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A system to improve the physical ergonomics in Human-Robot Collaboration

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Abstract

In the industry 4.0 era, pursuing social sustainability also means implementing a synergic collaboration between workers and robots. Indeed, robot behavior does not affect only worker safety, but it also influences his health and comfort. In this context, an important topic to be enhanced is the operator's physical monitoring aimed at reducing the risk of musculoskeletal disorders. Some research studies deal with the improvement of the worker's posture during human-robot collaboration; however, non-intrusive methods applicable in real industrial scenarios are lacking. To this ending, this paper proposes a system to avoid uncomfortable and unsafe postures based on workers' anthropometric characteristics, posture monitoring by inertial and visual systems, task requirements, and a real-time risk assessment by standard methodology. The system allows the optimization of the robot behavior in order to improve worker's well-being. Finally, the virtual simulation of a real case study is presented.

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Keywords: physical ergonomics; human factors; human-robot collaboration; industry 4.0

1. Introduction

The recent progress in robotics and automation allows the combination of industrial robots and humans in a shared space. This increases the benefits and flexibility of the entire process. Human-Robot Collaboration (HRC) clearly

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shows the advantages in manufacturing processes: robots have the capability of performing precise movements with repeatability while humans have the faculty of cognition, recognition, creativity, and adding value to the final product [1]. Collaborative robots, cobots, can work alongside humans without using barriers in a shared space. Humans can communicate with a cobot by using an interface where operators can manage inputs in a simple and interactive way [2],[3].

Collaborative robotics can help humans in performing not very ergonomic tasks. Robots can lift heavy objects and hold them in position for a long time for example for inspection, assembly, pick and place, screwdriver operations. This advantage is often neglected to the detriment of the operator himself, causing physical discomfort due to the repetitiveness of movements or uncomfortable postures that are inappropriate for the specific task. Otherwise, in the event of exposure to high risks for ergonomics or health in general, traditional robots are adopted to replace humans in certain tasks or environments, avoiding a collaborative application. However, the coexistence of the two “workers” and their synergic collaboration represent the greatest solution to guarantee the well-being of the human worker. The main aim of this paper is to improve human ergonomics in dynamic scenarios with the use of collaborative robots that monitor and track humans. In this context, complex models of the human body are not easily obtainable especially when they have to be calculated and used in real-time. In contrast, off-line techniques would not allow good adaptability and are not suitable for a dynamic environment. Although HRC is useful for improving working conditions by reducing the workload of the operator, attention must be paid to the safety of the collaborative system. The guarantee of safety is one of the fundamental keys of HRC and this is ensured by safety devices, force monitoring, and obstacle avoidance. In literature, many studies address how to manage HRC in dynamic scenarios [4], [5].

This work presents a system that improves the physical ergonomics and the human-machine interaction in HRC. The system is based on the needs and the requirements of a real industrial scenario to overcome the limits of existing approaches, which are applicable only in the laboratory. To this ending, the system combines workers' anthropometric characteristics, posture monitoring by inertial and visual systems, task requirements, and a real-time risk assessment by standard methodology. In this case, the innovative cooperation is realized using a vision system and a few hardware and software components. The vision system involves the use of two Intel RealSense D435 cameras. One of these frames the workstation, the operator, and the robot from the front, the other camera carries out the ergonomic analysis of the operator. In any case, one of the two cameras always frames the scene. In this way, it is always possible to have additional control for the safety of the operator. The inertial system is limited to the training phase to avoid the intrusiveness of wearable devices. In the proposed case study, which has been virtually simulated, the operator is at the end of a production line dedicated to furniture cleaning, quality inspection, and testing. The product, which can vary in size, weight, opening mechanism, etc., is recognized and lifted by the robot that places it in the most comfortable position for the operator. The scene is captured in real-time by the vision system that acts as a recognition of the human presence in the work area, recognizes the operator's gestures, and carries out the ergonomic analysis by giving feedback in real-time to the operator himself [6]. This case study lays the basis for defining a multi-disciplinary design method that is universally applicable to industrial cases for the real-time performance of the ergonomic analysis. This can support the operator and the recognition of gestures, products, and humans.

