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Experimental study of the physical impact regarding a passive exoskeleton on manual sanding operations

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Abstract

Every year, companies spend millions of euros for Work related musculoskeletal disorders (WMSDs). In order to solve this problem, they started to integrate Physical Assistance System(PAS) such as exoskeletons. These new products aim to provide physical assistance to the operator but their integration is facing many barriers such as morphological adaptability, bad usability and a negative perception among workers. Exoskeletons are bringing a new type of interaction with human that is crucial to take into account. Human factors must be integrated in the design process to insure the efficiency and the acceptability of such devices. This paper addresses the emerging issue of designing good Human – Exoskeleton interactions in work environment, as well as the challenge of better integrating human factors in the design process, thereby ensuring the positive impact of the assistance. The use case focuses on a sanding operation on a catamaran hull, with a passive exoskeleton (upper body). Experimental measurements such as cardiac cost, posture and assistance perception are carried out on a set of participants during finishing tasks. In order to better understand how exoskeletons help operators and reduce fatigue, we will present first results that show a positive impact of the assistance on physical workload that will help us to go further in characterizing fatigue reduction and product usability.

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1. Introduction

The development of assistance devices in the industry is nowadays noticeable with many projects on assisting operator's workload with robots, cobots or wearable assistance such as exoskeletons or PAD (Physical Assistance Device). A PAD is an external structure wearable by an operator to reduce strain during working tasks [1] It can be 'active' if it is motorized, or 'passive'(De Looze et al., 2014), and it is used in various applications such as logistic or various manufacturing processes to reduce physical strain. In this direction, PAD slowly appear as a complementary tool to reduce work hardness. On the other hand, most of them being still at a prototype state, facing physical and psychological barriers such as morphological adaptability, usability for various tasks and personal acceptance. In this paper, we propose to evaluate the physical workload of the finishing tasks in order to evaluate the relevance for placing a physical assistance system. We choose cardiac cost analysis developed by Meunier as a good indicator which bridges heart rates and physical strain[2] .The case study was set up with BJ Technologies that identified the finishing tasks as an heavy workload according to operators feedbacks and the amount of sick leaves dued to muscultoskeletal disorders. These tasks include physiopathogenic postures with arms above shoulders. Previously to integrate an exoskeleton in an industrial line, we had to prove the need for a physical

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assistance. There were different options, from subjective methods questionnaires [3] such as a simple form for operators to more objective methods [4]. We propose to observe physical workload with a method using heart beat datas to target variations in efforts, during working operations in order to characterize the effort related to the task and to evaluate the physical impact of a Physical Assistance Device (PAD). We based our method on previous research work that linked heart beat measurements as an indicator for physical effort (Meunier, 2014). Besides, Gellish & Coll. [5] developed a formula that estimates a Theorical Maximum Cardiac Frequency (TMCF), used to estimate where the human body can push his effort. On the other side, INBAR [6] recommend that the cardiac frequency should never go above (205,8- 0,685 x age) which had determined our top reference for analysis. From these methods we needed to figure out if the tasks observed are generating a high level of strain that would diagnostic the need for a physical assistance and to characterize the positive impact of it. The purpose of the present study was to firstly examine the extreme and average cardiac frequencies on working phase and establish related cardiac cost values. That permitted to formalize a next protocole in order to compare more results with and without physical assistance and help us hierarchize user's demands.

The remainder of the paper is organized as follows. Section 2 present the material and method and the description of the experiment. Results are presented in Section 3. The concluding Section 4 provides implications for research and design practice and perspectives for further research.

2. Materiel and methods

2.1 Activity

We observed finishing tasks on a catamaran Lagoon that include the following phases: sanding with 3 or 4 different papers, coating, polishing, painting. These tasks are repeated on faces and along a sealing edge produced by the assembling of the boat parts. We supposed that the tasks were done with requested quality standards.

