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Ergonomic contribution of ABLE exoskeleton in automotive industry

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ABSTRACT

In PSA Peugeot Citroen factories, high precision requirements of workstations make them being manual. One of the main goal of the car manufacturer is to minimize the pain of workers while maintaining high efficiency of production lines. Consequently, assisting operators with an exoskeleton is a potential solution for improving ergonomics of painful workstations while respecting industrial constraints. To determine ergonomic performances of an exoskeleton, human joint angles and torques, ground reaction forces, and duration of operations are analysed for eight subjects performing a representative screwing task. Experiments were performed using ABLE upper-limb exoskeleton, developed by the French Atomic Energy Commission (CEA), which has the functionality to compensate arm and tools loads. Results show a clear reduction of the sum of the joints torques, up to 38.9%, given by ABLE supply and invite to make concrete the use of exoskeletons in car assembly lines.

Relevance to industry: In industries, workers performing manual operations are subjected to musculoskeletal disorders (MSD). The usage of robotic devices such as exoskeletons might then be a relevant solution to reduce workers pain and prevent MSD. The paper describes how to assess ergonomic performances of such robotic devices for a future usage in industry.

1. Introduction

To face the always increasing international competition, factories are always aiming at improving the robustness or the accuracy of automated devices. However, some workstations require complex gestures, accurate grasping and dexterity whilst current robotics technologies show some limitations in terms of feasibility, perception, speed or flexibility. Consequently, most car manufacturing industries including PSA Peugeot Citroen present manual final assembly workstations. On the other hand, postural loads, repeatable motions and very short tasks duration which are unavoidable facts for profitability lead to Musculo-Skeletal Disorders (MSD) for an increasing part of workers population (Safety and Administration (2000)). Internal ergonomics standards at PSA Peugeot Citroen classify these workstations as 'heavy', because of awkward postures to adopt, heavy loads to carry or notable efforts to provide. One of the main goals is to eradicate every heavy workstation. One way toward this goal is the use of collaborative robotics devices.

In this study we focus on an under-car operation which consists of screwing pieces on cars located above operators' head and unfold every minute on average. This heavy operation is one of the most problematic due to significant upper-limb requests and human motion fastness requirements. One solution to improve the ergonomics is to fit cars position by tilting them similarly to Kafedors et al. (1996), thus allowing workers to have a suitable position. But this involves very expensive investments, and adopting this technology might induce heavy changes in every stage of the manufacturing process. Consequently the implementation of an assist device would be a great benefit to reduce operators' discomfort.

In PSA Peugeot Citroen factories, classical manipulators are handled to bear heavy loads or to reduce workers physical load. However, passivity, bulkiness, limited degrees of freedoms (DoF), high inertia and generally only vertical axis load compensation are main disadvantages of these technologies, involving their restricted usage. Regarding all the drawbacks of the targeted workstation (small space requirement, complex gestures needed and limited

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task duration), the usage of manipulators is not appropriate. In consequence, working with collaborative robots appears to be a relevant solution.

A collaborative robot, usually named 'cobot' (Akella et al. (1999)) or intelligent assistive device, is a particular robot designed to work in cooperation with humans for assisting them in performing a task. Two main types of applications with a cobot can be distinguished. The first one is the force amplification where the user is guiding the cobot and can also apply a conjoint force to the handle. In this mode, the cobot will apply a force to the environment so that the total force is equal to the operator's force times a tunable force amplification factor (Lamy et al. (2010a,b)). The second type of application is the weight compensation, where the device is supporting the weight of a tool or an object to be carried, and the operator is guiding along the desired trajectory.

Exoskeletons are particular cobots which present beneficial functionalities that might address industrial ergonomic needs like postural load compensation, upper limb request or adaptability in task choice. Several prototypes of exoskeletons are presented in the literature.

In military fields, whole body exoskeletons are designed to augment human performances. Berkeley Lower Extremity Exoskeleton, developed for battlefields, is used to protect soldiers, augment their strength and endurance, and to carry heavy loads during long distances (Zoss et al. (2005)). But its considerable workspace makes it bulky in addition to its heaviness and price, making it irrelevant for our application.

Exoskeletons are also employed in healthcare as assistive devices for elderly people or rehabilitation. The Hybrid Assistive Limb (HAL), developed by Tsukuba University is a lightweight wearable whole body exoskeleton suitable in walking and carrying heavy loads. HAL detects bio-signals which appear on the skin surface when the user intents to move, and generates required forces for effort compensation (Sankai (2006)). This system presents interesting functionalities, but it has never been used in an industrial application.

