



A New Conversion Method to Evaluate the Hazard Potential of Collaborative Robots in Free Collisions

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Abstract. With the increasing importance of collaborative robots in industrial manufacturing, their economic efficiency is becoming more and more important. Today, one approach to prevent collaborative robots from injuring humans is to assure that the robot cannot exceed biomechanical limits in the event of an accidental collision or clamping. The ability of the robot to avoid collision forces beyond the limits must be validated with a biofidelic measurement device that mimics the biomechanical behavior of the human. For reliable use, the measurement devices must be attached to a rigid frame. Consequently, the test setup is solely able to simulate the contact dynamics and biomechanical consequences of a clamping contact in which the human body part cannot move. Free collisions that allow the human to move freely reduce the collision forces, but can only be evaluated with such a measurement device. This technical limitation leads to slower robots and thus a loss of productivity. The study presents a method that increases the efficiency of safe collaborative robots by adding a new validation procedure. The presented method incorporates a model-based conversion of measurements that enables safety experts to validate robots in free collisions. Data from experimental tests with a collaborative robot and a biofidelic measurement device show a good fit of the model-based prediction and thus confirm our approach. This new approach has great potential to increase the productivity of collaborative robots, since our method will allow them to move at faster but still safe speeds.

1 Introduction

In the closest form of human-robot interaction, robots and humans complete common tasks next to each other at the same time [3]. At such workplaces, accidental contacts such as clamping or unconstrained collisions constitute a

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risk of human injury that technical measures cannot eliminate entirely, since there is always the possibility of a technical failure or foreseeable misuse. As a metric and reference for acceptable risks, ISO/TS 15066 defines biomechanical force and pressure limits for multiple body parts. The technical risk mitigation measures of the robot must reliably prevent these limits from being exceeded [7].

During the validation measurement, the velocity of the robot must be reduced until the measured contact forces and pressures do not exceed the applicable limit values [12]. The proper use of the PFMD requires mounting it on a rigid structure that avoids any undesired displacements of the PFMD. This requirement, however, does not reflect the conditions of an unconstrained contact in which the human body part hit by the robot can move freely.

Falco et al. and Oberer-Treitz presented moveable PFMDs that are capable of simulating the dynamics of free collisions [5,10]. They attached a PFMD to a linear guide rail and adhered additional weight, so that the total mass of the movable parts reflect exactly the mass of the human body part under test. The US American de-facto standard RIA T R15.806-2018 incorporated the concept of a free-moving PFMD and specifies that it should be used to evaluate free collisions instead of a fixed PFMD. However, a movable PFMD has the major limitation that it can only measure collisions within the horizontal plane.

This article presents a method that allows to convert the results recorded with a fixed PFMD into values that reflect the results taken with a free-moving PFMD. Validation experiments with three collaborative robots (UR3e, UR10e, Doosan M0607) and two different PFMDs confirm that our conversion method provides correct and sufficiently accurate results.

2 Technical Approach

The development of the proposed conversion method can be demonstrated by the analysis of an accurate and simplified impact model. The accurate model in Fig. 1 (top) reproduces the impact behavior of a compliant robot that collides with a biofidelic PFMD. The collaborative robot is modeled as a two mass oscillator [4,6]. The first mass represents the contribution of the robot's drive inertia m_D and the second the mass of its links m_L , while c_T describes the joints elasticity. The other part of the model covers the PFMD. The parameters c_D and d_D represent the damping behavior and elasticity of the damping material of the PFMD. The damper is attached to a bumper of mass m_B . A mechanical spring of stiffness c_S absorbs the impact energy from the bumper and transmits the generated force to a load cell that records the impact force $F_I(t)$. To simulate a properly fixed PFMD the housing is considered to be immovable. To simulate an unconstrained collision the load cell is attached to a body of mass m_M with static friction F_R .

