User centered design of a cyber-physical support solution for assembly processes

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Abstract

Human-machine cooperation in assembly processes will further increase in the course of the fourth industrial revolution, where digitalization entails many chances for improvement. Not only on the machine perspective – where most of the current developments in this field focus on – but also for the workers, which still play a central role while having to face rising requirements. Many workers are not aware of ergonomics. Therefore the user centered design process (UCDP) was used to develop a support solution that gives workers feedback on ergonomics during the assembly process. The concept is based on the idea to use sensors available in everyday-life technology like smartphones and –watches to track limb positions in real-time and notify the worker if he or she is not acting ergonomically. The corresponding App, currently available as digital interactive prototype, also gives advice about possible measures. The UCDP featured several iterations with user studies and expert evaluations to ensure high user friendliness.

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1. Introduction

Today, manufacturing companies find themselves confronted with various emerging challenges. The international competition rises, the market demands for ever faster innovation cycles at lower product prices and therefore shorter production times with less failure rates. In addition, customers ask for more options to individualize their products.

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This requires more flexible production processes and individual assembly up to batch size 1. The recently discussed approaches to face these challenges can be summed up in the term Industry 4.0 – the fourth industrial revolution. The term has its origin in Germany. Spath [1] as well as Botthof and Hartmann [2] give a detailed overview of this topic. A short overview is available from Brettel et al. [3]. The basic idea is to integrate modern IT and communication technologies into production processes and combine them with recent innovations within assembly technology. The long term vision is, that all participants of the production process – humans, machines and products – are connected with each other and that machines use different identification methods and sensors to detect the status of products and even workers, to be able to flexibly adapt to a given situation. Therefore, the amount of human-machine cooperation in assembly processes will further increase. The focus of most of the present developments in this field lies on the machine perspective. Still, humans will have an important part within these processes, since they have to make decisions in these systems of ever more complexity.

The Institute of Ergonomics and Human Factors at TU Darmstadt is part of the project SmartF-IT [4], which deals with the challenges but also the chances of Industry 4.0. One of the goals is to develop concepts for cyber-physical support solutions that actively provide a benefit for participants within the assembly process.

These solutions are developed using the user centered design process (UCDP) according to DIN EN ISO 9241-210 [4] in order to achieve a high user acceptance of the solution. Possible results are support solutions on different levels. On the organizational level the challenge is, that important information for leading positions about the assembly process is not available bundled, in real time and location-independent. A possible solution is a digital application on a mobile device that automatically collects all relevant information, notifies about human and machine failures, enables direct communication and recommends possible solutions [5].

On the ergonomic level, the high degree of adaptivity and sensor equipment planned within Industry 4.0 offers chances to detect individual ergonomic aspects of the workers in order to automatically adapt the machines to them where possible. Another possibility is to use available sensors to detect and report ergonomic malpractice of the individual worker and show possible improvements. A field study and interview conducted in the course of this project has shown that many workers are not aware of the ergonomic aspects of their work. This is mainly due to the fact that they have no references about how ergonomic postures and limb movements look like and which ones are ergonomically not recommended. Also, the threshold when a certain movement leaves the recommended area is not known. Instead, most workers follow motion sequences that they are familiar with because they seem to be comfortable or effective. Some of these motions might not be favorable, but workers will not necessarily notice that unless the motion immediately leads to pain or discomfort. Instead, the motion might have a negative long-term effect if repeated regularly. But if a long-term effect occurs, it is too late to intervene and the worker cannot relate it to the actions that have caused it. Several publications show, that work-related musculoskeletal issues are a common problem in the industry [6,7]. Therefore, this paper presents the user centered design of a support solution that gives workers direct feedback about the ergonomic quality of their motions during the assembly process by using the built in sensors of everyday-life technology like smartphones, smartwatches and activity trackers to monitor different parameters of ergonomics at work.

2. Methodology

Since the goal of the presented design was to provide a solution to be directly and actively used by the workers in order to improve their working conditions based on their specific working environment and requirements, it was obvious that the UCDP provided a suitable method to be used because it integrates the user perspective continuously from the beginning of the development. After the planning phase, the UCDP consists of the 4 main steps: understand and specify context of use, specify user requirements, produce solutions to meet user requirements, evaluate solutions against requirements. All these steps involve user participation or observation. This ensures that the requirements of the future users are considered in the design process from day one, in order to achieve solutions that feature a high usability and acceptance. The whole process is iterative, making it possible to jump back to any prior step as required to revise or complement the solution until it meets the user requirements. Fig. 1 shows the UCDP according to DIN EN ISO 9241-210 [8].
The following sub-chapters explain how the four main steps of the UCDP are conducted to design the desired support solution for workers in assembly processes.

