IFA
Institut für Arbeitsschutz der
Deutschen Gesetzlichen Unfallversicherung

Application Guideline: Conversion Table for Biomechanical Limit Values

A practical risk assessment guide for workplaces with cobots.

Version V0.4 Beta (as of 11 November 2022) – Translation

1 Introduction

The DGUV has funded several research projects (FP317, FP411 and FP430) in which the IFA, together with other research institutions, has identified certain biomechanical limit values that can now be used in the assessment of mechanical hazards arising from so-called collaborative robots (cobots). Different body locations with different tissue constellations (skin, muscle, fat, bone) can tolerate characteristic deformations depending on the force and pressure, resulting in specific stiffnesses. In day-to-day practice, the impact of cobots must be measured with suitable measuring devices in order to ensure compliance with the limit values. Since the stiffnesses determined for different body regions sometimes differ from the spring rates used in measuring devices, the measured force must be converted in a way that matches the actual constellation. This is where the IFA's practical guideline comes in: The Conversion Table determines energetically optimised values that take account of the actual stiffnesses of the individual measuring devices, thus allowing a risk assessment of dynamic impact loads with only a few measurements.

The Conversion Table was commissioned by the Social Accident Insurance Institution for Wood and Metal (BGHM) as part of project IFA 5160. The conversion is based on the biomechanical corridors determined in the Final Report. Another element that is taken into account is the detection threshold of the cobot, as it allows the determination of the energy fraction that needs to be used for the conversion. In addition to smoothed peak pressure values, the table also provides a value for the surface pressing (average pressure). Stiffnesses are set as defaults in five clusters; however, the table also allows assessments involving fewer measuring devices, and it is therefore also possible to enter a known measuring device stiffness manually.

The Conversion Table provided here by the IFA significantly simplifies the risk assessment for a workplace involving collaborative robots. Below you will find an overview of how exactly the critical test points can be identified with the help of the Conversion Table.

2 Origin

The development of safe control systems and monitored sensors for so-called collaborative robots (cobots) has made it possible to expand the classic protective mechanisms and to allow direct collaboration between humans and robots. – However, what if humans and robots do collide? If this ever happens, it must be possible to guarantee that there is no real risk of injury. So, in addition to the technical challenges, it was necessary to develop a methodology for measuring the forces that occur and to explore the biomechanical limits that minimise the risk of injury in a way that is verifiable.

The Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA) has developed and tested a measuring methodology on behalf of the German Social Accident Insurance Institution for the Woodworking and Metalworking Industries (BGHM) [1].

Thanks to research funding from the German Social Accident Insurance (DGUV), it was possible to carry out two additional DGUV research projects: “Follow-up tests to the BGHM Study ‘Collaborative robots: determination of pain thresholds at the human-machine interface’” (FP 411) and “Human-robot collaboration – – supplementary suitability tests of recent results for incorporating them into white papers of the DGUV and standards” (FP 430).

Working in cooperation with the Fraunhofer Institute for Factory Operation and Automation (IFF), it was possible to determine dynamic force limits and pressure limits for both semi-sharp and blunt impacts [2].

The IFA project 5160 “Development and evaluation of a metrological concept for collaborative robots” aimed to incorporate the scientific findings into state-of-the-art technology and apply them in engineering practice. This required a further evaluation of the resulting data material, based on stiffness parameters. This task was carried out by IFA and IFF in their study “Determination of biomechanical corridors for the evaluation of mechanical hazards and derivation of stiffness parameters for future measuring equipment” (Final Report [3]).

In practice, suitable measuring equipment can now be used in addition to the actual limit values. For this purpose, the different body locations were divided into five clusters and an error margin was permitted up to 25%. Basically, a principle applies whereby the number of clusters (i.e. measuring device stiffnesses) that are involved is in inverse proportion to the potential number of errors. In day-to-day practice, however, there are only a small number of measuring devices with different stiffnesses.

In order to meet the two requirements of accuracy and pragmatism in an actual risk assessment, the IFA Conversion Table provides an analytical approach that makes it easier and faster to assess risks in practice.

3 Purpose

In order to limit the residual risks of collaborating robots (which are safeguarded with the safety function of power and force limitation) to an acceptable level, limits for dynamic impact loads were researched. Force-deformation curves were identified for 24 different body locations allowing the determination of maximum values of the impact forces and stiffnesses. These can be used for a metrological check.

The Conversion Table presented here optimises the limit values for the measuring devices that are in use, so that an assessment can be delivered both quickly and effectively.

4 Start

The table can be implemented as a simple Excel spreadsheet in .xlsx format and uses standard functions only. Prior to implementation, an online check is required whether the available version is the latest and the table has not been recalled.