To convert the maximum contact force $\hat{F}_C$ from a fixed PFMD into the maximum contact force $\hat{F}_F$ of a movable PFMD, the complexity of the simulation model must be reduced. This ultimately leads to the model shown in Fig. 1 (bottom). This model assumes that m_D , m_L , and c_T are included in an apparent robot mass m_R^* . Due to its simplified structure, the comparison of the energies

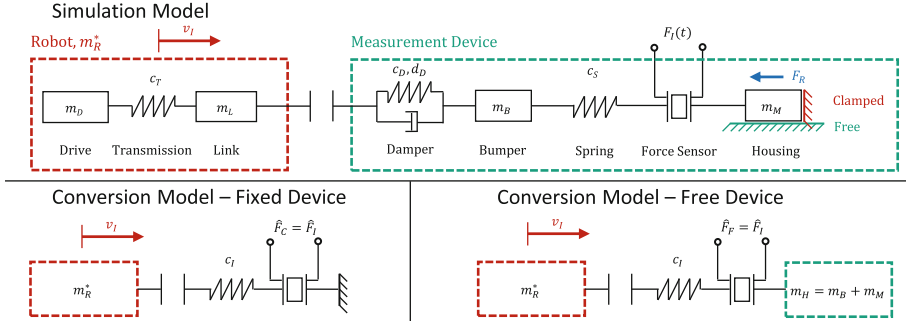


Fig. 1. Simulation and conversion model of a fixed and free measurement device

stored in elasticities and masses of both devices (fixed and free) lead to the following conversion

$$\hat{F}_F = \hat{F}_C \sqrt{\frac{m_H}{m_H + m_R^*}}. \quad (1)$$

The expression reflects the relative difference between the maximum force of a free $\hat{F}_F$ and a clamped collision $\hat{F}_C$. In contrast to m_H , the apparent robot mass m_R^* is unknown, but can be estimated with the momentum of the impact

$$p = m_R^* v_I = \int_{t_0}^{t_{max}} F_C(t) dt, \quad (2)$$

where v_I is the impact velocity, t_0 the time of initial contact and t_{max} the time at which the clamped measured impact force $F_C(t)$ reaches $\hat{F}_C$.

3 Model-Based Results

A simulation with the accurate model (Fig. 1, on the top) was performed to study the conversion method. Therefore, the applied model parameters were precisely adjusted to the robot and PFMD, that we later used in the experimental tests for model validation. The robot masses m_L and m_D have been calculated with the method presented by Khatib [8,9]. This method projects the mass matrix of the robot manipulator $\mathbf{M}^+$ (incl. the contribution of drives and links) to a directional point mass m_R that equals the sum of m_L and m_D

$$m_R = m_L + m_D. \quad (3)$$

In this context, m_L denotes the directional point mass that can be calculated with the mass matrix $\mathbf{M}$, which does not contain contributions from the joint inertias. Then, m_D can easily be calculated by subtracting m_L from m_R . The robot's effective stiffness c_T was obtained in a similar way, but based on the stiffness matrix $\mathbf{K}_q$ instead of the $\mathbf{M}$ [2,11]. The compliant configuration of the PFMD used for the simulation corresponded to the Back of the Hand (ID 25 in

ISO/TS 15066). A spring of 75 N mm^{-1} combined with a damping material of shore hardness 70 (SH70) simulates the biomechanical characteristics of this specific body part [12]. Both stiffness parameters, c_D for the damping material and c_S for the spring, were previously measured with a testing system and the same impactors that were used in the experiments. The damping parameter d_D was estimated in impact experiments at various collision speeds. Also, the friction F_R of the free PFMD was determined by measurements. Figure 2 shows the impact force over impact velocity obtained from the simulation with a PFMD for fixed and free conditions. The solid line in yellow indicates the results for the fixed PFMD. The results for the free PFMD (solid lines with red diamonds and blue boxes for 6 kg and 22 kg) clearly show that the impact force decreases in case m_H can move freely. The dashed lines in red and blue are the results obtained with the conversion method according to Eq. (1). For both masses ($m_H = 6 \text{ kg}$ and 22 kg) the curves confirm a good match with the simulation. The intersection points of all lines with the black horizontal line indicate the maximum allowable robot velocity when assuming a force limit of 280 N (here: Back of the Hand). For the given scenario, the maximum allowable robot velocity for the fixed PFMD is 271 mm s^{-1} . In contrast, the simulation of a free collision with a body part of 22 kg (which is far beyond the expected weight of an outreached hand) enables an increase of the safe velocity by 62 %. For the same configuration, the conversion method estimates an increase of 60 %. The considerable low difference between both results demonstrates that the proposed conversion method obtains sufficiently accurate results.