Honda Research department has developed two light weight lower limbs bodyweight support systems to help manufacturing workers and elderly people in walking tasks (Ikeuchi et al. (2009)). This exoskeleton is, to the best of the authors' knowledge, the only one used in industrial field. Unfortunately, despite its very interesting design it is so far only used for lower limb assistance.

Furthermore, exoskeletons can be employed for helping people when doing painful tasks. Naruse et al. have prototyped a simple 1 DoF exoskeleton located at the lower trunk level to assist bending movements of day-care workers (Naruse et al. (2005)). The parsimony principle leading this approach is interesting and is very similar to the one used in this study for upper limb, i.e. reducing the number of DoF in function of the task requirement.

In order to deploy the usage of exoskeleton in industry in coming years, assessing their ergonomic contribution with currently available prototypes is required. ABLE 7-axes upper-limb exoskeleton developed by the French Atomic Energy Commission (CEA) was retained for its transparency and modularity (Garrec et al. (2008)). An experimentation campaign has been performed with eight non-initiated subjects. A stereophotogrammetric system and dynamometric data were collected to estimate ground reaction forces components, joints torques and joints angles to evaluate and validate experimentally ABLE ergonomics supply.

2. Presentation of ABLE exoskeleton

ABLE upper limb exoskeleton is a versatile exoskeleton aiming at having different industrial and medical applications (Garrec et al. (2008)). It was at first designed and used as a rehabilitation tool for patients suffering of stroke (Jarrassé (2010)). It is a powerful haptic interface by enabling force feedback on the whole arm, contrary to the standard haptic interfaces which generally use only the hand. It was also used in telerobotics providing a high precision force feedback. Its open design allows the operator to enter and exit the exoskeleton easily, and its modular design allows two arms teleoperation with a single operator when needed (Garrec et al. (2011)).

The ABLE arm is composed of seven non-anthropomorphic axes whose combinations allow following human arm movements. The innovative wrist allows the arm to carry a tool that the user can manipulate and orientate to perform the required task (Garrec et al. (2011)) (Garrec and Verney (2010)). The exoskeleton and its wrist have an open design which allows the operator to enter and exit the exoskeleton easily.

The patented (Garrec (2006)) Screw and Cable System (SCS) transmission combines, as the name suggests, a screw and a cable in an original floating mounting principle. The main principle is that the ball-screw is isolated from perturbative bending moments resulting both from internal kinematic beating oscillation and external forces due to cable misalignment. This principle guarantees a very low and stable dry friction and is responsible of the highly linear torque transfer obtained. Its design and its use in various applications have been previously published in (Garrec (2010)).

To make the exoskeleton as transparent as possible for the user, the controller is based on two major functions: the dry friction compensation, and the weight compensation. Since it's not relevant for this study, the dry friction compensation won't be discussed here. The goal of the weight compensation is to compensate the effect of the gravity, so the user doesn't need any effort to maintain the robot in a given position. Given the standard Denavit-Hartenberg modelisation ((Khalil and Dombre, 2004)) commonly used in robotics, the torque exerted by ABLE kth axis is determined as follows:

$$\tau_k = \left(x_{g_k} m_k \cos\theta + y_{g_k} m_k \sin\theta\right) * g, \quad (1)$$

where x_{g_k} and y_{g_k} are the distances of the center of mass in x and y axis respectively, m_k the contribution of axis mass, θ the angle of the exoskeleton and g the gravity acceleration. The opposite torque of τ_k is used as a set-point to the motors controllers to compensate the gravity effect.

In this paper, the exoskeleton is used as a cobot to help workers who perform tasks with their hand above the head. In that case, the cobot will support the weight of the operator's arm, as well as the tool, thus alleviating the user's efforts.

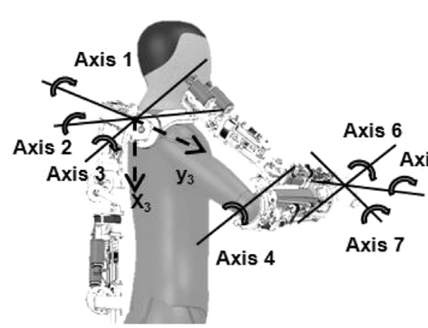

Fig. 1. The 7-axes ABLE exoskeleton.