5 Table structure

5.1 Overview

The spreadsheet comprises two worksheets: Sheet 1 is the actual conversion table, and Sheet 2 contains explanatory notes. The conversion table (Figure 1) consists of the following sections: The header (rows 1 to 6) contains general details, i.e. the table version, a user input section, the names of the columns and the legend. Underneath, from left to right, there is a list of the different locations parts, followed by basic data taken from the biomechanical corridors, and finally the results area with the calculated optimised values.

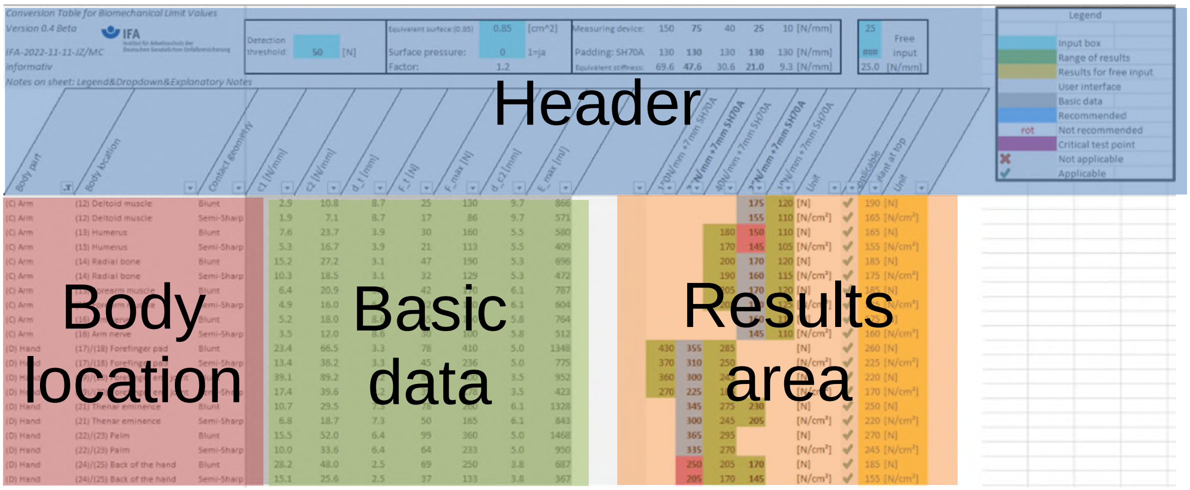

Figure 1: The labelled screenshot shows the different areas of the conversion table

5.2 Legend

The meanings of the fields, abbreviations and colours can be gathered from table 1.

Table 1: Conversion table legend and meaning

Legend	
	Input box
	Results area
	Results for free input
	User interface
	Basic data
	Recommended action
Red	Not recommended
	Critical test point
✖ 0	Not applicable
✔ 1	Applicable
SH70A	Shore A hardness 70 (7 mm)
c1 [N/mm]	Gradient up to transition point
c2 [N/mm]	Gradient from transition point
d_t [mm]	Deformation at transition point
F_t [N]	Force at transition point
F_max [N]	Maximum force
d_c2 [mm]	Maximum deformation
E_max [mJ]	Total energy

5.3 Input

It is possible to make slight modifications and settings in the input area (Figure 2).

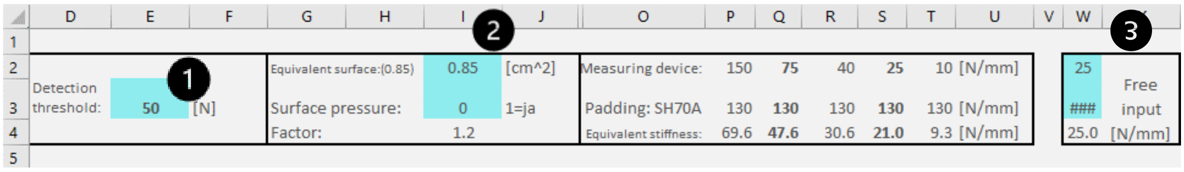

Figure 2: Input area with input fields highlighted in light blue

1. Enter here the detection threshold (cell E3), used to control the application. The drop-down menu allows the selection of the values 0, 25, 50, 75 or 100 N, with 50 N as the default.

2. To calculate peak pressure, an equivalent surface (cell I2) of the contact body used in the studies is used. The default 0.85 cm^2 has been derived from the study data of the research projects and must not be changed without technical expertise. There is also the option of using surface pressing (cell I3): If this value is set to 1, an average pressure value is output instead of a peak pressure value.

3. In addition to the five default measuring devices (columns P to T) with stiffnesses of 150 N/mm, 75 N/mm, 40 N/mm, 25 N/mm and 10 N/mm and with 7-mm padding (shore A hardness 70), any measuring device stiffness can be selected in the free input box (cell W2). Stiffnesses are provided for common devices available in the market. If no padding is used on the measuring device, the value in cell W3 should be `9999999(###)`, and we recommend using `130 N/mm` for the 7-mm padding (shore A hardness 70).