4 Experiments

As the analysis of the simulation data has shown, the mass of the free moving Pressure and Force Measurement Device (PFMD) significantly affects the maximum impact force. Therefore, it was necessary to gather results from collision experiments with a freely moving PFMD of different total masses. Figure 3 shows the test setup that was developed for the experiment. It is based on the concept of a freely movable PFMD as illustrated in RIA T R15.806-2018.

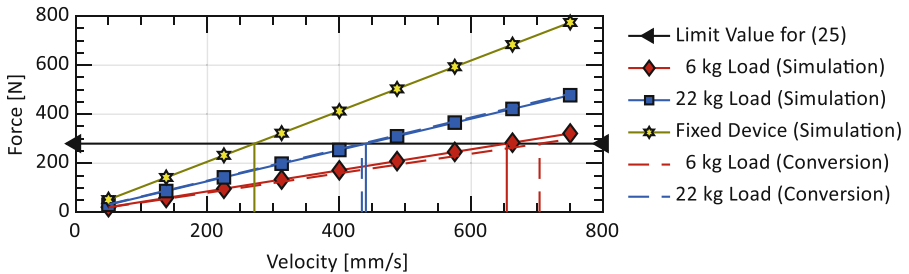


Fig. 2. Result of the simulated impact force compared to the predicted force of the conversion method for an UR10e robot with a payload of 66 %

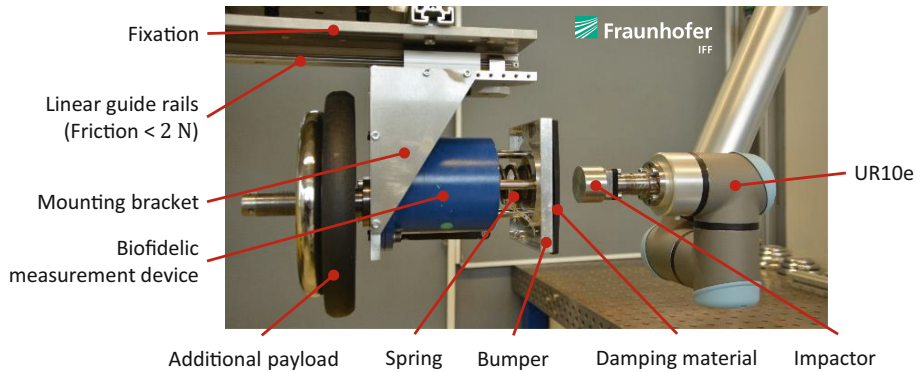


Fig. 3. Experimental test-setup to measure the impact force of a collaborative robot with a movable biofidelic measurement device

The PFMD was positioned on a movable carrier that was placed on low-friction linear guides with a static friction force of approximately 2 N. Tests with the simulation model revealed that a friction force within this range has a negligible influence on the measurement result. A large industrial robot was used to hold the assembly consisting of guides and the PFMD. Additional weights were mounted on the moveable PFMD to represent different body masses. For the measurement of the impact force, two different PFMDs with a similar design were used as listed in Table 1. The collisions were executed by three collaborative robots (UR3e, UR10e, Doosan M0607) that were equipped with a cylindrical impactor of 50 mm in diameter as a tool simulant. The robots were tested in the joint configuration listed in Table 2. In the test with free collisions, the total mass of the freely moving PFMD ranged from 4 to 22 kg (see Table 3.). For the tests with a fixed PFMD the movable carrier and the system's ground plate were connected. For a precise validation of the conversion method, the experiments aimed to obtain accurate results for any given combination of damping material and spring. Therefore, every test was performed with combinations that correspond to three different body parts, namely the Abdomen (10), the Sternum (8) and the Back of the Hand (25) (IDs according to ISO/TS 15066). Furthermore, three different payloads were tested with the UR10e in order to exclude possible negative influences of the robot's payload on the accuracy of the conversion method.

