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A Virtual Element-Based Postural Optimization Method for Improved Ergonomics during Human-Robot Collaboration

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***Abstract*—Human-robot collaboration is becoming increasingly popular in the manufacturing industry, opening the door to a large range of applications by combining the complementary skills of the human worker and the robot. Collaborative robots are also a solution to decrease the operator workload and indirectly reduce the risk of occupational injuries such as musculoskeletal disorders (MSDs). The latter represents one of the major causes of absenteeism at work. Thanks to the development of human tracking devices, it is possible to monitor the operator, analyze the postures, and assess the associated MSD risk. In this paper, we present a novel ergonomics optimization framework that performs postural optimization based on the virtual element method. A feedback interface is developed whereby the user is informed about non-ergonomic postures and an improved body pose is proposed. The workpiece position controller module acts on the cobot end-effector and indirectly on the co-manipulated part in such a way that the operator's posture is improved. The framework was validated by a user study performed on a human-robot collaboration task whereby the subject polishes a part hold by the robot. The conducted study of the user's perception and REBA scores showed promising results.**

***Keywords*—ergonomics, human-robot collaboration, optimization, posture, framework**

***Note to Practitioners*—This paper is motivated by the problem of non-ergonomic posture of workers in hybrid workcells. The proposed approach makes use of virtual elements (springs and dampers) to build a mechanical model of the human body posture and perform postural optimization. The obtained body joint angles are fed into two modules of the framework. First, a graphical interface displays the current pose of the user and proposes to him the improved posture. Second, a controller adapts the pose of the workpiece hold by the collaborative robot. This is realized by computing a displacement vector between the wrist current and optimized positions. The use of such a framework was demonstrated on a collaborative polishing task whereby the robot adjusts the position of the workpiece. After a user study test with 10 participants, joint data were collected and the REBA scores of different subtasks were measured and compared. The results from these preliminary experiments showed that the proposed approach improves the human body postures and offers a promising solution to enhance ergonomics by the robot assistance in case of robotic workcells. The conducted survey also shows an overall positive subject's perception of the system.**

I. Introduction

Human-robot collaboration, as part of the industry 4.0 [1], is increasingly adopted in the manufacturing industry where it shows all its potential when moving from mass production to customized part fabrication [2]. This is mainly due to the high flexibility that the human-robot provide through, amongst others, a more intuitive programming approach compared to traditional industrial robots using for instance programming by demonstration (PbD) and user-friendly interfaces. Examples of PbD tasks where the human skills are learned and reproduced by the robot include complex operations such as welding [3] [4] or painting [5]. The involvement of the human during the collaborative process also allows performing new types of applications thanks to the combination of the complementary capabilities of the robot and the human worker. Collaborative robots can also improve the working conditions of humans by decreasing the workload of human workers and by reducing the risk of workplace injuries [6].

Integrating a robot on the work-floor in close proximity of the operator raises safety concerns [7]. Recently, many efforts have been made to achieve a safer human-robot interaction. This includes, on one hand, control strategies [8] to avoid dangerous collisions and, on the other hand, compliance control methods [9][10]. However, implementing robot safety measures does not prevent harmful effects of non-ergonomic postures on the human body during task execution. Musculoskeletal disorders (MSDs) represent one of the major causes of absenteeism at work, leading to an important productivity loss in the manufacturing industry [11]. They are mainly due to a repetition of improper postures during a long period of time and high physical effort such as pulling, pushing, and lifting [12]. It is estimated that 40 million workers are affected by MSDs in Europe, leading to an associated yearly cost of 240 billion euros [11][13].

Improving ergonomics and decreasing the workload of the operator at his workstation has been investigated through different methods. In [14], a generic approach is proposed for the design of a workplace whereby the workstation layout is determined using the anthropometry of the user population. Immersive virtual reality is used in [15] to study and enhance the industrial workspace. Feyen et al. [16] developed a PC-based software that assesses the biomechanical risk of injuries in an environment of automotive assembly. In [17], a systematic design procedure is proposed for human-robot shared workspaces. The workstation layout is determined by assessing the ergonomics of the assembly tasks by deriving the subtasks requirements from the CAD models, the product and assembly sequence constraints.

Among the approaches to decrease the human physical workload, one can cite task allocation methods that alleviate the human worker's job by assigning tasks to the robot in case of high user effort, such as in [18], [19] and [20]. In order to improve the posture, human body measurement techniques are necessary. Observational methods are well-known ergonomic tools that apply to a wide range of applications [21]. They are systematic processes that consist in analyzing the body postures of the operator and encoding manually the estimated joint angles from a video recording of the task. However, since they are paper-based, they suffer from limited precision and are time-consuming. Vision-based human tracking devices such as time-of-flight cameras allow performing automatic postural assessment [22]. These provide a cost-effective solution to analyze the operator ergonomics on the work-floor. Aside from the human kinematics sensing, various models have been proposed to evaluate the human body dynamics [23][24]. Nevertheless, the on-line implementation of such models is often an issue due to their high complexity and is, therefore, limited to an off-line utilization. In [25], a method is proposed to estimate on-line the overloading joint torques using the human dynamic model. Peternel et al. [26], developed an approach for the estimation of the human effort model using muscle fatigue. In [27], the human manipulability is assessed for general and task-specific applications. Other methods to assist the worker include the development of co-manipulation controllers [28], wearable exoskeletons [29][30] and supernumerary robotic limbs [31].

Collaborative robots can help improving the ergonomics of the task executed by the human through the monitoring of the user state and appropriate control of the robot. In [32], a framework is developed where the robot motions minimize the overloading joint torques of an estimated dynamic state model of the human. Busch et al. [33] proposed an optimization method based on a personalized human kinematic model that adapts the robot behaviour to bring the worker pose to the improved posture. A similar multi-objective optimization method is used in [34] that determines the optimal trajectory that leads to the ergonomics posture. In [35], the robot is moved in such a way that the muscular fatigue of the human operator is minimized. In this paper, a novel framework is proposed for postural optimization that improve the worker comfort and avoid unsafe postures during human-robot collaborative tasks. The first contribution, compared to existing methods, is the use of a virtual spring model to determine the most ergonomic human joint angles. Unlike common optimization problems, this provides a simple and intuitive solution to the optimal posture computation. The second contribution, complementary to the positional robot adaptation of the co-manipulated part, is the display of the optimal pose to the user. This allows to lower the risk of MSD even during human-only capable tasks. Dynamics is not considered in the development of the method in this paper. The goal of the ergonomics optimization algorithm is to improve the user's posture during co-manipulation tasks such as during object handing-over, painting or polishing.

The ergonomics framework is composed of three modules. First, the 3D skeleton tracker determines the joint angles of the human body and transmits the data to the visualization and workpiece position controller modules of the ergonomics optimizer. The former informs online the user about his posture and proposes an optimal pose. Feedback is provided to the operator in case of a high-risk posture. The workpiece position controller adapts the robot's behavior to bring the user to an improved pose during co-manipulation/hand-over tasks. The method is validated on the assembly of a crusher unit from the smoothie machine manufactured by Alberts.

