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Article

Upper Limbs and Low-Back Loads Analysis in Workers Performing an Actual Industrial Use-Case with and without a Dual-Arm Cobot

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Abstract: In the industry 4.0 scenario, Human–Robot Collaboration (HRC) plays a key role in factories to reduce cost, increase production and help aged and/or sick workers maintain their job. The approaches of the ISO 11228 series commonly used for biomechanical risk assessment cannot be applied in Industry 4.0 as they do not involve interaction between workers and HRC technologies. The use of wearable sensor networks and software for biomechanical risk assessment could help us have a more reliable idea on the effectiveness of collaborative robot (coBots) in reducing biomechanical load for workers. The aim of the present study was to investigate some biomechanical parameters with 3D Static Strength Prediction Program (3DSSPP) software, on workers executing a practical manual material handling task, by comparing a dual arm cobot assisted scenario with a no cobot scenario. The parameters investigated were percent of Maximum Voluntary Contraction, Maximum static (continuous) allowed exertion time, Low back spine orthogonal compression forces at L4/L5 level and Strength Percent Capable. In this study, we calculated mean and the standard deviation (SD) values from eleven participants for some 3DSSPP parameters. We considered the following parameters: Percent of Maximum Voluntary Contraction (%MVC), Maximum static allowed exertion time (MaxST), Low back spine compression forces (L4Ort) and Strength Percent Capable (SPC). The advantages in introducing the cobot, according to our statistics, concern trunk flexion (SPC from 85.8% without cobot to 95.2%; %MVC from 63.5% without cobot Vs. 43.4%; MaxST from 33.9s without cobot to 86.2s), left shoulder abdo-adduction (%MVC from 46.1% without cobot Vs. 32.6%; MaxST from 32.7s without cobot to 65s) and right shoulder abdo-adduction (%MVC from 43.9% without cobot Vs. 30.0%; MaxST from 37.2s without cobot to 70.7s) in Phase 1; right shoulder humeral rotation (%MVC from 68.4% without cobot Vs. 7.4%; MaxST from 873.0s without cobot to 125.2s), right shoulder abdo-adduction (%MVC from 31.0% without cobot Vs. 18.3%; MaxST from 60.3s without cobot to 183.6s) and right wrist flex/extension rotation (%MVC from 50.2% without cobot Vs. 3.0%; MaxST from 58.8s without cobot to 1200.0s) in Phase 2. Moreover, Phase 3, consisting of another manual handling, would be removed by using the cobot. In summary using the cobot in this industrial scenario, would reduce the biomechanical risk for workers particularly for trunk, both shoulders and right wrist. Finally, 3DSSPP software could be an easy, fast and costless tools for biomechanical risk assessment in industry 4.0 scenario where ISO 11228 series can't be applied for occupational medicine physicians and health and safety technicians and helping employers to justify a long-term investment.

Keywords: Human-robot collaboration; motor coordination; manual material handling

1. Introduction

With millions of workers affected, work-related musculoskeletal disorders (WMDs) from neck, trunk and upper limb, are a major cause of lost workdays. Lost workdays come at a high cost to companies and public health systems, amounting to billions of dollars [1]. It has been known for a long time that the onset and progression of these illnesses are influenced by biomechanical overload [2]. For example, during heavy lifting activities, if the compressive and shear forces stressing the lumbosacral junction exceed tissue tolerance, damage can occur [3].

Industry

4.0

(https://www.bcg.com/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries.aspx) is the implementation of intelligent technologies to increase productivity and to reduce the associated biomechanical risks [4]. From a general point of view, the integration of ergonomic and human factor requirements in human-robot collaborative (HRC) systems, such as collaborative robots (coBots), represents a new option for reducing the physical effort of the workers, during the execution of manual material handling (MMH) activities, and for adopting new ergonomic interventions for preventing work-related musculoskeletal disorders (WMDs). In detail, the use of coBots in smart manufacturing environments is providing the unique opportunity to design MMH activities executed by hybrid human-robot teams, by reducing the physical exertion of the human member of the team [5].

As the use of coBots in manufacturing has recently increased considerably, all the potential benefits need to be investigated in depth and proven, especially in the MMH phases where the physical interaction of the worker with the coBot takes place. Indeed, while the issue of safety in this new hybrid scenario is currently widely investigated, the issue of health is still very little [6] also in consideration of the fact that the above-mentioned physical interaction was not foreseen by the methods listed in the International Ergonomics Standards Series [7,8,9,10] that had also other limitations [11,12,13]. For this reason, it will be crucial to include the broadest knowledge of the biomechanics of the occupational tasks performed with the aid of CoBots, within the new approaches that will be developed for biomechanical risk assessment [14,15,16,17]. On the other hand, the complexity of the problem requires to identify the risk of WMDs in MMH activities with a preference for instrumental-based and personalized analyses and models [16,17,18,19,20]. These include the need for assessing kinematic, kinetic and muscular behaviours.

While the measurement of kinematic and muscular behaviours is nowadays easier thanks to wearable sensor networks consisting of inertial measurement units (IMUs) and surface electromyography sensors (sEMG), the measurement of forces insisting on the body districts of interest is more difficult. In fact, force platforms are not usable in the field and shoes or sensor insoles are not yet precise and accurate enough, for measuring vector information [17].