2.2 Environment of the tests

BJ Technologies, a worldwide leader in boat manufacturing, allowed us to conduct our experimentations in the finishing workshop of his famous catamaran Lagoon. Roofs and hulls are done separately. We focused our observation on a dedicated hulls workstation in the first place. The figure (1) show catamaran sides (a) while the hatched zone indicates the manual sanding areas (b).

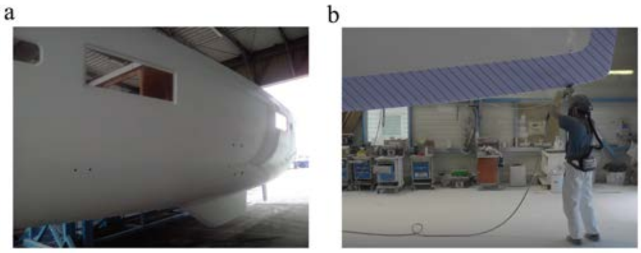

Fig. 1. (a) Side view of one catamaran hulls; (b) An operator is sanding the sealing edge. Hatches shows workzones for manual sanding.

Experiments took place between March and October 2017 on real site at BJ Technologies, Dompierre city. Finishing tasks including iterative phases of sanding and polishing, then gun painting.

This experimentation field offers postures that could be assisted by a PAD. The manufacturer Skel-Ex who provides us the PAD is quite collaborative to share our user centered approach and really consider our feedbacks to improve their product. Indeed, this study will also help to understand the physical impact of the product and might improve his design by first user's feedbacks. This paper reports on a physical workload analysis of working tasks using cardiac cost soliciting deleterious postures and a first usability evaluation.

2.1. Participants

9 operators (4 females) participated to the study. Their age span from 20 to 46 years old, with a minimum of 3 months experience according to the cardiac cost protocole from Meunier [6]. All participants were randomly selected among the daily crew working on the same operations. They were asked to follow their usual working process without any change. Some of the participants already felt injuries related to their work. Their physical state of health have been recorded with Nordic questionnaire [8] from 12 last month, the previous week and the day of the test. It helped us to complete the physical workload analysis and later follow up health evolutions. As one operator was under tension medication, we removed her measurements from the results according to cardiac cost protocole [6].

2.2. Equipment

The heart rate was measured in real time during the tasks. We used a heart rate computer POLAR RS800CX and its dedicated professional software POLAR Trainer 5. This system is composed of an emitter clipsable on a thoracic belt. The data transfer was realized from the emitter to the software by an infrared Usb adapter.

2.3. Cardiac cost protocole

Preliminary study of workload from operator's experience: we recorded previous perceived exertion (perception of physical workload) related to their tasks in order to identify occupational context. Operators were asked to describe all the tasks and targeted which tasks where the most difficult before the experimentations. Indirect estimations of Heart rates (HR) can be gained using ratings of perceived exertion (RPE) [9]. This process gave us objective strain levels and help us to identify the most demanding tasks. Afterwards, they were asked to rate a level of strain for these identified tasks on a Borg scale [10].

Cardiac cost: three complementary objectives

Experimentation 1 To correlate cardiac cost to perceived exertion
Experimentation 2 To study cardiac cost on targeted tasks
Experimentation 3 To compare study with/without PAD

Experimentation 1: two operators (o1, o2) were observed and measured during two long periods separated by a break equipped by the heart rate computer.
Experimentation 2 : four operators (o3, o4, o5, o6) were observed and measured on two higher strain periods separated by a break.
Experimentation 3: two operators (o1, o2) were observed and measured with and without PAD in targeted posture with the heart rate computer during two periods separated by a break.

<u>Concluding study of task usability:</u> We concluded the experiment set by a task usability test that gave us a first user feedback of DAP features using a global satisfaction scale [11].

3. Results and discussion

3.1 Previous perceived exertion

Prior to measurements, 9/9 operators agreed on defining operations under boat as the most demanding phase. In order to validate this subjective perception, we represent the evolution of cardiac cost in a first long period of work then we will be able to target shorter periods to easily repeat experimentations. The table 1 shows the results of eleven operator interviewed by questionnaire previous to measurements.

