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Transparency Analysis of a Passive Heavy Load Comanipulation Arm

Thomas Muller , Kévin Subrin , Denis Joncheray, Alain Billon, and Sébastien Garnier

Abstract—For collaborative robotics applications, many systems have addressed general handling issues in recent years. Depending on the industrial context, these systems bring physical and cognitive feelings that result in the acceptance of their users. Transparency qualifies the ability of a robot to follow the movements imposed by the operator without noting any resistant effort. The objective of this article is to develop a methodology that mixes the approach highlighting the human factors and their correlation to robotic criteria in the case of a passive manipulation arm with six degrees of freedom produced by the Neoditech company. An exploratory study was then conducted to measure criteria such as time, speed, and effort during manipulation along with criteria based on a technological level, personality and technology acceptance model-method questionnaires. From there, we uncovered a correlation between the user’s personality, particularly their lack of neuroticism, and their means of evaluating the device through its usefulness, comfort, and indicators of mechanical behavior. This study is a preliminary analysis of user behaviors and traits that affect technological acceptance when dealing with a comanipulation arm. This work offers a framework for similar future analyses and recommends mechanical adjustments to the arm for increased user acceptance.

Index Terms—Collaborative arm, collaborative robotics, comanipulation, force sensing, human–robot interaction, manipulation system, transparency.

I. INTRODUCTION

ROBOTIC comanipulation is defined as a human operator and a robot interacting without barriers to jointly manipulate a tool (or object) in the same workspace. When using a comanipulator system, the interaction between the human

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by CERNI ethics committee for noninterventional research under application No. 08032021 and performed in line with the regulatory qualification in non-interventional research.



Fig. 1. Example from washing-machine pick and place manipulation with a Neoditech Scara parts arm.

and the system must be of a high quality to make it acceptable to the user in everyday work. This interaction can be different depending on the type of comanipulator (serial, parallel, exoskeleton) [1] but also on the type of application (object handling, trajectory demonstration, effort multiplication, etc.).

The use of a Scara parts arm is a specific example of this interaction between a human and a comanipulator. Here, the arm is used as a parallel comanipulator allowing the handling of loads up to 100 kg by limiting the efforts made by the operator. The interest here is to eliminate musculoskeletal disorders (MSDs) for the user by not having him lift the load on pick and place applications [2]. Fig. 1 shows an example of comanipulation with a Neoditech arm and a washing machine. Here, a user uses the passive part of the arm to reach into a rack and pick up a washing machine using a parallel gripper, then lifts the load using the motorized vertical axis. He then places the washing machine on the pallet using the passive part of the arm to position itself on top of the pallet before lowering itself onto the pallet and dropping the part.

This type of system offers easy integration into a workshop in terms of infrastructure and money, but the acceptance by human remains an important issue. Some studies focused on human behavior during human–machine interactions [3] and in particular of their trust in the machine. It can be noted that this differs according to the cultural context of the person. Social cognitive and affective neuroscience (SCAN) can also be used to improve the team performance of the human–robot collaboration

group [4]. It helps to ask the right questions about the acceptance of a device requiring interaction. The mental workload of the operator must also be considered and assessed to ensure consistent user performance over time [5]. The optimization of human behavior while respecting the limits of ergonomics is also a subject of research [6]. This would help to avoid incidents and MSDs while increasing productivity in simple pick and place applications.

Matthews *et al.* [7] also presents work on a human–robot behavior model for an autonomous robot describing trust, situation awareness, and transparency in a collaborative application. In particular, transparency has a direct influence on trust through the cognitive model of the operator. Studies attempted to evaluate these types of approaches on an unmanned aerial vehicle group control applications with a human–robot interface [8]. Work has also been done on the design of robots to make them kinesthetically more acceptable and humanlike [9].

In this article, we present an overview of different definitions of transparency and how they can be evaluated to choose the most suitable definitions for our passive comanipulation system. We, then, discuss the methodology of transparency analysis that we can contribute to a passive system by developing and combining these two approaches. Thus, these two approaches are developed in an experimental protocol, one with mechanical measures and another with cognitive measures. We, then, present the results of the study of these factors and attempt to correlate them to obtain practical tools for the evaluation of a comanipulation system.

II. OVERVIEW OF TRANSPARENCY METRICS

Transparency has multiple definitions in robotics, notably in teleoperation, human–machine interfaces and direct manipulation of a robot. These definitions all come together around human comfort and have a sense of efficiency. Here, we give some examples of the application of these definitions to establish the best choice of an evaluation protocol.

A. Mechanical State-of-the-Art

The notion of transparency in comanipulation is strongly associated with the notion of impedance control on slaved robots. Bahloul [1] described the implementation of a control to optimize handling transparency, gesture assistance, and safety in heavy load handling with a collaborative robot. He referred to the scalar product of force and velocity at the robot’s end-effector to measure it. In addition, several types of impedance control and their feedback in terms of speed and force were evaluated in [10]. The stronger the identification of the impedance corresponding to the human, the better the feedback, which usually requires active impedance control to be as transparent as possible.

Several studies have also focused on the analysis of collaborative motion on linear trajectories with a simple linear motorized axis. Corteville [11] showed that the different speed profiles associated with the control of the axis allow a more or less good feeling of it. The bell-shaped profile seems to be the one adopted by a human when moving an object. The experiment is taken further in [12] where several masses and friction forces are applied to the end effector. Links with separate measurements on humans, notably at the level of the brain and muscles, are also made in addition to effort and speed measurements. The results

show a weak influence of friction on feelings, while inertia creates significant differences in brain and muscle activation.