The paper is organized as follows. First, Section II states the problem and the main addressed aspects. Section III presents the virtual element-based method that is used in the framework to determine the optimal posture as well as the theoretical background. Simulation results were run to validate the optimization method before the real implementation. The ergonomics optimization framework and its main modules are then described in Section IV. Section V presents the experimental validation on two different use cases. The first task consisted in a collaborative assembly whereby the user and the robot jointly assembled the manufacturing part. In the second task (collaborative polishing), a user study is performed where the participants are asked to polish a cylinder held by the robot. Finally, in Section VI, the results of the framework are discussed and future perspectives are presented.

II. Problem statement

During human-robot collaboration tasks, the cobot can physically assist the user. For instance, the manipulation of objects might lead to non-ergonomic postures such as in the case of a part placed on a low-height table. The operator would need to lean forward to pick up the desired piece. This might create (especially if repeated throughout the day) excessive load on the user's back. In this context, the robot can help the human by appropriately position and/or orient the object/tool such that the ergonomics is improved during the task. This is depicted in Figure 1. In case the object/tool's pose is constrained or the robot's intervention is not possible, feedback should be provided to the user if an improper posture is detected and an improved pose should be computed and displayed to the operator.

For this purpose, a mathematical method needs to be developed to determine the set of body joint angles that leads to an ergonomically optimal posture.

III. Virtual element-based postural optimization

In this section, the postural optimization method using virtual elements is detailed. First, the developed human model is presented, whereby the left and right kinematic chains of the body are separately considered. Second, the Rapid Entire

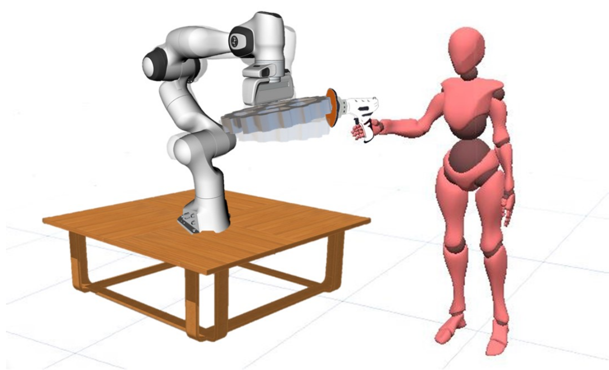


Fig. 1: Workpiece position control by the collaborative robot during a polishing process to improve the user's posture.

Body Assessment (REBA) method that is used to assess the ergonomics of the user posture is briefly described. Finally, simulations tests are performed to validate the proposed ergonomics optimization approach and assess the performance of the algorithm.

A. *Human model*

The human skeleton is modeled by kinematics chains with virtual mechanical elements namely springs and dampers, creating corresponding joint torques. Solving the Ordinary Differential Equations (ODE) of the model results in the body joint angles of the optimal static body pose. Torsional springs are attached to the body joints as depicted in Figure 2. Virtual dampers are also included along with the springs (not shown in the images). These allow to stabilize the system. Linear springs are attached to the wrist to bring the hand to the desired x, y, z position as shown in Figure 2.(a), (b), and (c) for respectively the 3D, 2D, and 1D constraint cases. Orientation's constraints of the hand are set using torsional springs (not shown in the Figure for clarity). In the case of situations where both position and orientation constraints need to be specified, both torsional and linear springs are used. The developed model considers the upper body part of the human where a serial chain is created from the trunk base to the right or left hand depending on the user handedness. Other models can be generated in the same fashion. A full body model would use serial chains that connect the feet to the hands with constraints specified at the extremities. A similar model for the two-arms case can be determined where two serial chains are used connecting respectively the left and right hands to the trunk base. The joint torsional springs free position is set to the joint angle that leads to the most ergonomic posture. In this case, these values have been selected based on the Rapid Entire Body Assessment method (REBA) [36]. The latter is an analysis of the human posture where scores are determined for every body part and coupled together with other considerations related to the activity and forces exerted to obtain the REBA score. Section III-B describes the main steps of the method. It should be noted that the REBA method was selected as it provides a general approach to the optimization of the body posture and is still applicable in the case of tasks where the lower body part is moving such as during the lifting of a load from the ground (legs are bent).

The equations of motion of the right/left human kinematic chain read as follows:

$$C_h\dot{\Theta}_h + K_h(\Theta_h - \Theta_h^*) = T_h \tag{1}$$

where h denotes the handedness (right/left), C_h is the damping matrix, K_h is the stiffness matrix, and T_h, the joint torques generated from the external forces on the wrist. Note that, the acceleration properties such as the masses and inertias of the links are neglected since a quasi-static system is considered.

Θ_h, $\dot{\Theta}_h$ and Θ_h^* represents respectively the vector of the joint angles, velocity, and free positions:

$$\Theta_h = \begin{bmatrix}\theta_1\\\theta_2\\\theta_3\\\theta_4\\\theta_5\\\theta_6\\\theta_7\end{bmatrix},\ \dot{\Theta}_h = \begin{bmatrix}\dot{\theta}_1\\\dot{\theta}_2\\\dot{\theta}_3\\\dot{\theta}_4\\\dot{\theta}_5\\\dot{\theta}_6\\\dot{\theta}_7\end{bmatrix},\ \Theta_h^* = \begin{bmatrix}\theta_1^*\\\theta_2^*\\\theta_3^*\\\theta_4^*\\\theta_5^*\\\theta_6^*\\\theta_7^*\end{bmatrix} \tag{2}$$

with the following indexing: 1 = trunk bending, 2 = trunk side bending, 3 = trunk twist, 4 = upper arm flexion, 5 = upper arm abduction, 6 = upper arm rotation, 7 = lower arm flexion.

The damping and stiffness matrices read as follows:

$$C_h = diag(c_1, c_2, c_3, c_4, c_5, c_6, c_7) \tag{3}$$

$$K_h = diag(k_1, k_2, k_3, k_4, k_5, k_6, k_7) \tag{4}$$

where c_i and k_i are the damping coefficient and stiffness at joint i.

The applied torques on the joints are expressed by:

$$T_h = J_h^T F_h \tag{5}$$

where the applied external force on the wrist, due to the virtual spring is:

$$F_h = \begin{bmatrix} -k_x(x-x_d) - k_{I,x}\int(x-x_d)dt \\ -k_y(y-y_d) - k_{I,y}\int(y-y_d)dt \\ -k_z(z-z_d) - k_{I,z}\int(z-z_d)dt \\ -k_\theta(\theta-\theta_d) - k_{I,\theta}\int(\theta-\theta_d)dt \\ -k_\beta(\beta-\beta_d) - k_{I,\beta}\int(\beta-\beta_d)dt \\ -k_\delta(\delta-\delta_d) - k_{I,\delta}\int(\delta-\delta_d)dt \end{bmatrix} \tag{6}$$

k_x, k_y, kz are the stiffness values of the virtual springs in the x, y and z directions and $k_\theta, k_\beta, k_\delta$ the x, y, z rotational spring stiffness. x_d, y_d, z_d, θ_d, β_d and δ_d are the coordinates of the desired 6DOF pose.