We also used a Borg scale to rank perceived exertion after cardiac cost measurements. We will correlate Borg scale ranking after related results.

Table 1. Results of eleven operator's votes for the most demanding working phase prior to measurements. Is table here really necessary?

Task	Front extremity	Under the boat	Back extremity
Number of votes	0	11	0

3.2 Experimentation 1: identifying the most demanding tasks.

Two operators (o1, o2) were observed and measured with the heart rate computer during two periods with a break in between. For operator 1 in the first period, the evolution of heart rate shows a first phase of top measures that corresponds to a part where she is sanding catamaran extremities (figure 1). After a break of 17 minutes, we observe a second major high heart rate phase in the second period between that corresponds to the tasks under the boat along the sealing edge. The most demanding phase is revealed by the highest heart rates above TMCF:180 heart rate per minute (hpm) for this operator, with a peak at 215 hpm. These extreme rates correspond to the phase qualified as the most demanding on the previous evaluation of effort questionnaire.

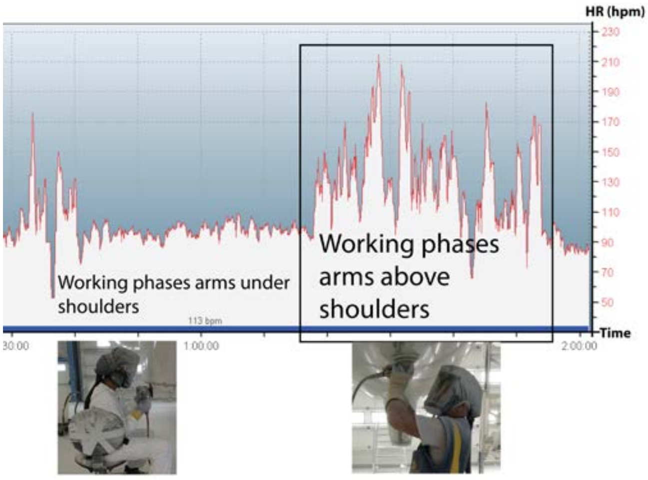

Fig. 1. (a) Evolution of heart rate for operator 1 during usual sanding process ; (b) Second measure after a break of 17 minutes. This curve will allow to identify extremum heart beats and average datas in the different levels of effort. The red curve indicates the evolution of heart rate, the coloured lines indicate intensity levels determined by the software.

For the second operator, a first phase of 30 minutes and a second 45 minutes after a break of 10 minutes shows also extremum heart rates during sanding tasks under the boat.

During the first period, we observe two high rate phase that corresponds to a part where he is sanding catamaran extremities then a second one. After the break, we observe two major phases of high heart rates. For operator 2, his heart rates exceed his TMCF of 178, with a peak at 196 during the second period measured at 0:25:00. Also, we observed that the moment where hear rates reach several times limit values of HRmax determined as follow: 220 hpm – age [12] = 180 for this participant) correspond to the tasks under the boat along the sealing edge.

These results validate operator's hypothesis described in the questionnaires: the strain is higher for sanding tasks along the sealing edge on extremities and specially under the boat.

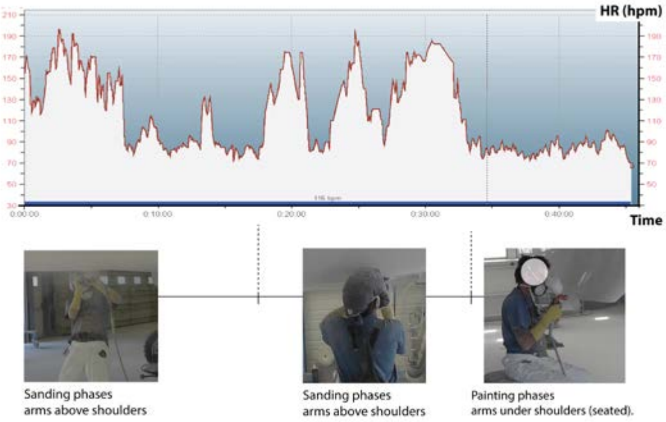

Fig. 2. Evolution of heart rate for operator during usual sanding process under the boat.

