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Usability of Human-Robot Interaction within Textile Production: Insights into the Acceptance of Different Collaboration Types

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ABSTRACT

The development towards Industry 4.0 and the increasing introduction of collaborative robots (cobots) open new possibilities. However, the automation of textile processes is complex because the behavior of limp materials is difficult to predict. Thus, the processing of textiles in human-robot interaction (HRI) offers a promising approach and the deployment of a cobot is regarded as an assistive remedy for performance optimization. So far, however, only technical and safety factors have been considered, while human factors are often neglected in recent research. Therefore, we present an empirical user-centered study ($n = 21$) which investigates how and whether the collaboration type in terms of role assignment influences the satisfaction of the performed task, perceived autonomy, and perceived control, as well as which factors predict and influence the acceptance. The results emphasize that generally the cobot contributes to satisfactory task performance and high perceived control, with a low perceived autonomy across all types of collaboration. The study identified usability, hedonic motivation, and experience in textile processing as acceptance-relevant factors.

Keywords: Human-robot interaction, Composite production, User-centered study, Acceptance, Internet of production

INTRODUCTION

Through the digital transformation of production, smarter control through machine learning, improved sensors and robot actuators, more previously exclusively manual production activities can be automated (Brauner et al. 2022, Villani et al. 2018). However, production processes using limp materials (e.g., textiles or foils) are more difficult to automate (Dammers et al., 2021). For example, in textile-based composite production about 40 % of all components are manufactured manually (Reux and Mikdam, 2019). Human experts are skilled in handling the limp textiles and have an excellent sense of materials, enabling them to flexibly manufacture even very complex components. Nevertheless, these manual processes cause problems like slow production speed as well as back or wrist problems for employees due to working in bent positions and applying a lot of force. Due to disproportionate costs, limited flexibility, or excessive complexity not all processes for manufacturing composite components can be fully automated (Elkington et al., 2015). To still save time, reduce costs, and improve working conditions human-robot interaction (HRI) is promising. A successful and appropriate integration can be achieved by considering the technical possibilities as well as the workers' specific needs. Yet, the current state of the art on HRI in composite production mostly focuses on technical factors (Dammers et al., 2021, Eitzinger et al., 2021) while neglecting the human perspective.

This study therefore focuses on the user and investigates satisfaction and acceptance-relevant factors that enable a valuable task sharing within HRI. In a user-centered design the acceptance of HRI during a textile composite production process is examined based on the technology acceptance model (TAM). Furthermore, ratings about satisfaction of performance, perceived autonomy, and control as well as mental and physical effort are surveyed. Three research questions are guiding our study: (1) Does the type of collaboration have an impact on the satisfaction rating? (2) To what extend does the type of collaboration influence the perceived autonomy and control?, and lastly (3) Which factors have an influence on the acceptance rating regarding the human-cobot-interaction? The sample is drawn from experts in the field ($n = 21$). In a within-subject design, participants are asked to form a textile into a three-dimensional shape to the best of their ability. The cobot acts as a technical assistant and supports the execution of three tasks in different collaboration types (low, medium, high).

STATE OF THE ART

To answer the research questions addressed, this chapter provides the basics of composite production, HRI and the investigated factors such as acceptance.

Composite Production

A textile-based composite is basically the combination of a textile reinforcement with a matrix material (e.g., plastic). They are typically used in applications where high strengths combined with low weight are demanded, e.g., in aviation, automotive, construction and sports sectors. (Fleischer et al., 2018) To produce a composite part, the so-called preforming can be used that consists of four process steps: cutting to size, handling to the mold, draping (forming) into the final three-dimensional shape, and joining the individual layers, for example by using spray adhesive. (Elkington et al., 2015) Especially demanding is the draping of the individual textile layers, since the fibers have to be aligned exactly in the direction of the occurring loads in order to achieve the required outstanding mechanical properties of the final component. In this context, the avoidance of wrinkles, fiber displacements or waviness is particularly important. Draping is not only the most error-prone but also the most time-consuming process step in sequential preforming and is therefore investigated in this study. (Chan et al., 2020; Dammers et al., 2021; Eitzinger et al., 2021; Elkington et al., 2015)