Additional integral gains are added in translation's and rotation's directions in order to cancel the end-effector steady-state error.

Joint limits are integrated during the resolution of the ODE equations as follows:

$$\dot{\theta}_i = 0 \;\; if \begin{cases} \theta_i \geq \theta_{i,max},\, \dot{\theta}_i > 0 \\ \theta_i \leq \theta_{i,min},\, \dot{\theta}_i < 0 \end{cases} \tag{7}$$

Cartesian limitation is converted into joint constraints using the pseudo-inverse jacobian $J^{\dagger}$, as shown below for the translation's degrees of freedom:

$$\begin{cases} \dot{x} = 0 \;\; if \begin{cases} x \geq x_{max},\, \dot{x} > 0 \\ x \leq x_{min},\, \dot{x} < 0 \end{cases} \\ \\ \dot{y} = 0 \;\; if \begin{cases} y \geq y_{max},\, \dot{y} > 0 \\ y \leq y_{min},\, \dot{y} < 0 \end{cases} \\ \\ \dot{z} = 0 \;\; if \begin{cases} z \geq z_{max},\, \dot{z} > 0 \\ z \leq z_{min},\, \dot{z} < 0 \end{cases} \end{cases} \Rightarrow \dot{\Theta} = J^{\dagger} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\theta} \\ \dot{\beta} \\ \dot{\delta} \end{bmatrix} \tag{8}$$

B. Rapid Entire Body Assessment (REBA)

The REBA method is a postural analysis tool to evaluate whole body Musculoskeletal disorders (MSDs). Figure 3 shows the main steps of the method. The analysis of the human body posture is split into the neck-trunk-legs and the arm-wrist studies. Scores are determined for every body of the part and coupled together with other considerations related to the activity and forces exerted to obtain the REBA score. A REBA score between 1 and 3 represents a low risk of MSD (ergonomic posture). Values ranging from 4 and 7 indicate a medium risk (non-ergonomic posture). Further investigations should be performed and adequate changes should be applied soon to the task. A score of 8 or more represents a high risk case where immediate changes are required.

C. Simulations

The set of ODE presented in the previous section is coded in Matlab using the ODE45 solver. MEX files are generated for the different functions of the algorithm in order to maximize the online speed performance. Computing the optimized posture is achieved within $\sim$5 ms on a Ryzen 9 3900x 12 core processor.

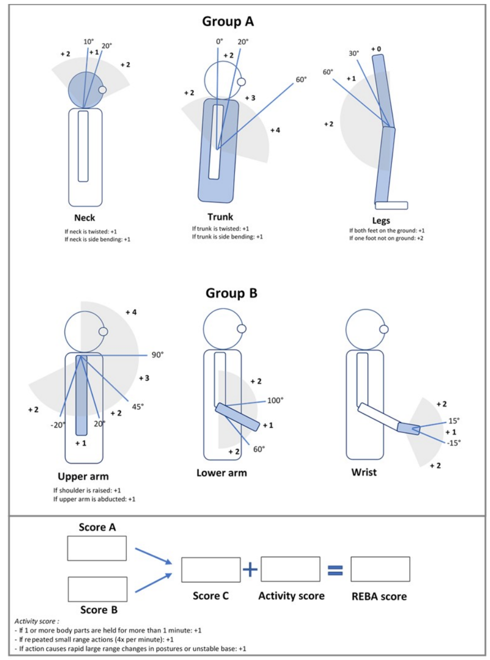
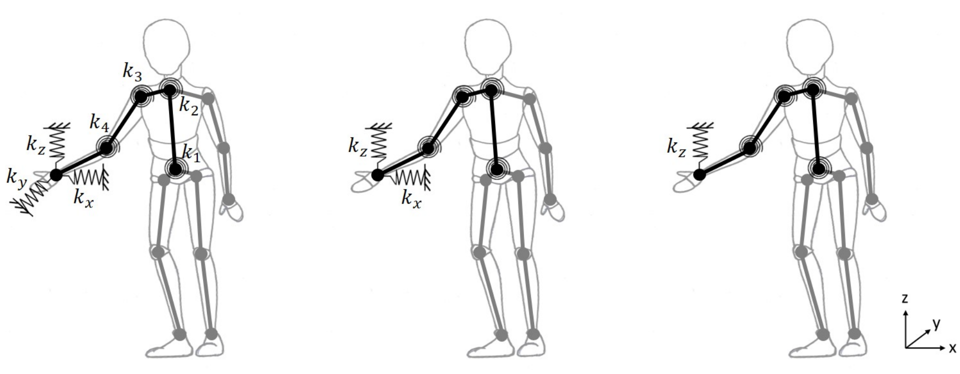


Fig. 3: Main steps of the REBA postural assessment technique. The analysis is split into the neck, trunk and legs part (Score A) and the arm and wrist part (Score B). Tables are used to determine the different scores [36].

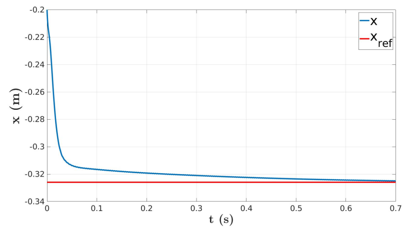
The simulation tests have been performed for the translation's constraint case whereby 1, 2, or 3 of the position coordinates of the wrist are locked and the optimal joint angles in terms of ergonomics load are found. Indeed, some tasks lead to a constrained location of the user's hand. This occurs, for instance, during the manipulation of a tool on an object. For example, polishing a plate implies that the sander remains in a normal contact which indirectly constrains 1 translational direction of the hand.

In order to find the optimal body posture, the forward kinematics is first applied to determine the current wrist pose from the joint angles. In case the error between the later and the desired position is higher than a given tolerance,

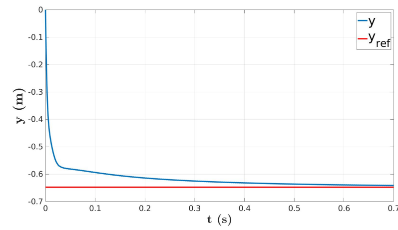


(a) Wrist's position locked (b) Wrists' y and z positions locked (c) Wrist's z position locked

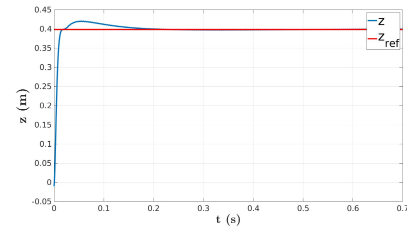
Fig. 2: Human body models using virtual torsional springs on the joints. The hand's position is locked by linear springs attached to the wrist along the desired direction. k_x, k_y and k_z represent respectively the stiffness of the springs along the x, y and z directions. k_1, k_2, k_3, k_4 and k_5 are the joint's spring stiffness.