Perceived exertion ranking questionnaire:

As a subjective study of effort, the results of Borg scale (CR10) surveys showed that all operators perceive the work along the sealing edge under the boat as the most demanding phase. This top strain phase is ranked as following: o1(10/11), o2(7/11), o3(6/11), o4(6/11), o5(05/11), o6(7/11), o8(7/11). We can conclude that we have the same trend for this subjective method than for cardiac cost measures that also targeted these phases.

3.3 Experimentation 2: characterizing physical workload levels by cardiac cost on targeted tasks.

Thanks to the experimentation 1 that helped us to target the most demanding phases, we were able to focus the next measures on the corresponding tasks. To conduct physical workload analysis with heart rate datas, we compared results obtained to limit values of indexes [9].

Figure 3 shows two types of model provided by the software to analyze heart rates for the operator o5. The first part (a) shows an histogram where we can see operator hear rates in percentage ad time for the test period. The part below (b) show the heart rate curves during the experiment time. Firstly, we calculated extreme reference values such as their maximum theorical heart rate (MTHR) and the HR99 (Heart rate of the 99th percentile) - 99% of heart rate measured are below this value. Then we identify on the histogram the percentages of time the results were above these values. For example the histogram for operator 5 indicates a HR99 of 152 and a percentage of 5,15% corresponding to 6:37 minutes, where hear rate exceeds maximum heart rate (HRmax) limit value: 145hpm for 5 minutes. We find HRmax by looking at the higher result on the curve. We also recorded reference heart rate (HRr) before the experimentation which is the HR value obtained after a rest of 10 minutes.

Secondly, we used average indexes values such as relative cardiac cost for the 99th percentile (CCR99), average heart rate (**HR av.**), average absolute cardiac cost (ACC av.) and average relative cardiac cost (ACC av.).

RCC99 : relative cardiac cost for the 99th percentile. Cardiac cost value reached only for 1% of working time.

$$RCC99 = \frac{HR99 - HRrelax}{(MTHR - HRrelax)} \quad (1)$$

ACC : absolute cardiac cost. Difference between average HR and reference HR (HRr).

$$ACC = \frac{HRav.}{HRr} \quad (2)$$

CCRav : average relative cardiac cost. It's the relation in percentage between ACC and the difference between MTHR and HRr.

$$RCCav. = \frac{ACC}{(MTHR - HRr)} \quad (3)$$

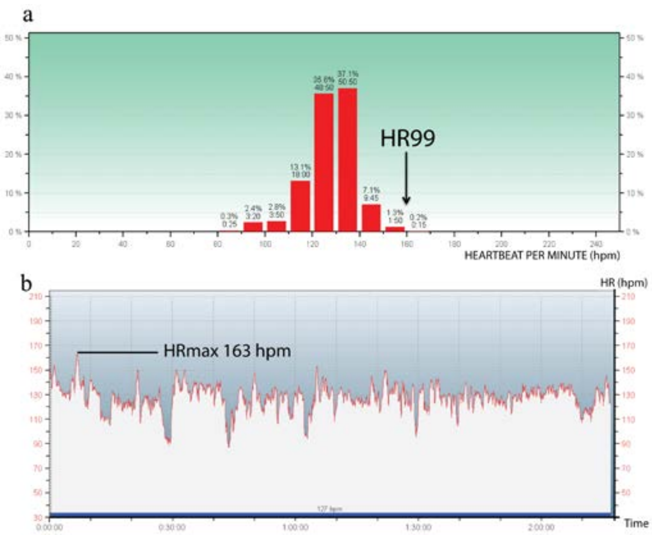

Fig. 3. (a) Exemple for operator 5: histogram related to the curve, showing heart rate averages during sanding task under boat ; (b) Exemple for operator 5: evolution of heart rate during the related task.