2.1. Context of use

The context of use can be deducted from the framework conditions given within the Project SmartF-IT. That includes cooperation with a large scale enterprise, which operates large assembly areas. In these areas a lot of assembly steps are performed manually by workers in cooperation with machines and tools of various types at the respective assembly workplaces. The workers receive a basic training according to the specific assembly task they have to perform which usually does not include information about ergonomic aspects of their work. The workers then perform the task more or less individually under the given boundary conditions. The topic of ergonomics is organized decentralized, so the focus on ergonomics varies significantly from plant to plant. Some plants temporarily employ a physiotherapist to teach workers ergonomic improvements in their motions and to teach team-leaders exercises that they can perform with their workers to prevent work related overstrain. Such ergonomic support might not be offered at other plants. In any case, the workers themselves have only very limited options to proactively take part in the question of how to organize their work ergonomically – apart from handing in suggestions for the continuous improvement process. In addition, most workers do not know about the necessity of ergonomic behavior at work or the possible risks of its absence. If they do, they do not necessarily know which motions are ergonomically recommended and which are not.

Some plants have their workplaces assessed by standardized methods to categorize them in different levels, based on the strain on the whole body. This enables a comparison between different workplaces which can be of help for the assignment of workers to workplaces. Team leaders for example can decide after what amount of time workers should rotate and where to. But since the assessment is always a full body assessment, it does not show the strain on specific limbs, which limits the significance of the method. Different workplaces on hydraulic presses for example are all rated with high strain which makes a rotation between them look useless, but there are differences in the details concerning strain on the respective limbs. If they were detected, a rotation might look useful again.
2.2. User requirements

The user requirements can be deducted mainly from the context of use. The requirements can be separated in two parts. Part one is to make the worker aware of ergonomics. Part two is to give recommendations in case the worker does not work ergonomically or if the workplace does not allow to work ergonomically. A third part could be how to use statistics of the collected data to initiate long-term improvements.

For the first part, the support solution should be able to give the workers feedback about the ergonomic quality of their motions during work. This feedback should be given in real time and should differentiate between specific limbs in order to enable the worker to directly relate it to the situation where it occurred. This requires real time tracking of the respective limbs. Since the assembly work usually requires flexibility and precision of the workers, the devices used for tracking must not significantly harm these requirements. Also, most workers work under a certain time-pressure, so the feedback should be presented clearly so that the worker can intuitively understand it and does not need to spend extra time on it. In addition, the worker has to be notified in an appropriate way, taking the surrounding condition of an assembly area into account.

For the second part, suitable counter measures have to be found and implemented into the concept. Again, these recommendations should be easy to understand and easy to put into practice.

2.3. Design solution

Based on the above requirements, a first design draft for a possible app on a mobile device was created in the form of a digital interactive prototype. This prototype showed the basic functionality of the proposed solution and thus served as a basis for discussion during the evaluations. The physical presence of a prototypical design facilitates the integration of the users, as they may comment on specific elements rather than to refer to a conceptual design, which is only described virtually and therefore interpreted differently by each person.

The concept for tracking the motions of the different limbs is based on the use of sensors available in everyday life technology like smartphones, smartwatches and activity trackers. This has several advantages. First, it should lead to a high user acceptance, since the workers already know the utilized technology. Second, the devices are comparatively small and the most workers wear them anyway. So the workers do not necessarily need to put on new devices and should not be significantly restricted in their movements.

2.4. Evaluation

Within the UCDP, evaluation plays an important part. Every evaluation bears the chance to unveil flaws and show room for improvement in order to make the solution more user-friendly. The concept presented in this paper had four major evaluations. The first evaluation was conducted in a lab with a set-up and simplified assembly workplace with random subjects. This evaluation enabled a first valuable feedback on the general practicability and user acceptance of the concept under conditions close to reality but without the high effort and time-pressure of an evaluation on a real assembly workplace. The feedback also helped to decide between different display and notification options which were presented to the subjects. The general feedback on the concept was positive, so that no major changes had to be considered.

The second evaluation was conducted with experts from the Institute of Ergonomics and Human Factors at TU Darmstadt. Here, the focus was on evaluating the optical and functional design of the clickdummy. These experts with their expertise in usability were able to give detailed feedback on different aspects of the design which lead to several improvements of the dummy.

The third evaluation was conducted with two industrial engineers, one ergonomics expert and two project leaders of the cooperating enterprise in order to evaluate the concept and the prototype through the enterprise perspective. The implemented features were focused within the third evaluation. The feedback on the general concept was again positive, yet three additional features were suggested.

All the feedback from the prior evaluations was implemented into an improved concept, which was then evaluated a fourth time. In this evaluation, the workers of the cooperating enterprise were equipped with the possible devices used for tracking – one smartwatch on the wrist, one smartphone on a strap on the upper arm and one chest
band. Also the general concept was explained and the prototype was presented to them. Then they were interviewed. All workers stated that they could imagine wearing a smartwatch permanently, but most of the workers said they would wear a strap only temporarily and would refuse to wear a chest band at all. This lead to the conclusion, that for permanent tracking, the sensors had to be light and wearable without a strap or band. The prototype itself was rated as clear and intuitive.