Human-Robot Interaction

There are four main types of HRI (Otto and Zunke, 2015): *Full automation.* Original form of robotic operation. HRI is not possible because protective fences hinder the human from entering the work area. Thus, human and robot workspaces are separate. *Human-robot coexistence.* Human and robot have separate workspaces and tasks. Physical contact between human and robot is not necessary or required but possible. *Human-robot cooperation.* Human and robot carry out joint tasks in joint workspaces. However, physical contact is not necessary to fulfil the given tasks. *Human-robot collaboration.* Physical contact between human and robot is required to successfully complete the given joint tasks in joint workspaces. We address the last two mentioned types of HRI. Previous publications on HRI in composite production concentrate mainly on improving efficiency and safety of the textile process with little or no attention to humans. (Dammers et al., 2021; Eitzinger et al., 2021) Thus, in our study, we focus on human factors such as acceptance, perceived autonomy, and satisfaction.

Measuring Acceptance and User Factors

With the increasing integration of HRI in production, considering acceptance becomes more important. To understand which aspects are decisive when humans and robots work as a team, it is necessary to identify the influencing acceptance factors. Here, we define acceptance as the willingness to use a cobot for textile composite production. Building on the Theories of Reasoned Action (TRA) and Planned Behavior (Ajzen and Fishbein, 1977), the Technology Acceptance Model (TAM) provides the theoretical basis by linking perceived usefulness and perceived ease of use to attitudes towards use, behavioral intention, and later actual use of a technology (Davis, 1989). In our study, we added two factors, as they likely relate to acceptance: hedonic motivation (Lin et al., 2020) and trust (Lee and See, 2004). Trust in automation is generated by the expected predictability, credibility, and usefulness of the technology. The current state of the art knows little about the keys of a successful HRI (Porubčinová and Fidlerová, 2020). At present, there is insufficient consideration of psychological factors. Affect, motivation, and perceived autonomy are likely promoters for successful HRI. Thus, this study also explores autonomy, seen as the quality of self-directedness, or freedom from outside control (Bradshaw et al., 2004).

METHODICAL PROCEDURE

The user-study is designed on the basis of the state of the art. The study design, the type of tasks, and the assessment are explained in detail in the following subsections.

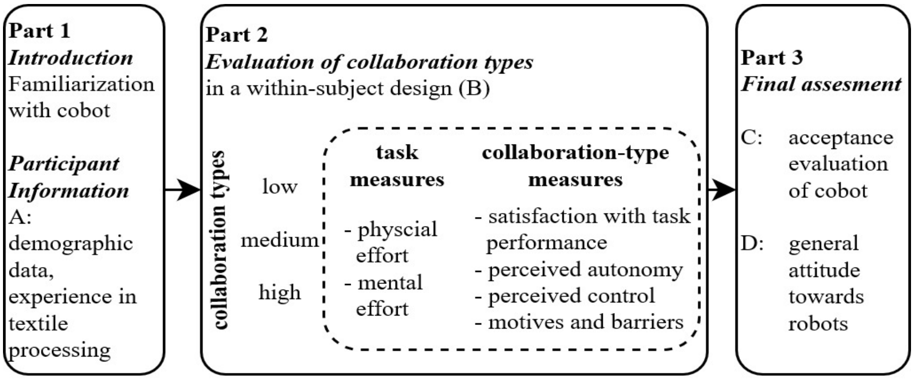

Figure 1: Overview of experimental procedure of the HRI acceptance study.

Study Design

Fig. 1 shows the study procedure. Overall, the study consists of three parts. The respective parts of the questionnaire are indicated in alphabetical order (A–D).

The first part introduces the participants to the topic of human-robot-interaction, makes them familiar with the Franka Emika robot and informs participants that participation is voluntary and withdrawing from the study is possible at any time. Additionally, part A of the questionnaire is examined (demographic data and prior experience). The second part covers the interaction with the robot. All participants are instructed to drape a rectangular layer of glass fiber fabric (twill weave, 200 g/m^2) accurately and flawlessly onto a mold in omega geometry with the support of the cobot. Participants repeat this task with three different collaboration types (low, medium, high) in a randomly assigned order (within-subject design). After each task, we assess the mental and physical effort scale, as well as the individual satisfaction with task performance, perceived autonomy, and perceived control, motives and barriers for collaboration (B). The third part assesses the acceptance using the TAM-items (C) and the attitude towards robots (D). The duration of the study is about 60 minutes.