As evidence of the above, some examples show that, with regards to the kinematic analysis, the improvement of physical ergonomics of MMH activities performed with the aid of coBots has been measured in a real-work scenario [6,15] through the application of the Occupational Repetitive Action (OCRA) [21] and Rapid Upper Limb Assessment (RULA) [22] methods. With regards to the estimation of muscular activities, an experimental session carried out under the aegis of the SOPHIA (Socio-Physical Interaction Skills for Cooperative Human-Robot Systems in Agile Production, <http://www.project-sophia.eu>, accessed on 12 March 2024) project, allowed the evaluation of upper limb muscle coordination and activation, by using a wearable sensors network, in workers performing an actual use-case MMH; with and without the help of a dual-arm coBot, namely BAZAR [23]. The results of this study showed that, when MMH was carried out with BAZAR, both upper limb and trunk muscular co-activations and activations were decreased, demonstrating that coBots have a positive impact on the workers motor strategy. For instance, with regards to the assessment of the forces acting on the spine, several studies have considered regression models based on the muscle activity or trunk posture [24,25], some optimization procedures [26,27,28,29], combination of sEMG measurements and data driven musculoskeletal models [30,31,32,33,34] and video-based software such as Static Strength Prediction Program (3DSSPP) [35,36].

Among the approaches for studying joint kinetics, the latter, designed by the University of Michigan, is a simple option for measuring compressive forces acting at the lumbo-sacral joint, during the execution of hybrid worker-coBot MMH tasks, under the hypotheses that this interaction may reduce the L4-L5 and L5-S1 forces and enhance the maximum static holding time. Besides, the use of 3DSSPP becomes even more interesting when the analysis of the human-coBot interaction reproduces an industrial use-case. The literature shows that the assessment of the kinetics of the lumbo-sacral joint indicates a robust correlation between the results carried out using 3DSSPP and other methods. It can satisfactorily predict the L4-L5 interdiscal pressure, including low exposures, and detect similar patterns for the compressive forces [37,38,39,40]. Furthermore, 3DSSPP has been applied for assessing biomechanical risks in several workplaces, tasks and conditions [41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56]. Hence, the aim of the present study was to compare kinetic variables in workers executing an actual industrial use-case performed with (wB) and without BAZAR (woB). It has been hypothesized that the load on the lumbosacral joints is reduced in wB activities.

We also had the aim to verify if 3DSSPP software could be a useful tool for biomechanical risk assessment in industry 4.0 scenario where ISO 11228 standards [7,8,9] can't be applied for occupational medicine physicians and health and safety technicians and if 3DSSPP can help employers to justify a long-term investment as could be a cobot.

The study has been performed as part of the SOPHIA project, funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 871237. The SOPHIA project has set the aim to provide a contribution in the development of new coBots to effectively mitigate the physical effort and reduce the WMDs associated to several MMH activities [57,58].

The paper is structured as follows: section II presents the setup, the experimental protocol, and the conducted analysis. Results are illustrated in Section III. Section IV contains a discussion on the work, and finally, Section V contains conclusions.

2. Materials and Methods

2.1. Participants

Eleven participants (5 females and 6 males; age: 27.73 ± 5.99 years; height: 175.4 ± 7.7 cm; weight: 71.3 ± 15.2 kg; body mass index [BMI]: 23.06 ± 3.93 kg/m²) took part in the study. The study was carried out at the University of Montpellier in accordance with the Helsinki Declaration and authorized by the University of Montpellier EuroMov's Laboratory Ethics Committee (Protocol number IRB-EM 2103A). Inability to give informed written consent, history of musculoskeletal disorders, upper, lower limb, or trunk surgery, orthopedic or neurological diseases, vestibular system disorders, visual impairments, or back pain, current pregnancy, current pharmacological treatment, and obesity were all exclusion criteria.

Each participant completed the task six times: three times wB and three times woB. We randomly ordered the two conditions (wB and woB) to avoid bias, for each subject. Before the participant performed either condition for the first time, we instructed him/her by showing a video of the task, and by letting him/her execute it once, without recording.

The sample size (11) was as large as possible due to the complexity of the task and limited time we had, one week, which involved performing the work task twice, without and with the BAZAR robot. In this week we recruited all the subjects who voluntarily decided to participate in the study and who met the inclusion criteria. We tried to acquire a sample as possible homogenous under the point of view of anthropometric characteristics. In the algorithm that 3DDSSP applies, anthropometry, the weight in particular, affect orthogonal compression forces at L4/L5 level. The sample has a near-average BMI because we want to minimize possible outlier data due to high or low BMI minimizing a remarkable bias.

2.2. Task Analysis

The experimental session is the same as that described in a previous article [23] so we recommend reading it for further information about the task analysis.

The differences between the two tasks were:

- Phase I: subtask 3 wB (Fig.1 - a1) replaced subtask 4 woB (Fig.1 - b1);
- Phase II: subtasks 7, 8 wB (Fig.1 - a2) replaced subtasks 8,9,10 woB(Fig.1 - b2);
- Phase III: subtask 9, 10 wB (Fig.1 - a3) replaced subtask 11 woB (Fig.1 - b3).

In this study we considered these three Phases for the tasks wB and woB.

The experiments are shown in the video available at: <https://www.youtube.com/watch?v=vul8iLO0Sdw>, accessed on 12 March 2024.