The paper is organized as follows: Section 2 reviews the literature related to the improvement of the worker’s posture during HRC to identify limitations to deal with; Section 3 describes the proposed system workflow and Section 4 details each aspect of the system architecture; a preliminary test of the architecture in the laboratory and a virtual simulation of a real case study are presented in Section 5; a preview of future work and concluding remarks are given in Section 6.

2. Related works

The working environment of the future will be characterized by a new production paradigm where human workers and automated systems (e.g., cyber-physical systems, cobots) synergically collaborate to improve flexibility and productivity. However, factories' performance is no longer sufficient as a driver of success since the intrinsic added value of human resources becomes more incisive in the factories of the future. Moreover, it is known that the whole industry's productivity and efficiency depend on worker's well-being and human performance (e.g., perceived comfort, physical and mental workload, simplicity of actions, personal satisfaction) [7]. In this context, the main prerequisite is the creation of a healthy and satisfying working environment. This requires several challenges to be addressed that include aging of the working population, the incidence of work-related risks, the higher cognitive workload, etc. Human-centered solutions 4.0 are called to support the human worker in reducing physical and cognitive stress. To this ending one of the major problems is the acceptance of new working tools and the realization that they help in a timely and healthy manner [8]. Understanding the key parameters of effective human-machine interaction and implementing adaptive control methodologies are fundamental to positively influence people's well-being and trust.

To ensure a safe collaboration between humans and robots is necessary to establish effective communication between them. Communication research is an emerging area focused on the study of the “creation of meaning between humans and machines” [9] that is to create easy and intuitive learning models for both humans and robots. The interaction modalities can be managed by multimedia interfaces allowing the operator to communicate with the system in many ways. This improves communication, reduces errors, and decreases the cognitive workload by increasing the ease of learning [10].

Some attempts to meet ergonomic criteria have been done by designing ergonomic-driven collaborative robotics workstations that lighten the worker workload [11], however, as stated by Ajoudani et al. in their review [12][11], the autonomous and dynamic adaptation of the robot to the human characteristics and behavior still appears in a premature state and must be deepened by the research community. In this direction, it would be more appropriate to refer to the reciprocal human-robot adaptation that cannot disregard trust, transparency, and value perception, as well as safety.

Gualtieri et al. [13] present a study that aims at improving the operators’ physical ergonomics by transforming a manual workstation for wire harness assembly into a collaborative and human-centered one. Their future research directions include the possibility of adapting the workstation elements according to operators’ psychophysical work conditions and needs.

Lorenzini et al [14] integrated a whole-body fatigue model into an HRC framework to trigger body posture optimization according to the subject-specific fatigue progression. An online adaptation of robot behavior based on human motor fatigue has been presented by Peternel et al. [15]. In this case, the fatigue is esteemed using the human muscle activity measured by electromyography, which limits the method implementation in a real industrial environment.

Focusing on postural optimization, different monitoring strategies have been investigated (e.g., inertial sensors, vision-based systems) at different operating levels (e.g., design, task allocation, online). El Makrini et al. [16] used a tracking system composed of a depth sensor to define the best worker (human or robot) for an assembly task based on capabilities and ergonomics considerations. Busch et al. [17] proposed a postural optimization framework that accounts for task constraints, safety, and acceptability combining a personalized human model, postural assessment techniques (REBA), and a motion tracking system (OptiTrack). Their method only considers static postures.

Ferraguti et al. [18] describe an ergonomic control architecture where the robot assists the worker by adjusting the position of objects of various shapes and weights to ensure the most comfortable working posture.

The aforementioned works allow also identifying several limitations to face, such as occlusion occurrences [16], marker tracking that may hinder the application in real industrial scenarios [17], and compliance with the current international regulations on safety [18].

As demonstrated by literature, existing approaches aim to optimize specific aspects of the interaction (e.g., force, posture) and do not consider the potential and limits of the interaction as a whole. As stated above, awareness, perception, and trust are key aspects that must be considered for success in a real industrial context.

In this context, the main novelties of this paper are: (i) human detection for a safe collaboration; (ii) postural monitoring and adaption (in terms of task configuration and online optimization) for worker’s health; (iii) gesture recognition for effective communication between co-workers. The main goal is to propose a solution suitable for a real case study, which satisfies the requirements of occupational health and safety 4.0.