Collaboration Types

To find out whether and which type of HRI is appropriate within preforming, three different collaboration types (see Fig. 2) are implemented differing in terms of the active division of labor between the robot and participant as well as the tool used.

Low collaboration type: *Robotic Draping with Silicone Roller-Tool*

The first collaboration type is considered as human-robot cooperation. The cobot autonomously drapes the textile layer that is positioned by the participant and takes over the main part of work by using a silicone roller. While the cobot is completing its task, the participant is checking the quality of work in order to intervene in the event of faults or unexpected complications. Meanwhile, the participant is encouraged to rework areas already done by the cobot to achieve the best possible draping result.

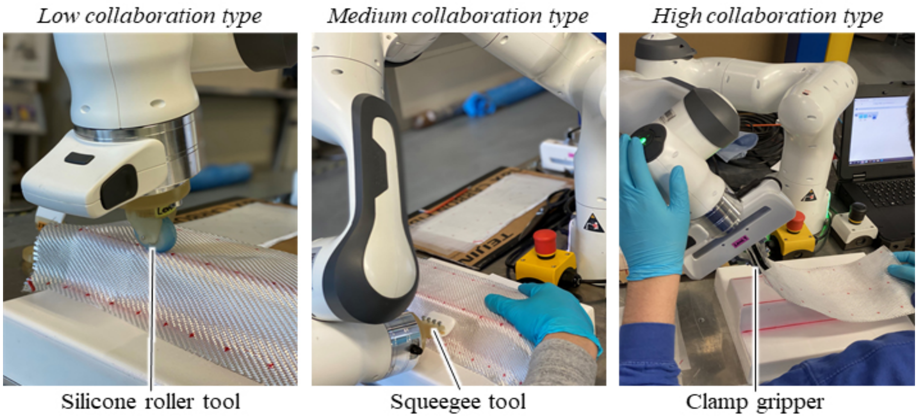

Figure 2: Low, medium and high collaboration type investigated with respective cobot tools.

Medium collaboration type: *Human-Robot Task Sharing with Squeegee-Tool*

In the medium collaboration type, the participant is instructed to position the textile layer on the mold without tightening or draping it. Afterwards, the participant initiates the cobot which is equipped with a squeegee-tool to drape the fabric on parts of the mold. The remaining parts are draped independently by the participant. Accordingly, in this task a sequential human-robot cooperation is aimed at.

High collaboration type: *Robotic Assistance with Clamp Gripper*

In the high collaboration type, a high level of autonomy is left to the human. Human and robot are intended to work together in human-robot collaboration. A clamp gripper is used as a cobot tool which holds one side of the glass fiber fabric while the participant manually adjusts the position and orientation of the cobot so that the textile layer can be draped manually in the best possible way. Thus, the cobot assists the participant in draping independently on the mold.

Study Measures

In the first part of the questionnaire (A), *demographic data and prior experience in textile process*ing is assessed. The participants' age, highest educational attainment, professional background and current profession is surveyed. Additionally, prior experience in textile processing with four items is evaluated on a 6-point-Likert scale from no agreement at all to total agreement. Technical knowledge in textile engineering, experience with composites, draping and experience with automated systems is assessed. The first three items are calculated to an overall experience score ($\alpha = .723$). The fourth item is kept single due to low scale reliability. Moreover, participants are asked to self-assess their experience of processing textile on a 10-point-sale ($1 =$ no experience, $10 =$ immense experience).

Table 1. Surveyed items - satisfaction of task performance, perceived autonomy and perceived control. Items marked with * are reversed.