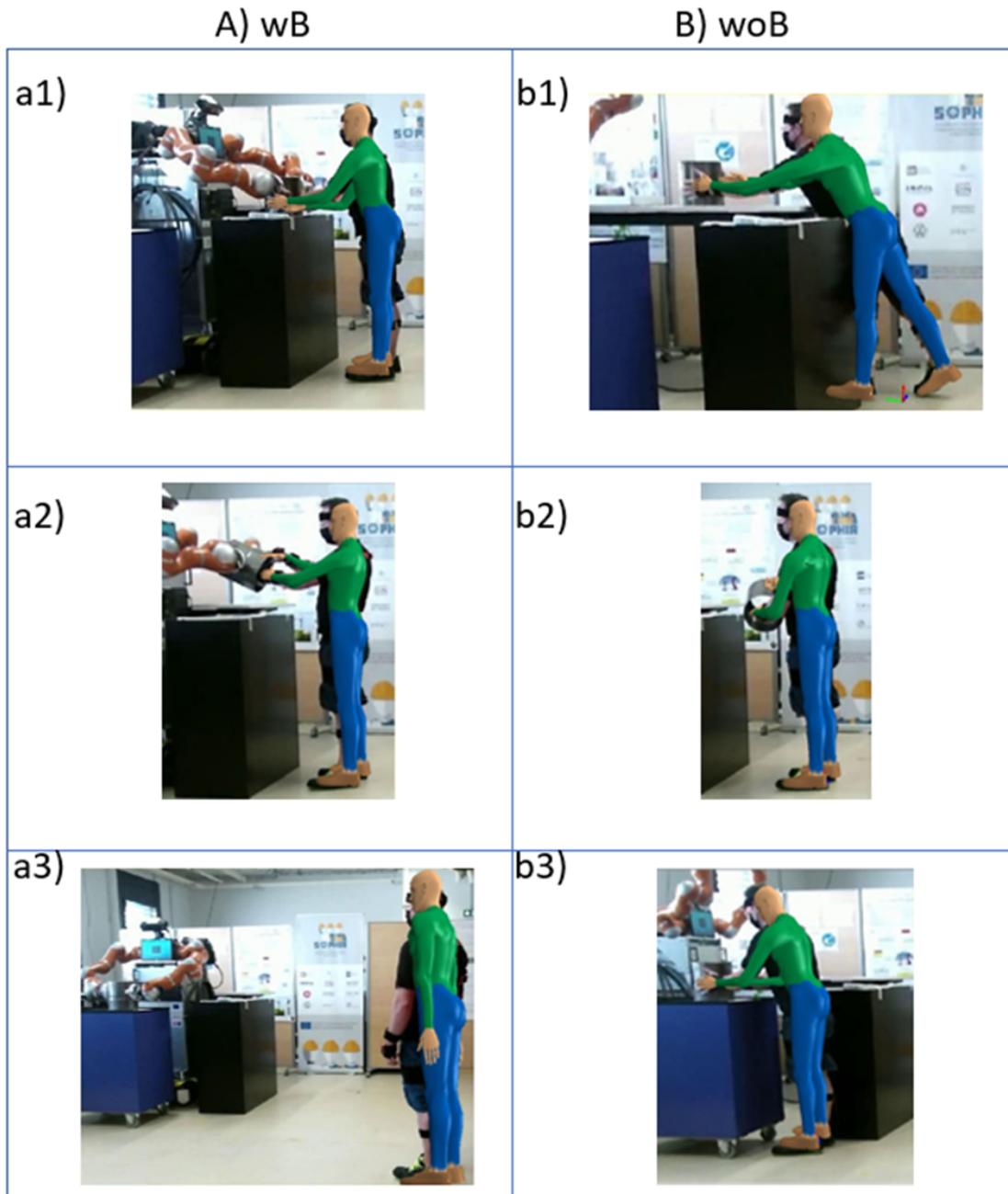


Figure 1. The figure shows some 3DSSPP reconstructions of the three subtask analyzed. Phase 1 with (a1) and without (b1) coBot; Phase 2 with (a2) and without (b2) coBot; Phase 3 with (a3) and without (b3) coBot.

2.3. 3D Static Strength Prediction Program (3DSSPP)

Through 3DSSPP, it is possible to recreate the worker's posture by overlaying an avatar model on a selected frame [35,36]. The entry data that the software requires are the worker gender, height and weight. These last two data could be from specific input data or through population percentile (95th, 50th, 5th). In this paper we used the real data of participants. The body segments of the avatar can be manipulated by clicking any joint and dragging it to a new location, through an angle dialog. We used this software because it is a good balance among accuracy of the data, costs for a biomechanical risk assessment for middle-low factories and user friendliness. Common biomechanical risk assessment tools in ISO standards [7,8,9] are cheaper but can't be applied in industry 4.0 scenario; posture analysis with optoelectronic systems or Inertial Measurement Units (IMUs) is very accurate but it's expensive and needs specialized skills. The reconstruction made with 3DSSPP suffers of accuracy because it depends on subjective eye visualization but can be used in our scenario, is easy to use, provides parameters that could be helpful for better understand biomechanical overload differences in our case scenario and it's cheaper than instrumental assessment.

In this study, we calculated mean and the standard deviation (SD) values from eleven participants for some 3DSSPP parameters. 3DSSPP parameters that we considered useful for the investigated task were the following: Percent of Maximum Voluntary Contraction (%MVC), Maximum static allowed exertion time (MaxST), Low back spine compression forces (L4Ort) and Strength Percent Capable (SPC). All the values of the parameters considered are referred to the reconstructions made with the software. For each participant, the best image was selected. The values are referred to three identified phases where the presence of the coBot changed significantly execution.