Also the aspect of data privacy was queried. The workers had no concerns that their data would be misused, but the works council that accompanied the evaluation did. They had a critical stance towards permanent tracking and stated that questions about privacy have to be discussed on a company level as well as on a political level.

3. Results

Result of the four evaluations is a revised, digital interactive prototype of an app for ergonomic feedback for workers in assembly processes. This interactive prototype includes all the features and the control logic of a later app to be programmed in the next step. However, in this state it is only a concept that works without real process data.

In the current status of the concept, a smartwatch on the wrist and a smartphone in the pocket should be combined with several small activity trackers in the form of a clip to track several ergonomic parameters of the worker and give them real time feedback through an app.

The main screen (Fig. 2) shows an overview over several ergonomic parameters where the upper tiles are arranged automatically based on the frequency of the occurrence of the ergonomic parameters which they show. The lower tiles can be arranged and exchanged manually according to personal preferences using the plus-tile.

Fig. 2. Main screen of the prototype.
The tiles show different independently monitored body parameters like angles and twists as well as environmental parameters like volume level. In addition a full body assessment is possible. The counters in the bottom left corner of the tiles show the number of threshold exceedances. If the number reaches an individually determinable count or a single exceedance into a critical area occurs, the display changes to a full screen view of the affected parameter (Fig. 3) to give the worker detailed information. After some seconds, the view changes back to the main screen and the counter is set to zero. If a maximum level of recommended short term strain is exceeded, the tile is colored red and the counter is not set back, unless the worker does it manually. The full screen view then shows recommended measures like compensatory exercises or short breaks. A similar sequence happens if the maximum level of recommended daily strain is exceeded. The full screen then recommends a rotation which is also indicated by a rotation symbol on the top left corner of the tile.

4. Discussion

The presented solution has possible benefits on different levels. The most obvious benefit is that workers become more aware of ergonomics at work – especially about which motions are ergonomically recommended and which ones are not. This can lead to a more ergonomic sensible behavior at work and may reduce work-related injuries and illness. An earlier study reported that from 110 interviewed workers, 85% experienced work-related symptoms, 50% had persistent work-related problems, but still less than 5% of them had officially reported their problems because of fear of negative consequences [9]. The advantage of tracking parameters in real-time is that the workers can directly relate the feedback to their actual work instead of having to transfer theoretical universal and abstract recommendations. This enables them to directly identify the problem themselves and autonomously act against it.

Fig. 3. Full screen view of the back parameter.
Sometimes specific workplaces demand specific motions that are not favorable. In these cases, the concept can still help by recommending compensatory exercises, workplace rotation or additional breaks. A possible negative effect of using the concept on such workplaces can be that workers might become scared or reluctant to work at this place if they permanently get the feedback that it is not ergonomically recommended. In this case, the team leaders should communicate openly with the workers how to interpret the given information and set it into the right context.

Team leaders are another group that may benefit from this concept. If data privacy regulations allow them to view the data of their workers, they could decide individually and precisely for each worker when he or she should rotate and whereto. If team leaders spot workers that have a very high rate of ergonomic malpractice they might initiate a training course in ergonomics for them. But even if team leaders only get anonymous data about the workplaces and not the single workers, they may use this quantified information to improve rotation schemes or to assign workers with specific limitations to workplaces that are well suited for them. That information may also be embedded into the concept of a team leader app that has been developed earlier [5].

Moreover, the production planning department may use the data of this concept to get more detailed information about the workplaces, especially the ones that seemed very similar on conventional strain assessments. More differentiated information about the strain of single limbs can help to figure out more specific solutions for the individual improvement of the respective workplaces. Also the statistic data that can be accessed for a daily, weekly, monthly or yearly overview can be used to keep track of positive or negative effects of certain measures.

5. Conclusion

The feedback from the evaluations conducted within the UCDP, have shown that the presented concept is a suitable support solution for the workers and other employees connected to the assembly process. It gives workers direct feedback and can help to improve their ergonomics at work. The utilization of the UCDP has helped to reach a high user-friendliness and acceptance. Yet, at this point the presented solution is only available on a conceptual level. The next step would be to develop a real app from this prototype in order to process real data and do more evaluations under real circumstances over a longer period to validate this data and further improve the solution.

Another important point that has to be considered is the question about data privacy. This topic should be discussed by the responsible persons in the responsible councils and boards. General decisions and regulations should be made as soon as possible since it also affects other developments in the course of industry 4.0, especially the development of apps that rely on this data. Many developments also outside the project SmartF-IT show that apps are an important topic of industry 4.0 in general [10].

With the ongoing progress of industry 4.0, more and more parts and participants of the production process will be digitalized and connected [11], thus making it conceivable that all technical specifications of tools and even single components are digitally retrievable at some point. If this information is integrated into the presented solution, the app could also dynamically include weight of the currently handled objects into the ergonomic feedback which would add another valuable aspect to the concept.

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