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COLLABORATIVE ROBOTICS: CASE STUDY, OPPORTUNITY AND CHALLENGES

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Abstract: *The technological advances emerging with Industry 5.0 and the difficulties of maintaining flexibility and competitiveness are pushing companies towards new work scenarios that involve the use of collaborative robots. However, such developments are throwing up new challenges in terms of occupational health/safety. the purpose of this paper is to present real case feedback and associated challenges related with collaborative robots as well as different tools and methods to face it. The presented results show that cobots are still at the "test level" and their design must overtake the internal contradiction in the human (variability)-robot (invariant) system. Different tools and methods are proposed such as VR or usage method. The new challenges need to be undertaken by considering new knowledge and preventive measures. This is vital for employee health and overall business success.*

Keywords: *human-robot collaboration, simulation, virtual reality, design method*

1. INTRODUCTION

The technological advances emerging with Industry 5.0 [1] and the difficulties of maintaining flexibility and competitiveness are pushing companies towards new work scenarios that involve the use of collaborative robots. The International Organization for Standardization (ISO) defines the collaborative robot as being "a robot designed for direct interaction with a human" [2]. According to International Federation of Robotics, different levels of human-robot collaboration can be developed [3]: separate workspace with fences, separate workspace without fences (coexistence), shared workspace - sequential actions (sequential collaboration), simultaneous actions on shared tasks (cooperation), real-time adaptation to human movements (response collaboration). This new work situation, and especially response collaboration, may associate the precision and the robustness of the robot with the sensing and dexterity of the human worker. These new forms of work are one of the concerns of specialized occupational health and safety organizations [4]. However, such developments are throwing up new challenges in terms of occupational health/safety, mechanical and musculoskeletal disorders (MSD), for which research needs to invest. Multidisciplinary studies are encouraged to take into account the complexity of these work situations in relation to occupational health and safety [5]. There is still very little scientific literature analysing collaborative robot use and its impacts on user exposure to MSD risk factors. In concrete terms, a robot taking charge of an object's weight would reduce the operator's exposure to biomechanical risk factors, in terms of forces and kinematics. Few studies have been carried out in numerical simulation situations, bringing into question the various limitations of simulation assessments. While laboratory studies are very useful, analysing biomechanical factors in real work situations remains a challenge and is absent from the literature.

In this context, the aim of this paper is to present a real case feedback and associated challenges related with collaborative robots (section 2) as well as different tools and methods to face it, namely simulation of human features (section 3), virtual reality (section 4) and usage model (section 5). Indeed, addressing these challenges with new knowledge and preventive measures is vital for employee health and overall business success.

2. COLLABORATIVE ROBOT FOR GRINDING TASKS

To fit the high demanded flexibility and competitiveness, companies move to a new manufacturing environment combining human workers and robots. Even if real work situations including this type of collaborative robot are still at the project levels, some papers underline the importance of human-oriented design of collaborative robots [6]. With a view of musculoskeletal disorders (MSD) prevention perspective, the aim of this study was to analyze the postures of the upper arm in a controlled work environment situations when using a handled collaborative robot (cobot) during industrial grinding task. Indeed, in this actual application, the cobot's contribution can be analyzed. The cobot's ability to take on the weight of the grinding machine and the reduction in vibrations induced by the design of the cobot terminal suggested that the use of the cobot would have a valuable contribution on MSD prevention.

2.1 Cobot assisted grinding tasks experimentation

With this aim, five (70% of total grinding activity workers) right-handed volunteer men participate to experimentation. They have no back or shoulder pathologies at the time of recording of the data (age: 49.2 years (± 6.2)). They performed grinding tasks, on the horizontal plane, following four different directions of movement (from the left to the right - LR, from the right to the left - RL, from the bottom to the top – BT and from the top to the bottom - TB). Two levels of force (F1 = 35N, F2 = 70N) were required. The fixing device of the workpiece was set up on an adjustable height table (to take into account the anthropometry of the subject). The experiment was carried out under two conditions: traditional (using a manual grinding wheel) and with a collaborative robot (COBOT 7A15, RB3D, Moneteau, France). Data were collected by measuring: the estimated bilateral shoulder joint angles (Magneto-Inertial Measurement Units – MIMUs, XSENS, Netherlands): bilateral flexion/extension (F/E), abduction/adduction (Abd/Add), axial rotation (Rot) and the resultant force exerted by the user and recorded between the tool and the workpiece (force plate BP600900-1000, AMTI, USA) and.

