DOI: 10.21062/mft.2023.007 http://www.journalmt.com

Research of Robots in Cooperative Mode in Human Body Part Detection

Josef Ponikelský (0000-0001-9781-0832), Vít Černohlávek (0000-0001-6816-1124), Jan Štěrba (0000-0002-2676-3562), Pavel Houška (0000-0003-4295-258X)
Faculty of Mechanical Engineering, J. E. Purkyne University in Usti nad Labem. Pasteurova 3334/7, 400 01 Usti nad Labem. Czech Republic. E-mail: josefponikelsky@seznam.cz

The aim of this article is to carry out experimental measurements and evaluate the real possibility of practical usability of the proposed methodology for measuring forces and pressures of collaborative robots, which are one of the determining parameters for a safe collaborative workplace. In the article, research will be carried out on the measurement of forces and pressures of a collaborative robot before its deployment in a real application. Force and pressure values will be measured using appropriate measuring devices. The measured results will be compared with the ISO/TS 15066:2016 technical specification and then evaluated. Following the evaluation of the results, steps will be recommended to follow the collaborative method. The procedure of measuring the collaborative application for real use in practice will be evaluated.

Keywords: Collaborative robot, measurement of forces and pressures, occupational safety, ISO/TS 15066:2016

1 Introduction

The safety of collaborative robots is a big topic in the field of robotics and automation today. A collaborative robot is made in such a way that it can be used to cooperate with a human in performing their joint work. Each such application must undergo a risk assessment and evaluation of the potential risk. Part of the assessment of the risks of co-borative robots is the determination of the methodology of use, such as the limitation of power and force. In this method, the robot is preset with a force that it can safely perform at its speeds, weights and other parameters. To find out these forces, we need to measure and evaluate them. [1]

Collaborative bots were brought to market in a quick time frame, predating legislation that would have made users aware of these risks. Recently, the technical specification ISO/TS 15066:2016 [2] was issued, which issues a recommendation to users of collaborative robots, what forces and pressures can be in a certain part of the human body when impacting a person. This issue is a new topic that most robot users cannot deal with and thus apply the robot to applications where they may endanger human health. For these reasons, the collaborative robot was tested for safe cooperation with a person as part of the research. The forces exerted by the robot when impacting a person must not cause pain. The robot was tested in the application of the manufacturing company before commissioning. The measured force and pressure parameters in the connections will be examined and compared with the mentioned technical specification ISO/TS 15066:2016. [3]

The output of the article will be the verification of the measurement methodology and the evaluation of the forces and pressures of the collaborative robot in connection with the speed and position of the measurement. The article will benefit every user of a collaborative robot, which can be, for example:

- a company that wants to introduce this type of collaborative robots into its production,
- a company that uses a collaborative robot and needs to verify whether their robot application is secure,
- an integrator who will implement the collaborative robot into a new application,
- scientific and technological worker using a collaborative robot for his research.

Based on this article, the user of the robot will have some guidance on how to measure force and pressure parameters, what risks arise from use in a given application, and an overview of the procedure for measuring the forces that the collaborative robot will perform when hitting an obstacle. The methodology of measuring and evaluating the results is also used as a basis for teaching subjects with a focus on the field of robotics or automation. The measured data can also be used in the future to specify parameters for the safe use of collaborative robots. If a large number of measurements are carried out in the following researches, there is potential for the parameterization of movements, speeds and other parameters for certain brands of collaborative robots. Based on these measurement data, there is a prerequisite for developing software for easier and faster evaluation of the safe cooperation of collaborative robots. [3]

In order to comply with the permissible limit values of force and pressure according to ISO/TS 15066:2016, which recommend limit values, it is necessary to measure these values during the given movements of the collaborative robot. A measuring device is used for this, which in its mechanical properties resembles the human body. Testing the allowable stress level according to existing standards requires the measurement, analysis and evaluation of the maximum collision force and the local maximum pressure occurring in the collision plane. These two stress criteria must be established and reviewed from both dynamic and quasi-static collision effects.

The technical specification ISO/TS 15066:2016 provides guidance for robot collaboration, where a robotic system and humans share the same workspace. In such operations, the integrity of the safety-related control system is critical, especially when process parameters such as speed and force are controlled. In order to assess not only the robotic system itself, but also the environment in which it is located, i.e. the workplace, a comprehensive risk assessment is necessary. When implementing applications in which humans and robotic systems work together, ergonomic benefits can also result, e.g. improving the worker's posture. This technical specification complements and supports the industrial robot safety standards ISO 10218-1 and ISO 10218-2 and provides additional guidance on the operational functions of collaborative robots. [5], [6]

2 Preparation of measurements

A collaborative robot from the manufacturer Hanwha was chosen for the measurement and is made in South Korea. Its arm is made of metal materials with a reach of 915 mm and a maximum load of 5 kg. It is a six-axis robot, the individual joints are marked in Fig. 1., together with the accessories needed to operate the robot. There are no edges on the robot that could cause injury. The robot has collision detection in the range of 25-150 Nm. The functions and interface of the robot are certified EN ISO13849-1:2008 with performance level d (PLd). The program is created in the Rodi software. [4]