2.3.1. Percent of Maximum Voluntary Contraction (%MVC)

According to 3DSSPP the percent of maximum voluntary contraction (%MVC) is the required effort at each joint. Unlike what is done for sEMG, where the %MVC is determined for each individual muscle, in 3DSSPP the values are referred to a joint district, so several muscles can be part of the district, for a selected population.

In the software, it is possible to choose the %MVC of a selected population corresponding to the 5th, 25th, or 50th, percentile. These values represent workers very weak, weak, and with average strength. In our study we considered the %MVC bilaterally for:

- wrist flexion/extension (wrist flex/ext), ulnar/radial deviation (wrist uln/rad) and rotation (wrist rot);
- elbow flexion/extension (elbow flex/ext);
- shoulder humeral rotation (shoulder hum rot), backward/forward rotation (shoulder bk/fw) and abduction/adduction (shoulder abd/add);
- neck flexion/extension (neck flex/ext);
- trunk flexion/extension (trunk flex/ext).

We considered these %MVC values because we want to analyze the most involved joints.

2.3.2. Maximum Static (Continuous) Allowed Exertion Time (MaxST)

This parameter is referred to the maximum static exertion. ACGIH embedded a refitted curve from Potvin's data [59,60] in the ACGIH TLVs and BEIs [61] for localized fatigue of the upper limb and for the trunk. The maximum static exertion duration time is 20 minutes (1200 seconds). The static duration is strictly correlated to %MVC. Also for static duration, it is possible to select the population strength percentile and gender. As for the %MVC, we estimated the MaxST bilaterally of the most involved joints in the task:

- wrist flexion/extension, ulnar/radial deviation and rotation;
- elbow flexion/extension;
- shoulder humeral rotation, backward/forward rotation and abduction/adduction;
- neck flexion/extension;

- trunk flexion/extension.

2.3.3. Low Back Spine Compression Forces (L4Ort)

The software provides values for orthogonal forces acting on the spine. The biomechanical model is optimized for the L4/L5 level, but it also provides values at L5/S1 level. 3DSSPP indicates the Strength Design Limit (SDL) and the Strength Upper Limit (SUL) corresponding to the NIOSH Action Limit (3400N) [62] and Maximum Permissible Limit (6400N) [63]. The SDL designation is set at 99% for men or 75% for women. The SUL designation is set at 25% for men or 1% for women as for NIOSH. In this paper, we only used data from compression forces at L4/L5 level, since it is the most considered joint in biomechanics.

2.3.4. Strength Percent Capable (SPC)

The Strength Percent Capable parameter analyzes the strength for the major joints (wrist, elbow, shoulder, trunk, hip, knee, and ankle). It indicates the percentage of the selected population capable of performing the analyzed task, without injuries. In our study, we only considered SPC values that were most relevant for our task (wrist, elbow, shoulder and trunk).

2.4. Statistical Analysis

To check differences between the two conditions (wB and woB), the statistical analysis was carried out using PASW Statistics 18. The Shapiro–Wilk test was used to verify the normality of the data distribution for each parameter. The paired sample t-test was then used to evaluate whether the help of the coBot had determined significant changes in each parameter. The significance level for all statistical analyses was set at p-value < 0.05.

3. Results

3.1. Phase 1

Figure 2 shows the mean results of the reconstructions of the 11 subjects in Phase 1 wB and woB. In this Phase, the only parameter presenting a significant statistical difference in favour of not using the coBot was the left shoulder bk/fw movement (3.5% Vs 5.7%, $p=0.028$).

Several parameters, meanwhile, showed statistically significant differences in support of coBot use. Results show a statistically significant reduction of orthogonal force at L4/L5 level (1675.5N Vs 2365N, $p\leq 0.01$). Reduced risk for the trunk is also confirmed in the corresponding SPC parameter (95.2% Vs 85.8%, $p\leq 0.01$), trunk %MVC (43.4% Vs 63.5%, $p\leq 0.01$) and maximum static holding time (63.5s Vs 43.4s, $p\leq 0.01$). A further value of SPC in supporting the use of the coBot is that of the shoulders (99.1% Vs 97.4%, $p=0.0388$). As regards the left arm, a statistically significant reduction in %MVC was found for wrist flex/ext (9.5% Vs 16.6%, $p=0.0018$), shoulder hum rot (6.5% Vs 11.8%, $p\leq 0.01$) and shoulder abd/add (32.6% Vs 46.1%, $p\leq 0.01$). The right arm had statistically significant reduction only in shoulder abd/add (30% Vs 43.9%, $p\leq 0.01$).

The maximum static continuous allowed exertion time parameter is strongly related to %MVC. The same %MVC results were statistically significant. MaxST parameters of the left arm increased in wrist flex/ext (783s Vs 384s, $p\leq 0.01$), shoulder hum rot (1007.9s Vs 481.3s, $p\leq 0.01$) and shoulder abd/add (65s Vs 32.7s, $p\leq 0.01$). For the right arm, abd/add of the shoulder was the only statistically significant difference (70.7s Vs 37.2s, $p\leq 0.01$) in which MaxST increased.