3. System workflow

The proposed system presents the integration of different devices ensuring a complete and real-time mapping of the working area. The architecture has been developed for an HRC workstation in which the robot moves the object to the best position for the operator allowing him to work correctly, safely, and comfortably. The main goal is to create a system able to recognize the human presence, the product characteristics, and the task requirements, and adapt the robot configuration and the product position accordingly to prevent or reduce the operator ergonomic risks. The identification of the optimal posture depends on the anthropometric characteristics and the ergonomic guidelines, according to which a database of postures and end effector positions is created. During the regular operation, the system recognizes the operator, the product, and the task and retrieves from the database the correct end-effector position.

As shown in Fig. 1, the system workflow is divided into two main phases: the former is the training of the system in which the databases are created, the latter is the real-time system operation.

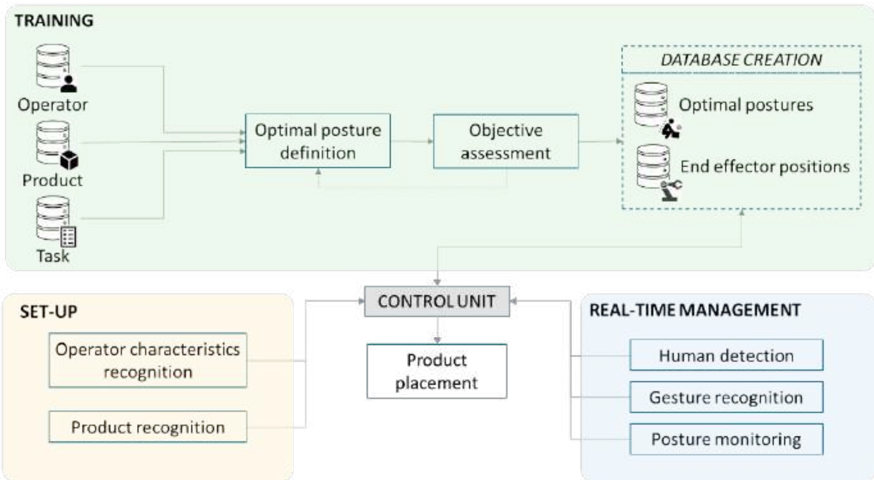

Fig. 1. System workflow.

3.1. System training

The first step of the workflow is the system training that allows the definition and creation of the databases. In particular, the goal is to identify the robot configuration, related to the desired product position and worker posture, to be set before the operator enters the collaborative workspace and executes the task. Indeed, a real-time adaptation of the product placement, especially if large or heavy, represents a high risk for the operator due to the possibility that the product or the robot could hit him. Moreover, the real-time change of the product placement might negatively affect the robot operation, which either cannot reach the desired position or can assume an improper configuration.

The input data for the system training are:

- Operator. The operator identification allows considering his anthropometric characteristics to set the ideal positions and his habits and needs to increase the trust and the system value perception.
- Product, whose dimensions and characteristics necessarily influence its final position and the sequence of tasks respectively.
- Task. Its characteristics, specifications, constraints, etc. give useful indications on the area of the product on which the task will be executed and the movements to be performed by the operator.

For each combination of the input data, the ideal posture of the worker is calculated. The posture can be defined based on standard guidelines for the ergonomic design of a workstation. Generally, they recommend a range of values in which to identify the most suitable for a specific situation. Once the optimal posture is identified, it is necessary to calculate the related position of the product and define the robot configuration.

The next phase involves the objective assessment of all the postures from an ergonomic point of view. This analysis allows the identification of ergonomic risks and the consideration of operator habits to find the best tradeoff. To track the human posture, it is possible to use inertial sensors to capture motion data or a combination of depth cameras. The former is an intrusive system for the operator, but it ensures high accuracy of the results, the latter provides a non-intrusive and programmable solution that can be easily developed in a real manufacturing environment. In the first solution, the operator wears several interconnected inertial measurement unit (IMU) sensors that capture motion data while he is performing the task. This must comply with all the conditions defined in the previous steps. Once he concludes the operations, the acquired data are processed and analyzed through a standard methodology for the ergonomic risk assessment (e.g., RULA, OCRA, REBA). When the analysis shows that the assumed postures present some risks for the operator, the procedure for the identification of new postures must be repeated and the same ergonomics analysis must be performed. In the second solution, using depth cameras, it is possible to implement real-time feedback of the assumed posture in order to allow the operator to immediately correct his posture reducing the ergonomic risks.