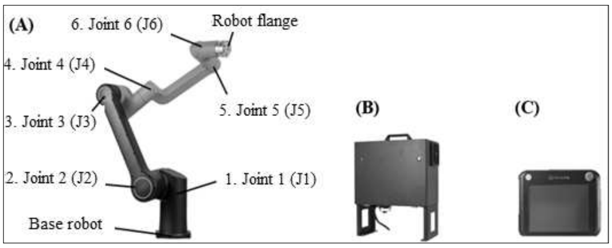


Fig. 1 *Hanwha Collaborative Robot; (A) Robotic 6-Axis Arm, (B) Robotic Switchboard, (C) Robotic teach-pendant to control the robot*

The device for measuring forces and pressure is equipped with springs and sensors that measure the forces acting on the human body. Nine different springs with different set constant values in the range of 10-150 N/mm are used to simulate different parts of the body during force measurement. The local pressure is determined using measuring foils and compared with the limit values according to the standard. Foils that indicate pressure upon contact are used to measure pressure. After the measurement, the foils are then scanned with a scanner and then compared with the established threshold values. [2]

3 Solution

According to the division of operational cooperation, the measured application falls into the group of performance and power limitations. A vertically suspended robot that moves molds for extruding plastic for the production of air filters for tractor cabins has a gripper at the end of its arm designed to fit from top to bottom on a protrusion on the mold to allow it to be manipulated across the L-shaped table surface, from the heating oven to extruder. (see Fig. 2)

Fig. 2 *Measured robotic application with Hanwha HCR-5 robot*

The robot cycle can be divided into five phases:

- The robot waits just above the mold for a new mold in the exit position of the heating furnace, then descends vertically downwards, hands and fingers are at risk.
- The robot pulls the mold from the exit of the oven towards the center of the table, the chest (and thus the upper limbs) is at risk.
- The robot pulls the mold parallel to the injection machine to the end position, the chest is at risk.
- The robot rises vertically to release the mold - no risk.
- The robot returns folded to the position of phase 1, the chest is in danger.

4 Measurement

4.1 Measurement No. 1 – measurement in the 5th joint of the robot

Measurement of phase 3 - the final approach of the mold to the final position. This is a linear movement parallel to the feeder. Here, the chest in the area of the pectoral muscle is evaluated as the collision area of the body. This part of the body was evaluated based on the height of the movement and the distance from the place of possible occurrence of the operator. For this part of the human body, the value for quasi-static contact corresponds to a maximum force of 140 N. We measure the transient contact in this phase, which corresponds to twice the value of the maximum force for quasi-static transition. The maximum permissible value is therefore 280 N for the pectoral muscle area. Taking into account the possibility of potential arm intervention with a maximum allowable tolerance of 300 N for transient contact, a 5% force tolerance will be considered for the measurement. The robot's collision detection is set to the highest possible sensitivity of 100 N.

4.1.1 Measurement path

The starting position from which the robot starts moving towards the measuring device can be seen in Fig. 3. This is the position where, in a real application, the robot takes the mold and moves it towards the injection machine.

Fig. 3 *Start position*

In Fig. 4 we can see the robot in the position when it hit the measuring fixture. This is an impact in linear motion. The preparation was placed so that we hit the 5th Joint. In the picture, you can clearly see the measuring device, with a blue silicone compression element that simulates a part of the body. Its parameters are thickness 14 mm, hardness Shore A 30.

Fig. 4 *Measurement collision position*

In Fig. 5, the position of the robot after hitting the measuring fixture can be seen. Its position did not change after the impact and the joints remained in the same distribution as before the impact. The end point moved away from the measuring fixture only minimally.

Fig. 5 *Measurement end point*

In Tab. 1 the measurement parameters are listed.

***Tab. 1** Measurement conditions No.1*

Contact type	Transient	Spring [N/mm]	25
Collision area of the body	Pectoral muscle (chest)	**Pad**	blue
Max. permissible force [N]	280-300	**Humidity [%]**	33
Robot force limit [N]	100	**Temperature [°C]**	25
Pressure foil	LLW range 50-300 N/cm²	**Speed robot [mms-1]**	200

Tab. 2 shows the measured data. The measurement was repeated 5 times in the same position with changes in speed. The first measurement was at a speed of 200 mms-1, the measured values corresponded to the limits according to ISO/TS 15066:2016, i.e. maximum permissible force of 280 N and pressure of 340 N/cm-2.

***Tab. 2** Measured values No.1 (green – within tolerance, orange – within error tolerance 5 %, red – above tolerance)*

Measurement number	Speed robot [mms-1]	Measured force FT [N]	Pressure P [N/cm2]
1.	200	278	166
2.	250	326	195
3.	200	284	208
4.	200	283	>300 (foil must be used LW)
5.	150	204	277
Limits according to ISO/TS 15066:2016	**-**	**280**	**340**

In Fig. 6, you can see the graph from measurement 1, which corresponds to the limits according to ISO/TS 15066:2016, i.e. the measured value of 278 N is below the limit and is therefore OK. In measurement 2 at speeds of 250 mms-1, a value of 326 N was measured and is therefore above the recommended limit.