Referring to the ABLE axes definition, the performed movement is mainly led by its third axis, located at the level of the shoulder. In order to compensate the weight of the operator's arm, the mass contribution of the third *x*-axis (see Fig. 1), called m_{x_3} is increased. This will make the robot compensate more than its own weight, and as a result, will also compensate the arms weight. Values of m_{x_3} parameter chosen in this experiment are determined from previous unpublished studies led by the CEA.

3. Experimentation

To determine the ergonomic contribution of ABLE exoskeleton, the screwing movement without assistance was compared to the one performed with ABLE. Using a Vicon motion capture system in combination with LifeMod analysis software, subjects' foot/floor contact forces, joints angles, joint torques and movement durations were measured to perform the comparative analysis.

3.1. Participants and task description

Eight right handed volunteers (stature: 1.70 m $\pm$ 5 cm, weight: 63 kg $\pm$ 11 kg, age: 24years $\pm$ 7 years), not familiar with the investigated task participated in this study after signing a consent form. Volunteers were asked to exert holding on a 950 g screw gun in their right hand. Starting from a standing position with both hands along the body side, they had to reach at their preferred velocity a target located 2 m above the ground. Hearing a sound signal, subjects were then instructed to go back to their initial position.

In order to compare the motion of each subject, the screwing task, described in Fig. 2, was subdivided in five elementary movements normalized as follow:

- from 0 to 20% of the movement, subjects stay in the initial position, hands along the body side,
- from 20% to 30% of the movement, subjects raise their arm to reach the target,
- from 30% to 70% of the movement, subjects maintain the screwing position,
- from 70% to 80% of the movement, subjects return to their initial position,
- from 80% to 100% of the movement, subjects stay again in the initial position.

The same task was repeated by each subject, in five different conditions. The first trial was carried out without exoskeleton while for the four followings, different shoulder compensative torques in sagittal plane were applied by ABLE exoskeleton onto the subject arm. Compensative torques are generated by setting m_{x_3} parameter as follow:

- in trial 1, subjects are not assisted,
- in trial 2, $m_{x_3} = 1.035$ kg m,
- in trial 3, $m_{x_3} = 1.335$ kg m,
- in trial 4, $m_{x_3} = 1.635$ kg m,
- in trial 5, $m_{x_3} = 1.935$ kg m.

When subjects operate with ABLE, the screw gun is held by the device. Setting up m_{x_3} to its minimum value (1.035 kg m) allows the exoskeleton to compensate only its own arm and the screw gun weights.

3.2. Measurements

3D kinematic quantities were recorded using a stereophotogrammetric system (6 MX cameras, VICON, 100 Hz) in combination with a set of 38 retro-reflective markers. Markers were placed on anatomical landmarks in accordance with the Plug-in-Gait whole body marker template (Vicon Motion Systems). Dynamometric data were collected in a synchronized fashion using two 6-axis force-plate (OR-6, AMTI, 100 Hz) localized under each foot (see Fig. 3).

Markers trajectories and dynamometric data, i.e. force-plate and measured torques applied by ABLE exoskeleton, have then been imported in LifeMod biomechanical analysis software (LifeModeler, Inc), which use inverse dynamic simulation associated to anthropometric table to estimate whole body joint trajectories and joint torques (Agnesia and Taïar (2006)). All measured and estimated data were resampled to be 100 samples to allow a direct comparison between quantities.

3.3. Quantitative analysis

To evaluate the performance of ABLE when interacting with subjects, inter-subject averages of relevant biomechanical parameters were compared between all trials. The inter-subject average function, defined as M_{IS}, corresponds to the mean of a function f relatively to subjects:

$$M_{\mathrm{IS}}(f) = \frac{\sum_{i=1}^{n}(f_i)}{n}, \quad (2)$$

with f_i the value of f for the ith subject, and n the number of subjects.

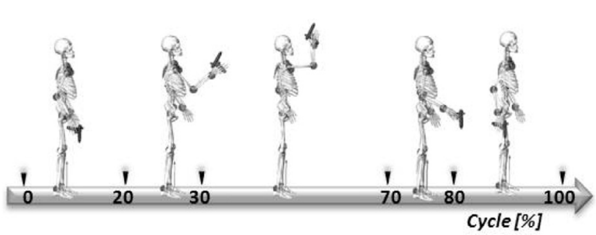

Fig. 2. Screwing task cycle description.