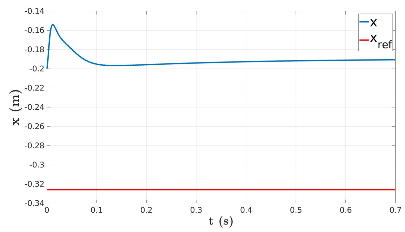
(a) 3D lock - wrist's x position



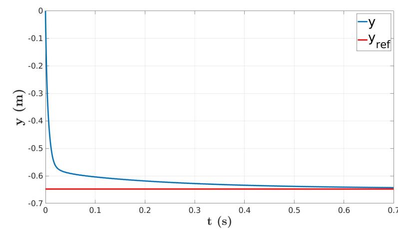
(b) 3D lock - wrist's y position



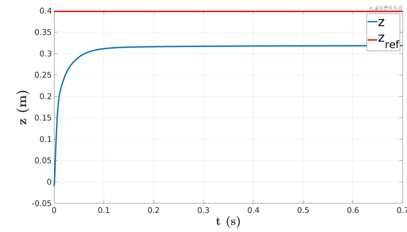
(c) 3D lock - wrist's z position



(d) 1D lock - wrist's x position



(e) 1D lock - wrist's y position



(f) 1D lock - wrist's z position

Fig. 4: Simulation test results of the right wrist's position during the postural optimization for a fully constrained case (x, y and z wrist's position fixed) and a 1D constrained situation (wrist's y position locked). The corresponding joint angles are $\theta_1 = 16.36°$, $\theta_2 = 6.39°$, $\theta_3 = 14.79°$, $\theta_4 = 43.65°$, $\theta_5 = 34.19°$, $\theta_6 = -17.53°$, $\theta_7 = 65.83°$ and $\theta_1 = 16.39°$, $\theta_2 = 9.08°$, $\theta_3 = 14.74°$, $\theta_4 = 40.62°$, $\theta_5 = 21.81°$, $\theta_6 = -7.62°$, $\theta_7 = 32.46°$. The associated REBA values are 2 and 1. The desired x, y and z positions are displayed by the red lines.

the algorithm resolves the set of ODE equations taking into account the joint and cartesian limitations as long as the desired accuracy is not reached. Figure 4 shows the results obtained in the fully constrained case (x, y, and z coordinates are fixed) as well as the wrist's position in the 1D constraint situation. The reduction of constraints leads, as expected, to an improved posture, i.e. lower REBA score. The stiffness of the virtual trunk springs are set to a higher value ($k_1 = 2000$, $k_2 = 2000$, $k_3 = 2000$) compared to the arm ($k_4 = 100$, $k_5 = 100$, $k_6 = 100$, $k_7 = 100$) since the motion of this body part is more critical in terms of ergonomics, i.e. leads to a higher MSD risk. Also, this allows to favour the arm motions over the trunk movement during the task to enable a more natural posture. The stiffness values (and damping) have been determined in the same fashion as in the tuning of a PID system where the gains are adjusted to obtain a stable solution that converges fast to the reference.

The postural optimization using the virtual element method is the core of the ergonomics framework. The determined posture is used by the feedback interface that displays the optimal pose to the user as well as the robot controller that brings the part/workpiece to a position with a lower REBA score.

IV. Ergonomics Optimization

Figure 5 shows the proposed ergonomics optimization framework to solve the improper postures of the operator during collaborative tasks. First, the 3D skeleton tracking module performs a user's spatial joint detection. This information is then fed into the feedback interface to animate online a 3D character and determine the associated REBA score. Second, the body joint angles are sent to the postural optimization module of the workpiece-position controller. The latter computes the optimal ergonomics body pose by taking into account the task constraints (e.g. orientation of the workpiece) and returns it back to the feedback interface. Finally, in case the co-manipulated part is free to move in one or more of the 6 DOFs, the end-effector control module adjusts the workpiece position in such a way that the user's posture is brought to the optimal pose.

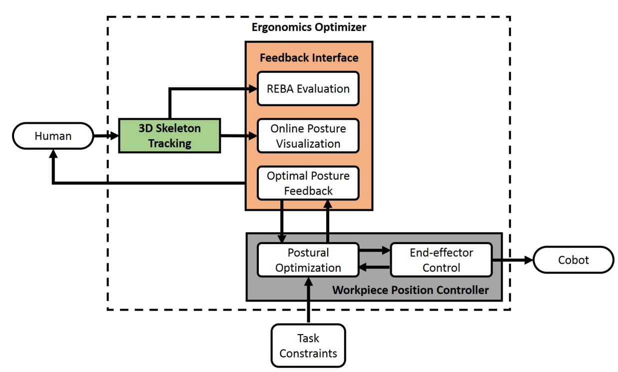


Fig. 5: Ergonomics controller scheme. Based on the ergonomics analysis and the task data (workpiece constraints) optimal postures are suggested to the user or the cobot configuration is adapted.

A. 3D Skeleton Tracking

In order to monitor the user posture, a tracking system composed of a depth sensor was selected as it provides a non-intrusive low-cost solution and an easy deployment in real manufacturing settings. Other tracking solutions such as marker-based optical systems and motion tracking using inertial sensors can also be integrated.

The skeleton tracking is performed by a Kinect v1 camera. The middleware Nuitrack is used to process the Kinect data. The latter utilizes the depth and color information of the camera to perform hand locating and tracking, accurate and robust 3D localization of the human body joints, face detection, and various gesture recognition. Skeletal tracking is used to determine the user's upper body joint angles as shown in Figure 6. The provided skeleton joint positions include the head, neck, trunk, shoulders, and arms.

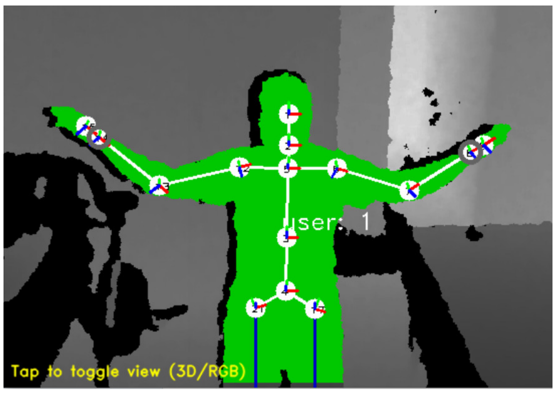


Fig. 6: Full-body skeletal tracking with the Nuitrack middleware and the Kinect v1 camera.