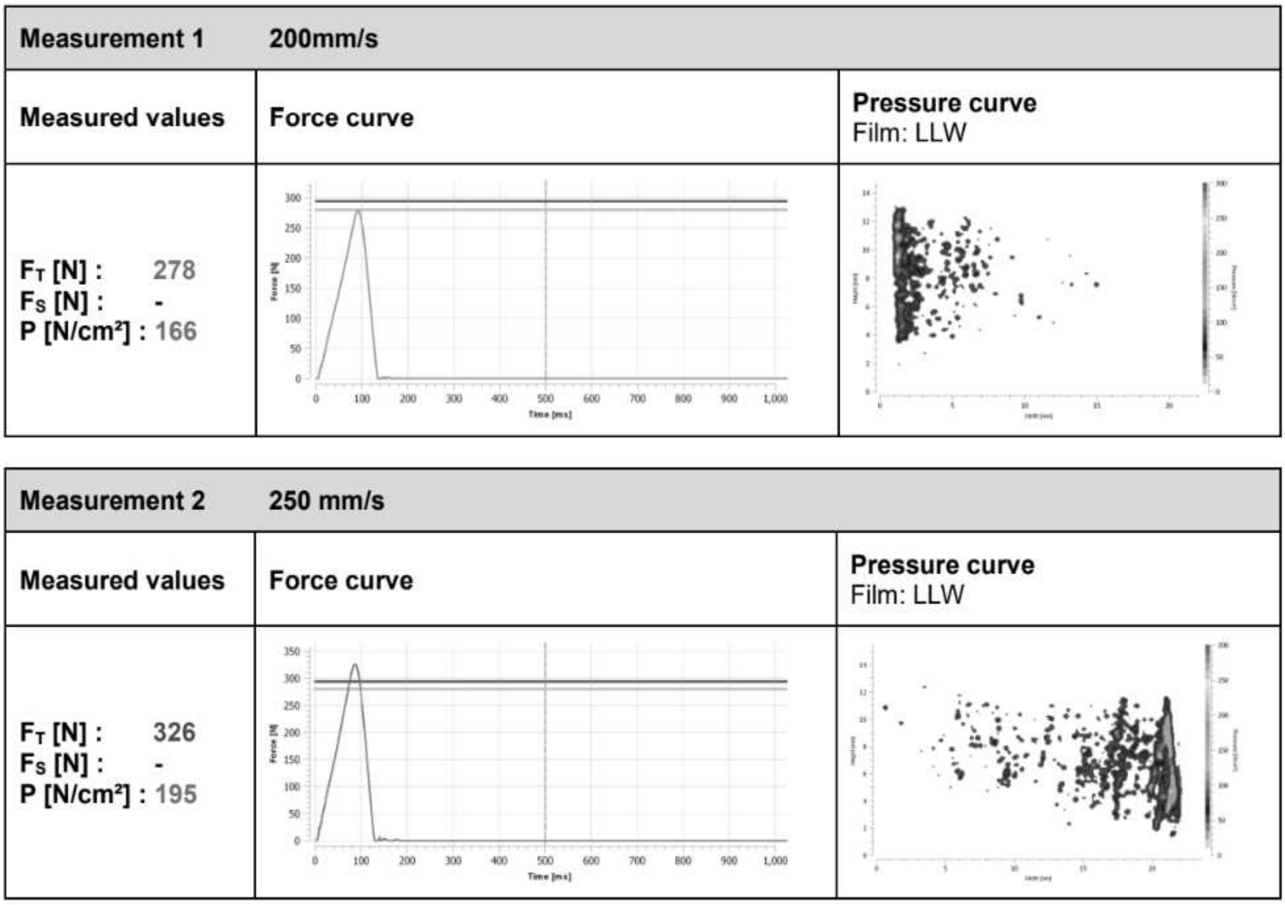


***Fig. 6** Selected graphs of measured forces and pressures for measurement no.1*

4.2 Measurement No. 2 – measurement at the place of the gripper

These are the same movements of the robot as in measurement No. 1. with the difference of the collision point. In this measurement, the fixture will be positioned to measure force and pressure values at the point of collision with the gripper. Here, the chest in the area of the pectoral muscle is evaluated as the collision area of the body, taking into account the possible place of impact of the upper arm with the maximum possible force of 300 N for transient contact. [7]

4.2.1 Measurement path

In Fig. 7 you can see the position from which the robot will start into the fixture. A black compression element has now been applied to the product to match the body and chest area.