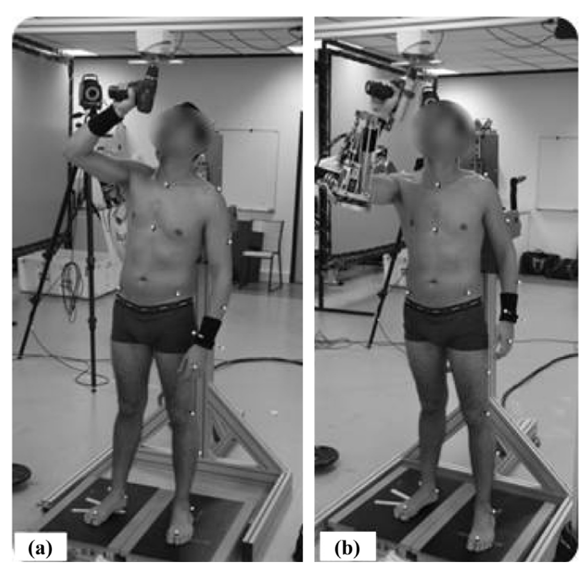

Fig. 3. Free-screwing motion (a) and motion realized with the ABLE exoskeleton (b).

- Foot/floor contact forces: Vertical Ground Reaction Forces (GRF) analysis was performed to asses subjects' postural behaviour with the exoskeleton. Considering anthropomorphic differences between subjects, values were normalized relatively to subjects' bodyweight and reported in Body Weight (BW) units as defined in (Feltner et al. (1999)), according to the following equation:

$$C_F = M_{\mathrm{IS}}\left(\frac{\overline{F}_z}{\mathrm{BW}}\right), \tag{3}$$

where C_F is the normalised GRF value, $\overline{F}_z$ the average of vertical ground reaction forces, and BW the subjects' bodyweight force.

- Joint angles: Right shoulder, elbow and wrist angles, defined as θ_1, θ_2, θ_3, θ_4, θ_5, θ_6, and θ_7 in Fig. 4, were compared between trials to evaluate human/exoskeleton kinematic interaction. The observed task results in small amplitude movements in the transverse plane. Indeed, measured values of joint angles in the transverse plane (θ_3 and θ_7) are within the resolution of the stereophotogrammetric system. Consequently, these angles have not been reported and are considered as negligible.
- Joint torques: The following criterion, here called C_T, is used to study the energetic behaviour of human segments:

$$C_T = M_{\mathrm{IS}}\left(\sum_{j=1}^{n}\left(\sum_{i=1}^{100}\left|\Gamma_{i_j}\right|\right)\right), \tag{4}$$

where j corresponds to one joint segment, Γ the joint torque value, and i the percentage of the cycle.

From (4), right arm joint torque criterion is deducted:

$$C_{T_{\mathrm{arm}}} = M_{\mathrm{IS}}\left(\sum_{i=1}^{100}\left|\Gamma_{i_{\mathrm{sh}}}\right| + \left|\Gamma_{i_{\mathrm{elb}}}\right| + \left|\Gamma_{i_{\mathrm{wr}}}\right|\right). \tag{5}$$

Γ_{sh},Γ_{elb},Γ_{wr} are respectively the normalized shoulder, elbow and wrist joint torques, relatively to frontal, sagittal and transverse plans, at i% of the cycle, given as in Feltner et al. (1999) by:

$$\Gamma = \frac{\tau}{m^{*}H^{2}}. \tag{6}$$

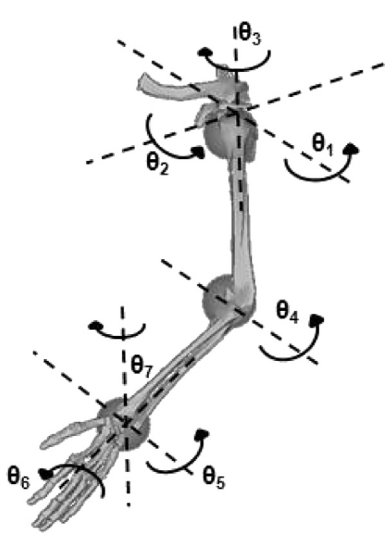

Fig. 4. Right arm joints definition.

τ designate the joint torque estimated by LifeMod, H is the height of subjects (in m), and m the subjects' mass (in kg). Maximum values of shoulder and elbow normalized torques ($|\Gamma_{sh}|$ and $|\Gamma_{elb}|$) are also compared between trials and reported in the results.

- Task duration: To maintain and improve the daily production in car factories, efficiency is required. In final assembly lines, cycle times are very short (less than 2 min on average). Consequently, when modifying a post, an important criterion to evaluate is the impact on the duration of operations.