Table 2 shows the results of extreme indexes and averages for the four participants mentioned.

Table 2. Results of cardiac cost values for the four operators monitored.

Indexes	**3**	**4**	**5**	**6**	**Limit values**
MTHR	190	189	192	179	INBAR 205,8-(0,685xage)
HR max	99 (197 not exceeded)	132 (196 not exceeded)	163 (145 exceeded for more than 5 minutes.)	133 (181 not exceeded)	WHO. not above 220bpm-age
HR99	99	128	152	125	INRS. 140 hpm
RCC99	32	54	77	60	Monod. 50% for

					30min
HR av.	27	99	114	99	INRS. 105 hpm female Male 100hpm
ACC av.	21,5	34	49	34	Monod, Lehman. 30 bpm
RCC av.	34	27	38,5	30	INRS, Chamoux , heavy from 30%.

From RCC averages and RCC 99 results we determined cardiac cost profile [4]. Figure 4 shows the cardiac cost profile for operators 3,4,4,6.

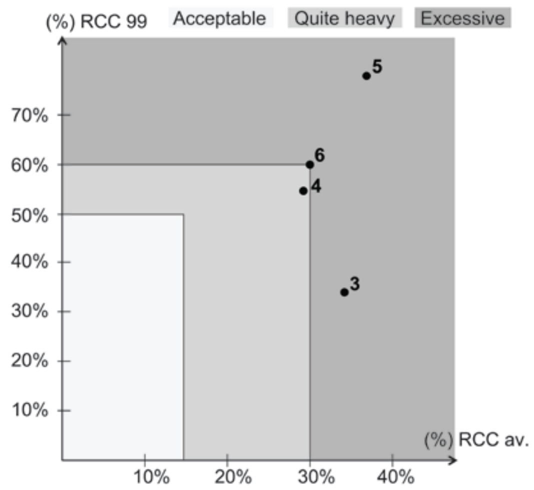

Fig. 4. Profile of cardiac cost of related task for operator 3 to 6... Numbers 3 to 6 = operator o3 to o6.

For operators 5 and 6, the profile is clearly excessive. For the operator 6, his profile is at the limit between quite heavy and excessive. For the operator 4, the profile is quite heavy. These results of heavy cardiac costs trough different profiles validate the need of customized solutions to reduce strain.

3.4 Experimentation 3: does wearing an exoskeleton has an impact on cardiac cost for this task?

Utility and choice of PAD : Prior to propose an adapted PAD for the test, we checked ergonomic standards for the most demanding postures related to the maximum heart rates. With the videos recorded, we can match these extremum heart beats with postures : they happen when operators work hands above shoulders which is a posture referenced as deleterious according ergonomics standards [13]. Besides, OSHA checklist that evaluates MSD upperlimb risk indicates a value of 19. A score >5 indicates a need for ergonomic intervention [14].

Figure 5 shows our approach to determine the right physical assistance system according to the observed posture. The PAD chosen for further tests was selected by its ability to reduce upper body strain. Its performance was tested in similar posture by an independent laboratory [15].

Fig. 5. Process of identifying an adapted PAD for the observed postures. Hh = Hands height; sh = shoulders height. The PAD selected is a prototype of Skel-Ex.

The comparative study on two operators (operator 7 and 8) shows that wearing the PAD has an effect on cardiac cost. The table shows four colons indicating results with and without PAD for both operators. The first tree lines show the extreme values (MTHR,HRmax, HR99) and the following lines show the averages (for RCC99, HRav., ACCav.,RCCav.).

Table 2. Experimentation 3 : results of cardiac cost values for a comparative study on two operators.

