the worker interacts with a cobot or uses an exoskeleton. Previous studies have involved studies of non-fatiguing lifts, where the movement and relative risk of single repetitions of lifting were studied. Currently, we wonder what happens when the work activity becomes fatiguing and whether it is still possible to use these methods to classify risk. In addition, another unexplored question concerns the presence of workers who continue to perform work activity during the first phase of onset of musculoskeletal disorders: can the risk to which these workers are exposed be considered the same as that involving workers without pain? To answer these questions, we conducted an experimental campaign at the University of Birmingham in collaboration with Roma Tre University and INAIL in which subjects with and without back disorders performed fatiguing lifts of 15 minutes in three risk levels determined by three different lifting frequencies. We studied trunk muscle activity in terms of muscle coactivation of the trunk flexor and extensor muscles. The results show how coactivation can classify risk during manual load lifting activities by distinguishing not only the level of risk but also the presence or absence of back disorders. These results suggest that the use of electromyographic features to assess the biomechanical risk associated with work activities can also be used in the presence of fatiguing lifting also to distinguish the risk in case of subjects with back pain. This methodology could be used to monitor fatigue and extend the possibilities offered by currently available instrumental-based approaches.

INTRODUCTION

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tal number of diseases reported to INAIL (INAIL, 2019). Many factors can contribute to the establishment of a condition of biomechanical overload and therefore to the onset of work-related musculoskeletal disorders (WMSDs) (Kuijer et al., 2014; Garg et al., 2014; Waters et al., 1998). Among these, work-related low-back disorders (LBDs), caused mainly by handling heavy loads, are very common (Le et al., 2017a, 2017b; Waters et al., 2011; Marras et al., 2010; NIOSH, 1981).

In recent years, several methods have been developed to assess the risk of biomechanical overload, included in several international standards (ISO-11228, ISO-11226, ISO/TR 12295 and 12296) aimed at identifying high-risk work activities and assessing the effectiveness of ergonomic interventions. Among the best known, with regard to the manual lifting of heavy loads, there is the Revised NIOSH Lifting Equation (Waters et al., 1993, 1994) that, while presenting many advantages (cost-effectiveness, non-invasiveness, speed of application ...) at the same time also has limitations concerning mainly the high subjectivity (subject of scientific debate) and the impossibility of these methods to assess all work tasks.

From these premises, it is clear the usefulness of being able to use new quantitative risk assessment methodologies, objectifiable and repeatable, which provide for the possibility of assessing the risk from biomechanical overload even in modern working scenarios (Ranavolo et al. 2020) where the use of exoskeletons by workers and the sharing of working space with cobots is becoming increasingly widespread. In fact, the methods currently used are incomplete and ineffective in assessing the real impact that these technologies have on the health and safety of workers in Industry 4.0.

Recent studies (Ranavolo et al. 2015, 2017, 2018a, 2018b; Varrecchia et al. 2018, 2020, 2021) have introduced the possibilities offered by optoelectronic systems, inertial sensors (IMUs) and surface electromyography (sEMG), to integrate the most widely used observational methodologies. These modern technologies, evaluating how a subject moves his joints and uses his muscles during the execution of a work task, can integrate the observational methods, quantify the elements that characterize the risk minimizing the evaluation errors caused by individual subjectivity and allow to carry out the assessment of biomechanical risk even in those areas where the currently most widespread methodologies are not able to give exhaustive answers.

Previous studies (Ranavolo et al. 2015, 2017, 2018a, 2018b; Varrecchia et al., 2018, 2020, 2021) have involved studies of non-fatiguing lifts, where the movement and relative risk of single repetitions of lifting were studied. Only in very recent studies (Varrecchia et al., 2021), the possibility of performing an instrumental risk assessment even when the manual load lifting activity becomes fatiguing has been investigated. Another unexplored issue concerns the presence of workers who continue to perform work activities during the first phase of onset of musculoskeletal disorders. In fact, when back disorders occur, many workers, especially in the early stage, continue to work despite the painful condition, exposing themselves to an unknown risk that cannot be considered equal to that of pain-free workers. In fact, low back