Finally, transparency is especially a topic in assistive and collaborative robots. Fong [13], described a semipassive collaborative robot on a load balancing application, similar to ours and an exoskeleton. Five performance indicators are defined: the peak speed, the time of peak speed, the smoothness [14], the curvature, and the accuracy. These parameters are observed with and without assistance from the robot and at the first and last manipulations (120 manipulations over three sessions). The assignment of the movements of the two devices is then quantified, which characterizes the incoherence or the lack of transparency of the systems. Similarly, in [15], we characterize different indicators on a manipulation with an exoskeleton by measurements on the end effector, the articular coordinates and the efforts on the end effector. Similar indicators to [13] are found in [15], to which rotating joints range of motion (ROM), cyclograms of shoulder angles versus elbow velocity and terminal angles absolute values can be added. These measurements are then studied to enable future training of the exoskeleton to make it more transparent.

Transparency in teleoperation is the most complex because it includes coupled phenomena, such as the delay between the command and the realization of the movement as well as all the other parameters inherent to comanipulation. More precisely, it can be decomposed into three phenomena: perceptual transparency (feeling felt by the person), local motor transparency (transparency of the control means), and remote motor transparency (transparency of the actuated system) [16]. In the context of remote manipulation of objects, several indicators, such as task completion time, human effort, and damage possibility were measured in [17] to improve task performance by changing the assistance function. Finally, in [18], multiple sizes of grippers and objects were tested in a telemanipulation system to measure transparency. Several indicators, such as transport time, speed, and distance were measured and statistically analyzed to obtain physical measures of transparency of grasping.

B. Cognitive State-of-the-Art

Exploratory cognitive studies most often involve statistical studies of well-known questionnaires with verified measurement scales, as individual interviews are more difficult to set up and use objectively. These questionnaires make it possible to establish dimensions by performing algebraic operations on the results of the various questions, which enables us to give a score to each of the characteristics of the interaction. Among the most recognized for cobotic systems are the Godspeed questionnaire for human–robot interactions, the rapid upper limb assessment (RULA) for measuring human movements, the technology acceptance model (TAM) for measuring the use of the system and the situation awareness rating technique (SART) for measuring situation awareness.

One of the most widespread surveys in the context of a human–robot interaction is the Godspeed questionnaire. This allows to establish from a survey of 23 questions on a five-point Likert scale the following properties: anthropomorphism (the robot seems to have human characteristics), animacy (the robot seems to have emotion), likeability (positive impression

about the robot), perceived intelligence, and perceived safety of robots [19], [20]. A similar concept is that of Anshin in Japan [21], which describes the feeling of wellbeing next to the robot. This has been broken down into five subcategories: comfort, performance, peace of mind, controllability, and robot-likeness.

The RULA method, which was designed to allow analysis of a worker's upper limb stresses for MSD risk screening purposes, provides an objective measure of MSD risk caused by tasks with high upper-body stresses and relatively low lower-body stresses. Using sensor tracking or human observation, the ROM performed by the operator can be determined so that a RULA rating can be given for each movement. A high index characterizes a tiring movement and a risk of MSD for the operator [22].

The TAM method evaluates three essential variables: perceived ease of use, perceived usefulness (PU), and behavioral intention to use. Each variable was assessed by means of questionnaires with a five- or seven-point Likert scale. It can be used in particular to validate the acceptance of a technology [23] by validation of hypotheses. Work has been done on the looping of this method with semidirective interviews to improve the approach [24], [25]. This method can also be linked to the person technology level [26]. For this purpose, a questionnaire with a seven-point Likert scale on the mastery of different technologies is asked as an opening to the main questionnaire. Moreover, studies have also been conducted on an electric walker [27], which used the same principles of mechanical evaluation, but on populations of various ages. The results demonstrate that the technological context of the person has an influence on these parameters. A correlation can also be made to the culture/nationality of the user [28]. A well-known personality questionnaire, the Big Five, can also be linked to this type of study [29]. It is also asked as an opening to the main questionnaire on the system.

The SART is a questionnaire with a seven-point Likert scale and ten (or three) dimensions able to measure situation awareness (perception of environmental elements and events with respect to time or space), which can also be implemented in this type of study [30].

Finally, when designing a first experimental questionnaire, several precautions must be considered. We have, thus, followed the approach described in [31] to construct our questionnaire and to verify it while trying to keep the measurement scales harmonized with the literature questionnaire.

C. Discussion

The literature review of mechanical indicators allows us to establish a database of indicators that we can evaluate during a manipulation. Initially, we limited ourselves to a reduced list of common indicators from our database to which we added indicators defining transparency. The manipulation time and the force produced by the user are thus natural indicators that we can consider. The study of the trajectory conducted by the operator and thus the distance and the speed of manipulation are also of interest since they are directly related to the manipulation time of the part. The strong anisotropy of the manipulator in terms of inertia and lengths led us to measure the ROM of the rotating joints. As the scalar product of force and velocity is the only definition of mechanical transparency on systems similar to the

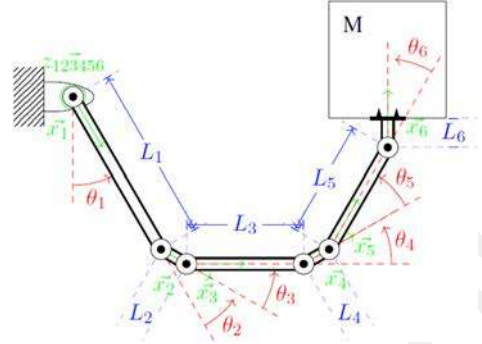


Fig. 2. Neoditech Scara parts parametrization.

arm studied, it seems natural to study it. However, the variation of the user's efforts induced by the carrying of a load by the arm also leads us to look at the force/velocity angle to be separated from this variation.