The statistical analysis starts with the independence of the trials. The sample analyzed was made up of the measurements of the 164 trials. The trial was considered as statistical unit. To determine the factors influencing the different degrees of freedom at the shoulder level, a linear mixed model was used. The explanatory variables were the tool (conventional grinder and Cobot), the force exerted (two force levels: F1 and F2), and the direction of movement (four: RL, LR, BT, TB). The residual normality of the models was verified. The magnitude of the effects was measured using Cohen's d (COHEN, 1988, 2nd Edition). The residual normality of the models was verified. Significant differences ($p>0.05$) with Cohen's d less than or equal to 0.20 were not considered (small effect size). A post-hoc comparison using the Bonferroni correction was performed to identify significant differences in the groups' means. The significance threshold was set at 5%. Statistical analyze was performed using Stata software versions 17.

2.2 Results for comparative grinding tasks analysis

The presented results take into account all movement directions and force levels. The type of grinding tool (traditional and assisted by the Cobot) have a significant effect on all degrees of freedom of the right and left shoulder except for the abduction/adduction of the right shoulder (Fig. 1). Indeed, for the right shoulder, compared to traditional grinding, Cobot-assisted grinding has an effect on flexion/extension (F/E, +7.2°) and rotation of the shoulder (Rot I/E, +4.0°). For the left shoulder, compared to traditional grinding, Cobot-assisted grinding has a significant effect on flexion/extension (F/E, +2.1°), abduction/adduction (AB/AD, -2.7°) and rotation (Rot I/E, +3.7°). In almost all cases, these joint angles are higher in cobot assisted grinding and not always in favor of MSD prevention.

Moreover, the precision (the percentage of time the recorded force level was in the tolerance zone of the requested force) was significantly lower when using the cobot assisted grinding (51.8% for F1 and 44.1 for F2) compared with the traditional grinding tool (81.9% for F1 and 78.8% for F2).

These results follow existing literature regarding collaborative robots [6], [7] or exoskeletons [8].

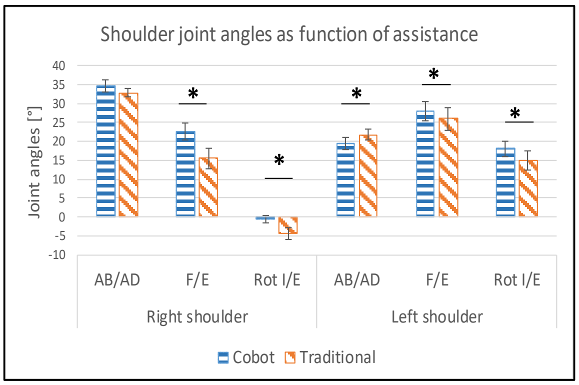

Fig. 1. Shoulder joint angles [°] estimated for cobot assisted grinding (blue) and traditional grinding (orange). All degrees of freedom (abduction/adduction ABD/ADD, flexion/extension F/E, and internal/external axial rotation Rot I/E) for right and left shoulder are presented. * represents statistical significant difference between cases.

These results show the complexity of the work situation including collaborative robots. This study results highlight the importance of understanding the various characteristics of the task intended for collaborative robot use when speculating on their potential effectiveness on occupational safety and health and company performance.

The development of a new work situation including a collaborative robot must take into account the real needs of the company [9] and the involvement of the end-user [article ergo participative].

3. FROM COLLABORATIVE ROBOTS TO COLLABORATIVE OPERATIONS

3.1 Variability, an essential feature of human movement

An essential characteristic of human movement is its variability: "a movement is never performed identically twice" [10]. This motor variability (MV) is linked to the kinematic and muscular redundancy of the human body. It is influenced by the characteristics of the individual (height, weight, age, experience, fatigue level, motor strategies, etc.) and of the task itself (cadence, cognitive load, workstation geometry, etc.).