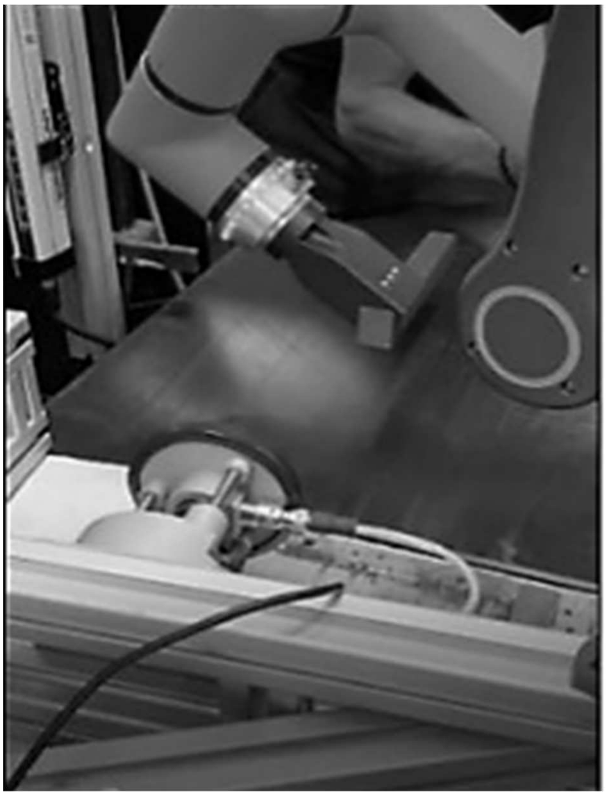


Fig. 7 *Start position*

In Fig. 8, the robot is caught in a position just before hitting the measuring fixture. The device was positioned so that the impact was performed by the robot tool, which is attached to the last joint of the robot.

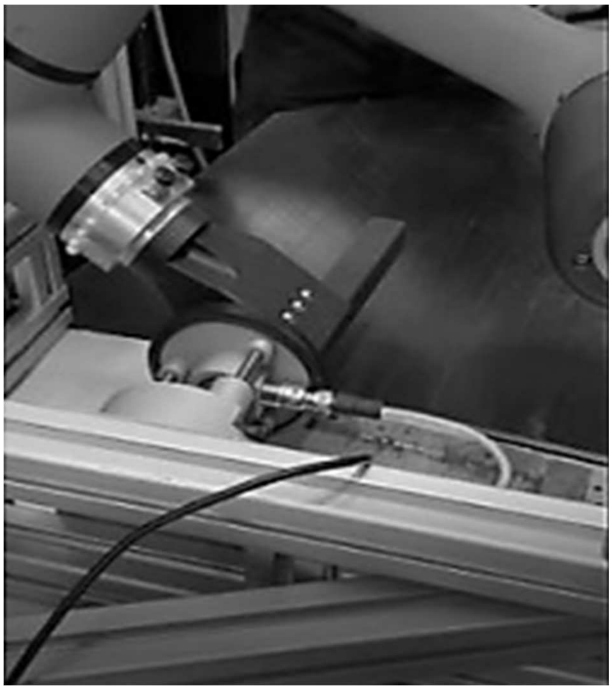


Fig. 8 *Measurement collision position*

In Fig. 9, the robot is caught just after hitting the measuring fixture. The end tool of the robot moved only minimally after hitting the preparation.

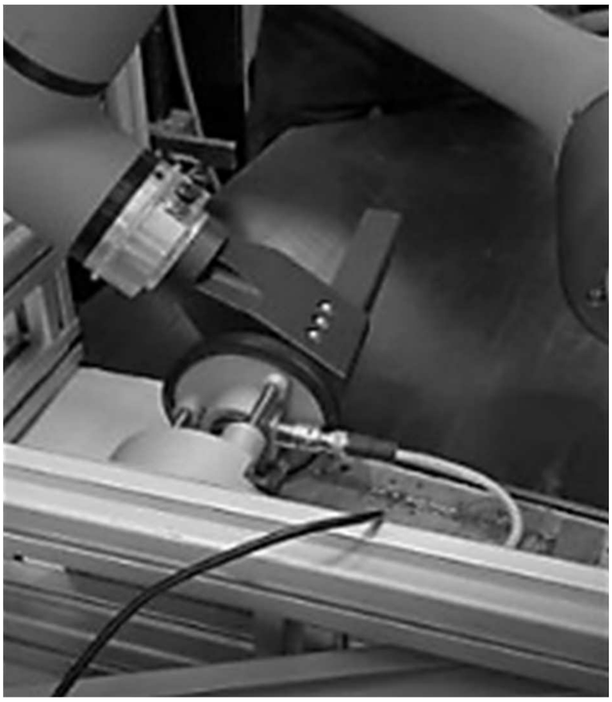


Fig. 9 *Measurement end point*

Tab. 3 *Measurement conditions No.2*

Contact type	Transient	**Spring [N/mm]**	**25**
Collision area of the body	Pectoral muscle (chest)	**Pad**	**black**
Max. permissible force [N]	280-300	**Humidity [%]**	**33**
Robot force limit [N]	100	**Temperature [°C]**	**25**
Pressure foil	LLW range 50-300 N/cm²	**Speed robot [mms-1]**	**200**

***Tab. 4** Measured values of measurement No.2 (green –in tolerance, red –above tolerances)*

Measurement number	Speed robot [mms-1]	Measured force FT [N]	Pressure P [N/cm2]
1.	200	205	253
2.	250	225	>300 (foil must be used LW)
3.	300	250	92
4.	350	264	370
5.	350	271	671
6.	400	282	1014
7.	350	268	844
Limits according to ISO/TS 15066:2016	-	280	340

In Fig. 10, the graph from measurements 4 and 5 can be observed, which correspond to the limits according to ISO/TS 15066:2016, i.e. the measured values of 264 N and 271 N are below the limit of the maximum permissible force and are therefore in order. However, the measured pressure values of 370 N/cm2 and 671 N/cm2 are above the limit in both cases and are inadmissible.