In our application, cognitive transparency refers to a reduced learning time and the completion of a manipulation movement in accordance with the user's will. Therefore, the Godspeed questionnaire is too focused on actuated robotics, as the dimensions assessed seemed further away from our application. The RULA method requires either to use a sensor to objectively postprocess the user's movements or to let the user describe their situation, which is not very objective. Furthermore, the use of exteroceptive sensors is not desired and the variations in movement are too small between the users. Therefore, we have chosen not to evaluate them. Finally, the TAM method describes dimensions that are more relevant to our application [25], as it deals with the usefulness and usability of a system, which use was verified in this type of application.

As the factors and data measured correspond to an exploratory study, we chose a Pearson correlation coefficient approach to compare the transparency indicators to human factors and an uncorrected T-test because it is difficult to show the independence of the data between the studies [29], [32].

III. EXPERIMENTAL SETUP

In this section, we describe the experiment we conducted to evaluate a mechanism in a comanipulation context.

A. Neoditech Arm

The Neoditech Scara parts arm is a passive handling arm in the horizontal plane and remote controlled arm in the vertical direction. The vertical axis is performed by a motorized ball screw linkage that is controlled by an analog control handle that allows management of the up/down speed of the arm along \vec{z}_1 . This vertical axis is mounted on a slewing bearing, which makes the first passive rotating joint of the arm along \vec{z}_1 represented by θ_1 . Attached to the nut of this ball screw, there is a series of five passive rotating joints along \vec{z}_i represented by θ_i , $i \in [2, 6]$ made with ball bearings mounted in exactly the same way with symmetrical male and female parts. At the end of the arm, there is an interfacing plate to attach any gripper.

Fig. 2 and Table I show the parameters of the arm as well as the mechanical properties of the arm. The first passive axis has a high inertia as well as a high mass due to the weights of the motorized ball screw system. The slewing ring also has

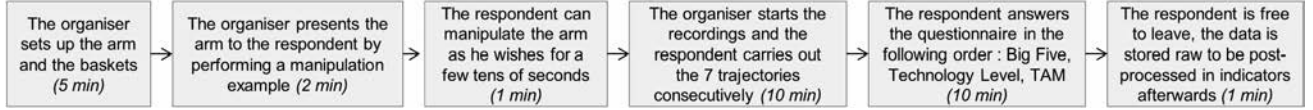


Fig. 3. Experimental process.

TABLE I
MECHANICAL PROPERTIES OF SCARA PARTS ARM

Property	1	2	3	4	5	6
Length (mm)	602	90	580	90	580	58
Mass (kg)	162	4.82	6.94	4.82	6.94	3.31
Angular momentum around $O_i(kgm^2)$	3.7	0.020	0.88	0.020	0.88	0.014

higher friction properties than other ball-bearing rotating links. The inertia properties of the arm links have been designed to be as low as possible, but they are still present as the arm has to withstand loads of up to 50 kg.

B. Sensors and Measurements

Several sensors are attached to Neoditech’s Scara arm to measure the forces and displacements associated with the manipulation. An Optoforce HEX-H sensor is fixed between the end of the arm and the gripper, which will allow us to measure the three forces and the three torques in a 3-D space. We use the measurements of the forces in the plane of manipulation with a precision of 0.13 N to obtain the feeling of the user as well as the force perpendicular to this plane. It helps us to measure the beginning and the end of the experiment by knowing if the sensor senses the weight of the tool and the part moved. Six RLS RM44 Hall effect rotation sensors are fixed on each of the rotating joints to measure the displacement of each of the rotating joints without affecting the internal frictional forces of the link without contact. The analog signals transmitted by these sensors are acquired by an Arduino MEGA board with an analog-to-digital converter of ten bits equal to a resolution of 0.17° . The direct geometrical model of the arm then allows us to reconstitute the displacement of the arm end effector using these measured angles. The various velocities are obtained by deriving the model.

The signals are then postprocessed to provide the time taken for each experiment T_e , the average force applied by the user in the manipulation plane F_e , the average speed of the end effector during the manipulation V_e , the maximum speed during the manipulation V_{me} , the total distance D_e made by the end effector, the path followed by each of the rotating joints $R_{1e}, R_{2e}, \dots, R_{6e}$, the apparent mass M_e , the mean over time of the scalar product of force, speed at the end effector Ps_e , and the average force and speed angle α_e . This makes a total of 14 indicators for each experiment. The pictures of a scenario are presented in Fig. 3, as the experimental process is depicted in Fig. 4.

C. Survey

All participants in the experiment completed a questionnaire under the cover of an anonymity number, lasting approximately 15 min and divided into four sections. This experiment validated



Fig. 4. (a) User performing the experiment. (b) Sensor setup, weight manipulated.

by the ethics committee from Nantes University is composed of a technology-level questionnaire, the Big Five personality questionnaire, the questionnaire on the feeling of the experience, and general information of the participant. An overview of the questionnaire can be found in Fig. 5.

The technology-level questionnaire defines the overall level of mastery of common technologies used in workshops, where a Neoditech handling arm is located. The user answers on a seven-point Likert scale (never heard of it, not sure what it is, never used it, used it once in a lifetime, used it once a year, used it several times a year, used it once a week [Literal translation from French]) about his mastery of the proposed tool. The list of tools is also defined in Fig. 5.