At the workstation, MV induces variations in postures, movements and coordination between the operator's body segments during the repetitions of the task observed. It is supposed to have a beneficial effect on operator health. "Sufficient" MV is thought to help reduce fatigue, for example by varying and distributing biomechanical demands on the whole musculoskeletal system. On the contrary, a "limited" MV (channeled movements) may increase this exposure. These hypotheses have not been demonstrated in the literature, but converging evidences have been established in the last decade. Moreover, MV is thought to play a role in the learning of motor skills.

3.2 Human physical performance

Because of the structure and the actuation of the human body, operators' physical performance depends on their postures and movements (joint angles and speeds). Sizing the maximum mechanical capabilities of a collaborative robot, as well as the level of assistance provided to the operator during the execution of his task, therefore requires being able to estimate its dynamic physical performance. This estimation must be as close as possible with the human dynamic functional abilities, rather than only static, as is the case of most estimation tools currently available to designers and integrators of robots, whether collaborative or not.

3.3 Direct human-robot collaboration: an internal contradiction?

An internal contradiction in the operator-robot system arises. Firstly, the movement of the former is variable by nature, while the latter is generally invariant (the robot's trajectory is usually repeated identically). Hence, in the context of direct human-robot interaction, if the robot always executes the same trajectory, the operators' MV may be impaired. This could be detrimental to their health (risk of MSD). What's more, if the robot always provides the same assistance, irrespective of the operators' physical capabilities, it is again up to them to adapt to the robot, which may adversely affect the quality of execution.

3.4 How to account for MV and operator performance at the design stage of a collaborative responsive task?

Implementing responsive human-robot interactive tasks requires accounting for the actual behavior and capabilities of operators. To date, there are no "off-the-shelf" tools, but recent work has opened up new perspectives:

- advanced virtual human models accounting for some sources of MV have been developed (for instance, muscle fatigue) [11];
- maximum human force production capacities can be simulated dynamically, according to the operator's joint angles and speeds, using musculoskeletal models. This approach has been implemented to adapt the assistance offered to the operator according to his movement, in real time [12].

Improving these two techniques and implementing them early in the design of human-robot collaborative operations will undoubtedly enable fluid, responsive interactions between cobot and operators. For instance, they could be combined to make robots able to adapt to human motor variability. Designing robotic control laws modulated by the operators' VM would not only preserve their intrinsic VM, but also help them to explore and exploit their full VM.

4. VIRTUAL REALITY: A TOOL FOR COLLABORATIVE ROBOTICS DESIGN

Virtual Reality (VR) is a technology of Industry 5.0, which allows immersion of a user into virtual workspaces for the purpose of training, conception assistance or tele-operation. In the context of human-robot collaboration, it aims to accelerate iterative design of the collaborative workstation with a human-centered approach, and address the challenge posed by the great variety of functional and safety choices available. By immersing operators in a virtual mock-up of the future workstation and collecting feedback, design choices can be revised when necessary.

VR can be characterized by its capacity to simulate a virtual environment in real-time, with which the user can interact, and experience a feeling of *presence*, that is the subjective perception of being in the simulated environment. This is achieved through a variety of display and input devices, such as head-mounted displays, immersive rooms, motion-tracked controllers, force-feedback devices, etc.

4.1 Robotic Simulation and Human Interaction

VR tools can now integrate robotics simulation frameworks, such as ROS (Robot Operating System), to reproduce robot control and behavior accurately [13]. ROS in particular is an open-source framework, to which many robot and cobot manufacturers contribute with simulation tools for their own products. Furthermore, ROS integration plugins exists for many 3D and VR engines.

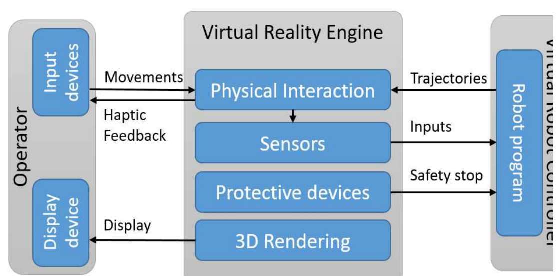

Fig. 2. Integration of a simulated robot in a virtual environment

A general overview of how the simulation of a robot can be integrated in a VR engine is presented in Fig. 2. Both the operator and virtual robot act on their environment through the simulated physics of the virtual environment, through the user movements captured by the VR system and the trajectories generated by the robot controller.

4.2 VR in the design process and its limitations

The use of VR in conception raises the question of its validity: its capacity to produce observations that generalize to the real workspace [14].