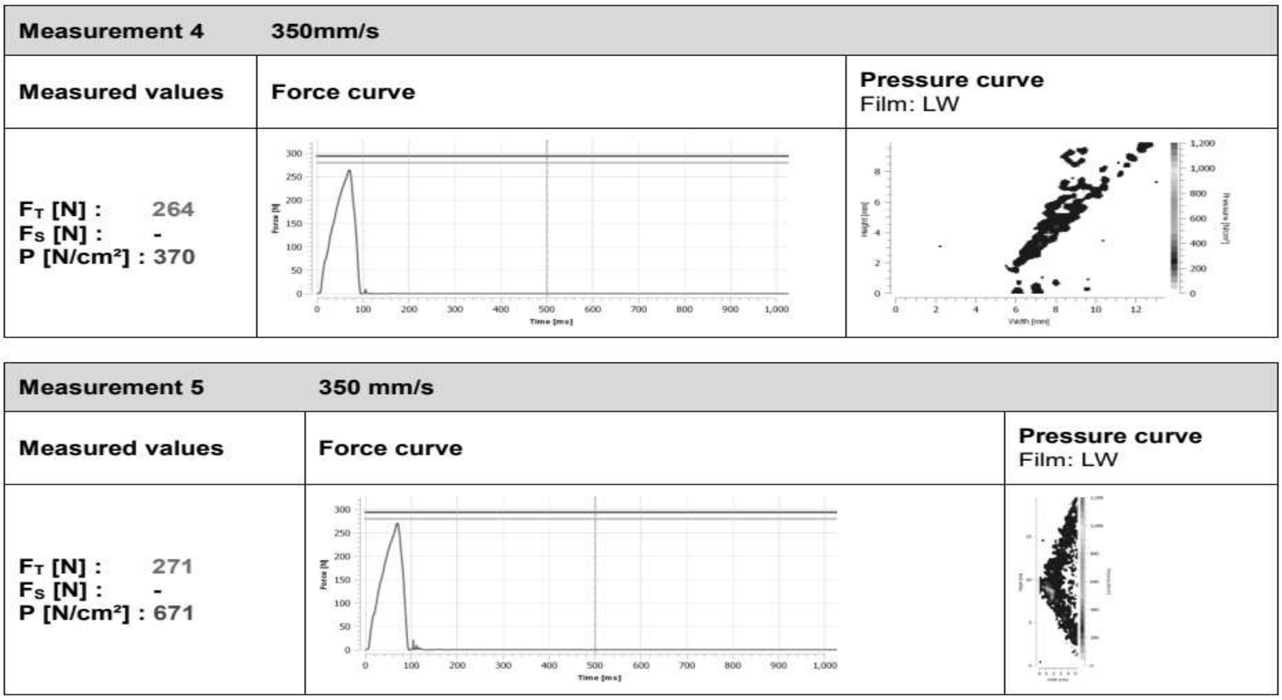


***Fig. 10** Selected graphs of measured forces and pressures for measurement No.2*

4.3 Measurement No. 3 – measurement in the 3rd joint of the robot

Measurements in phase 2 - which starts with pulling the mold from the heating furnace and continues to phase 3 movements in a linear motion. The collision area of the body that can be hit by the robot has been evaluated, the chest part in the pectoral muscle area and the upper arms part, which is more likely with a higher limit of 300 N, and therefore a 5% force tolerance is used. The robot's collision detection is set to the highest possible sensitivity of 100 N.

4.3.1 Measurement path

In Fig. 11 you can see the starting position of the robot, from which it will move towards the fixture. Now the product will be fixed in such a way that it hits the place where the lump is expected to appear.

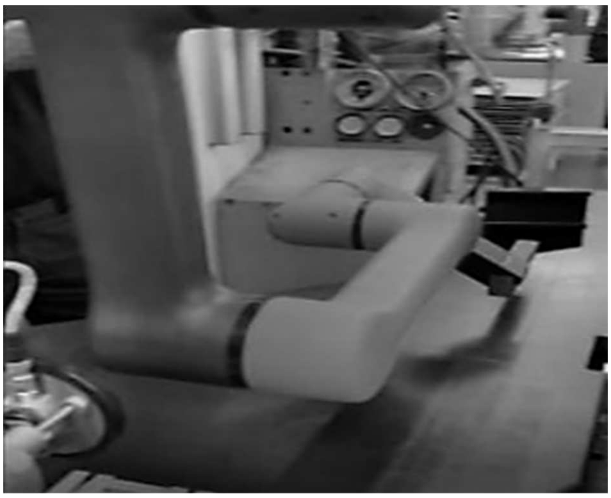


***Fig. 11** Start position*

In Fig. 12, the robot is caught in a position just before hitting the measuring fixture.