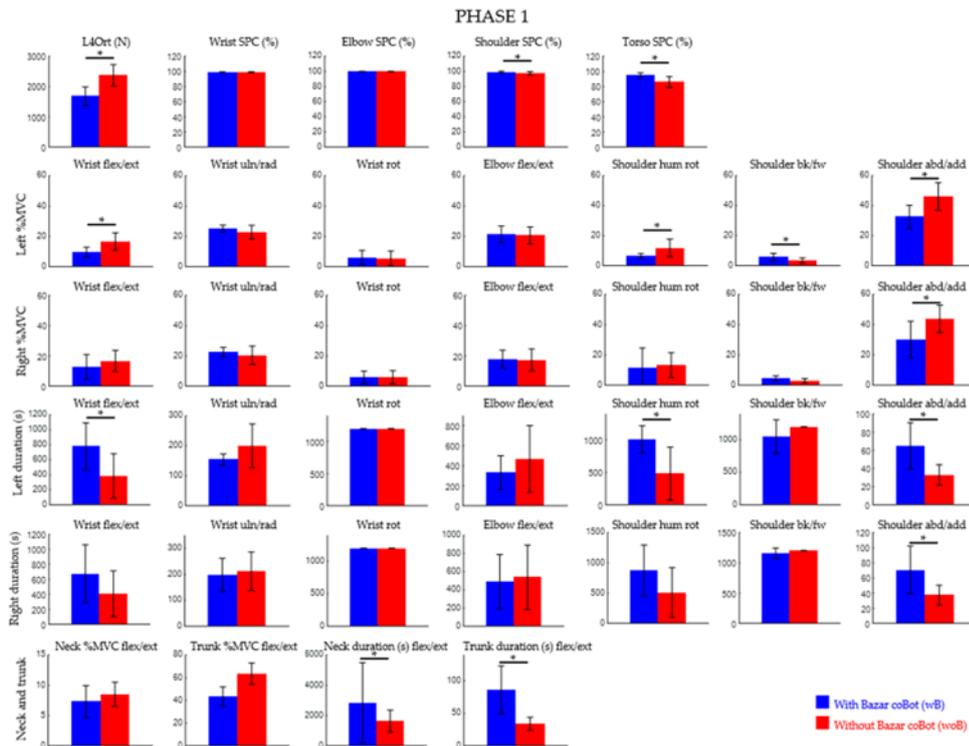


Figure 2. Mean and SD values for Phase 1, with Bazar (wB) in blue and without Bazar (woB) in red, for the investigated parameters (L4-L5 orthogonal forces, Strength Percent Capable, %MVC and maximum holding time). Star over the bars shows a statistical significance.

3.2. Phase 2

Figure 3 shows the mean results of the reconstructions of the 11 subjects in Phase 2.

This Phase reported, only on the left arm, three parameters unfavorable for using coBot for the %MVC and one parameter for the maximum holding time. For the %MVC, there was a drawback in the use of the coBot in wrist rot (1.6% Vs 1.0%, $p \leq 0.01$) shoulder hum rot (4.5% Vs 1.8%, $p \leq 0.01$) and shoulder abd/add (14.7% Vs 5.4%, $p \leq 0.01$); for the maximum holding time, the drawback in the use of the coBot was only for left shoulder abd/add (294s Vs 1025.6s, $p \leq 0.01$).

Many parameters argue in favor of using the coBot. Statistically significant differences can be seen in orthogonal force at L4/L5 level (628.5N Vs 1066.6N, $p \leq 0.01$) and in th SPC for the wrist (100% Vs 89.3%, $p \leq 0.01$), elbow (100% Vs 99.6%, $p = 0.0171$) and shoulder (100% Vs 80.4%, $p \leq 0.01$). The %MVC parameter was unfavorable only for the left shoulder bk/fw (2.0% Vs 3.1%, $p = 0.0226$). All %MVC parameters of the right arm resulted statistically significant in favor of coBot use: wrist flex/ext (3.0% Vs 50.2%, $p \leq 0.01$), wrist uln/rad 1.7% Vs 31.9%, $p \leq 0.01$, wrist rot (1.0% Vs 20.0%, $p \leq 0.01$), elbow flex/ext (2.6% Vs 20.1%, $p \leq 0.01$), shoulder hum rot (7.4% Vs 68.4%, $p \leq 0.01$), shoulder bk/fw (2.4% Vs 13.2%, $p \leq 0.01$) and shoulder abd/add (18.3% Vs 31.0%, $p = 0.0235$). Favorable statistically significant differences also emerged in the neck (4.0% Vs 8.9%, $p \leq 0.01$) and trunk (13% Vs 22.2%, $p \leq 0.01$) %MVCs. Statistically significant differences in maximum holding time are found - only on the right upper arm for: wrist flex/ext (1200s Vs 58.8s, $p \leq 0.01$), wrist uln/rad (1200s Vs 494.7s, $p \leq 0.01$), elbow flex/ext (1200s Vs 531.5s, $p = 0.00009$), shoulder hum rot (873s Vs 125.2s, $p \leq 0.01$) and shoulder bk/fw (1200s Vs 656.9s, $p \leq 0.01$).

Lastly, the neck's maximum holding time also proved to be statistically significant (13282.7s Vs 1803.4s, $p = 0.0109$).