The Big Five questionnaire exists in different versions with various degrees of detail. We have chosen to use a more compressed version with only 15 questions, so three per dimension as in [29], but we have chosen to extend the scale to a seven-point scale to harmonize the scales throughout the questionnaire (strongly disagree, disagree, somewhat disagree, neither agree nor disagree, somewhat agree, agree, strongly agree). Each subgroup of questions will be averaged to obtain a score for each participant on the following five characteristics: openness to experience, conscientiousness, extraversion, agreeableness, and neuroticism.

The TAM questionnaire attempts to assess several factors using simple questions following the experience. A significant proportion of these questions are taken from previous studies of cobots in the context of gesture assistance [24], [25], while another proportion have been specifically designed for use with a passive manipulator arm. Factors include the performance of the arm, which describes the user’s sense of improved working conditions. In addition, the usefulness of the arm describes its relevance to the task being performed. Safety describes the user’s confidence and sense of safety from danger. Self-efficacy describes an individual’s belief in his ability to perform a task. Aesthetics describes the confidence provided by the visual of the arm. Comfort indicates whether the user feels that their body positions are comfortable. This is followed by specific questions about the experiment: the feeling of speed describes if

<p>Technology Level : "Have you ever used this kind of system?" Overhead crane, Drilling/Screwing machine, Grinding/Sawing machine, Multimeter, Electric trolley, Hydraulic press, Robot arm, Lathe/Milling machine, Construction equipment, CAD software, Jack, 3D printer</p> <p>Big Five Personality test: See [33]</p> <p>TAM test : [29], [30]</p> <p>Performance: (5 questions) "The arm would allow me to improve my efficiency" "I am satisfied with the actions taken", ...</p> <p>Usefulness: (6 questions) "I can do my work more easily" "This arm will help me to become more autonomous", ...</p> <p>Security: (3 questions) "I feel safe with it", "This arm seems reliable", ...</p> <p>Auto-efficiency: (3 questions) "I am able to use it if there is no one to tell me how", ...</p> <p>Aesthetic: (5 questions) "The aesthetics of the arm suit me" "The appearance of the arm gives me confidence", ...</p>	<p>Comfort: (6 questions) "I like using this arm", "I feel comfortable using this arm", ...</p> <p>Speed Feeling: (3 questions) "I feel I have achieved the fastest trajectory for my tasks" "The arm allowed me to position the object quickly", ...</p> <p>Intention Tracking: (3 questions) "I feel that the arm followed my intention during the tasks" "The architecture of the arm didn't bother me in the tasks", ...</p> <p>Precision: (3 questions) "The arm allowed me to position the object accurately" "I did not feel any jerks during the tasks", ...</p> <p>Weight Feeling: (3 questions) "I found the arm light to move" "I felt the mass of the moved object in the movement", ...</p> <p>Additional Questions (7 questions) "I feel that I improved between the first and last trajectory" "The arm length/number of pivots was adapted to the tasks" "A shorter/longer arm would have been suitable for the tasks" "A larger/smaller number of pivots would have been suitable for the tasks", ...</p>
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Fig. 5. Overview of the survey completed by participants.

the user seemed to be fast during the tasks, the intention tracking indicates if the arm hindered him by not following the movement he wanted to make during the task, the precision shows the ability to have a right positioning of the part by the arm, and finally the feeling of inertia describes the feeling by the operator of the inertia of the arm and the embedded mass. Finally, additional non-dimensional questions are added, such as the feeling of the length of the arm, the number of rotating joints of the arm, and the feeling of improvement between trajectories.

Finally, the user filled in his or her age, height, gender, and handedness to finalize the survey.

D. Trajectories

The subject of the experiment will have to conduct seven trajectories between a starting point and an arrival point materialized by baskets. These baskets are made up of a profiled foot and a high-density polyethylene ring adjusted to the diameter of the part to be maneuvered to be able to slide the part inside. This activity is close to conventional activities performed with the arm, such as machine tool loading or picking up from a rack to put on a pallet. The start is materialized by the lifting of the piece with remote control, while the arrival at the vertical stop ends the experiment and stops the active movement of the arm. The subject used vertical control in this way only at the beginning and at the end of the experiment.

Several factors were identified as fundamental to the study. First, the start and end points are the two most clearest parameters, so we chose to discriminate between two possibilities: small radius (0.9 m) and high radius (1.9 m) representing the front and back of a pallet: pallet picking or placing being a standard application. The points are positioned according to what the company's expertise advises in relation to the task performed. We chose to separate these two start and end points by 90° in relation to the first axis of the arm to approximate a standard movement performed with the arm. These two parameters allow us to observe four different trajectories: work at low radius, work at high radius, work by increasing the radius, and work by reducing the radius. To quantify the importance of the manipulated mass we chose to manipulate a 25-kg turning block by a gripper with a butterfly screw to make the system more easily dismountable and to keep the same manipulation radius (see Fig. 4). Two tests are conducted on a short radius and on a

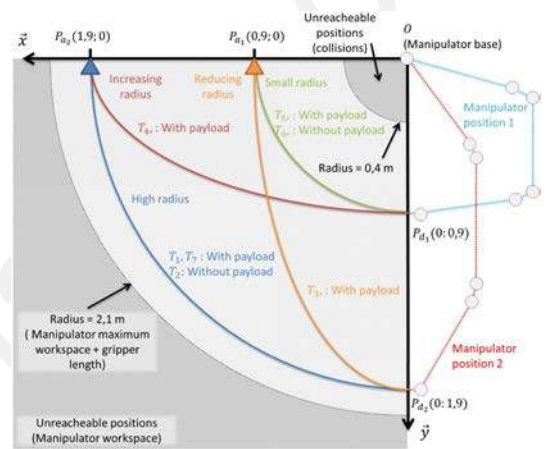


Fig. 6. Seven trajectories followed by the subject.

standard radius to compare the influence of this handling load. Finally, we observe the learning ability of the person during the manipulation by performing a last trajectory similar to the first trajectory. Of the four possible trajectories, only the two most different trajectories were carried out without a mass to limit the handling time of the subject, giving priority to the study of the arm with the mass as it represents the most important issue. All these trajectories are described in Fig. 6.