Fig. 12 *Collision position of measurement*

In Fig. 13, the robot is caught just after hitting the measuring fixture. The 3rd joint of the robot hit the fixture

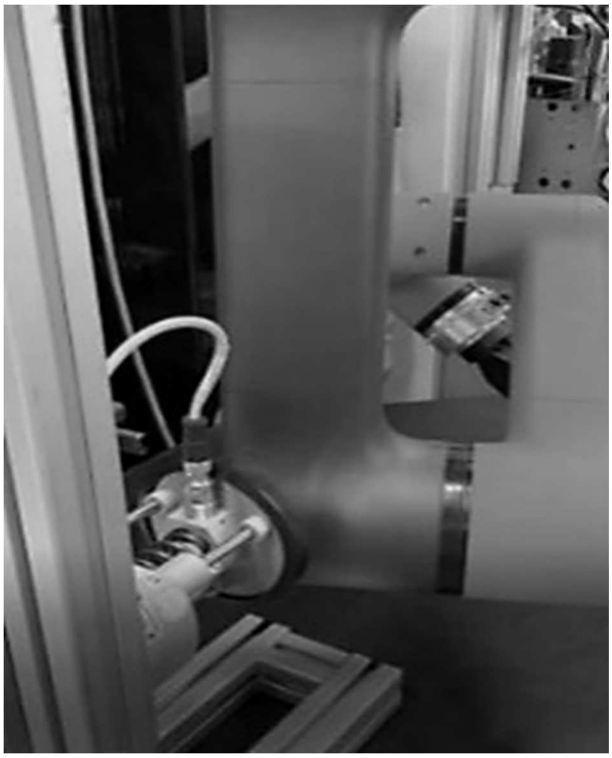


Fig. 13 *Measurement end point*

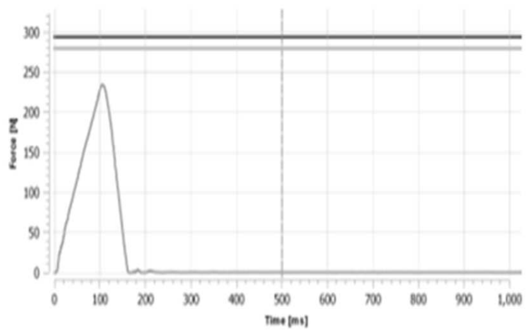
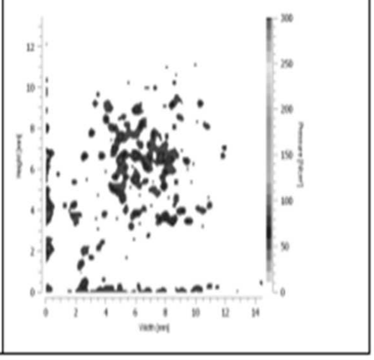
Tab. 5 *Measurement conditions No.3*

Contact type	Transient	Spring [N/mm]	25
Collision area of the body	Pectoral muscle (chest)	Pad	black
Max. permissible force [N]	280-300	Humidity [%]	33
Robot force limit [N]	100	Temperature [°C]	25
Pressure foil	LLW range 50-300 N/cm²	Speed robot [mms-1]	200

Tab. 6 *Measured values of measurement No.3 (green –in tolerance, orange –in error tolerance 5 %)*

Measurement number	Speed robot [mms-1]	Measured force FT [N]	Pressure P [N/cm2]
1.	400	234	100
2.	450	239	<50
3.	500	259	<50
4.	550	280	<50
Limits according to ISO/TS 15066:2016	-	280	340

In Fig. 14 you can see the graph from measurement 1 and measurement 2, phase 2. Measurement 1 corresponds to the force and pressure limits according to ISO/TS 15066:2016, i.e. the measured values of 234 N and 100 N/cm2 are below the limit of the maximum permissible force and pressure and are therefore OK. In measurement 3, the measured force and pressure were also consistent, however, the pressure was measured so low (less than 50 N/cm2) that the pressure foil could not record it, since its range is 50-300 N/cm².

Measurement 1	400 mm/s	
Measured values	**Force curve**	**Pressure curve** Film: LLW
F_T [N] : 234 F_S [N] : - P [N/cm²] : 100		

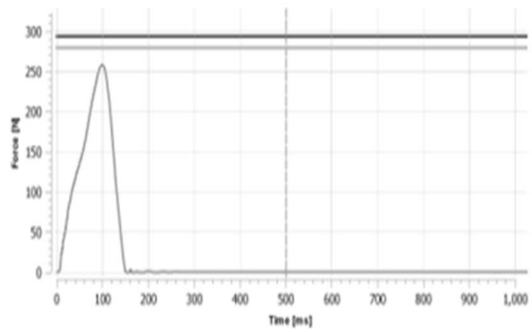
Measurement 3	500 mm/s	
Measured values	**Force curve**	**Pressure curve** Film: -
F_T [N] : 259 F_S [N] : - P [N/cm²] : <50		

Fig. 14 *Selected graphs of measured forces and pressures for measurement No.3*

4.4 Measurement No. 4 – measurement at the place of the gripper when returning the robot to the collection point

This is phase 5 - the return movement of the robot to the collection point. The gripper moves linearly parallel to the feeder. The measuring device is positioned so that the collision point is the gripper. Here too, the chest in the area of the pectoral muscle is evaluated as a collision area of the body, taking into account the possible place of impact of the upper arm with the maximum possible force of 300 N for transient contact. The robot's collision detection is set to the highest possible sensitivity of 100 N.

4.4.1 Measurement path

In Fig. 15 you can see the starting position of the robot, from which it will move towards the fixture. The yellow arrow indicates the path of the end tool of the robot into the measuring fixture.