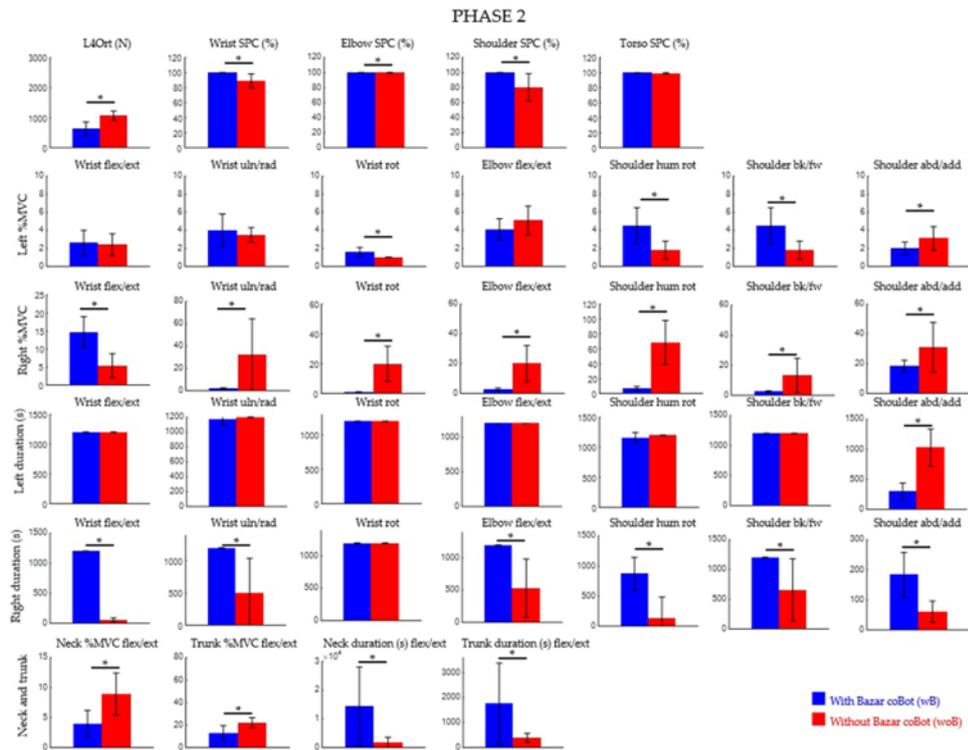


Figure 3. Mean and SD values for Phase 2, with Bazar (wB) in blue and without Bazar (woB) in red, for the investigated parameters (L4-L5 orthogonal forces, Strength Percent Capable, %MVC and maximum holding time). Star over the bars shows a statistical significance.

3.3. Phase 3

Figure 4 shows the mean results of the reconstructions of the 11 subjects in Phase 3. This figure only shows values of the task performed without the coBot, since this Phase is eliminated with the coBot.

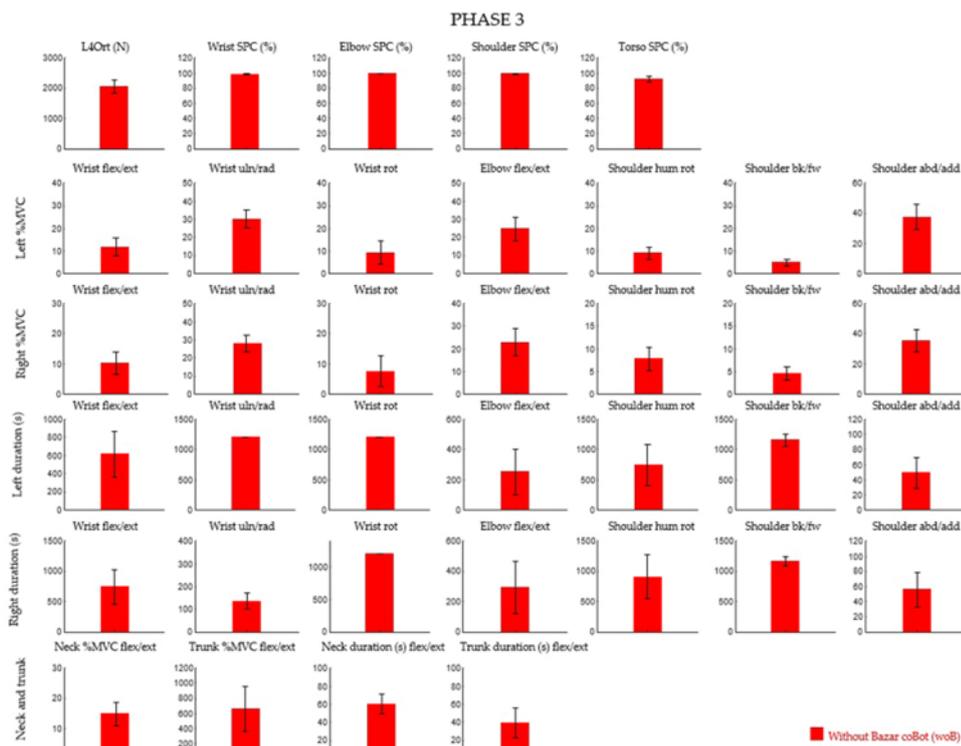


Figure 4. Mean and SD values for Phase 3 without Bazar (woB) in red, for the investigated parameters (L4-L5 orthogonal forces, Strength Percent Capable, %MVC and maximum holding time). Using Bazar cobot this phase will be totally automatized, so we don't have values with Bazar (wB) and blue bars.