4. Results

4.1. Ground reaction forces

Fig. 5a represents the mean inter-subjects values of measured vertical GRF for both legs, relatively to the five trials. Results show that ABLE exoskeleton is reducing vertical GRF up to 19.07% (Trial 4) relatively to the arm free condition (Trial 1). But the high value of the standard deviation in Trial 4 questions the supply of ABLE in view of GRF. The global reaction force was reduced for only three of the eight subjects indeed. The effect of the exoskeleton in reducing ground reaction forces is then not clear, and further experiments with more subjects have to be performed to conclude about these results.

Splitting up left and right vertical GRF (Fig. 5b and c) reveals that forces on the right foot are higher than ones applied on the left one, even in the first trial when subjects are not assisted. This observation is in accordance with Gutnik et al. (2008), who demonstrated that unequal weight distribution is related to subjects handedness. In addition, the weight of the screw gun held by subjects when performing screwing tasks increase right foot loads values. When subjects are assisted by ABLE, contrary to left foot loads which decrease, right foot loads increase. Subjects lean more on their right foot hence. Analysis of foot forces on medio-lateral and antero–posterior planes reveals that subjects slightly lean aside or bend forward to maintain their balance with the exoskeleton worn. Note that subjects were not informed about how to use the system, and this asymmetry might lead to postural problems in case of extensive use of the system.

4.2. Joint angles

Right arm joint angles associated to the corresponding kinematic model were estimated for each subject and trial. From Figs. 6–8 slight differences can be observed between angles values measured in Trial 1 and ones in Trial 2, 3 and 4, which mean and standard deviation values are reported in Table 1. Table 2 presents range of differences between trials, i.e. maximum and minimum absolute differences of joint angles between trials. Results are consistent with Jarrasse et al. study (Jarrasse et al. (2008)), which

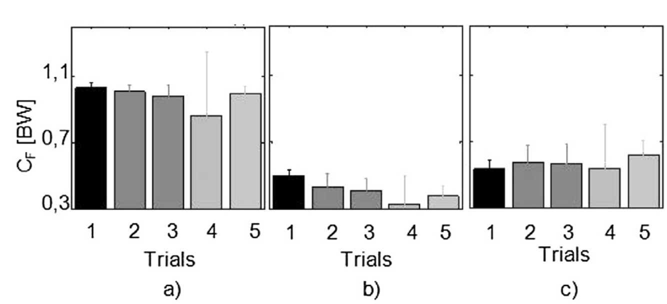

Fig. 5. Global (a), left (b) and right (c) vertical component of ground reaction forces.

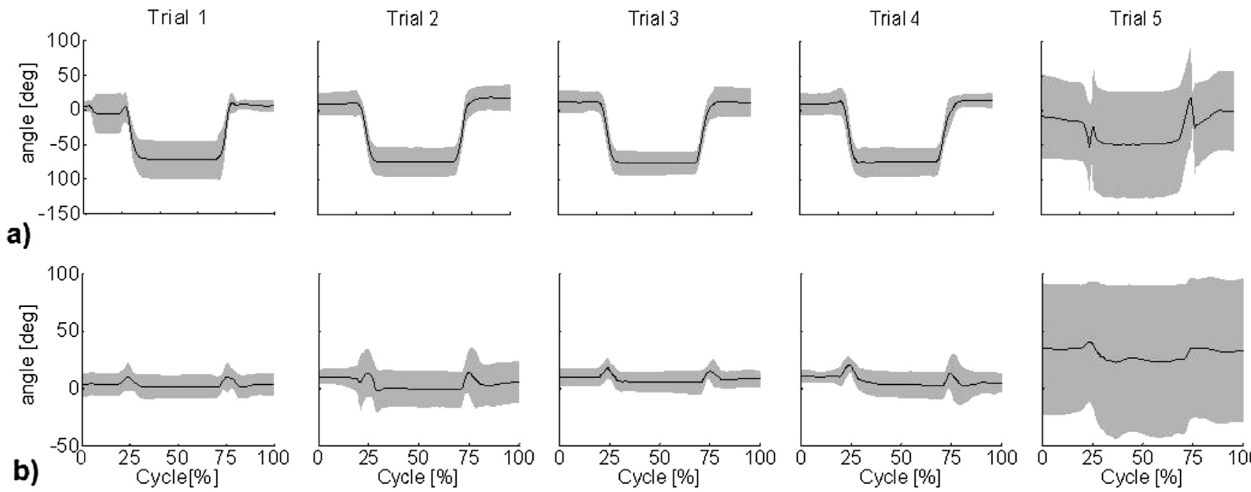

Fig. 6. Values of shoulder angles (θ_1 (a), andθ_2 (b).