IV. RESULTS

Thirty-one people conducted the manipulation of the arm on the seven proposed trajectories as well as the questionnaire provided. The data collected made it possible to calculate the various indicators presented before. A statistical analysis of the results is presented in the following section. The results are observed independently and then in common to obtain conclusions on the feeling and the transparency of the arm. The average age of the participants was 21 years old, their average height was 176 cm, and 26% of respondents were women and 74% were men.

A. Mechanical Analysis

1) *Variation in Terms of Speed and Time of Manipulation:* Fig. 7 shows the distribution of the completion times of the

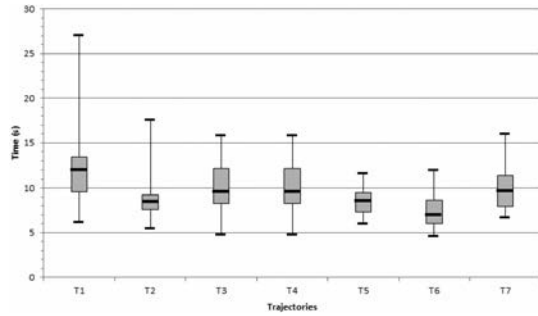


Fig. 7. Time necessary to perform all seven trajectories.

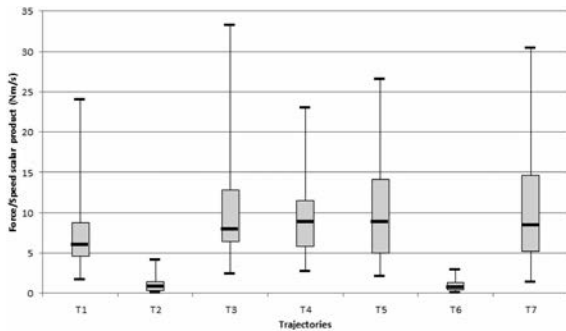


Fig. 8. Force speed scalar product for the seven experiments based on [1].

manipulation experiment on all users. First, trajectory 1 is on average the longest to be completed (12 s). The variability is also high, with a range of 6 to 27 s for the same trajectory. It is interesting to compare the results with trajectory 7, which is the same after using the arm on the previous trajectories. The variability in terms of the range is considerably reduced, while the interquartile range is slightly reduced. There is a median improvement of 2.5 s in overall times or an average improvement of 16% in travel time between the two points. In terms of speed, the median handling speed increased from 0.3 to 0.37 m/s, but the variability was slightly higher, indicating that learning was not equal among all participants.

Manipulation on the same trajectories with and without mass shows that the user can go faster with the arm when it is not carrying a load. The differences show a median improvement of 2 s between trajectories 2 and 7 and trajectories 5 and 6. The median speed is also close to 0.35 m/s on both trajectories.

Trajectories 3 and 4 show similar times and variabilities, although the trajectories are reversed in terms of radius evolution, which shows homogeneity in the behavior of the arm at a constant distance between two points. This is a good indicator of a similar feeling of the arm throughout its working space.

Furthermore, in general, the 3, 4, 5, and 7 trajectory time and speed results are sorted according to the distance between the arrival and departure points. It shows that although the median speed is 0.28 m/s on the smallest trajectory (the fifth), it is at 0.36 m/s for the longer trajectory (the seventh), trajectories are still sorted in the distance order.

2) *Variation in Terms of distance/Joints ROM:* In terms of trajectories, the paths followed with and without mass do not show a significant difference. Nevertheless, a greater variation can be observed with a mass, because some novice users may

underestimate the inertia of the manipulator induced by the on-board mass and arrive too quickly at the arrival point and pass it. They, thus, make a loop to return to the arrival point, which will lengthen their path up to one meter.

We also observe a greater variability in the small trajectories, which seems rather unintuitive at first. The visual observations as well as the trajectories show that with a radius of the arm close to the maximum, one will try to extend it to the maximum and carry out a trajectory by extending the arm, which will result in an arc of circle. This is confirmed by the joint ROM indicators, where we notice that rotating joint 1 has a higher ROM than 2 and 3 and even 4 and 5 on certain trajectories. On shorter radius trajectories, some subjects use less on this first rotating joint and have slightly tighter trajectories, while others tend to extend the arm more. This can be seen by observing the ROM of rotating joint 1 on trajectories 3, 5, and 6, where we observe a fairly high variability with respect to the median value. By way of comparison, the ratio of interquartile range to median is close to one on these trajectories, whereas it is 0.3 on the other trajectories. We can thus deduce that on small handling radii, the quality of users' subjective experience is more variable and widely distributed. This is due to the redundant architecture of the arm, as well as the low use of the pivot one, which by its inertia does not influence the other links. The user is then more free on these movements, experiencing a lower overall inertia, which causes this variability.