When the posture is confirmed as riskless, the system has to save and store in a database the product position and the robot configuration. The whole procedure has to be repeated for each operator, product, and task that have to be considered. In this way, it is possible to create a database with all the optimal identified postures and the corresponding end-effector position.

3.2. System operation

Once the database is created, it is possible to test the system real-time operation. The proposed architecture allows integrating different methods and tools with multiple purposes to take advantage of their potentialities.

3.2.1. System set-up

Every time the operator or product changes, the system carries out the set-up, which includes the implementation of the initial configuration for the execution of the first task. When the operator enters the workstation, the system has to recognize his characteristics and send the information to the control unit. The company management system can be used to retrieve all information related to the worker when it keeps track of the operators that work in the considered workstation. Otherwise, the operator could be recognized by a common camera. After the worker information has been retrieved, the product the operator has to work on needs to be identified. This could be easily recognized by his barcode or his QR code. A vision-based system can also be used for object recognition. The object identification is sent to the control unit that queries the databases. This allows the robot to place the product as memorized during the system training phase.

3.2.2. System real-time management

The system application to a real industrial scenario requires a safe collaboration between humans and robots and requires effective communication between them. For this reason, the proposed architecture provides the real-time management of human presence for guaranteeing a safe collaboration, the gesture recognition for supervising the communication between co-workers, and the monitoring of operator’s posture for his well-being.

The system has to detect the human presence in order to control the robot, stopping it when the operator is inside the working area. To this ending, a safety system that is able to recognize the worker's presence and send the information to the control unit must be implemented. If the product is bulky and heavy, it is crucial to ensure that the robot works only when the operator is outside the working area. The information related to the task that has to be performed can be provided to the robot through human gestures. Indeed, a system based on depth cameras could recognize the operator’s gesture and send the information to the control unit. The worker can indicate the exact operation that he has to perform, or, if the task’s sequence is known, he has to start and stop the robot with the proper gesture. Moreover, the architecture allows the evaluation of the operator posture in real-time. Generally, workers are not aware of their risky postures, thus direct feedback could help them correct a wrong posture or maintain a good one. Depth cameras, appropriately positioned, can track the human skeleton in order to calculate the ergonomic risk index in real-time.

4. System architecture

The system architecture is the result of careful analysis of essential aspects that are necessary for the layout: risk assessment, safety, and ergonomics. At the same time quality of the product and performance are important. Thus, the application workflow, the station layout, and the assignment of the roles between the robot and the human operator must be considered. The proposed architecture can be applied regardless of the type of robot chosen. The robot selection considers the application to be performed and the weight to be handled.

The collaborative system provides the implementation of five different aspects: operator characteristics recognition, human detection, posture monitoring, gesture recognition, and product recognition. The workstation layout is shown in Fig. 2. The workstation is equipped with a barcode reader for product recognition. The optimal posture, during the training phase, is verified by XSens® MVN inertial motion capture system. For operator characteristics recognition, human detection, gesture recognition, and real-time posture monitoring a vision system is chosen. At first, only one Intel® RealSense™ depth camera D435 is used (Camera 1 in Fig. 2). The camera has a range up to 10 meters, a global shutter on the depth sensor (ideal for fast-moving applications), Depth Field of View (FOV) of 87° × 58°, RGB frame resolution of 1920 × 1080 and it can be easily integrated into any solution. After some tests, a second depth camera has been introduced to manage the gesture recognition more accurately. The two cameras are organized as follows: one of these is responsible for the recognition of the operator and the gestures that the operator performs, the other camera deals with the ergonomic analysis in real-time. In front of the operator there is a screen showing:

- the recognition of the gesture by the vision system;
- the ergonomic analysis in real-time that allows the operator to understand if he is performing the task with a correct posture or not.

To ensure the safety of the operator it will be also included a laser scanner to detect the presence of the operator in the shared workspace.