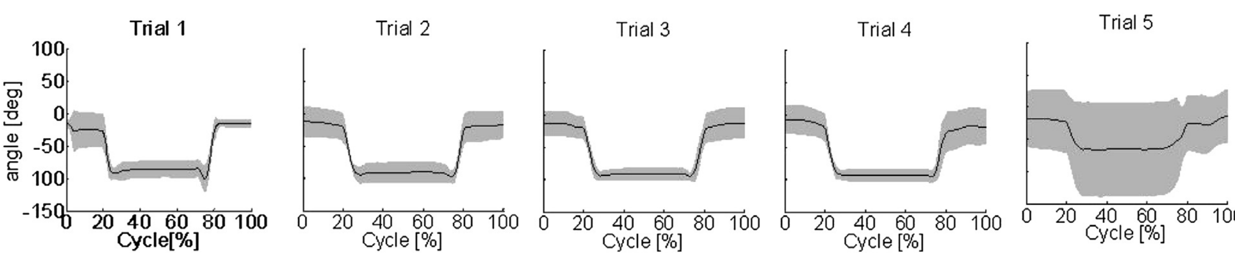

Fig. 7. Values of elbow angle (θ_4).

proved that ABLE induces slight modifications of arms movements. In the case of Trial 5, high variability is observed (standard deviation up to 62° for shoulder abduction/adduction). Note that when asking subjects their feelings during the experiments, they point out that in the case of Trial 5, the exoskeleton imposes subjects to follow its own movement, which do not necessary corresponds to natural human movements. Setting m_{x_3} to 1.935 kg m involves over-compensation, leading to disturbance of subjects' natural movements.

4.3. Joint torques

Right arm and whole body joint torques criteria were estimated for every trial to determine the mechanical expense reduction given by this kind of assistance device. Both arm (Fig. 9a) and whole body (Fig. 9b) joint torques increase significantly when setting up the exoskeleton with parameters values of Trial 5. The compensation level appears to be inappropriate in this case, making subjects produce more effort than necessary to perform the task.

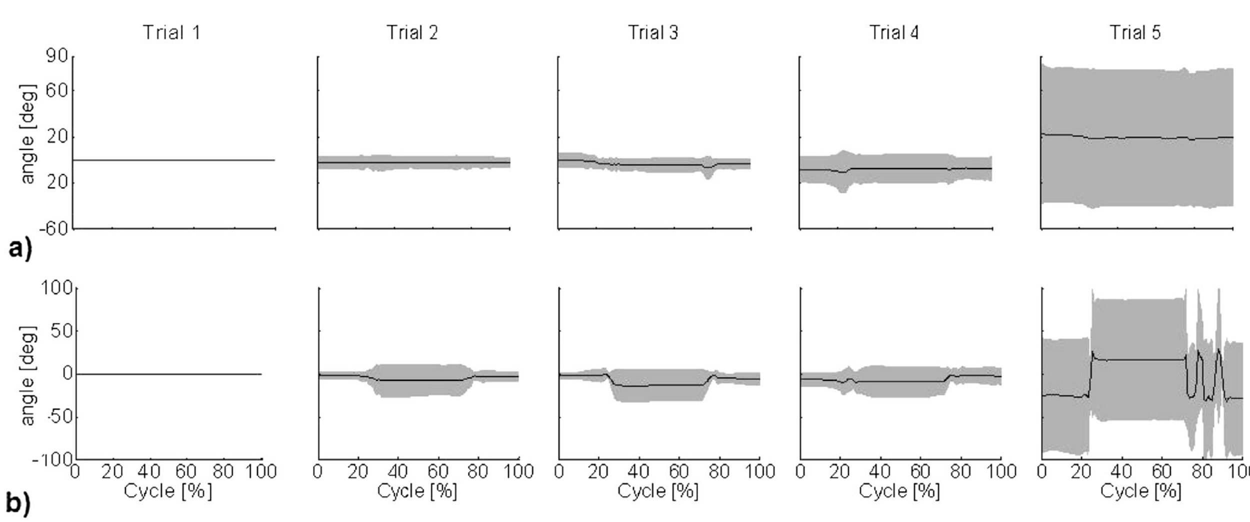

Fig. 8. Values of wrist angles (θ_5 (a) and θ_6 (b).