pain (LBP) involves the adoption of different motor strategies aimed at reducing pain. A common strategy adopted by the central nervous system to protect and stabilize the spine from pain and injury is to increase trunk stiffness by enhancing the coactivation of antagonistic trunk muscles (Ranavolo et al., 2015, 2018). This mechanism regulates the simultaneous activity of antagonistic muscles around the same joint (Le et al., 2017a, 2017b) becoming functionally unfavorable in some cases (Falconer & Winter, 1985; Brookham et al., 2011). Furthermore, increased muscle coactivation implies increased compressive and shear forces on the spine (Collins et al. 2011) and consequently further increases the risk of LBDs (Granata & Marras, 2000). On the other hand, several studies have shown that during lifting tasks, trunk muscle coactivation increases as the risk level increases to increase spinal stability and prevent the development of LBDs (Granata & Marras 2000; Ranavolo et al., 2015, 2018). We hypothesize that workers with LBP coactivate more than people with pain-free condition by developing early muscle fatigue.

To verify our hypothesis INAIL and Roma Tre University conducted an experimental campaign at the University of Birmingham in which subjects with and without low back disorders performed fatiguing lifts of 15 minutes in three risk levels. The aim of the study is to verify how trunk muscle activity changes in terms of muscle coactivation of the trunk flexor and extensor muscles in different risk conditions and in subjects with LBP.

■ MATERIALS AND METHODOLOGIES

Participants

Fifteen healthy control (HC) participants (9 females and 6 males; age: 27.87±3.98 years; body mass index [BMI]: 25.26±3.21 kg/m²) and eight (4 female and 4 males; age: 25.15±6.5 years; BMI: 23.51±4.59 kg/m²) subjects with LBP were enrolled in this study. All the subjects gave their informed written consent before taking part in the study that was conducted according to the Declaration of Helsinki at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), the University of Birmingham, approved by the School of Sport, Exercise & Rehabilitation Sciences Ethics Committee (protocol number MCR260319-1). No information regarding the expected results have been provided to the subjects in order to avoid biasing the results. The following inclusion and exclusion criteria were used: both groups hadn't concurrent systemic, rheumatic or neuro-musculoskeletal disorders which may confound testing, current pregnancy, currently on high doses of opioids (> 30 mg of morphine equivalent dose); HC hadn't relevant history, over the last three years, of back and lower limb pain or injury that limited their function and/or required treatment from a health professional; LBP hadn't a specific cause, but it persisted for at least 3 months and has resulted in pain on at least half the days in the past 6 months; they hadn't serious pathologies and weren't in treatment for LBP by therapists for more than three months from the date of enrolment.

Experimental procedure

The experimental procedure is the same presented in Varrecchia et al. 2021. The participants performed lifting task in the three different lifting conditions that

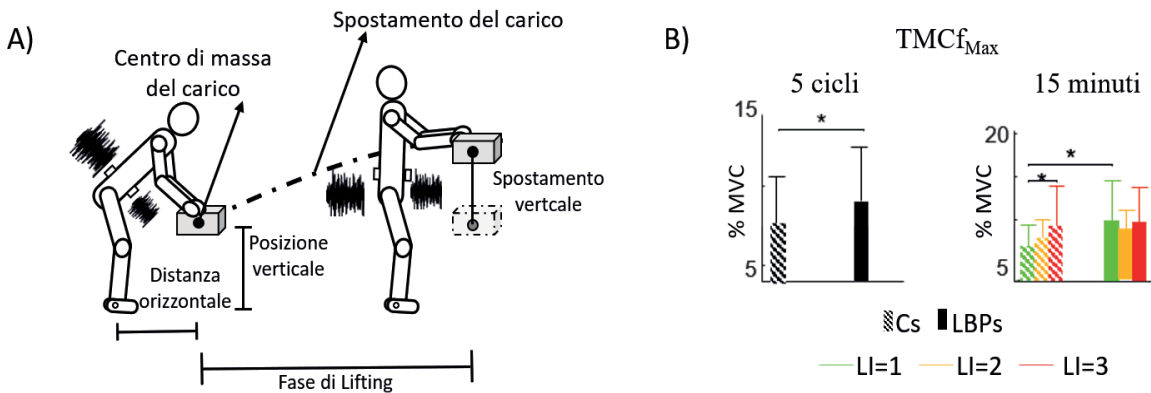


Fig. 1 - A) Description of the experimental setup. B) Results of the coactivation index ($TMCf_{Max}$) considering the first 5 cycles for all risk levels on the left and considering the 15 minutes for each risk level on the right. LI: lifting index; Cs: control subjects; LBPs: subjects with back disorders. * indicates statistically significant difference.

