Improving User Ergonomics through Adaptable Cobot Behaviour

Part 1: A Generic Algorithm for the Computation of Optimal Ergonomic Postures

Ilias El Makrini[1,4], Greet Van De Perre[1,4], Glenn Mathijssen[1,3,4], Victor Van Wymeersch[2,4], Maxim Vochten[2,4], Wilm Decré[2,4], and Bram Vanderborght[1,4]

[1]Robotics and Multibody Mechanics Research Group, Vrije UniversiteitBrussel, Belgium, www.brubotics.eu
[2]Robotics Research Group, PMA Division, KU Leuven, Belgium
[3]Alberts NV, Bijkhoevelaan 32C, B-2110, Belgium
[4]Flexible Assembly, Flanders Make, Belgium
Corresponding author: Ilias.El.Makrini@vub.be

***Abstract*—Collaborative robots or cobots are gaining ground in the manufacturing industry. Unlike classical robot, they are more flexible and open the door to a large panel of applications whereby the human and the robot's skills are combined to achieve tasks jointly. Cobots can also help decreasing the workload of the operator. Nowadays, musculoskeletal disorders (MSDs) represent the main cause of absenteeism at work. This is accentuated by the ageing of the population. Thanks to the development of human tracking systems, it is possible to monitor the operator in his workstation and analyze his postures. Using ergonomic measures such as the Rapid Entire Body Assessment (REBA) method, the risk related to a non-ergonomic posture can be determined. In this paper, we present an algorithm to compute ergonomic postures based on the object/tool pose to be manipulated. Optimal postures are determined using an inverse kinematics method and the data returned by the ergonomics monitoring system.**

I. Introduction

Musculoskeletal disorders (MSDs) are the major cause of absenteeism and productivity loss in the manufacturing industry. MSDs are often due to a repetition of a wrong posture over a long period of time. It is estimated that 40 million workers are affected by MSDs in Europe, leading to an associated yearly cost of 240 billion euros [1]. To solve this problem, different approaches exist to improve the ergonomics of the job task and enhance the working conditions of the operator at its workstation. In Feyen et al. [2], a PC-based software is proposed to evaluate the biomechanical risk of injuries based on a workplace design of an automotive assembly task. Das et al. [3] developed a systematic ergonomics approach for the design of industrial workplace that determines the workstation dimensions and layout based on the anthropometry of the user population. In [4], a generic design methodology is provided for human-robot collaborative workplaces. Based on CAD models, product and assembly sequence constraints are extracted and subtasks functional requirements are determined. This information is then used to assess ergonomics and identify the corresponding layout constraints.

Collaborative robots can improve the working conditions of humans by decreasing the workload of human workers and by reducing the risk of workplace injuries [5]. Studies have demonstrated that common injuries are the result of high physical effort and repetitive motions such as pulling, pushing and lifting [6]. To solve this problem, different methods have been developed to measure the human body posture at their workstation [7]. Among them, one can cite the observational methods that can be applied to a large variety of situations. These have, however, a limited accuracy due to their paper-based approach and are time-consuming. With the development of non-intrusive human tracking technologies such as depth cameras, this process can be automatized [8]. These new assessment techniques offer a promising solution for the industry as they allow reducing significantly the costs related to ergonomics. Moreover, they provide an in-depth analysis of the human coworker during human-robot interactions. Recent efforts have been made to assess and improve the body posture of workers during human-robot interaction [9]. Approaches have been proposed to estimate the human effort model by using for instance muscle fatigue [10]. In [11], a method is developed where the human body overloading joint torques are determined on-line using a dynamic model of the human. Other methods to assist the worker include the development of co-manipulation controllers [12][13].

In this paper, we present a generic algorithm that determines an optimal posture of the human such that ergonomics is improved during human-robot collaborative tasks. Based on the hand position and orientation imposed by the workpiece's pose during the task (e.g. object handover to the user, tool/part orientation by the robot such as in a polishing process or co-manipulation applications). This work is the continuation of the ergonomics-based task allocation framework of our recent research [14]. The paper is organized as follows. First, Section II states the problem and gives an overview of the ergonomics controller. Section III presents the optimal posture algorithm. The ergonomics assessment tool used in this method is briefly discussed in Section III-A. Finally, Section III-B describes the main principles behind the algorithm and its implementation.

II. Problem statement

During human-robot collaboration tasks, the cobot can physically help 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 user would need to lean forward to pick up the desired piece. This might create (especially if repeated throughout the day) excessive load on the back of the operator. 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.