Table 1
Average of joint angles differences between trials.

	T1–T2 (deg)	T1–T3 (deg)	T1–T4 (deg)
θ_1	7.1 ± 5.1	7.51 ± 5	6.72 ± 4.70
θ_2	2.2 ± 1.9	4.99 ± 1.1	3.6 ± 2.8
θ_3	–	–	–
θ_4	5.6 ± 3.3	6.1 ± 4.1	8.3 ± 4.6
θ_5	2.2 ± 0.2	3.4 ± 1.6	8 ± 0.7
θ_6	4.6 ± 2.4	8.0 ± 5.0	6.5 ± 2.9
θ_7	–	–	–

Excluding Trial 5, Fig. 10c shows that the strongest arm torques reduction occurs for Trial 3 for the whole movement, with a diminution of 38.8% of the free arm condition criterion value. However, during the critical phase were right arm is maintained over the head (i.e. from 30% to 70% of the movement), the m_{x_3} parameter appears to be more efficient in Trial 4 (Fig. 10d). This is also verified by maximums of right arm normalized joint torque, reported in Fig. 11. Note that negligible values of wrist torque due to low movement of the right wrist are not reported on the results. From this figure, one can see that maximum torque of the right shoulder, which is the most requested joint in the movement, are less in Trial 4 than in Trial 1 (Fig. 11a), and low differences are observed between elbow peak torque of Trial 3 and 4 (Fig. 11b).

Concerning whole body joint torques, slight differences of means are observed between the first four trials (Fig. 10a). When focusing on the critical phase (Fig. 10b), the compensation is notable with a loss of up to 15% of energetic expense. Knowing that ergonomics of the targeted workstation is essentially degraded by this posture which is repeated 35% on the cycle time on average, the supply of the exoskeleton for assistance is then consequent.

4.4. Duration of movements

Taking Trial 1 as a reference, we can notice in Fig. 12 that subjects take on average 1 s more to perform a movement with ABLE weight compensation set. Regarding the fact that a cycle include multiple operations, if we consider that every operation lasts 1 s more, repercussions on the cycle duration will be consequent. This difference can't be neglected this context where workers' fastness is primordial.

5. Discussion

ABLE exoskeleton, initially designed for rehabilitation, is used here as an assistive device to improve ergonomics of a manual operation in car manufacturing.

The study aims to evaluate the use of ABLE exoskeleton and to propose a quantitative methodology to assess the level of assistance offered to workers wearing exoskeleton. The assumption that the human motion recorded while performing the task without any assistive device produces "optimal" kinematic was taken in this study.

Table 2
Range of differences between trials.

	T1–T2		T1–T3		T1–T4	
	Min (deg)	Max (deg)	min (deg)	Max (deg)	Min (deg)	Max (deg)
θ_1	0.5	13.8	0.1	13.1	0.2	13.5
θ_2	0.2	7.1	2.3	7.6	0.5	10.8
θ_3	–	–	–	–	–	–
θ_4	0.2	13.9	0.1	13.5	0.3	14
θ_5	1.2	2.7	0.3	6.9	7.1	10.6
θ_6	1.9	7.6	0.2	13.8	1.0	10.2
θ_7	–	–	–	–	–	–

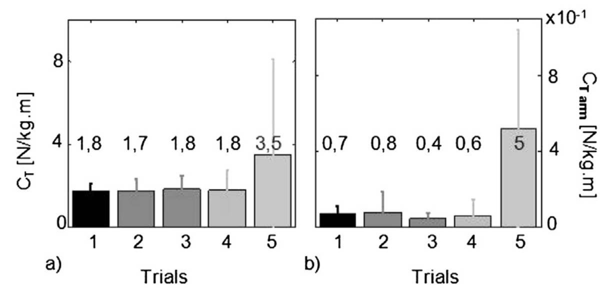

Fig. 9. C_T (a) and $C_{T_{arm}}$ (b) criteria relative to the study of joint torques sum for all trials during the whole movement.

Starting form this, results have shown a clear reduction of the mechanical energy, i.e. the sum of the joint torques (see Figs. 9 and 10), slight differences between joint angles trajectories (Figs. 6–8) and an increase of the cycle time when using ABLE exoskeleton for screwing task.

The best trade-off between time execution (difference of 1.061 s from Trial 1) and force compensation (reduction of 16.72% of the total sum of the joint torque for the whole movement, and 15% during the critical phase) was found for a compensation of the shoulder contribution in the sagittal plane (m_{x_3}) set to 1.635 kg m.