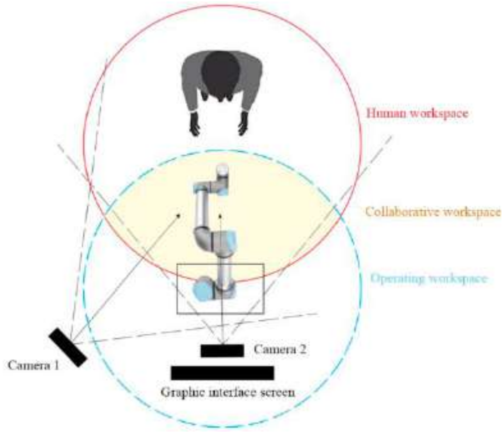

Fig. 2. Collaborative system layout.

4.1. Operator characteristics recognition

The aim is to have an application that is as flexible and suitable as possible with any operator. Since the workers have different heights, it will be appropriate to have a system that takes care of the recognition of this feature so that the robot can lift the object to the appropriate height. Thanks to the use of the Cubemos Skeleton Tracking SDK, the Intel cameras D435 allow human tracking and identifying simultaneously 18 body feature points corresponding to the body joints. For each body feature point, the camera records three coordinates (x, y, z) representing the absolute joint position. For the identification of the operator, it is possible to obtain his height by the position of the shoulders and the head joints. In particular, the distance between the floor and the average of these three points could be used to recognize the operator.

4.2. Human detection

The human detection feature is of utmost importance in the described system, for two main reasons:

- Since robots and workers interact in a shared space, it is essential to know the updated position of the human.
- The robots could be dangerous and harm the workers thus it is important to reduce their speed in proportion to the distance from the operator until it stops completely in case of contact.

The needs described above brought to the necessity of a human detection implementation, which would allow easy and safe interaction between the two.

Human detection is an essential capability the system has to offer. This is needed to achieve all the other features that rely on it: using the Intel RealSense camera, it can be achieved pretty much with any library.

Human detection has also been developed around two main concepts:

- If nobody is detected inside the camera's field of view, it is possible to assume the working area is clear and the robot can proceed with its tasks;
- If a human is instead detected inside the camera's field of view, there must be a way to ensure whether he is inside or outside the working area in order to stop or activate the robot, respectively.

To comply with this specification, and especially with its second concept, the Cubemos Skeleton Tracking SDK can be used for both posture monitoring and human detection: while tracking the skeletal human points in a 3D space, such space can also be used to define a limited working area, and those same points can be exploited to check whether the human appears to be inside working area. Fig. 3 shows the ordered actions that are performed by the application that are: acquisition by using a depth camera, collection of the data, and reprocessing of data by using our C # application. This is combined with the Cubemos Skeleton Tracking SDK to obtain all the joints available (in x, y, z coordinates).

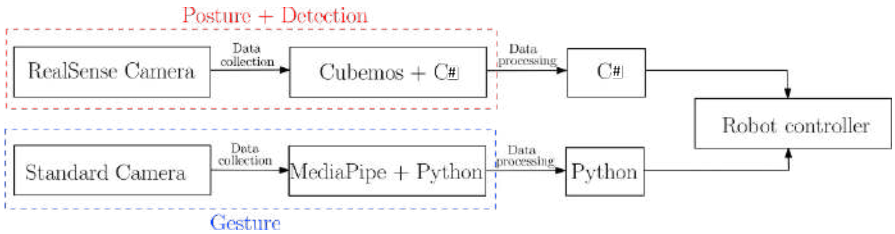

Fig. 3 Software architecture.

4.3 Posture monitoring

Posture monitoring is the main part of the proposed architecture system. This is essential in order to improve the operators working conditions and protect their health and physical well-being.

The focus is on using the Intel RealSense technologies since they proved very reliable and trustworthy: in particular, the Cubemos Skeleton Tracking SDK offers a cheap but complete alternative to several premium products of the same kind. SDK exploits the RealSense cameras' modules, which include depth perception capabilities, to identify a total of 18 body feature points, corresponding to the joints (i.e., nose, eyes, ears, spine, shoulders, elbows, wrists, hips, knees, and ankles). The points represent the coordinates in a three-dimensional reference system (x, y, z). Once the posture is known, it is compared with the reference its correctness or the need for modifications, which require the measurement system to get enough data in order to give accurate suggestions. These are communicated to the workers in order to improve their stance. Posture management is analogous to human detection (see Fig. 3 for details).