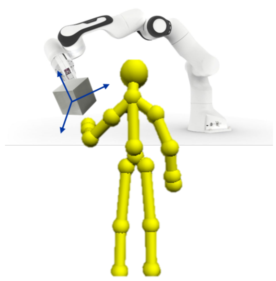


Fig. 1. Object handover by the robot to the human in a specific pose.

Figure 2 shows the proposed ergonomics controller to solve the non-ergonomic postures of the operator during collaborative tasks. First, an ergonomics analysis module monitors the human. If a non-ergonomic posture is detected, the controller checks whether the workpiece pose can be changed. If this is the case, the object/tool placement is adapted by the cobot. Otherwise, an optimal posture is determined based on the task constraints and the user data (left/right handedness, body dimensions). This is informed to the user via a visual feedback. In this paper we describe the optimal posture finder module highlighted in green in the scheme. The aim is to develop a generic real-time algorithm, i.e. human morphology independent, based on an inverse kinematics solver to determine the user joint angles.

III. Optimal Posture Algorithm

This section describes the developed method. It is based on the FABRIK algorithm (Forward and Backward Reaching Inverse Kinematics). The latter is a recent IK (Inverse Kinematics) solver that computes smooth postures in real-time [15].

A. Ergonomics Assessment

The ergonomics evaluation is performed via the Rapid Entire Body Assessment (REBA) method. This is a postural analysis tool to evaluate whole body MSDs [16]. 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. Values ranging from 4 and 7 indicate a medium risk. 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. Some examples of joint motion ranges for different REBA scores are given here below for the arm part:

- REBA = 1: $-20^\circ < ua_f < 20^\circ, 60^\circ < la_f < 100^\circ$, $-15^\circ < w_f < 15^\circ$.
- REBA = 2: $-80^\circ < ua_f < 45^\circ, 0^\circ < la_f < 170^\circ$, $-40^\circ < w_f < 40^\circ$.
- REBA = 3: $-80^\circ < ua_f < 90^\circ, 0^\circ < la_f < 170^\circ$, $-40^\circ < w_f < 40^\circ$.

where ua_f, la_f and w_f are respectively the upper arm, lower arm and wrist flexion.

B. Optimal Posture Computation

The low level of the ergonomics posture module is based on the FABRIK method. FABRIK uses the joint locations of the kinematic chain instead of the angle rotations. By crossing the chain forward and backwards, it determines iteratively the joint positions for a certain end-effector pose. The method has been augmented to an extended version in [17]. This handles problems with leaf joints and closed-loop chains. Anthropometric and robotic joint models are also considered. The FABRIK IK solver is chosen as the basis of the developed optimal posture algorithm for several reasons. First, its efficiency allows to integrate the method in a real-time control loop. This is essential during tasks involving robot-human co-manipulation. Second, FABRIK offers the possibility to perform multiple end-effector tracking. Every hand of the user can be constrained to a desired pose depending on the object/tool position and orientation to be manipulated. Finally, the IK solver handles well joint limits and leads to realistic body postures.

In order to take into account the ergonomics during the end-effector calculation process, joint limits are introduced. First, the full joint range is used for the inverse kinematics. Then, the boundaries are progressively decreased such that the generated leads to a reduction of the associated REBA score.

Figure 3 shows the adaptation of the FABRIK method using variation of the joint allowed range of for ergonomics optimization purposes. In this case, the upper arm is restricted to angular rotations in the ellipsoidal cone. Figure 3.a represents the case where the full range of motion is used while in Figure 3.b depicts a higher restriction that leads to a lower REBA score.

The main steps of the method are detailed in Algorithm 1. This shows the pseudo-code for the arm part of the body. First, depending on the handedness of the user (left or right), the left or right arm joint positions are considered. Then, the fabrik algorithm is run for a first time with the full joint motion range and the REBA score is determined. In a third phase, the ergonomic optimization runs to decrease the overall REBA score. At every loop step, the new associated joint limits are calculated and applied to FABRIK function to determine the new joint position. The algorithm stops when no solution is found that meets the specified tolerance.