B. Feedback Interface

The graphical feedback interface is implemented in the Unity 3D game engine. Figure 7.a shows the main components. The current human body pose is updated from the Kinect data and visualized online through an animated character. The detailed ergonomic REBA scores are displayed through a text box. The feedback module also includes the visualization of the optimal body pose that is determined by the postural optimizer. Control buttons are implemented to interact with the graphical user interface and access functions such as the selection of the male or female character. The human models were obtained from the Mixamo website with no licensing or limitations. In Figure 7.b, a screenshot of the interface shows the visual feedback in case of a non-ergonomic posture. The background light as well as the REBA score are displayed in red and a beep alarm sound is activated.

C. Workpiece position controller

The workpiece position controller module performs the postural optimization using the body joint angles from the feedback interface and adapts accordingly the position of the co-manipulated part through the control of the robot end-effector. The implementation of the functions of this module includes a Matlab script that performs postural optimization and C++ codes that control the robot using the *libfranka* library.

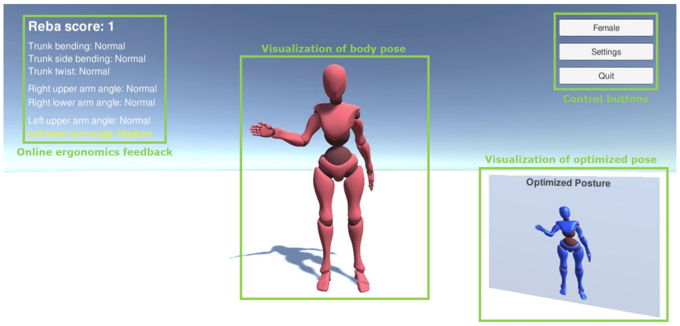
The main steps of the method are detailed in Algorithm 1. This shows the pseudo-code for the translational case, i.e. optimization of the user posture by moving the wrist in the x, y, and z directions. First, depending on the handedness of the user, the left or right body joint angles are considered as well as the associated variables, namely the free position vector Θ^*, the stiffness and damping matrices K and C. Then, the wrist's position of the current posture ($\bar{x}_i$) is found using the *getTransform* function (time complexity: 0.2ms) that applies the forward kinematics from the joint angular values. The postural optimization function (*PostureOptimizer*) determines the optimal joint angles based on the body state and the human model by solving the ODE equations of Section III-A. This is achieved in less than 5ms on a Intel-i7 processor. A tolerance tol is also fed into the function to stop the optimization once the error between the wrist's position and the desired task positional constraint is sufficiently small. A displacement vector $\Delta\bar{x}$ is computed from the wrist's position of the optimized posture and the one from the initial body configuration. The *endEffectorControl* function (time complexity: 1-5s) implements an inverse kinematics solver that applies joint motions to the robot to move the end-effector with a displacement of $\Delta\bar{x}$. The motion of the robot stops when the displacement falls below the error tolerance tol. The corresponding codes can be found on github[1].

Algorithm 1: Workpiece position controller

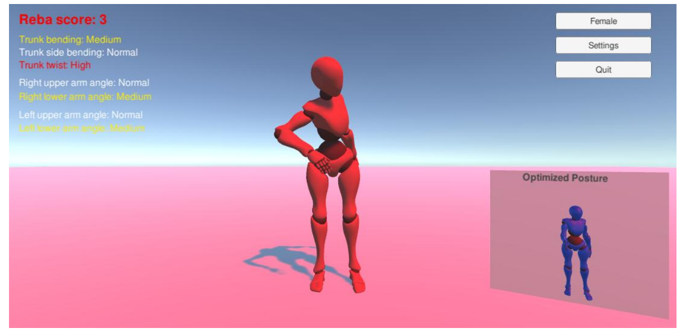
Input: Vector of booleans enabling the optimization in the x, y and z directions $\bar{\mathbf{O}} = [O_x, O_y, O_z]$, the handedness **h** of the user, the current left and right body joint angles p_l and p_r, the stiffness vector of the wrist's virtual linear springs $\bar{\mathbf{k}} = [k_x, k_y, k_z]$, the end-effector integral gain vector $\bar{\mathbf{k}}_{\mathbf{I}} = [k_{I_x}, k_{I_y}, k_{I_z}]$ and the error tolerance tol.
Output: The end-effector displacement $\Delta\bar{\mathbf{x}}$ that optimizes the user posture.

```
if h == left then
    p = p_l;
else
    p = p_r;
end
while optimizing do
    // Find the wrist's position of the
       current body joint angles p
    x̄_i = getTransform(p);
    // New body joint angles p* found
       after the optimization of the
       user posture
    p* = PostureOptimizer(p,Ō,k̄,k̄_I,tol);
    x̄_opt = getTransform(p*);
    Δx̄ = x̄_opt - x̄_i;
    while Δx̄ > tol do
        endEffectorControl(Δx̄);
        Δx̄ = x̄_opt - getTransform(p);
    end
end
```

[1]https://github.com/rmm-VUB/ErgoVirtualControl



(a) Feedback interface's overview



(b) Notification of non-ergonomic posture

Fig. 7: Graphical interface in Unity. (a) Overview of the feedback module displaying online the body pose of the user, the associated detailed REBA scores, the optimized posture and control buttons. (b) Bad posture detected. The user is notified through a red light feedback and a beep alarm sound.

V. Experimental validation

This section presents the implementation of the postural optimization framework on two use cases. The first human-robot collaborative task consists in assembling the crusher unit from the smoothie machine manufactured by the Alberts company, as shown in Figure 8. The second application presents a collaborative task where the user polishes a cylinder that is hold by the franka robot at an optimised position. The latter experiment is applied on real users and also evaluate subject's perception. During these tests, the feedback interface was not shown to the users in order to avoid any influence from the displayed optimal posture on the task execution.

A. Collaborative assembly

Fig. 8: The smoothie vending machine developed by Alberts (A) is composed of several cartridges containing the smoothie ingredients (B). The crusher unit is located in the bottom of the cartridges (C).

1) Experimental setup: The assembly task is realized with the collaborative robot Franka as shown in Figure 9. A screen placed close to the user displays the feedback interface. The dismounted parts of the assembly are laid down on a table along with the screws and the screwdrivers. The human and the robot jointly assemble the crusher unit. The subtasks are assigned to one of the agents by taking into account their capability and availability. Since the robot is not equipped, in this case, with a screwdriver, the screwing task is performed by the human. The tasks, in order, and their respective assignments are:

1) Pick up rod (Robot)
2) Pick up blades and spacers (Human)
3) Stack blades and spacers (Human)
4) Place rod (Human)
5) Pick up left and right plates (Robot)
6) Place left and right plates (Robot)
7) Screw left and right plates (Human)
8) Pick up motor hub (Robot)
9) Place motor hub (Human)
10) Slide motor (Robot)
11) Screw motor shaft (Human)

The robot is position-controlled at a frequency of 1 kHz. Interactions with the user are implemented using force sensing on the end-effector. The operator, for instance, informs the robot that his/her task is completed by touching Franka's hand. This method is also used to detect when an external force is applied to the co-manipulated object and activates the workpiece position controller.