4.4. Gesture recognition

The gesture recognition feature is the actual link that connects the human workers to their robotic "counterpart", by giving them the chance to command robots and their actions.

Gesture recognition fulfills two different needs belonging to the same scope:

- Distinct gestures can activate different robot's tasks, which gives workers flexibility and immediacy;
- Regardless of the task, there is always a gesture to immediately stop the robot or resume its scheduled task.

The gesture recognition is carried out with a camera, the data is collected and processed through MediaPipe and Python (Fig. 3). Data is sent to the robot controller that will respond based on the selected gesture. It is possible to define an activation area, different from the working area, in which the operator has to perform the gesture. The gesture is identified by the camera when the operator is inside this selected area and he has real-time feedback displayed on the screen.

The following three gestures have been implemented:

- OK: activates the current robot task;
- STOP: stops the current robot task;
- Raised index: offers the possibility of associating a particular task to the robot, in this case for example to lift the object for further inspection at a comfortable height for the operator.

The third gesture can be chosen and managed according to the task. If there are more applications present, additional gestures can be imported.

4.5 Product recognition

The products can have different characteristics (e.g., dimensions and weights) and can require different work cycles. A barcode reader is set up to have real-time object recognition. The reader could be fixed on one side of the conveyor belt in order to have an automatic reading process. The object in question is identified and shown on the screen placed in front of the operator, together with the operations to be carried out.

For example, in the case of quality control, it could be useful to facilitate the inspection of the entire product by making the various parts comfortably accessible. In the case of an assembly operation, the product should be placed in the position capable of guaranteeing the least possible effort for the operator.

5. Experimental study and results

The architecture has been preliminarily tested in the laboratory. The human detection and posture monitoring were determined by Cubemos Skeleton Tracking SDK. Fig. 4 shows the human skeleton and the 18 identified body feature points. Simultaneously, the posture was monitored by XSens® technology, the user wore 17 inertial sensors that tracked the motion data during the activities. In this way, it was possible to verify the reliability and accuracy of the posture monitoring system with depth cameras. The inertial sensors could be used for the training system in the real case study, while the cameras might be employed for real-time posture monitoring.

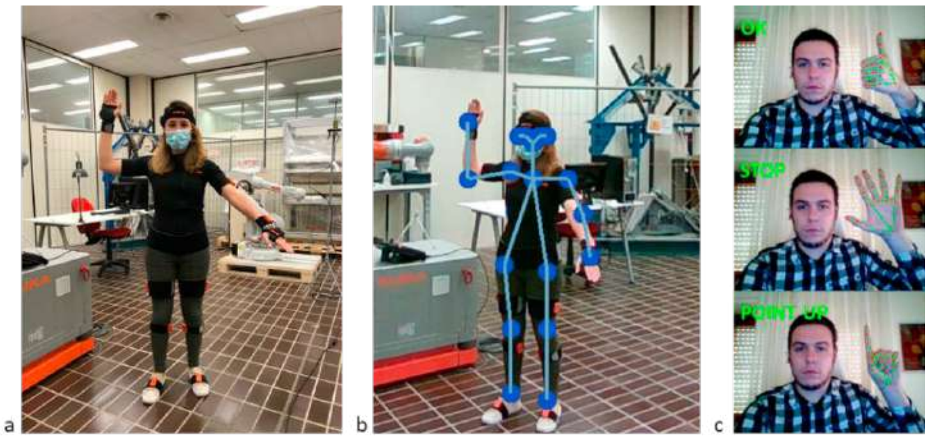

Fig. 4. Ergonomic objective assessment by the inertial system (a), posture monitoring by the vision system (b), and gesture recognition by the vision system (c).

The performed tests allowed the identification of some limits of the real-time posture identification system developed with Cubemos Skeleton Tracking SDK. It is not always able to detect all the 18 body points. When the human changes his position rapidly and in particular postures, such as trunk or neck rotation, some parts of the body are hidden and the system cannot identify some points, generally eyes and ears. To overcome this limitation, it is possible to implement an artificial intelligence algorithm that allows defining the missing point coordinates by calculating the average between the previous and the next points. Moreover, combine two depth cameras could solve the occlusion problem and the failure of detecting all the feature points.