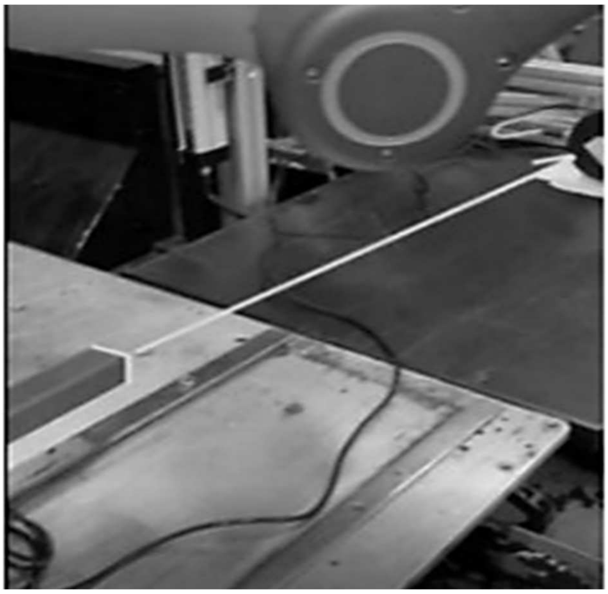


Fig. 15 *Start position*

In Fig. 16, the end tool of the robot can be observed impacting the measuring fixture.

Fig. 16 *Collision position of measurement*

In Fig. 17, the robot is caught just after hitting the measuring fixture with the end tool. Le observe a considerable rebound of the end tool from the measuring fixture.

Fig. 17 *Measurement end point*

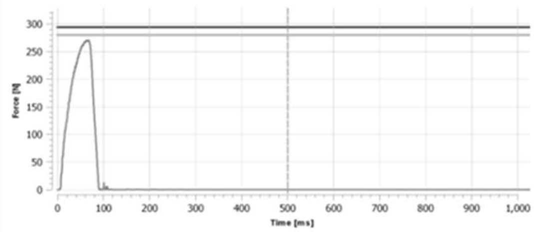
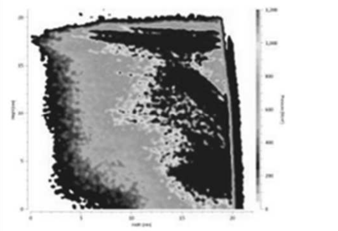
Tab. 7 *Measurement conditions No.4*

Contact type	Transient	**Spring [N/mm]**	25
Collision area of the body	Pectoral muscle (chest)	**Pad**	black
Max. permissible force [N]	280-300	**Humidity [%]**	33
Robot force limit [N]	100	**Temperature [°C]**	25
Pressure foil	LLW range 50-300 N/cm²	**Speed robot [mms-1]**	200

Tab. 8 *Measured values of measurement No.4 (green –in tolerance, red –above tolerances)*

Measurement number	Speed robot [mms-1]	Measured force FT [N]	Pressure P [N/cm2]
1.	1000	335	>1200
2.	800	325	754
3.	700	271	>1200
4.	750	303	>1200
5.	750	300	<250
Limits according to ISO/TS 15066:2016	**-**	**280**	**340**

In Fig. 18 can be clearly observed in both measurements of exceeding the permissible pressure. In measure-ment 4, we can also see an excess of the permissible force at measurement speeds of 750 mms-1.

Measurement 3	700 mm/s	
Measured values	Force curve	Pressure curve Film: LW
F_T [N] : 271 F_S [N] : - P [N/cm^2] : >1200		

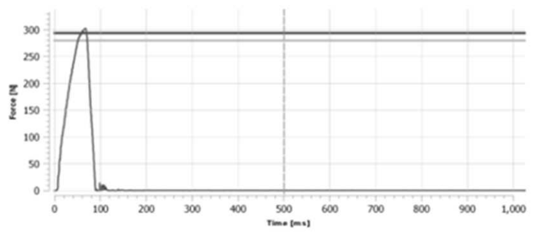
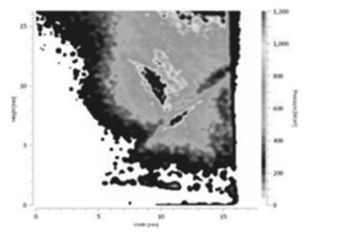
Measurement 4	750 mm/s	
Measured values	Force curve	Pressure curve Film: LW
F_T [N] : 303 F_S [N] : - P [N/cm^2] : >1200		

Fig. 18 *Selected graphs of measured forces and pressures for measurement no.4*

5 Discussion

When measuring the maximum permissible force of the collaborative robot, it was found that after optimizing (slowing down) the speed of the robot in various phases of the cycle, the maximum force values according to the ISO/TS 15066:2016 specification were observed. By evaluating the pressure, it was found that the limits are met where the robot collides with its own structure, i.e. with a surface that is adapted to this due to its large area and area. In contrast, where a 3D-printed gripper with a rectangular cross-section with rounded edges collided, the pressure significantly exceeded the permitted limits. Here, it is recommended to change the design of the gripper so that its edges are more rounded and do not cause such high values upon impact. The investigated values were measured using appropriate measuring devices and compared with the technical specification ISO/TS 15066:2016. The speed limits were obtained by optimizing the cycle of the robot by repeatedly measuring the transient forces during the impact, taking into account the required clock rate of 13s per cycle. The resulting cycle time after optimization was around 12.3s. Throughout the measurement, the robot was set to the most sensitive possible collision detection (Fmax = 100 N, lowest moment, collision detection enabled). In phase 1 position, when the robot descends to grasp the mold, only the reading of the pressure through the film was performed, because in this position it was not possible to place the gauge, and the force is analogous to movements with a speed of 250 mms-1.