5.4 Body locations

The affected body locations must be selected via the dropdown menu in row 6. The default settings are the body regions “Upper extremities” and “Hands & fingers”. Under contact geometry, a distinction is made between blunt and semi-sharp geometry. For blunt geometries the result is specified in Newton [N], while for edge geometries it is shown as a pressure value in N/cm².

5.5 Basic data

In the table, columns D to J contain basic data from the study on the determination of biomechanical corridors, presented in the Final Report. This data is required for calculation and conversion [3]. This basic data is provided for information only. A brief description of the basic calculation procedure is provided below, under “Background information”.

5.6 Results area

For the five default stiffnesses, the results area shows force and pressure values. These are available for risk assessment purposes. This is where different body locations can be compared, and it can be determined which value is the most critical. The critical test point should always be the measuring device constellation that shows the lowest values within the relevant region of the body. For the areas on and around the hand and arm, the two critical test points are highlighted in purple. To look at other body regions, the most critical points manually need to be identified manually. If the stiffness of the measuring device is clearly outside the expected range, only white cells are visible. In addition, the results calculated for stiffness from the free import are shown in the area highlighted in yellow. Column V also includes a check whether the calculated value is applicable (green checkmark) or whether there were calculation problems so that it is not applicable (red cross). Errors may occur if detection thresholds are set at a high level. The results are rounded to 5 N and 5 N/cm², as applicable.

6 Application example

An integrator has defined certain work areas and activities for a risk assessment. It was found that, if a collaborative robot is used at a workplace, hazards may occur on and around a person's hands and arms. The integrator therefore set a reduced speed for the robot and set its detection threshold to 50 N in the safety settings. Two measuring devices are to be used now with a view to determining any residual hazards that may still exist. One of the measuring devices has a stiffness of 75 N/mm, and the other 25 N/mm. Each has a 7-mm pad with shore A hardness 70. After measuring, the integrator can check the limit values with the help of the conversion table and can thus assess the hazards.

Using the Conversion Table (Figure 3), the integrator goes through the body locations on and around the hands and arms and identifies the two critical test points. On and around the hand, values are lowest for the back of the hand, thus defining the critical threshold: here, 250 N and 205 N/cm² must not be exceeded when using the 75 N/mm measuring device. On and around the arm, the integrator determines that, with the 25 N/mm measuring device, the limit values that must not be exceeded are 150 N and 145 N/cm².

It is now possible to carry out the measurements and check whether the limit values are met. If the measurements show that the values are not met, further protective measures must be specified and implemented. For example, the monitored speed can be further reduced and the measurement repeated until it can be demonstrated that all values are complied with. The results of the measurement and the relevant safely reduced speed must be documented in the risk assessment, and information must be given to machine operators, users and any other staff handling the machine.

Please note: A reference guide for carrying out measurements can be found, for example, in the "Measurement specification for force and pressure measurements on applications of collaborative robot systems" [4].

Body region	Body location	Contact geometry	[illegible]N/mm +7mm SH70A	[illegible]N/mm +7mm SH70A	40N/mm +7mm SH70A	[illegible]N/mm +7mm SH70A	[illegible]N/mm +7mm SH70A	Unit	
(C) Arm	(12) Deltoid muscle	Blunt				175	120	[N]	✓
(C) Arm	(12) Deltoid muscle	Semi-Sharp				155	110	[N/cm²]	✓
(C) Arm	(13) Humerus	Blunt			180	150	110	[N]	✓
(C) Arm	(13) Humerus	Semi-Sharp			170	145	105	[N/cm²]	✓
(C) Arm	(14) Radial bone	Blunt			200	170	120	[N]	✓
(C) Arm	(14) Radial bone	Semi-Sharp			190	160	115	[N/cm²]	✓
(C) Arm	(15) Forearm muscle	Blunt			205	170	120	[N]	✓
(C) Arm	(15) Forearm muscle	Semi-Sharp			205	170	125	[N/cm²]	✓
(C) Arm	(16) Arm nerve	Blunt				160	115	[N]	✓
(C) Arm	(16) Arm nerve	Semi-Sharp				145	110	[N/cm²]	✓
(D) Hand	(17)/(18) Forefinger pad	Blunt	430	355	285			[N]	✓
(D) Hand	(17)/(18) Forefinger pad	Semi-Sharp	370	310	250			[N/cm²]	✓
(D) Hand	(19)/(20) Forefinger end joint	Blunt	360	300	245			[N]	✓
(D) Hand	(19)/(20) Forefinger end joint	Semi-Sharp	270	225	185			[N/cm²]	✓
(D) Hand	(21) Thenar eminence	Blunt		345	275	230		[N]	✓
(D) Hand	(21) Thenar eminence	Semi-Sharp		300	245	205		[N/cm²]	✓
(D) Hand	(22)/(23) Palm	Blunt		365	295			[N]	✓
(D) Hand	(22)/(23) Palm	Semi-Sharp		335	270			[N/cm²]	✓
(D) Hand	(24)/(25) Back of the hand	Blunt		250	205	170		[N]	✓
(D) Hand	(24)/(25) Back of the hand	Semi-Sharp		205	170	145		[N/cm²]	✓