4. Discussion

The 3DSSPP is a software developed by the University of Michigan based on studies and research which lasted over 40 years in the field of biomechanics [35,36]. This software is a useful tool, in both proactive and reactive ergonomics, for designing and assessing workplaces and work tasks and for showing the effectiveness of an ergonomic intervention.

In our study, unskilled participants performed a real work task which we replicated in the laboratory. We assessed, through 3DSSPP software, the different biomechanical loads in executing the task with and without a coBot. Introducing the coBot involves changes in task execution. Main differences were the change in lifting (Phase 1), support during workpiece cleaning (step 2) and the removal, with the coBot, of a further lifting (Phase 3). From 3DSSPP we obtained various parameters that can help us in a biomechanical risk assessment. The percent of maximum voluntary contraction (%MVC) is the required effort at each joint and it's a parameter that can be helpful to estimate workers' muscle activity without using surface electromyography, that is a more objective tool for quantify muscle activity but is not cheaper and easy to use as 3DSSPP [64]. Maximum Static (Continuous) Allowed Exertion Time (MaxST), it's a parameter that helped us to know how much increased the time that a worker can assume the analyzed posture before fatigue appears; also this parameter could be estimated through a surface electromyography analysis. However, in our lab simulation the task is performed only for few minutes and sEMG could not provide fatigue data after a so short time. Low Back Spine Compression Forces (L4Ort) is a parameter that help us to quantify the reduction of orthogonal forces acting at low back. It's well known that low back compression and shear force are among the most relevant causes of Lower-back MSDs [3]. Strength Percent Capable (SPC) parameter indicates the percentage of the selected population capable of performing the analyzed task without injuries for several joints of the body; this parameter could be helpful for employer to quantify the reduction of lost days dues to MSDs and help them to justify a long-term investment such as acquiring a coBot.

The possibility of estimating the variables above described directly involved in the generation of damage with a video-based approach is particularly relevant. In fact, this would allow the worker to be monitored, even during interaction with the coBots, without altering his natural motor strategy and without interfering with his work. Currently, when analyzing occupational tasks, marker/sensor-based approaches are largely used. A further strength of this study relates to its being a use-case simulated in the Lab in the same way as it is executed in the workplace since the task is an actual industrial case. Our experimental data helped the factory to justify long term investment of coBots in this task.

As regards the downsides, in Phase 1 the statistically significant increase of %MVC of left shoulder back/forward (5.7% Vs 3.5%, $p=0.028$, Figure 2) does not correspond to a statistically significant decrease in the maximum holding time (1049.1s Vs 1200s, $p=0.0689$, Figure 2). In addition to this, we must consider the effective duration of the task (about 180s), which is well below the maximum holding time allowed by the algorithm of the software, meaning this negative data is negligible. Same conclusions apply in Phase 2 for the left wrist rot (1.6% Vs 1.0%, $p\leq 0.01$, Figure 3) and for the left shoulder hum rot (4.5% Vs 1.8%, $p\leq 0.01$, Figure 3) which do not match statistically significantly in maximum holding time (1200s Vs 1200s. left wrist rot $p=1$, Figure 3; 1200s Vs 1160.2s, left shoulder hum rot, $p=0.1536$, Figure 3). The only movement showing a statistical significance against coBot use for both %MVC and maximum holding time is left shoulder abd/add (5.7% Vs 14.7%, $p\leq 0.01$, Figure 3; 1025.6s Vs 294s, $p\leq 0.01$, Figure 3). For Phase 1 as well, the maximum holding time, based on 3DSSPP data, is higher than the effective task duration.

Remarks analogous to the negative aspects can also be done about the positive ones. Although largely within the thresholds proposed by Jager [65], there is a statistically significant reduction for L4/L5 orthogonal force in all Phases. In detail, 2365N Vs 1675.5N in Phase 1 ($p\leq 0.01$, Figure 2), 1066.6N Vs 628.5N in Phase 2 ($p\leq 0.01$, Figure 3); in Phase 3 the 2046.1N mean (Figure 4) is eliminated since the task is fully performed by the coBot. Therefore, in these phases there is a reduction in biomechanical effort

when the coBot is used. These results could be attributed to the fact the coBot helps the worker in the analyzed phases reducing his/her biomechanical risk without obstructing him/her. Indeed, the coBot works synchronized with the worker and does not hinder him from working.

Notable statistically significant reductions in the SPC parameter involved the trunk in Phase 1 (95.2% Vs 85.8%, $p \leq 0.01$, Figure 2), and the shoulders (100% Vs 80.4%, $p \leq 0.01$, Figure 3) in Phase 2.

As for the %MVC, most relevant results of Phase 1 concerned the reduction of abdo-adduction values for both shoulders and for the trunk, (Figure 2). Contextually, we found an increase in maximum exposure times from 32.7s to 65s for the left shoulder, from 37.2s to 70.7s for the right shoulder, and from 33.9s to 86.2s for trunk flexion (Figure 2). Though the lifting Phase 1 only lasts few seconds, relatively to the overall length of the task, the maximum exposure time is about double, leading to the reduction of the biomechanical risk for the worker, when the task is executed with the coBot. To play an important role in reducing the risk in this Phase is that the worker, through the coBot, performs the lifting with a reduced trunk flexion and shoulder extension, as the coBot helps move the load/gear closer to the worker than the usual position without the coBot (Fig.1 a1 e b1).