Also, the gesture recognition system has been experimented in the laboratory. Fig. 4 shows the three gestures that were implemented. During the tests, the system gave rise to some false-negative and false-positive errors. To avoid registering a wrong input, the same gesture has to be recognized for 15 frames before activating the relative robot task: this significantly improves the identification since false positives usually last only for 2 to 5 frames. To further avoid accidental inputs, an activation area has also been created, so that gestures are only registered if they are executed while the hand is in the appropriate camera area. To reduce false-negative results and guarantee gesture recognition even when the operator is not perfectly in front of the camera, it will be necessary to enhance the algorithm and combine two depth cameras.

5.1 Virtual simulation of a real case study

The proposed workflow has been applied and tested in the quality control workstation at the end of a kitchen furniture production line. The product, which can have different sizes and weights, moves on a conveyor belt and the operator has to clean it, test the hinge mechanisms, and perform the quality control. In the as-is workstation, the product is fixed at the same height on the conveyor belt, so the operator has to assume risky postures in order to complete all the different tasks. The use of the system in this workstation allows the robot to lift and move the product at the proper height for each activity. This allows the operator to perform the tasks safely and comfortably. Once finished, the object will be repositioned on the tape and will run to the packaging station.

The proposed system has been simulated by the software Tecnomatix Process Simulate before realizing a physical prototype. Both the as-is and to-be workstations were simulated in order to compare the ergonomic analysis results according to the RULA (Rapid Upper Limb Assessment) method. Ergonomic risks of the as-is workstation have been also objectively evaluated with the inertial system, validating the simulation results. Fig. 5 shows the simulation of the most critical task, the test of hinges, while other activities present comparable low risks. In the as-is workstation, the operator has to bend his back and flex his neck to complete the task, so the ergonomic analysis points out high risks for the upper body (RULA final score: 7). The fixed height of the product forces the operator to assume this awkward posture. In the to-be workstation, the robot lifts the product at the most proper height allowing performing the activity with a riskless posture. The RULA final score confirms the enhancement of worker well-being and the reduction of ergonomic risk (RULA final score: 4).

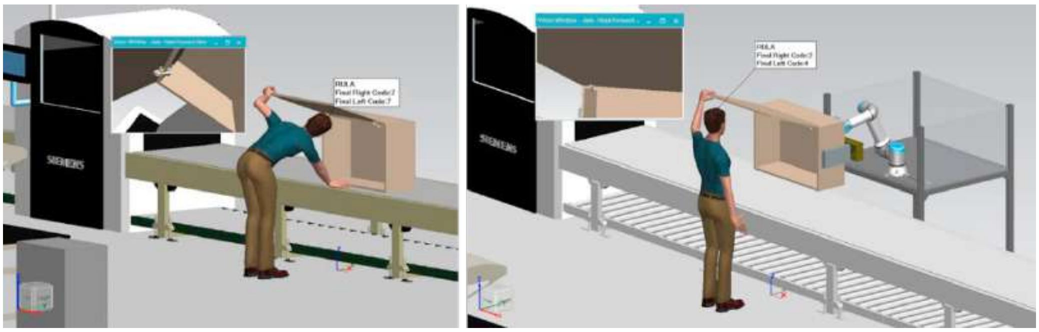

Fig. 5. As-is (left) and to-be (right) simulation of the quality control workstation.

6. Conclusions

The paper proposes a comprehensive system for improving the HRC from both an ergonomic and communicative point of view. The aim is to merge robot capabilities and human skills to ensure a safe and ergonomic collaboration where the robot holds and moves the product while the operator performs his tasks in a comfortable posture. To manage a safe collaboration the system allows detecting the human presence, recognizing gesture controls, and monitoring human posture in real-time. The proposed system has been preliminary experimented in the laboratory, obtaining satisfactory results in terms of posture and gesture recognition. Moreover, it has been virtually simulated, based on a real case study, with significant benefits from an ergonomic point of view.

Future works will focus on overcoming limits for posture monitoring and gesture recognition using the combination of two depth cameras, properly synchronized, and artificial intelligence algorithms. The goal is to develop a system able to recreate the complete human skeleton even when some points are not detected. Moreover, a model to calculate the real-time ergonomic risk index will be developed. The whole system will be tested in a real industrial environment and some activities of the training phase that could be too time-consuming will be automated.

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