Scale	Items	Cronbach's Alpha (α)
Satisfactionwith task performance	I am satisfied with the result of the draping in collaboration with the cobot. I could have achieved a better result without the cooperation with the cobot.* For an optimal draping result, I had to manually rework the processed area of the cobot.*	$\alpha_{low} = .682$ $\alpha_{medium} = .842$ $\alpha_{high} = .647$
Perceived autonomy	If I could have chosen, I would have preferred to drape in a different way.* The way I draped was according to my ideas. I had the choice to drape as I wanted. I was very restricted by the cobot when draping.* I was able to do the draping in my own way.	$\alpha_{low} = .918$ $\alpha_{medium} = .715$ $\alpha_{high} = .868$
Perceived control	The cobot responded to my commands by touching the arm accordingly. I was afraid that the cobot would hurt me.* I thought the cobot's movement was predictable. I felt like I was in control.	$\alpha_{low} = .772$ $\alpha_{medium} = .655$ $\alpha_{high} = .785$

Part 2 is the main part of the study and evaluates each collaboration type with the Rating Scale of Mental Effort (RSME) by Paas ("How much mental/physical effort did you invest in the task?") on a 10-point Likert-Scale (Paas, 1992). To evaluate the collaboration types, we surveyed three self-administered scales: the individual satisfaction of task performance, perceived autonomy, and perceived control. For the assessment of the used tool, one single item is surveyed ("I found the tool useful for performing the task"). Table 1 lists the individual items of the scales with additional information about the internal reliability (Cronbach's Alpha). Moreover, qualitative data concerning motives and barriers of each collaboration type are collected.

Part 3 of the study includes the final assessment according to the acceptance model of (Venkatesh et al., 2012). Four dimensions are rated each with three items: Usability (e.g., "I am convinced that the cobot works well"), ease of use (e.g., "Dealing with the cobot will be clear and easy for me."), hedonic motivation (e.g., "Using the cobot will be fun") and behavioral intention (e.g., "I can imagine myself working together with the cobot"). Additionally, trust is added as an extended dimension (e.g., "I will trust the cobot."). Items with sufficient internal consistency with one another are summed up into an overall score. (Venkatesh et al., 2012). The study ends with a scale on attitude towards robots with seven items (GESIS, 2018).

Sample Description and Statistical Analysis

The user study was conducted at the Institut für Textiltechnik (ITA) at RWTH Aachen University, Germany, with 21 male participants in the age range from 21 to 35 years ($M = 24.6$, $SD = 3.8$). Most participants ($n = 13$, 62 %) are studying engineering. Seven participants (33 %) had a university degree while one participant had completed vocational training (5 %). Since only participants from the field took part, 95 % had a degree in mechanical engineering as a technical background, one came from the field of materials science. The information on current jobs ranged from student, research assistant, bachelor candidate, to PhD student. Prior experience in textile processing was very high (M = 5.02, SD = 0.62). The same picture occurred in the self-rating with a mean of 7.05 (max.10, SD = 1.63). Experience with automated systems within the textile production was low (M = 2.76, SD = 1.51). The attitude towards robots was slightly positive (M = 4.25, SD = 0.65).

For the various variables we report descriptive statistics. Due to the small sample size, we use non-parametric tests: Spearman's rank correlation coefficient r, Friedman's test for analysing differences in means, Cohen's d to determine effect sizes, and χ^2 tests. We set the level of significance to 5 % (p).

RESULTS

The evaluation of the collaboration types is reported firstly, followed by the results of the acceptance evaluation and completed by the description of the qualitative results. The significance level of the correlations is identified with * (* indicates a significance level of $p < .05$, ** represents a significance level of $p < .01$)

Evaluation of Collaboration Types

Satisfaction rating of performance. The ratings according to the individual satisfaction of performance with the cobot are positively evaluated with an average value rating above 3.5 (min.1, max.6). The highest rating is recorded for the high collaboration type (M = 3.93, SD = 1.22), followed by the medium (M = 3.88, SD = .9) and finally the low collaboration type (M = 3.77, SD = 1.38). Even though small descriptive statistical differences are noted, the type of collaboration does not have any statistically significant impact on the satisfaction rating ($\chi^2(2) = 1.132$, $p = .568$, $n = 21$).