3) *Variation in Terms of Force:* We chose to exploit the effort measurements by observing the average effort during the handling. Indeed, the observation of effort curves normally leads to the evaluation of two types of effort, the initial effort and the holding effort (NF X-35 109, ISO 11228-1). Nevertheless, the difference observed between the two was not very significant on the measurements due to the arm inertia, which is why we simplified the analysis by looking only at the average effort.

First, it can be observed that the handling forces are much lower than those prescribed by the international and French standards cited below. We also observed a significant difference between handling with (40 N) and without mass (2.3 N). However, it can be noted that the deflection of the arm due to the load (max 10 mm) implies an additional variation of the measured force due to a projection of the force generated by the weight due to gravity, which can increase the values obtained by an order of 5 to 10 N.

The efforts have increased their median and their variability between trajectories 1 and 7, which correlates to the fact that the user goes faster during the last manipulation and is rougher with the arm. We also observe this increasing evolution of the effort during all manipulations. The forces also seem to be higher (45 N) on the small radius trajectories, which is notably due to the lower lever arm in relation to rotating joint one.

4) *Evaluation of Mechanical Transparency:* The force-velocity scalar product increased by 40% between experiments 1 and 7, with the median increasing from 6 to 8.5 Nm/s, which is mainly due to the increase in force and speed on the latter trajectory. Indeed, the force/speed angle was reduced from 8.4° to 7.3°, which is also a positive evolution of the indicator. We can nevertheless conclude by comparing the global indicator that the user has better apprehended the arm during his second use by going faster, and stronger, and by pushing in a direction where

TABLE II
CRONBACH ALPHA'S OF ALL SURVEY DIMENSIONS

All	Technology Level	Personality Test				
		Extraversion	Neuroticism	Openness	Consciousness	Agreeableness
0.79	0.82	0.59	0.66	0.64	0.42	0.60

TAM Survey									
Performance	Usefulness	Safety	Self-efficacy	Aesthetic	Comfort	Speed Feeling	Intention Tracing	Precision	Weight Feeling
0.55	0.53	0.78	0.55	0.69	0.69	0.78	0.77	0.67	0.81

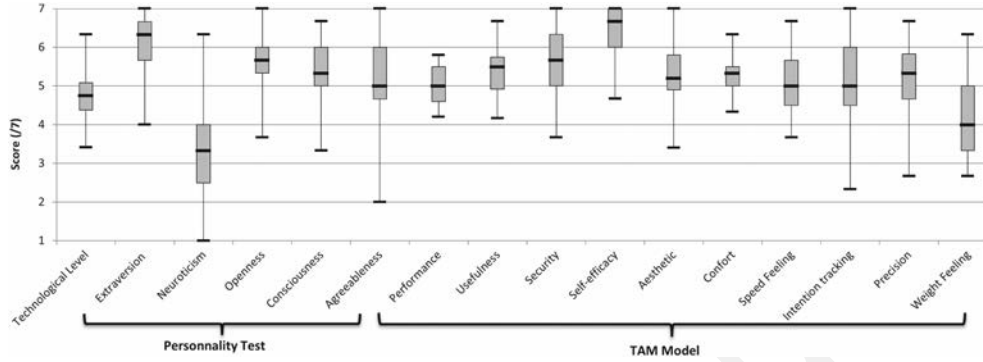


Fig. 9. Results of all the questionnaire dimensions.

the arm would move easily. Furthermore, this scalar product globally increases over the course of all experiments, which supports our statement. The results are presented in Fig. 8.

The force/velocity angles associated with the movement without load carriage are significantly lower (5°) because the geometric constraints of the manipulator (manipulability) are predominant, since the inertia of the end-effector weight no longer guides the movement.

Trajectories 3 and 4 have similar results, but slightly better overall for trajectory 3, which means that the folding movement is easier to achieve than the unfolding movement. Trajectory 5 gives quite similar results to trajectory 7, which means that not using the first rotating joint on a trajectory improves the result.

B. Validation of the Measurement Scales and Questionnaire Dimensions

To validate the measurement scales used, we chose to conduct a Cronbach's alpha study on the overall questionnaire and on those dimensions composed of algebraic operations on particular questions in the questionnaire. We considered that a value higher than 0.6 is acceptable given the small number of samples measured [33]. If this value is too low, we allow us to delete a question to improve the internal consistency of the dimension.

The full questionnaire has a Cronbach's alpha of approximately 0.79, which allows us to show its relevance. Similarly, the technology questionnaire has a relevant score of 0.82. The Big Five questionnaire offers average results with a Cronbach's alpha close to 0.6 on all dimensions, but its recognition in the field still offers us a guarantee regarding its use. Finally, the last section of the questionnaire offers more contrasting results on these dimensions, with the questions being taken from less widespread and proven questionnaires. We, therefore, had to delete some of them on different dimensions to obtain scores that would allow us to validate these measurement scales. Therefore, the safety

item and the feeling of mass item were shortened by one question to increase Cronbach's alpha, while the results of one respondent were removed for a wrong answer to a randomly placed attention question. The set of Cronbach's alphas of dimensions can be found in Table II.

C. Questionnaire Results

We first analyzed the results of the questionnaire directly before performing a correlation coefficient analysis.