The master node runs on Matlab and performs postural optimization. The latter receives the online joint angles from the feedback interface and returns the optimized posture. When a request is received from the workpiece position controller module, the optimal angles are also transferred to the robot's computer. The interfacing between the different modules is realized using UDP sockets (in order to maximize the transmission time for an online use).

2) Results: The developed framework is validated by comparing two cases. The first case corresponds to the collaborative assembly of the crusher unit with the ergonomics feedback and the workpiece position control. In the second case, the two modules are disabled. Certain tasks that can only be performed by the human lead to a notification (beep sound and light) from the graphical interface when a non-ergonomic posture is detected. For instance, picking up the blades of the crusher or screwing the side plates. The user corrects then his posture according to the displayed body pose. During co-manipulation

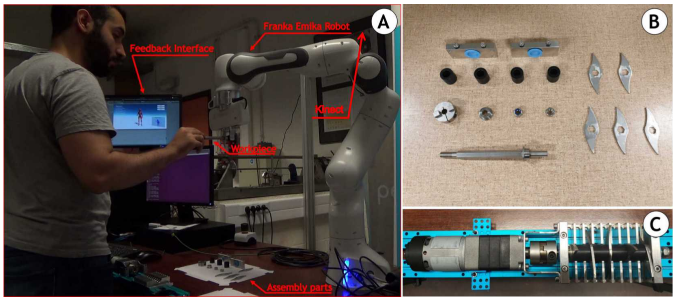


Fig. 9: The experimental setup of the collaborative assembly use case consists of the collaborative Franka robot (A). The dismounted parts of the assembly (B) are placed on the table along with the screws and the screwdrivers. The robot and the operator collaboratively assemble the crusher unit (C). A screen displays the feedback interface to the user. The skeleton tracking is achieved using a Kinect v1 camera.

of objects by the robot and the human, for instance, when stacking of the blades and spacers onto the rod hold by the robot, the workpiece position controller can act on the end-effector position to adjust the latter in such a way that the user posture is improved. It should be noted that the end-effector final position will vary depending on the detected initial human pose. This can sometimes generate large displacement of the robot, beyond its workspace, to correct the posture. Example of body poses include a fully stretched arm. In order to deal with the aforementioned situations, cartesian limits have been implemented in the robot controller. The assembly setup has also been designed to limit as much as possible large movements from the human. During the validation tests, we consider that the user reacts to the received feedback and modifies his posture. In this example, a right-handed person is interacting with the robot.

The pictures of the collaborative assembly with the Franka robot are shown in Figure 10. Two tasks are represented. The first task is the picking up of blades on the table. A non-ergonomic posture is detected (Figure 10.a). The associated REBA score is 3. The user receives a notification as shown in Figure 10.c and corrects his posture (Figure 10.b). The REBA score of the improved body pose is 2. The second task is the stacking of the crusher's blades onto the rod. The latter is held by the robot. The insertion of blades by the user is detected using force sensing on the end-effector. Once the interaction force exceeds the desired threshold, the workpiece position controller is triggered. Figure 10.d and Figure 10.e show the user during the co-manipulation process in the fixed robot position and adjusted workpiece position cases.

Figure 11 shows the REBA scores for 4 different tasks of the assembly, namely picking up the blades, screwing the plates, stacking the blades and the hub handover to the user by the robot. These were performed by a user repetitively for 10 iterations. The data presents the scores related to the different parts of the body, i.e. the trunk, the lower arm, and upper arm. The tasks shown in Figure 11.a and Figure 11.b are performed by the human. The posture is improved through the feedback interface. It can be observed from Figure 11.a that the total REBA value is improved from 3 to 2 for the picking up of blades. The main posture change consists in a straighter trunk pose. In the plate screwing task, the REBA score is decreased from 4 to 1 as shown in Figure 11.b. The scores of the various body parts are also improved. The postural optimization data using the workpiece position controller are depicted in Figure 11.c and Figure 11.d for respectively the blade stacking and the hub handover. In the first case, no change in the total REBA value is observed. However, the lower arm angle (elbow) is enhanced in the new body pose. The handover position is also adjusted as shown in Figure 11.d during the exchange of the hub from the robot to the user. It can be noted that a lower REBA score is achieved, by improving mainly the upper arm angles.

B. Collaborative polishing

1) Experimental setup: The experimental validation involved a human-robot collaboration task whereby the robot held a metallic cylinder that is polished by the user using a hand-held drill as shown in Figure 12. The Kinect camera was placed in a location where occlusion with the robot is reduced as much as possible. The task of the robot consisted in bringing the cylinder to the human in a position that leads to the optimal ergonomic posture.

We have conducted a user study with 10 participants (8 males, 2 females, 2 left-handed, aged 26 $\pm$ 3.36). Three robot behaviours have been implemented (*fixed*, *relative* and *optimal*) During the experiment, two behaviours, chosen randomly, are presented to the participant. More information about the behaviors are detailed in the following.

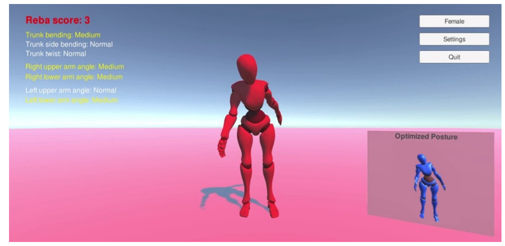
- *Fixed:* The robot presents the object at a fixed pose. The user posture is not take into account.
- *Relative:* Ergonomic studies from the literature suggest to hand over the object at torso height at two-third of user's arm maximum elongation [37]. During the task, the user's torso is tracked using the Kinect camera and the cylinder is positioned accordingly.
- *Optimal:* The robot end-effector is controlled by the workpiece position controller to move the object to an optimal position that leads to a better ergonomics posture.

2) Results: After the interaction with the robot, the subjects were asked to fill in a survey, for every behaviour, composed of 12 Likert scale items ranked from 1 to 5 based on the System Usability Scale methodology [38]. Subjects were also asked to order the behaviours according to their preferences. The questions represented three categories: *task constraints*, *acceptability* and *safety*. The subjects were not aware of this subdivision. The 12 affirmations were presented in a random order. The results of the survey can be found in Figure 13. The negative affirmations are displayed in a range from -5 to -1.