were selected to obtain the values of LI equal to 1, 2, and 3 (Waters et al., 1994) calculating it as follows:

$$LI = \frac{L}{RWL} = \frac{L}{LCxHMxVMxDMxAMxFMxCM} \quad (1)$$

where:

- L= 10 kg is the actual weight of the lifted load;
- RWL is the recommended weight limit (Waters et al., 1994);
- is the load constant of 23 kg (Waters et al. 1994);
- HM=0.57, VM=0.99, DM=0.93 and AM=1 are the horizontal distance, vertical location, vertical displacement and symmetry multipliers calculated by using equations by measuring the following parameters (see Figure 1A): horizontal distance (H=44 cm); vertical location (V=75 cm); vertical displacement (D=40 cm); angle of asymmetry (A=0°) (Waters et al. 1994);
- CM is the coupling multiplier for the quality of gripping that depends on hand-object coupling (C) that has been defined as “good” for all three lifting tasks (Waters et al., 1994);
- FM is the frequency multiplier depending on lifting frequency (F), lifting duration and vertical location (Waters et al 1994).

The three conditions differed only the values attributed to F (4, 11 and 15 lifts per minute for LI=1, 2 e 3 respectively) and FM (0.83, 0.41 e 0.28 for LI=1, 2 e 3 respectively) while remaining parameters and multipliers assumed the same values for all conditions. Participants lifted a plastic box (34x29x13 cm) using both hands in three different sessions performed on three different days, one for each LI (Varrecchia et al., 2021). The number of repetitions was determined by the frequency parameter used to obtain the specific LI for each session so that the duration of the lifting task was 15 minutes. Participants with LBP were asked to perform the lifting repetitions to exhaustion even if they lasted less than 15 minutes. Acoustic feedback was used to monitor the frequency of the tasks. In addition, voluntary maximal isometric contractions (iMVCs) for the trunk flexor and extensor muscles were performed in each of the three sessions before the lifting tasks.

Electromyographic and Inertial Measurement Unit recordings

Muscle activity was recorded using four wireless bipolar sEMG sensors (Ultimum EMG system, Noraxon, USA Inc. Scottsdale, AZ) placed over the right and left erector spinae longissimus (RESL and LESL) and the right and left rectus abdominis superior (RRAS and LRAS) (www.seniam.org; Barbero et al., 2012). The sampling frequency for the bipolar sEMG was set at 2000 Hz. Furthermore, an IMU was placed on the plastic crate (z-axis in the vertical direction; sampling frequency 2000 Hz). Data from the bipolar sEMG and Inertial Measurement Unit (IMU) were acquired simultaneously and synchronized with a synchronizing device.

Data analysis

Data were processed using Matlab (version 2018b 9.5.0.1178774, MathWorks, Natick, MA, USA) software. The IMU and sEMG data during the lifting task were time-normalized to the duration of the task phase (lifting and lowering) and reduced to 200 samples per phase using a linear interpolation procedure. This interpolation procedure allows a comparison between different lifting tasks with different durations (Varrecchia et al 2021).

Lifting cycles detection

The vertical displacement and velocity of the IMU placed over the crate were calculated integrating the filtered acceleration of the IMU (3rd order low-pass Butterworth filtered by applying a 10Hz cut-off frequency) once and twice respectively, and the drift was corrected assuming that before and after lifting, the vertical acceleration and speed were zero. The onset and termination of the lifting phase were defined as the time point at which the IMU velocity exceeded a velocity threshold of 0.025 m/s along the vertical axis and the maximum point of the vertical displacement of the IMU respectively (Figure 1A; Ranavolo et al., 2015; Varrecchia et al., 2021).