While many robots have existing simulations tools available, this may not be the case of other equipment of the collaborative robot workstation, such as safety equipment, third-party or custom cobot tools, or any equipment used by the operator.

functionality in the real workspace. While virtual reality can identify some risks or issues at an early stage, it remains a limited simulation and the real situation must still be assessed. Furthermore, different characteristics and devices of VR system carries different limitations and biases. They should be chosen with respect to a particular aspect of the work situation one wants to assess.

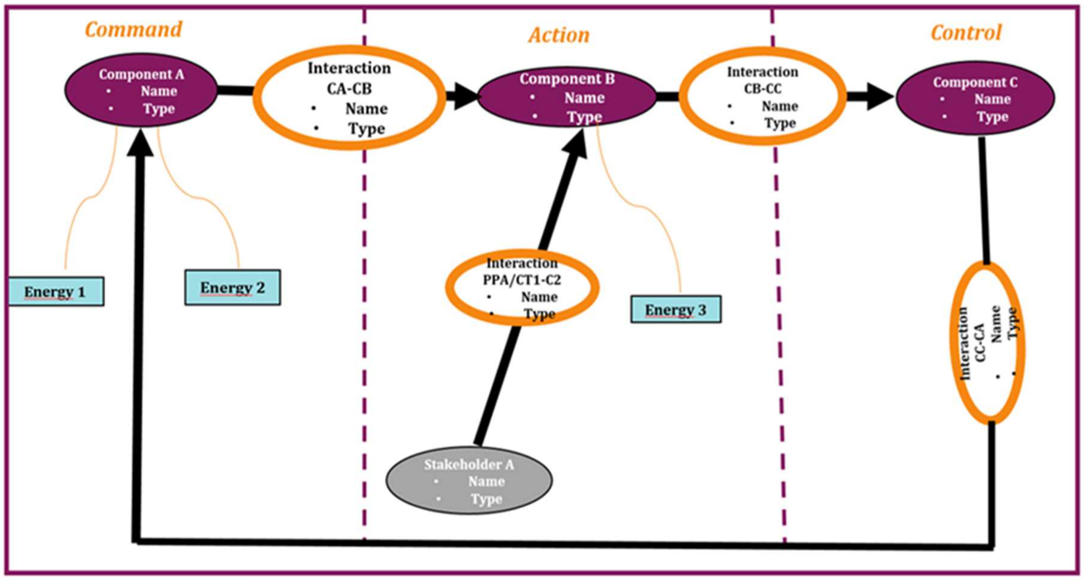

Fig. 3. The usage model graph.

Furthermore, input devices restrict the ways in which the operator can interact with their environment: for instance, they often lack individual finger tracking for natural object grasping, which is then performed using a button press instead which abstracts the real gesture. More complex systems, such as hand-tracking or haptic force-feedback, can be used to increase realism of the interaction. However, all these input systems are not transparent for the operator. They require familiarization and add to mental load of the simulated task itself.

VR also affects risk perception: while the operator or integrator may accurately assess the risks in a collaborative situation using objective information (e.g. protective devices, speed and distances), immersion in the virtual environment may elicit a lower subjective reaction to the risk. Thus, VR cannot provide an accurate assessment of acceptability of the collaborative task.

VR places the future operator at the center of the collaborative robotic integration process in its early stages. It can provide valuable feedback for human-robot collaboration design, which must be operator-centered. However, iterative conception must focus on insuring safety and

5. USAGE MODEL: A METHOD FOR COLLABORATIVE ROBOTICS DESIGN

To design collaborative robots, and the associated work situation, designers are faced with a double challenge. On one hand, in terms of law, they must take into account operators health and safety as early as possible during work equipment design [15]. On the other hand, by taking into account a greater variability of products and flexibility of resources lay out by the Industry 5.0 paradigm [1]. In this context, designers see their work changing and being more complex.

Collaborative robotics leads to a multiplication of the possible uses of work equipment. However, the law obliges designers to take into account all uses before risk analysis. The familiar ISO12100 risk checklist can't help the designers. They need new methods to identify these uses and deduce the risks incurred by operators. In a previous work [16], it was highlighted that taking into account the operators health and safety as early as possible during design could be established according to two assumptions. The first is the knowledge of the uses of the future machine, the actual use that operators will make of it in their industrial context. The second is based on the systematic determination of the presence of energies in the machine to identify the dangerous phenomena.