In Phase 2, most notable results concern flexion/extension of the right wrist and humeral rotation of the right shoulder. The %MVC of the wrist decreased from 50.2% to 3.0% and the shoulder from 68.4% to 7.4%, (Figure 3). Contemporary maximum exposure times increased from 58.8s to 1200s for the wrist and from 125.2s to 873.0s for the shoulder (Figure 3). In this Phase, the worker cleans the load/gear and its weight, unassisted by the coBot, is fully sustained by his/her right limb. Together with the hooking grip that workers used, it is possible to better understand how much this task is overloading for shoulder and wrist joints (Fig.1 a2). By using the coBot, the load/gear would be completely supported by it. The worker would only locate the load/gear in the most correct position for his/her anthropometric characteristics without holding it (Fig.1 b2).

As mentioned previously, finally, by using the coBot, there would not be Phase 3. In this Phase, the lifting of the load/gear inside the packaging would be fully automated (Fig.1 a3 e b3).

A few remarks are also to be made concerning this paper. A limitation of the study is the small sample size. It is due to the lengthy and intricate nature of the experimental session, which entailed performing the work task twice, once with and once without the BAZAR robot. Moreover, the experiments were only feasible for a brief period, during which two research groups collaborated and shared technologies and knowledge at the University of Montpellier as part of the EU's Horizon 2020 SOPHIA project (refer to the "funding" section for more information). Greater sample sizes in subsequent research will be helpful in validating the findings of this investigation.

About the methodology, a recent article [66] reported that the output of the 3DSSPP software did not accurately correlate with the estimated linear arm strength values and percent capable values, in female, for the range of conditions tested, likely due to the overly simplified assumptions made to estimate triaxial shoulder strength. Data affected relate to shoulder results and not to those of trunk and wrist. With regards to Phase 1, our data are mediated by a mixed sample of men and women, resulting in a narrow margin of error. As far as Phase 2 data is concerned, however, the difference observed is sufficiently wide, to overcome the method error margins shown by Hall. Moreover, in contrast to these considerations, there are also findings in another article [67] stating that static models underestimate joint loads and that therefore the risk under real, dynamic working conditions could be potentially higher than in our results. Finally, the reconstructions are not as accurate as could be with optoelectronic and IMUs systems and suffers from subjective perception of who did the reconstructions. We tried to minimize this bias making two different reconstructions of the same picture from two different authors in double blind. At the end all the authors discussed all the reconstructions together trying to reduce subjective perception.

5. Conclusions

The data presented last year by the President of Italian Workers' Compensation Authority [68] to the Italian Parliament demonstrates that Italian occupational illness caused by Work-related Musculoskeletal Disorders (WR-MSDs) have increased continuously since 2011, in both absolute terms and percentage terms [68]. The most recent data shows that WR-MSDs represent, with 41.960 reports

in 2022, 69.17% of all occupational illnesses reported to the Institute. Due to the exponential increasing trend of WR-MSDs in the last decade, INAIL promotes the research of industry 4.0 technologies, such as exoskeletons, coBots and robots, to mitigate the occurrence of WR-MSDs in work environments.

A long-term investment in industry 4.0 technologies is justified because introducing coBots can lead to decrease the cost associated to sick leave, rehabilitation, health insurance premium for the factory. Moreover, coBots can improve production quality and reduce the waste of resources [69,70].

In our study we used 3DSSPP software to assess biomechanical risk in an actual scenario analyzing some parameters without and with the use of a coBot. The parameters we investigated with 3DSSPP have not a correlation with injury but 3DSSPP Strength Percent Capable that correlates only to the reconstructed posture not considering other additional risk factors. This because Work-related musculoskeletal disorders have a multifactorial etiology that includes not only physical stressors but also psychosocial risk factors, such as job strain, social support at work, job dissatisfaction [2,71].

The results of our study show that in some occupational tasks, collaboration with coBots allows a decrease in joint loads. Furthermore, the use of easy and cheap risk assessment tools such as 3DSSPP software allows a complete biomechanical risk assessment in industry 4.0. Future developments of the present study could be aimed at in-depth correlation of the extracted parameters with sEMG-based indexes. Our paper finally shows that for biomechanical risk assessment in industry 4.0, where is not possible to use common standardized protocols of standard ISO 11228 series [7,8,9], is it possible, in our scenario, to use easy and cheaper risk assessment tools such 3DSSPP software than sEMG, IMU and optoelectronic system [64].

In conclusion, we can claim that using the coBot, in this industrial scenario, would reduce the biomechanical risk for workers. The advantages in Phase 1 concern trunk flexion and abdo-adduction of both shoulders, since the coBot helps the worker reduce the horizontal distance during manual handling; the advantages in Phase 2 concern the reduced humeral rotation of the right shoulder and the reduced flex/extension of the right wrist, since the coBot helps the worker holding the workpiece in the cleaning task, allowing a better posture. The advantages in Phase 3 consist in removing another task of manual handling that is totally automated, giving the worker a well-deserved rest.

As shown in several previous papers, the use of coBots is a promising way to reduce the biomechanical load of workers in MMH activities in industrial settings.

In the next future it would be useful to integrate artificial intelligence algorithms into marker-less motion analysis to investigate motion in real work environment also through smartphone-based tools [72] as they don't interfere with workers movement in the real work environment and to provide accurate feedback stimuli. These tools, nowadays, are still in an early stage, but over the coming years, could provide useful and objective information of workers' biomechanical risk in real time with more accuracy than 3DSSPP that suffers of subjective perception.

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