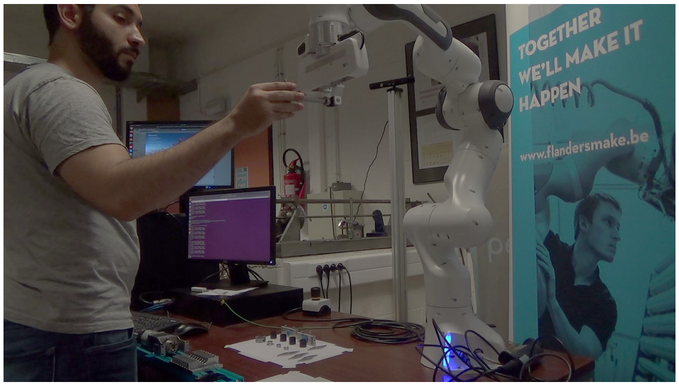
All users having experienced the *optimal* mode ranked it as their preferred behaviour. The second preferred behaviour is the *relative* mode. From the affirmations of Figure 13, the *optimal* behaviour shows the most positive results for the three categories. The Mann-Whitney U test has been performed on the *optimal* condition affirmations with a significant preference

(a) Picking up blade (non-ergonomic posture)

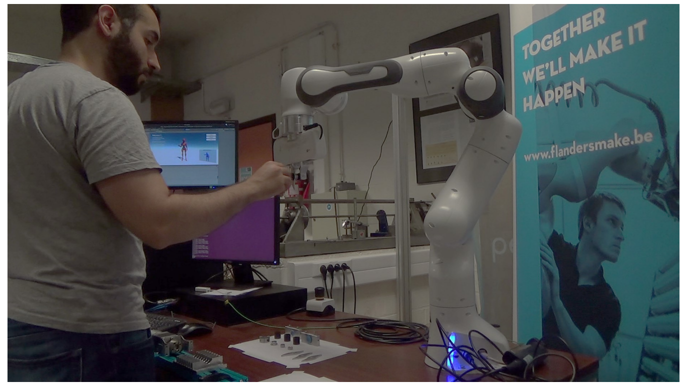
(b) Picking up blade (ergonomic posture)



(c) Feedback interface's view



(d) Stacking blade (fixed robot position)



(e) Stacking blade (adjusted workpiece position)

Fig. 10: Pictures of the collaborative assembly of the crusher unit for two different tasks, namely picking up blades (a, b, c) and stacking them by sliding the pieces onto the rod hold by the robot (d, e). In the first task, a non-ergonomic posture (REBA = 3) of the user is detected. The operator receives a notification from the feedback interface (c) and adapts his posture (REBA = 2). In the second task, the workpiece position controller module adjusts the rod position to improve the human pose. Link: https://youtu.be/o-Mf_wpKiEQ

($p < 0.05$). Due to the low number of left-handed people, no conclusion can be withdrawn regarding laterality.

During the collaborative polishing, the user's postures have been recorded and evaluated using the REBA method. The body pose used for comparison is the one captured when the robot motion is over in the case of the *optimal* condition. The results depicted in Figure 14 show that the REBA scores of the trunk, upper arm and lower arm are lower in the *optimal* behaviour condition. The total *optimal* behaviour score is about 0.6 below the *fixed* condition score. The *relative* and *fixed* modes present similar results.

VI. Discussion

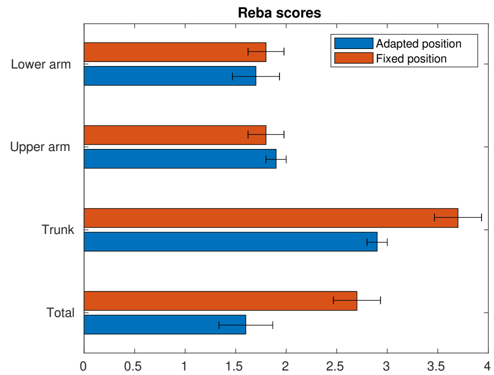
From the results of the experimental tests, we can observe in the *collaborative assembly* case, an overall decrease of the REBA scores using either the feedback interface or the workpiece position controller module of the developed postural optimization framework. Even though the total value is not always decreased, the optimizer allows enhancing some body part's poses. The average REBA score of the four assembly subtasks presented in the last section without and with postural optimization are respectively 2 and 1, i.e. a decrease of 42%. The posture correction by the feedback system during human-only capable tasks had a relatively low impact on the performances of the assembly process. Corrections are made 2 to 3 times during the crusher unit assembly and take about 2 seconds. This represents in the worst case 1.8% of the total assembly time.

From the user study in the *collaborative polishing* case, the *optimal* condition significantly reduce the body posture score. Even though the improvement is not spectacular, the method can show better results for tasks where more constraints is put on all the body parts, e.g. that requires trunk bending. The survey conducted with the subjects showed an overall positive user's perception of the developed method.

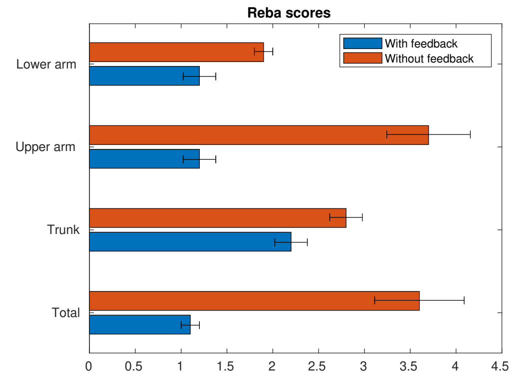
It should be noted that different parameters of the framework should be adjusted in function of the industrial case. This includes, for instance, the REBA threshold value. Some tasks require a higher body load thus an increase of the latter parameter might be needed. The cartesian limits of the robot controller should also be adapted to the application. Indeed, some tasks lead to high motion ranges such as during the painting of large parts.

The main advantage of the proposed framework lies in its simplicity, making it suitable for real-time purposes. The possibility to select the locked directions allows a fast adaptation of the robot behavior to the new task constraints. The use of non-intrusive motion capture devices, such as the Microsoft Kinect camera, enables easy deployment in real manufacturing settings. The developed software is modular. Therefore, the feedback interface could also be utilized as a standalone module to analyze the body posture of the user in "human-only" workstations and assess the ergonomics of the performed tasks. The developed framework is also not dependent on tracking device and other sensory systems could be interfaced.

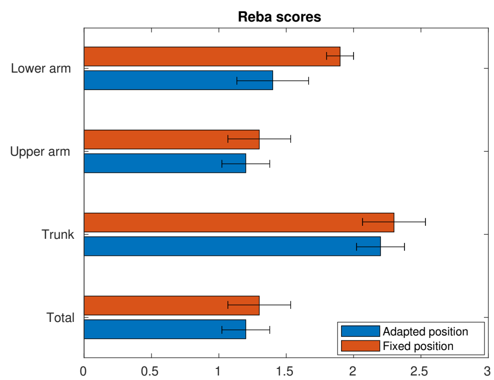
Different improvements could be integrated into the current



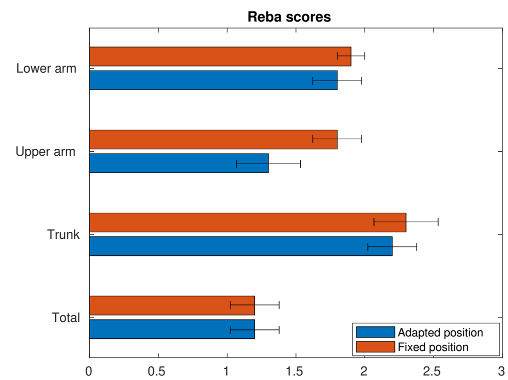
(a) Pick up blade



(b) Screw plate



(c) Stack blades



(d) Hub handover

Fig. 11: Averaged total REBA values and individual body part's scores for 4 different tasks over ten runs with standard errors (collaborative assembly use case). A better posture is achieved during human-only capable tasks (picking up the blades and plate screwing) through the feedback interface. During co-manipulation tasks (blade stacking and hub handover), the workpiece position controller is used to improve the human body pose.