1) *Direct Analysis:* The results of the questionnaire are presented in Fig. 9. First, the technological level of the participants was quite high with an average of 4.8 and fairly low variability. This is because the population is mainly composed of students aged between 18 to 25 in fields close to mechanical engineering. Nevertheless, the population is close to the technological level of the usual users of the arm who generally have practical knowledge of mechanical engineering. The results of the personality questionnaire show that the population is rather extroverted (median score of 6.5), open (5.7), and conscientious (5.4). However, the population has a rather variable emotional stability since the average neuroticism is centered with high variability. Agreeableness is also slightly more variable but is more highly centered.

The results of the experiment questionnaire show that the subjects think that their performance is slightly improved with the arm (5) and that the arm is useful for this task (5.6). The safety associated with the arm is more debatable because despite a median score of 5.8, the variability is quite high, and some subjects did not feel safe with the arm, giving it a score below the average. The self-efficacy of the subjects was very high; more than 75% of the subjects gave a score higher than six and could use the arm very quickly without help from anyone. The aesthetics of the arm is also debated and does not suit all users, whose massive aspect gives an appearance of robustness but can impress the user by its aestheticism. The comfort gives an above

TABLE III
PEARSON CORRELATION COEFFICIENTS BETWEEN COGNITIVE INDICATORS
(BIG FIVE AND TAM TEST)

Consciousness	Extraversion** , Neuroticism*, Safety*, Precision*
Agreeableness	Performance** , Safety** , Self-efficacy** , Intention Tracking** , Comfort*, Speed Feeling*, Precision*, Weight Feeling*
Performance	Self-efficacy** , Comfort** , Neuroticism*, Safety*, Precision*
Usefulness	Extraversion*
Safety	Self-efficacy** , Intention Tracking** , Comfort*, Speed Feeling*, Precision*
Self-efficacy	Openness*, Comfort*
Comfort	Weight Feeling** , Intention Tracking*, Precision*
Precision	Intention Tracking** , Neuroticism**

Note: Correlation coefficient : p-value<0.05 : * / p-value<0.01 : **

average result even if it is not remarkable. In addition, the user's feeling of speed, intention tracking, and precision were mixed, even though 75% of the users gave the arm an above average score for these qualities. The weight feeling is felt differently by people during handling with scores ranging from 2.7 to 6.5. This confirms that some people are hampered in their handling by the inertia of the arm. Finally, users do not favor longer/smaller lengths or different numbers of rotating joints on the arm and find that the arm is a good compromise of these two parameters for the performed tasks.

2) *Correlation Coefficient Analysis*: We, then, chose to conduct an analysis by using the Pearson correlation coefficient between each dimension of the questionnaire. This is presented in Table III and describes two p-value levels of T-test significance (0.05 and 0.01). The purpose of this analysis is to show that some dimensions of the questionnaire are correlated with each other, which represents the same user experience.

First, the most notable personality traits found are agreeableness, neuroticism, and openness. It is interesting to note that people with higher agreeableness overrated the arm qualities. In addition, neuroticism and conscientiousness are also related to the precision of the arm, indicating that a relatively low-anxiety and disciplined person will see precision in the arm while the opposite will have a more chaotic functioning. The positive correlation between the openness of the person and the notion of self-efficacy is also demonstrated, which seems coherent since a person may be more open and curious about using new things.

Second, the data suggest a strong positive correlation between performance and self-efficacy, comfort, precision, and safety. This seems coherent since to be efficient, one must be able to quickly take control of the arm's operation, be comfortable and have precise movements in complete safety. This analysis allows us to remove the questions on the performance of the questionnaire because it can be defined by these five other questionnaire dimensions. In addition, positive correlations are made between safety and self-efficacy, comfort, speed, intention tracking, and accuracy. Some of these elements seem logical, as an arm that is easy to understand and to use is likely to create fewer incidents. Similarly, having control over one's movements will also limit the risks. Finally, the data suggest that comfort is positively correlated to the notion of following the intention, precision, feeling the mass, and self-efficacy. Indeed, if it has controlled movements and the user feels little inertia of the arm, then the user will be more comfortable.

TABLE IV
QUANTITY OF MECHANICAL INDICATORS CORRELATED
WITH SURVEY DIMENSIONS

Neuroticism	17
Comfort	15
Usefulness	10
Self-efficacy	9
Precision	7
Openness	6
Aesthetic	5
Technological level	5
Weight feeling	4
Safety	4
Extraversion	3
Speed feeling	3
Intention tracking	3
Agreeableness	3
Conscientiousness	2
Performance	0

D. Mechanical and Cognitive Analysis Correlation

To correlate the mechanical and cognitive measures, we first chose to look at the Pearson correlation coefficients between all the mechanical indicators measured and/or calculated for each experiment and the dimensions of the cognitive indicators. To simplify this approach, Table IV shows the number of times that the different dimensions of the questionnaire appeared to correlate at a 5% risk with all the mechanical indicators of each experiment. The mechanical indicators were 14 in each of the seven experiments, i.e., a maximum of 98. The elements that appear the most (>10% of the indicators) are neuroticism, comfort, usefulness, and self-efficacy. High neuroticism causes carelessness or stress felt by the user, which lowers his mechanical performance. The presence of usefulness and comfort of the arm shows that good sensations with the arm are noted in the questionnaire and in the mechanical indicators. Similarly, self-efficacy is among the top items, so easy handling is found in the mechanical indicators.

To see synthetically how mechanical parameters affect cognitive parameters, we have chosen to group the measurements from the seven experiments into four measurements, an average of Experiments 1, 3, 4, 5, and 7 (with mass), an average of Experiments 2 and 6, an average of all the experiments, and the difference between Experiments 1 and 7. The results of the Pearson correlation coefficients between these indicators and the questionnaire dimensions are presented in Table V. Time and force/velocity angle indicators are negatively correlated with the presented indicators.