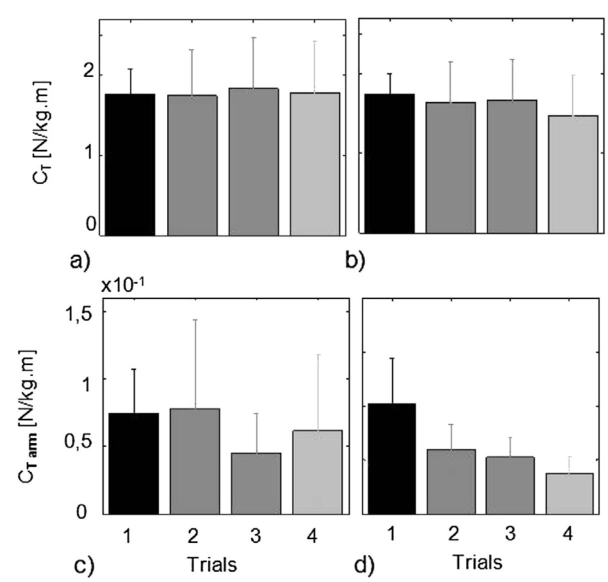

Fig. 10. C_T criterion for Trial 1 to 4 during the whole movement (a), and between 30% and 70% of the cycle (b), and $C_{T_{arm}}$ criterion for Trial 1 to 4 during the whole movement (c), and between 30% and 70% of the cycle (d).

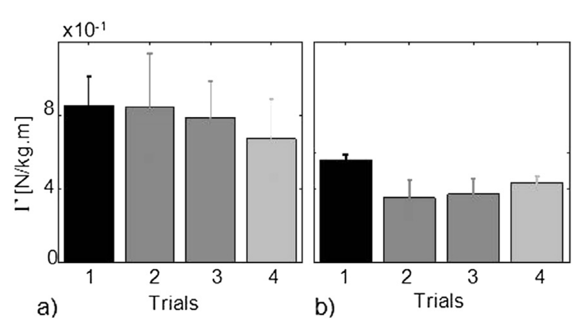

Fig. 11. Shoulder (a) and elbow (b) peak torques for all trials.

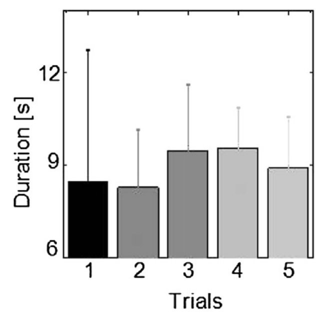

Fig. 12. Screwing task durations.

Concerning reaction forces, although the reduction of mean GRF, high variability is observed in Trial 4, and the way balance is maintained differs from a subject to another, making the reduction of contact forces contestable, relatively to subjects. These differences can be due to the fact that subjects were not taught on how on wear the exoskeleton, and the hereafter measurements results are spontaneous behaviours. Future work will concern further study of ground reaction force with trained subjects to conclude about the influence of exoskeleton in subjects posture.

Performances of exoskeleton are mainly qualified by their ability to interact with humans and to modify as less as possible human motion observed without wearing assistive device (Gopura (2009), Yali and Xingsong (2010)). In the literature, human/exoskeleton interactions are generally evaluated by defining indices of performances such as joint velocity, minimum jerk or final joint posture (Jarrassé (2010)), or by measuring interaction forces (Schiele (2008)). However, these studies concern rehabilitation applications, that deal with a very different context. The study here presented defines the performance of the exoskeleton as a set of measured and estimated biomechanical kinematic and kinetic quantities. The approach allows to perform post-processing analysis, after capturing motion in a real environment, and prone to be used with any collaborative device to assess biomechanics parameters. Regarding that standard ergonomics evaluation method in PSA Peugeot Citroen qualify a workstation relatively to workers postures and tasks repetitions, using the proposed method complementary to the standard one will provide a detailed description of workstation ergonomics.

Regarding the results, the appropriate value of m_{x_3} could be different from one subject to another, relatively to their height or limbs length. The target of future work is to automatically adapt the value of m_{x_3} to users anthropometry.

Additionally, the screwing operation performed here implies essentially movement in the sagittal plane. The use of all 7 DoFs of ABLE exoskeleton might not be justified since only axis 3, 4 and 5 of are solicited during the task. Future work will determine the minimum number of DoFs required to assist this type of movement.

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