Perceived autonomy. The rating about the perceived autonomy shows a similar result. Again, all collaboration types are associated with an existing perceived autonomy, when interacting with the cobot by ratings above the average scale of 3.5. The highest collaboration type enables the highest sense of autonomy (M = 3.93, SD = 1.32), followed by the low type (M = 3.62, SD = 1.02). The least perceived autonomy is observed with the medium collaboration type (M = 3.54, SD = .86). No significant impact is detected between the collaboration types concerning the perceived autonomy ($\chi^2(2) = 1.904$, $p = .386$, $n = 21$).

Perceived control. On average, the perceived control while interacting with the cobot is high. The highest perceived control is attributed to type high (M = 5.05, SD = .88). Type medium achieves the second-best evaluation (M = 4.95, SD = .72), followed by type low (M = 4.74, SD = .96). Since all types are generally rated almost equally positive, no significant differences are found ($\chi^2(2) = 2.113$, $p = .348$, $n = 21$).

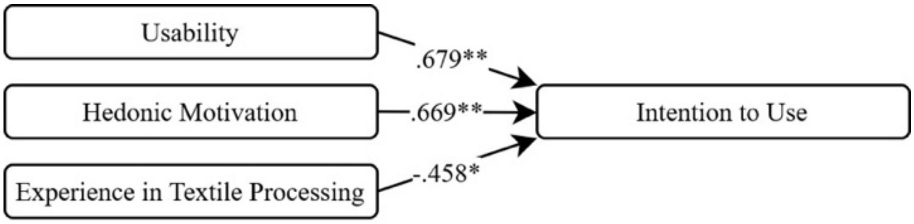

Figure 3: Significant correlations between usability, hedonic motivation and experience in textile processing on intention to use cobot (n = 21).

Mental and physical rating of collaboration type. Both efforts are rated relatively low and below the center of the scale (4.5). Collaboration type high gets the highest rating (M_{mental} = 3.67, SD = 1.88/ $M_{physical}$ = 1.76, SD = 0.99), followed by the lowest (M_{mental} = 2.95, SD = 1.88/ $M_{physical}$ = 1.19, SD = 0.4) and lastly the medium collaboration type (M_{mental} = 2.14, SD = 1.62/ $M_{physical}$ = 1.05, SD = 0.22). The collaboration types medium and high differ significantly on both effort scales ($\chi 2_{mental}(2) = 12.237$, p = .002, r = .20, n = 21 / $\chi^2_{physical}(2) = 13.867$, p = .001, r = .15, n = 21). Thus, in both collaboration types where the human is left with more autonomy (medium, high), more effort is required in the first place mentally and in the second place physically.

Evaluation of Acceptance

Generally, the evaluation of all acceptance-relevant factors is positive above the center of the scale (3.5). Ease of use is rated highest (M = 5.29, SD = .56), followed by trust (M = 5.02, SD = .63). Hedonic motivation turns out to be high (M = 4.94, SD = 1.81). The intention to use (M = 4.35, SD = 1.11) and usability (M = 4.01, SD = 1.21) are given a barely positive rating. Determining which factors predict usage intention, usability (r = .679**) and hedonic motivation (r = .669**) are decisive. The other TAM factors do not show any significant correlations. User factors such as experience or attitude-related factors moderate the relationship to the predicted intention to use (Venkatesh et al., 2012). Therefore, in this study correlations are calculated as an exploratory attempt to get first hints what may influence the intention to use. Figure 3 illustrates the significant findings of one additional factor, in particular the experience in textile processing.

The results imply that the higher the usability of the cobot, the more fun it is to interact and the less experienced users are with textile processing the higher the predicted usage intention.

Motives and Barriers

Asked about *motives and barriers* of using a cobot for textile processing, participants associated more negative (n_{red} = 82) than positive ideas (n_{green} = 78) (see figure 4).

Motives. For the low collaboration type, using the roller tool, most of the participants state that the tool is suitable for draping corners (n = 10) and that

Figure 4: Qualitative statements: motives (green) and barriers (red) for HRI in draping. The size of the words corresponds to the frequency of namings.

robot-human task sharing is satisfactory (n = 5). Due to the good repeatability of the process, the high automation level is mentioned as an advantage (n = 4). Similar applies for the medium collaboration type, where the squeegee tool to a s suitable for flat surfaces (n = 8) and the high automation level (n = 7) is commended for allowing parallel work on multiple molds. Most participants mention the use of the clamp gripper as a third hand as major advantage for the high collaboration type (n = 17). They also find precision high (n = 6) and robot control pleasant (n = 6).