In measurement No. 1, the collision target was in the 5th joint of the robot. The speed of the robot was adjusted from 500 mms-1 until it was reduced to an optimal 200 mms-1 at a force of 278 N. This force is acceptable. Unexpectedly worse sensitivity was observed for this joint of the robot. The pressure measurement showed that the large rounded areas of the robot body are within the limits of ISO/TS 15066:2016. LLW foil was used for the measurements. In experiment no. 4, it was necessary to use LW foil, which detects a larger pressure range. Measurement No. 2 was the collision target at the gripper location. The speed optimization was carried out from 400 mms-1 to 200 mms-1 as an acceptable speed, a speed of 350 mms-1 with a force of F=264 N was determined. The pressure measurement showed that even at this safe speed of 350 mms-1, the gripper edges generate too much pressure (more than 370 N/cm2) which is above the limits of ISO/TS 15066:2016. Based on these values, the design of the gripper must be modified in order to make the edges of the gripper more rounded. Measurement No. 3 aimed at a collision in the 3rd joint of the robot. Speed optimization from 5500 mms-1 to 400 mms^{-1}. Where the acceptable speed is 500 mms-1 with the measured force F= 259 N. In case of non-observance of the cycle time, the speed of the robot can be increased to 550 mms-1 as it is still within 5% tolerance. The pressure measurement showed that the large rounded areas of the robot body do not show high pressure values and are within the limits of ISO/TS 15066:2016. Measurement No. 4 took place at the place of the gripper when returning the robot to the sampling point. Speed optimization from 1000 mms-1 to 700 mms-1 where 700 mms-1 was determined as an acceptable speed with a measured force of F=271 N. Pressure measurements showed that the gripper edges generate too much pressure above the ISO/TS 15066:2016 limits and it is therefore necessary to modify its design so that the edges are more rounded.

6 Conclusion

The procedure for determining the degree of collaborativeness at learned speeds and movements of the robot was verified. The measured results are easily comparable with the technical specification ISO/TS 15066:2016 and subsequently easily evaluated. The measurement consists in verifying that the application does not exceed the permitted limits of force and pressure, which are given in ISO/TS 15066:2016 acting on the human body. The measurement points (positions) were determined before the measurement after consultation with experts. It can be stated that the verification by measuring the forces and pressures of the proposed workplace determined the maximum possible speeds for the individual phases of the robot's movement, which in the case of forces correspond to the maximum values in accordance with ISO/TS 15066:2016. The pressure values showed higher values during measurements No. 2 and No. 4 and therefore do not correspond to the recommended values of ISO/TS 15066:2016. It is recommended to redesign the gripper so that its edges are more rounded.

After the measurement has been carried out, it can be concluded that the measurement is visible in practice, but only on the condition that it is carried out by a person familiar with the given issue and capable of operating the measuring device. Setting up the device and fixing it in the right position is time-consuming. An important fact is that the measurement is performed only after the robot and all accessories have been deployed in the final application. At the moment when we evaluate the measured results as inadmissible for collaborative application, part or even the entire workplace must be reworked (structurally or use safety elements, e.g. safety scanner, safety light barriers or cage). All this will cause a large financial increase in the acquisition of the application. For these reasons, I recommend finding another way to verify the collaborative method, preferably before deploying it in a real application, e.g. using a software program.

Acknowledgement

The article was created with the contribution of Grant support of SGS 48206/15/2029/01.

References

[1] KLIMENDA, F., ŠTĚRBA, J., ČERNOHLÁVEK, V., PONIKELSKÝ, J., MAŘAN, P.: Draft of robotic workstation for laser engraving. In: *Manufacturing Technology*. Vol. 21, No. 3 (2021) pp 357-363. ISSN: 1213-2489. DOI: 10.21062/mft.2021.049

[2] ISO / TS 15066 Robots and robotic devices - Collaborative robots," International Organization for Standardization, Geneva, CH, Tech. Rep., 2016

[3] Secure Human-Robot Collaboration (HRC) (pilz.com)

[4] https://automa.cz/cz/casopis-clanky/bezpecnost-kolaborativnich-robotu-2017_08_0_11040/

[5] Hanwha Corporation/Machinery (hanwharobotics.com)

[6] ČSN EN ISO 10218-1. Roboty a robotická zařízení - Požadavky na bezpečnost průmyslových robotů: Část 1: Roboty. Praha: Český normalizační institut, 2011

[7] ČSN EN ISO 10218-2. Roboty a robotická zařízení - Požadavky na bezpečnost průmyslových robotů: Část 2: Systémy robotů a integrace. Praha: Český normalizační institut, 2011

[8] PONIKELSKY J, ZURAVSKY I, CERNOHLAVEK V, CAIS J, STERBA J.: Influence of production technology on selected polymer properties. *Manufacturing Technology*. 2021;21(4):520-530. DOI: 10.21062/mft.2021.051