Figure 3: Conversion table with critical test points (highlighted purple) on and around the hands and arms.

7 Limitations

Important: The Conversion Table only provides an idealised reference value. Any possible further biomechanical factors have been disregarded in this version, as it can be expected that potential differences for closely spaced stiffnesses are in the same order of magnitude as the rounding that is carried out.

For the five default measuring devices, the equivalent stiffness was determined from a series connection of the spring stiffness and the padding (~130 N/mm). This calculation appears to be sufficiently conservative and can be optimised with more exact data, if necessary.

The conversion table ignores the control characteristics of the technical system, which is why the systems should be tested with several stiffnesses, as described in the application example.

Please note: If the safety parameters on the applications are set incorrectly, the target value cannot be achieved. Previous studies have shown that many applications with incorrectly set safety parameters unnecessarily exceed the limits and thus present avoidable hazards.

To ensure sufficiently safe application, we recommend carrying out at least two measurements – one with a hard and one with a soft configuration of measuring devices.

8 Background information

8.1 Principle of energy conversion

Based on the characteristic curves f(x) of the biomechanical corridors (see [3]), we calculate the permitted energy E by integrating the detection threshold F_D and the maximum F_{max}. Taking account of the actual characteristic curve k of the measuring device, we calculate an optimised equivalent value F_{NEW}, so that the measuring device absorbs the same energy after reaching the detection threshold. The formula shows the underlying mathematical equation that is solved in the Conversion Table.

$$E = \int_{x(F_D)}^{x(F_{Max})} f(x)\, dx$$

$$= 0.5 * \Delta x^2 * k + \Delta x * F_D$$

$$with\ \Delta x = (F_{Neu} - F_D)/k$$

The equivalent value can be used for a simplified practical check if the stiffness of the measuring device and the biomechanical corridor are close to each other. (Please note: Conversions to very different stiffnesses are technically possible, but biomechanically not always helpful. Experience gathered so far shows that measurements with *lower* stiffnesses potentially lead to more reliable results, as the effective masses that occur in many systems actually increase under softer constellations.)

8.2 Determining peak pressure and surface pressing:

The procedure for pressure is the same, although there is an additional factor that must be considered. It is calculated from the equivalent surface of the test specimen (F-Q10) used in the research project (average equivalent surface F-Q10=~0.85 cm²). This analytical method eliminates potential outliers in the original data, resulting in a smoothing of the peak pressure values and better comparability.

In addition, it is possible to use the “surface pressing” option, which distributes the force evenly over the total surface (experimentally determined total surface F-Q10=~1.2 cm²). (The equivalent surfaces used here may depend on filter and resolution properties of the measuring technique that is used).

9 Portability

The assessment presented here with the example of collaborative robots can in principle also be applied to mechanical hazards in general. IFA’s technical experts would be happy to provide help and advice in deciding what kind of adjustments may be necessary.

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10 Contact

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11 References

[1] Huelke, M. and Ottersbach, H.-J.: How to Approve Collaborating Robots: The IFA Force Pressure Measurement System, in: Proceedings of the 7th International Conference on the Safety of Industrial Automated Systems, vol. 7th International Conference on the Safety of Industrial Automated Systems (SIAS), Montreal, Canada, October 11-12, 2012. Institut de Recherche Robert-Sauvé en Santé et en Sécurité du Travail (IRSST).

[2] Behrens, R., Pliske, G., Umbreit, M., Piatek, S., Walcher, F. and Elkmann, N.: A Statistical Model to Determine Biomechanical Limits for Physically Safe Interactions With Collaborative Robots: Front. Robot. AI (2022), doi: 10.3389/frobt.2021.667818

[3] Behrens, R. and Zimmermann, J.: “Determination of biomechanical corridors for the evaluation of mechanical hazards and derivation of stiffness parameters for future measuring devices”, Final Report, 2022

[4] BG ETEM: “Messspezifikation für Kraft- und Druckmessungen an Applikationen von kollaborierenden Robotersystemen” (Measurement specification for force and pressure measurements on applications of collaborative robot systems) MS-ET-01, 2018 (only in German)

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