Taking into account these assumptions, a new method was proposed to determine the uses of the future machine: the usage model. This proposal uses systems engineering to describe work equipment’s environment, resources and stakeholders. Around this well-known base is added a description of each function, its technical solutions and its stakeholders according to three categories: command (analyzing, deciding and ordering), action and control (measuring, processing and inform). Then, this function can be described in one or a few sentences. From this description, a graph is drawn (Fig. 3) showing the stakeholders and the links between them: the interactions. Each identified interaction is then the subject of a description necessarily including energy, geometry and objective criteria. By this way, designers have a better knowledge of the use of the tool. Nevertheless, this method has a limit: if a new interaction appears or is modified during a recombination of the work equipment within the framework of Industry 5.0 (e.g. different types of human-robot collaboration), then the previous health and safety validation is no longer valid and this point should be precised before allowing the work equipment to be put back into production.

Taking as an example the collaborative robot described in this paper (§ 2), if the workpiece material change (aluminum or steel) or the aim of the task (draft or finishing), the interaction between the workpiece and the tool change (pressure applied on the part). So, designers have to re-design or valid the collaborative robot to ensure the worker’s health and safety on this new configuration. The usage model can be applied when designing a production line or machine. Special development is underway for end-of-life vehicle dismantling workshops.

6. LIMITATIONS AND FUTURE RESEARCH

The real case study presented in this paper analyses grinding task performed by grinding activity professionals. They were able to perform grinding operations using traditional grinding machine and cobot. The presented study conditions have the advantage of providing results in an actual work situation and of responding to the company's concerns. At the same time, other questions may arise which deserve to be explored. What would be the results when the tasks where provided by novices, or in situations of fatigue? Similarly, in the light of these results, how can professionals be trained to use the cobot? For what type of operation?

Using Virtual Reality in the design stage of the collaborative workstation could provide better understanding of its advantages and drawbacks. Eventually, it could promote a safer and more efficient integration of the cobot by centering the future operator in the design process. This approach is currently limited by the difficulty of simulating the robot, the operator and a skilled task together. Furthermore, the choice of the type of VR interfaces and of the characteristics of the simulation can be a challenge: they each bring their own set of limitations and biases. Further research would be required to provide a better understanding of each system with respect to particular workplace health and safety concerns.

With regard to modeling MV and taking it into account to create MV-modulated robotic control laws, this involves overcoming scientific and technical challenges such as characterizing, modeling and representing occupational MV with respect to task- and individual-specific constraints. For this purpose, computation tools and experiment-based models need to be developed at the crossroads of biomechanics, mathematics and robotics.

7. CONCLUSION

This paper underlines the complexity of the design process in the new paradigm of Industry 5.0. If the flexibility of the work situation is coveted and the human-centered design is considered as a priority, in reality, these new work situations must face new challenges. Indeed, cobots are still at the “test level” and their design must overtake the internal contradiction in the human (variability)-robot (invariant) system. Different tools and methods are proposed such as VR or usage method. While these solutions can identify some risks or issues at an early stage, it remains a limited simulation and the real collaborative situation must be assessed.

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Robotica colaborativă: studiu de caz concret, oportunități si provocări

Progresele tehnologice apărute odată cu Industria 5.0 și dificultățile de menținere a flexibilității și competitivității împing companiile către noi scenarii de lucru care implică utilizarea roboților colaborativi. Cu toate acestea, astfel de evoluții implică noi provocări în ceea ce privește sănătatea si securitatea muncii. Scopul acestui articol este de a prezenta un caz de studiu și provocările asociate roboților colaborativi, precum și diferite instrumente și metode pentru a le face față. Rezultatele prezentate arată că coboții sunt încă la „nivelul de test" și designul lor trebuie să depășească contradicția între sistemul uman (variabilitate) si robot (invariant). Sunt propuse diferite instrumente și metode, cum ar fi Realitatea Virtuală sau „metoda de utilizare". Noile provocări trebuie abordate prin luarea în considerare a noilor cunoștințe și măsuri preventive. Aceste considerații sunt vitale pentru sănătatea angajaților și pentru performanța globală a întreprinderii.

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