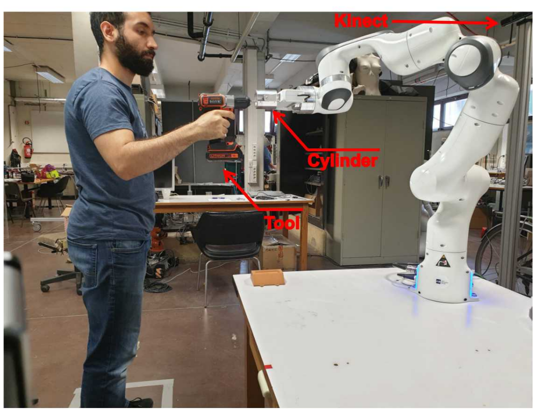


Fig. 12: The experimental setup of the collaborative polishing use case consisted of a cylinder hold by the Franka robot and polished by the user using a drilling machine equipped with a polishing wheel. A Kinect camera was placed in proximity to track the body postures.

postural optimization. First, manipulability considerations can be taken into account. This would allow exploiting the human arm joint angles to maximize the kinematic/dynamic characteristics of the co-manipulation task. The visibility aspect can also be considered in the framework. Indeed, it is important that the object hold by the cobot remains visible to the user when moved to avoid situations where he/she would be startled by the robot. This behavior also enhances the cobot social acceptability. It should also be noted that the robot's reach was limited in the presented use cases but this can be overcome using a mobile platform to increase the reachable workspace.

Another limitation concerns the use of a depth camera. This tracking solution leads to occlusions. Therefore other human tracking devices such as suits incorporated with Inertial Measurement Units (IMUs) could be investigated to achieve a better ergonomics monitoring.

The impact of the posture corrections on task performances was relatively low in the industrial cases presented in this paper. However, it is interesting to perform an in-depth study of the feedback interface to assess its efficiency in terms of postural improvement.

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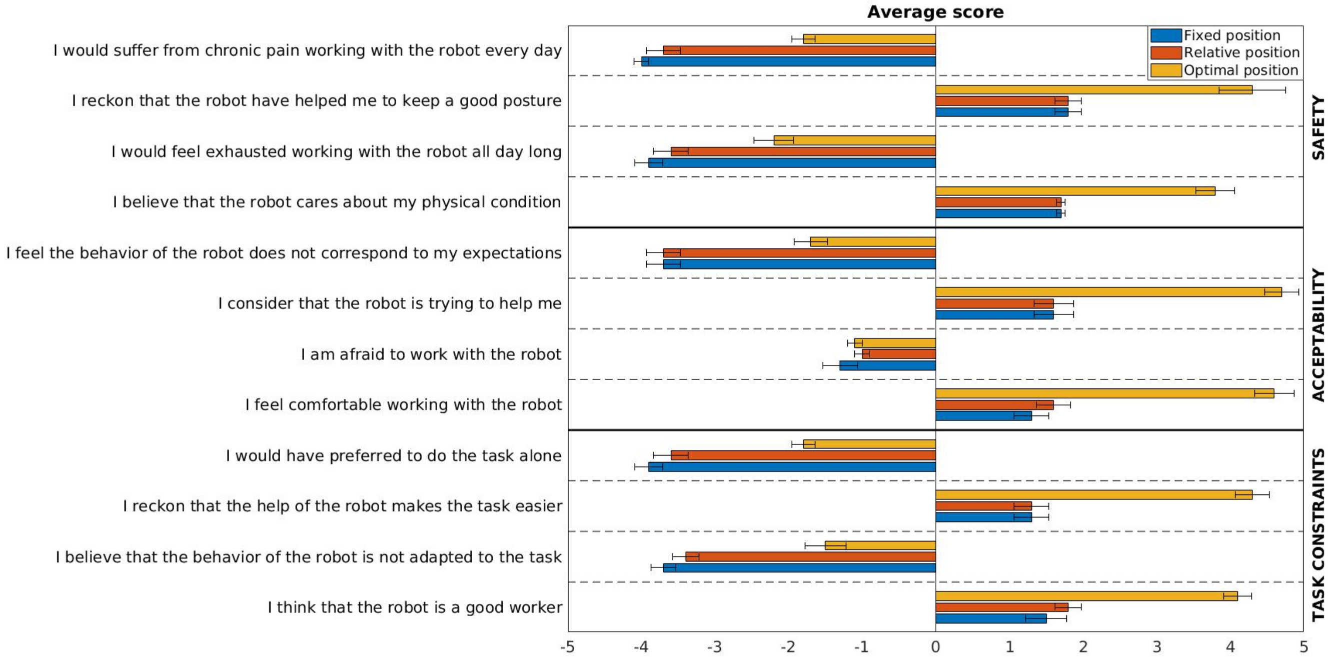

Fig. 13: Average results of the questions to the survey (collaborative polishing use case). 12 Likert scale items based on the SUS methodology [38] are ranked from 1 to 5. Negative values are used for the affirmation of negative type for a better representation. Significance of the results has been verified using the the Mann-Whitney U test.

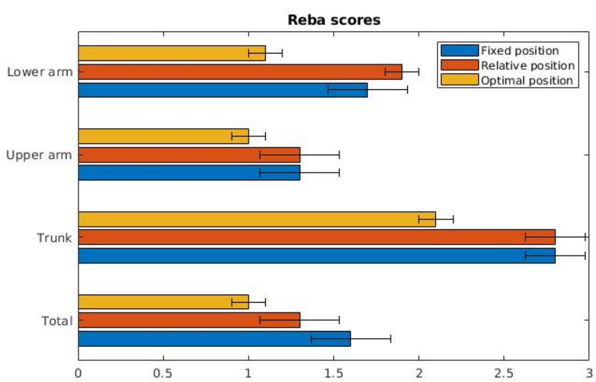

Fig. 14: Average score and standard error of the mean of the REBA scores for the different body parts (collaborative polishing use case). The *optimal* behaviour present a lower REBA score. The *relative* and *fixed* conditions show similar results.

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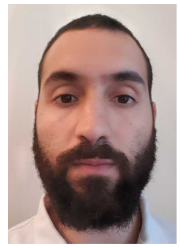

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