Indexes	**7 with PAS**	**7 without PAS**	**8 with PAS**	**8 without PAS**	**Limit values**
MTHR	190	189	192	179	INBAR 205, 8-(0,685xage)
HR max	128	145	98	110	WHO. Over 145 bpm for 5 minutes max
HR99	128	138	98	108	INRS. 140 hpm
RCC99	51,5	59	33	42	Monod. 50% for 30min
HR av.	94	102,5	79	85	INRS. 105 hpm female Male 100hpm
ACC av.	34	42,5	19	25	Monod, Lehman. 30 bpm
RCC av.	18,6	32,1	16	21,9	INRS, Chamoux, heavy from 30%.

Firstly, we compare extreme hear rates with /without PAD. Secondly, by comparing the cardiac cost values for the two phase of work (with/without wearing the PAD), we found for both operators a decrease of cardiac cost when wearing the PAD. We concluded that all the results for extreme and averages indexes values are inferior when wearing the PAD. Figure 6 shows the evolution of heart rates during the two compared phases of work for operator 8. The blurred period in the middle represents the phase that corresponds to both taking off the PAD and a posture not adapted to observation protocole (arms under shoulders). This phase was ignored in the analysis. For operator 7, the results show that when wearing the PAD during the first phase, the average heart rate (HRav. = 128 bpm) is lower than whithout PAD (HRav. = 145 bpm). We observe the same trend with the results of operator 8 : during the first phase, the average heart rate (HRav. = 98 bpm) is lower than whithout PAD (HRav. = 110 bpm).

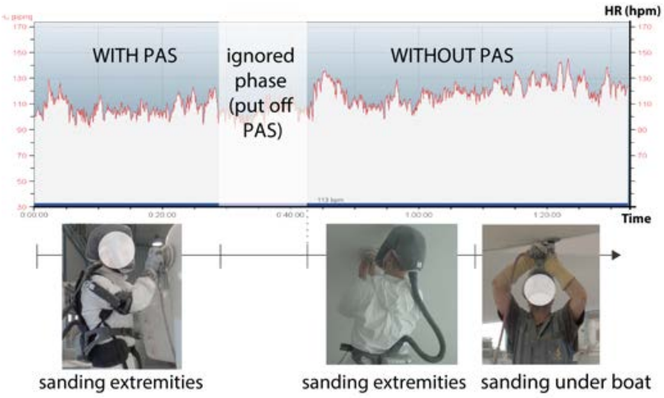

Fig. 6. Evolution of operator 8 heart rate measured for the usual tasks wearing the PAD at first then without PAD.

Task related usability questionnaire: The results for the qualitative questionnaire on the first two operators measured showed a global satisfaction for their first experience with the product. Both operator ranked their global satisfaction around 5,5/7. The extra four operators confirmed this tendency with a ranking of about 5,5/7 for two of them and one of them ranked about 5/7. These results shows a global acceptation among operator's work even if a lot of improvements have to be done. This first positive contact with operator and this first evaluation iteration will prepare fertile feedbacks for conception in further steps.

3.5 Discussion and future work

Firstly, from the proposed methods, we could identify some interesting contributions to PAD evaluation such as an effective positive impact on physical workload. However the comparative study was measured only on two operators, we could repeat it on more operators in order to get a statistic significance.

Secondly, our complementary experimentations for cardiac cost helped us to design an easily repeatable protocole using short times of testing.

Thirdly, our user centered design approach helped us to understand and identify strain context in order to propose the best solutions to answer operator's demands.

Limitations and perspective

The curves indicate high variations that would be interesting to link more precisely to postures to have more accurate informations about posture influence of cardiac cost. Moreover, the comparative study needs to be done on multiple volunteers to confirm the trend. The PAD tested seemed useless for the task where the arms were under the shoulders, so that question the ability of the product to be easy to install/uninstall in order to be integrated in their daily work.

4. Conclusion

This study identified the most demanding phase of work among operators in an industrial environment and validate the positive impact on cardiac cost of a prototype of Physical Assistance System (PAD). This first step of diagnostic of human-PAS system is positive, especially proving a physical help on workload. This first positive contact with operator and this first evaluation iteration will prepare fertile feedbacks for conception in further steps.

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