Time-varying multi-muscle coactivation function (TMCf)

The sEMG signals recorded for both iMVC and lifting tasks were band-pass filtered using a 3rd-order Butterworth filter of 25–400 Hz to reduce low-frequency ar-

tifacts and high-frequency noise (Butler et al. 2009). To extract the envelope of sEMG signals of each lifting task, full-wave rectification, and low-pass filtering (4th-order Butterworth filter at 5 Hz) were applied (Winter, 2009). For each muscle, the sEMG envelope was amplitude-normalized to the average iMVC peak value (Ranavolo A, 2021, Hermens et al., 2000).

The time-varying multi-muscle coactivation function (TMCf) (Ranavolo et al., 2015 and 2018) was computed to estimate the co-activation of the four trunk muscles during lifting task using the following formula:

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

with

$$(3) \quad d(k) = \frac{\sum_{m=1}^{M-1} \sum_{n=m+1}^M |sEMG_m(k) - sEMG_n(k)|}{J \binom{M}{2}}$$

where $d(k)$ is the mean of the differences between the k th samples of each pair of sEMG signals; J is the length of the signal; M is the number of considered muscles; and $sEMG_m(k)$ and $sEMG_n(k)$ are the k th sample value of the envelope of the sEMG signals of the m th and n th muscles respectively. As co-activation synthetic indices, the maximum (TMCf_{Max}) values within the cycles were calculated. TMCf_{Max} in all the conditions (LI=1, 2 and 3) of all the lifting tasks were time-averaged considering all cycles in the 15 minutes. Furthermore, the first 5 cycles of each lifting condition were averaged to compare the two groups removing the fatiguing effect.

STATISTICAL ANALYSIS

The statistical analysis was performed by using Matlab software (version 2018b 9.5.0.1178774, MathWorks, Natick, MA, USA) to verify the difference between Cs and LBPs, and the effect of the risk levels on TMCf_{Max} considering all lifting repetitions. Furthermore, considering the first five cycles for each lifting condition, the statistical analysis was performed to verify the group effect on TMCf_{Max}. The normality of data distribution was checked using the Shapiro-Walk test. Then, in each group (HC and LBP), one-way repeated-measures analysis of variance (ANOVA) or

corresponding Friedman t-test (if data not normally distributed) was performed to determine whether LI levels determine significant changes in the parameter. Post-hoc analyses were performed using a paired t-test with Bonferroni's corrections when significant differences were observed. Furthermore, for each LI, the unpaired two-sample t test or Mann-Whitney (MW) test was used to evaluate differences in the TMCf_{Max} parameter between Cs and LBPs. For all statistical analysis the significance level was set at p-value<0.05.

RESULTS AND DISCUSSION

The results of the study are shown in Figure 1B. Statistical analysis showed a statistically significant difference between the two populations (p<0.05): LBPs coactivate more during lifting already at the beginning of the activity and independently of the risk level (Figure 1B left). Moreover, for Cs, the coactivation index, considering 15 minutes of manual lifting activity, allows to classify the risk level (Figure 1B right). These results suggest that the use of electromyographic indices to assess biomechanical risk associated with work activities can also be used in the presence of fatiguing lifting and also to distinguish risk in the case of subjects with low back disorders. Future developments could include investigating how the time factor may affect the risk classification by going to perform the analysis proposed in this study in time windows of one minute verifying if the risk classification and the distinction of the two population groups is more evident as the duration of the task increases. In conclusion, the innovative methodologies based on IMUs and sEMG, could facilitate an instrumental and quantitative assessment of biomechanical risk even in fatiguing frequency-dependent lifting activities directly in the workplace due to the fact that the sensors are miniaturized, wearable, easily transportable and based on "wireless" transmission of data acquired on the worker performing the task. These aspects facilitate data recording, allowing accurate signal acquisition even in unfavorable environments and in work situations where the worker interacts with a cobot or uses an exoskeleton.

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