In order to compute the whole body joint angles, a hierarchical method is used. Constraints are imposed to the end-effectors, namely the hands and the feet of the skeleton

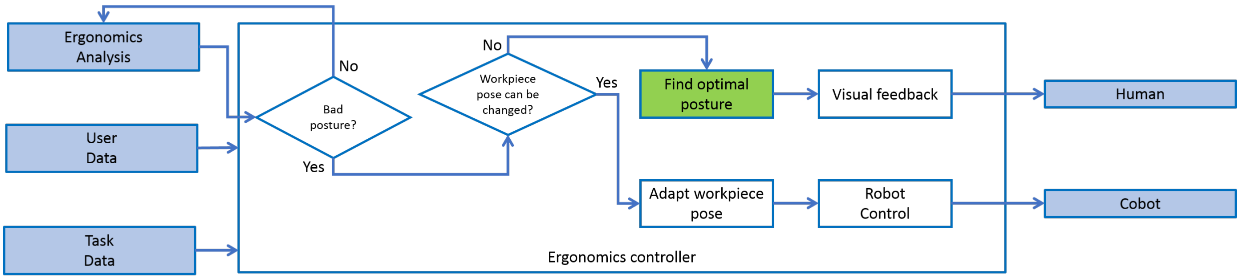
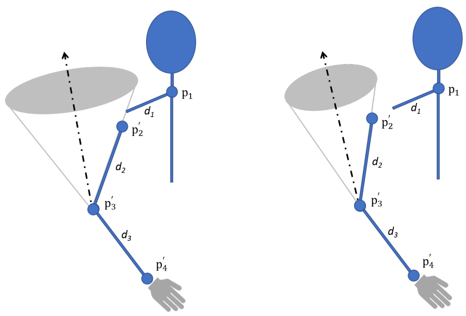


Fig. 2. Ergonomics controller scheme. Based on the ergonomics analysis and the task data (workpiece constaints) optimal postures are suggested to the user or the cobot configuration is adapted. The algorithm descrived in this paper is highlighted in green in the diagram.



(a) Full motion range (b) Restricted motion range

Fig. 3. Adaptation of the FABRIK solver with varying joint limits to optimize the REBA score of the posture associated to a desired end-effector pose.

Algorithm 1: Optimal posture algorithm (arm part)

Input: Target pose **t**, left arm joint positions p_l and right arm joint positions p_r, the joint limits θ, the tolerance tol and the handedness **h** of the user.
Output: New joint positions **p** that minimizes **REBA(p)**

if $h == left$ **then**
  p = p_l;
else
  p = p_r;
end
`// If a solution is found the function returns solFound = True`
[**p**, solFound] = FABRIK(t,p,θ,tol);
currentREBA = REBA(p);
while $solFound$ ***and*** $currentREBA > 1$ **do**
  currentREBA = currentREBA - 1;
  θ = jointLimits(currentREBA);
  [**p**, solFound] = FABRIK(t,p,θ,tol);
end

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as shown in Figure 4. In this example, the two feet remain constant and the two hands track the targets. The left and right arm joint positions are first adjusted. The algorithm relocates then the arms and the upper body triangle to meet the inter-joint distances as depicted in Figure 4.b. The sub-base model (Figure 4.c) is then moved to its new position. In the last stage of the method, the lower body triangle and legs are re-positioned. The algorithm continues iteratively until the distance between the end-effectors and the targets is less than a desirable tolerance (Figure 4.d-e).

IV. Conclusions

The high number of MSDs shows that the performed worker tasks leads to excessive work load linked to non-ergonomic body postures. In this work we introduced a novel generic algorithm for the computation of optimal ergonomic posture. An appropriate algorithm (FABRIK) is selected according to the postural computation needs, namely the real-time and handling of joint limits criteria as well as the possibility to achieve multi-effector tracking. The ergonomics assessment module is based on the REBA evaluation measure that provide a generic method to determine the MSD risk of the corresponding posture. The latter was introduced into the postural computation algorithm to vary the joint limits during the iterative process of FABRIK and optimize the ergonomics of the calculated posture.

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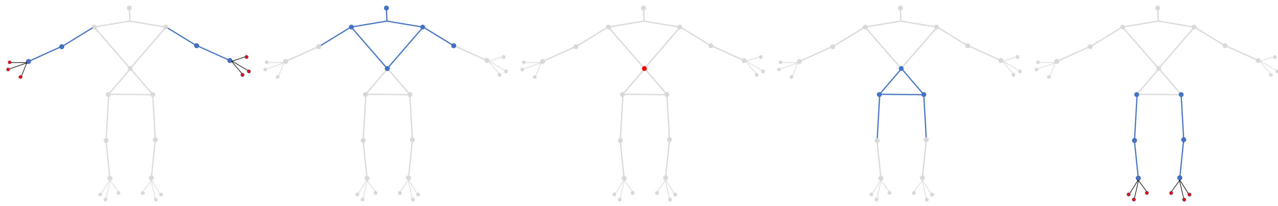

(a) (b) (c) (d) (e)

Fig. 4. Humandoid model: the different part of the body in a hierarchical fashion. The whole body movement is controlled in this order: (a) hand chains, (b) upper body triangle, (c) sub-base, (d) lower body triangle, (e) feet chains.

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