Barriers. In all collaboration types, low (n = 5), medium (n = 9) and high (n = 9), a major barrier is seen in the limited freedom of action for the human, as the robot obstructs human movements. Besides, participants mention that the draping result is highly dependent on the initial manual positioning (low: n = 5, medium: n = 4). In addition, for the low type, the tool is mentioned as not suitable for flat surfaces (n = 5). In the medium type, the participants consider the robot speed to be too low. For the high collaboration type, undesired robot movements (n = 7) as well as cumbersome operation (n = 7) and cumbersome clamping (n = 5) are mentioned as disadvantages.

DISCUSSION AND RECOMMENDATIONS

We presented an empirical user study on the acceptance of HRI in textile production with different collaboration types varying in the degree of autonomy from the human perspective (low, medium, high). In summary, the evaluation shows that the cobot is seen as a technical assistant which enables carrying out the given draping task well. However, no dependence on the collaboration type is discernible regarding the specific tasks given (research question 1). Therefore, future research should address the extend of interaction and the differences between collaboration types. In addition, the disadvantages and perceived barriers of the different tools (e.g., poor suitability for certain mold areas) should be mitigated or eliminated in future developments.

Regarding the second question, perceived autonomy tends to be positive for all three collaboration types, with no major differences. Overall, perceived control is rated higher than perceived autonomy for all types. It is perceived to be the highest for the high collaboration type. This can be attributed to the possibility of adapting the robot's movements to the worker's own movements. Nevertheless, many participants mention the restriction of their freedom of action and undesired robot movements as disadvantages. Mental and physical effort are rated as low in all collaboration types, with tasks being more mentally than physically challenging. More effort is required in the medium and high collaboration type, where more autonomy is left to the individual. The Self-Determination Theory suggests that autonomy and control are related to higher task performance and job satisfaction (Deci and Ryan 2008). For higher autonomy, we recommend adapting the robot movements and workflows to the workers and setting up smart interfaces for improved individual robotic support.

The third research question referred to the general acceptance. In general, all investigated factors are rated positively, with ease of use, trust, and hedonic motivation rated highest, and intention to use as well as usability rated barely positive. The results show that usage intention depends mainly on hedonic motivation, usability, and experience in textile processing. Limited usability can be attributed to the low complexity of the geometry and thus the draping task. Within the qualitative statements, some participants refer to the possibility of improving the used robot tools, as well as the use of the technology for large plies and complex geometries. Furthermore, the results show that participants with little experience in textile processing rate usability higher. This could be explained by the fact that more experienced individuals do already have accustomed workflows. Thus, they perceive the cobot to limit their freedom and restrict possibilities to intervene. To increase usability and acceptance of HRI, workflows and robot operation should be improved and user diversity factors should be more deeply illuminated.

LIMITATIONS AND FUTURE RESEARCH

The small sample size impacts the results of this study. For future studies, we suggest investigating a broader and more diverse sample, particularly including women and a wider age range. Also, the consideration of different professional and educational backgrounds is interesting. An experimental study design was chosen to investigate the cobot and its tool specifically for textile processing. Thus, the (free-form) answers mostly refer to concrete robot movements or tools depending on the respective draping tasks. For this specific use case, the interaction and task sharing between human and robot should be redefined in further research, as well as more complex tasks should be chosen. Due to the very specific use case, it is difficult to transfer the results to HRI in general, so that further factors should be investigated independently. This could include the use of human digital shadows to detect the worker in the work environment (e.g., position tracking, fatigue detection) to achieve improved collaboration and adaption of tasks (Mertens et al. 2021). As a result, other human factors such as information privacy become relevant. Questions arise such as: What can and should technology know about the user for productive and pleasant HRI? In this context, trust in automation becomes particularly relevant and should be investigated in further studies.

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