The time to complete the experiment was mostly correlated with the subject's neuroticism, comfort, and usefulness of the arm. It is thus possible, for example, to use only the data from the questionnaire on these three dimensions to anticipate the users handling time. Therefore, people who are calm and not prone to anxiety (low neuroticism) are generally faster to complete the task, while people who are vulnerable to stress are generally slower. In addition, the comfort of use as well as the usefulness improves the experience times. The efforts exerted are hardly correlated with the extraversion of the user and the feeling of heaviness of the arm. However, the correlation is only visible for movements without a weight at a 5% risk. The average speed has correlation coefficients that are quite similar to those at the time of the experiment. The same correlations were found

TABLE V
PEARSON CORRELATION COEFFICIENTS BETWEEN MECHANICAL AND
COGNITIVE INDICATORS

Compressed Mechanical Indicator	Big Five Indicator	TAM Indicator
Average Time with weight	Non-Neuroticism*	Usefulness*, Comfort*
Average Time without weight	/	Comfort**
Average Time	Non-Neuroticism*	Usefulness*, Comfort*
Time improvement	/	Usefulness** , Speed Feeling * Weight Feeling**
Average Force without weight	Extraversion**	/
Average Distance with weight	Neuroticism*	/
Average Distance without weight	/	Aesthetic**
Average Speed with weight	/	Comfort*
Average Speed without weight	Non-Neuroticism*	/
Average Speed average	/	Comfort*
Average Speed improvement	/	Safety**
Maximum Speed improvement	/	Safety** , Comfort*
Average Force/speed angle with weight	/	No Weight Feeling *
Average Force/speed angle without weight	Extraversion*	Intention tracking*
Force/speed angle improvement	/	Consciousness*
Average Force/speed scalar product with weight	/	Comfort**
Average Force/speed scalar product without weight	Extraversion**	Weight Feeling *
Average Force/speed scalar product	Extraversion *	Comfort**
Force/speed scalar product improvement	/	Comfort**

Note: Correlation coefficient : p-value<0.05 : * / p-value<0.01 : **

with comfort, usefulness, and neuroticism. However, it can be seen that the safety indicator has an influence on the average and maximum speed of the operator. Finally, on the angles and scalar product force/velocity, we found mostly two dimensions correlated: the feeling of mass and the extraversion. Extraversion is correlated with a higher scalar product, while the angle is lower. The feeling of weight gives a higher angle and a higher scalar product, which corresponds to a poor comprehension of the arm kinematics.

We were also able to observe the correlation coefficients by the ROM of the rotating joints. The data suggest that high neuroticism leads to a decrease in the use of the first rotating joint in favor of the second joint. This is explained by the slowness of the movement, which means that the first rotating joint is not pulled directly, as it has more inertia. Self-efficacy also has a negative influence on the ROM, which shows that people who think they have taken control of the arm very quickly have fairly direct trajectories.

V. CONCLUSION

In this article, after a literature review of mechanical and cognitive indicators, we set up an experiment to evaluate the most relevant indicators in our case study. The physical measurements were then processed into indicators, while the questionnaires were processed into dimensions. The values obtained were then analyzed independently and correlated to understand the human factors influencing the results.

The results in terms of mechanical indicators were very interesting and led to coherent conclusions about the different manipulation approaches to the arm by the participants. To develop them further, we can extract more complex indicators,

such as trajectory curvature, directional manipulability, and decomposition of the effort into several stages. Furthermore, a complete kinematic analysis of the arm could be correlated by analyzing indicators, such as manipulability and dexterity of the arm during movement [34]. Other physical measures could also be added to the study, such as electromyograms, which are widely used in human-machine relationship studies.

The technology-level and Big Five questionnaires provided contrasting results. The technology-level questionnaire is relevant in our opinion, but the population surveyed could be extended, so the variability would be sufficient to correlate with other indicators. However, we believe that on a large scale, this may remain relevant only if participants can be the target of this product. On the Big Five questionnaire, two dimensions of the questionnaire emerged predominantly, namely, neuroticism and agreeableness. Neuroticism was related more to the slowness and anxiousness of the person handling the arm, while agreeableness corresponded to higher scores on the questionnaire. It is also useful to better identify the personality traits of the future user to accentuate the training beforehand to obtain the best user acceptance.

The TAM questionnaire gave satisfaction with its results. The most represented dimensions are self-efficacy, comfort, safety, and usefulness. These dimensions of the questionnaire should be addressed first in the future (for example more questions, qualitative studies, etc.) and may be sufficient dimensions to validate the device acceptance. More specialized questions at the end of the questionnaire, such as weight feeling and precision, could also be correlated. This shows that the inertias on the different parts of the arm need to be reduced to have a better experience. Nevertheless, the high variability in these dimensions shows that certain approaches to the arm provide a better experience. Thus, although the self-efficacy is very high, it is still necessary to focus on training in the use of the arm. It will help us limit the user's focus on the arm and to direct his interest toward the object to be manipulated.

The results obtained made it possible to establish a first behavioral approach to the feeling of transparency of a passive handling system in a mechanical or cognitive manner. This will allow us to anticipate the strengths and weaknesses of a mechanical system by carrying out a behavioral approach, based on the one carried out here, on users of a future system. It will then be possible to adjust the system according to the behaviors of the system's user database. Moreover, this study will also help to better direct training regarding user personality. This can lead to the implementation of, for example, an innovative adjustable brake system in passive rotary joints to allow the user to perform his task efficiently.

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