During the experiments the collaborative robot executes a linear movement at different velocities (starting from 50 and increasing to 650 mm s^{-1}) perpendicular towards the PFMD. The robot's starting position was chosen so that the desired velocity was ensured to be reached before colliding with the PFMD. The safety

Table 1. Characteristics of the biofidelic PFMDs used for the experimental validation

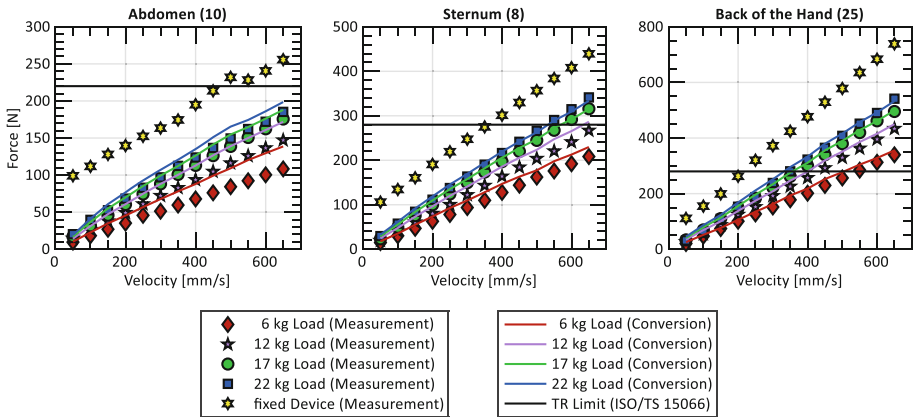
Name	Manufacturer	Force range [N]	Sampling frequency [kHz]
PRMS	PILZ	0 ... 500	2
KOLROBOT	IFA	0 ... 1000	10

Table 2. Joint configurations of the robots at the impact position

Robot	q_1 [deg]	q_2 [deg]	q_3 [deg]	q_4 [deg]	q_5 [deg]	q_6 [deg]
UR3e	0	-120	-126	247	-90	0
UR10e	0	-120	-126	67	90	0
Doosan M0607	0	-45	-90	0	45	0

Table 3. Test configurations of the different robots

	UR3e	UR10e	Doosan M0607
Payload robot [kg]	2.1	3.6; 6.9; 10.2	0.6
Payload robot [%]	70	36; 69; 102	10
Force threshold for safety stop [N]	50	100	50
Impact velocity [mm s ⁻¹]	50 ... 450	50 ... 650	50 ... 650
Velocity steps	9	13	13
Repetitions per velocity step	1	5 at Payload 6.9 kg	1
PFMD	KOLROBOT	KOLROBOT, PRMS	KOLROBOT
Mass of free PFMD [kg]	KOLROBOT: 6; 12; 17; 22 PRMS: 4; 10; 15; 20		
Biofidelic configuration	Abdomen (10): Spring: 10 N mm ⁻¹ ; Damper: SH10		
	Sternum (8): Spring: 25 N mm ⁻¹ ; Damper: SH70		
	Back of the Hand (25): Spr.: 75 N mm ⁻¹ ; Damp.: SH70		

**Fig. 4.** Comparison of maximum forces from tests with a fixed and moveable PFMD with those obtained with the conversion method (UR10e with Payload 6.9 kg, Measurement Device: KOLROBOT)

functions of the robot monitored the external forces acting on the robot. They triggered an emergency stop, if the magnitude of these forces exceeded the configured threshold (see Table 3).

5 Experimental Results

The analysis of the experimental results compares the maximum impact forces of the moveable PFMD with those that were obtained with the conversion method. For the conversion method, the impact force recorded by the fixed PFMD was used. Figure 4 shows one sample of the obtained experimental results. Each of the three diagrams illustrates the results measured with different configurations of the examined PFMD. The markers indicate mean values of the measurement results from tests with the fixed and moveable PFMD. The corresponding mean standard deviation over all measurements shown in Fig. 4 was $\pm 3.4\text{ N}$ for the fixed and $\pm 2.8\text{ N}$ for the moveable measurement device. The solid lines represent the results obtained with the conversion method. The results confirm a linear relationship between the impact force and the impact velocity. Moreover, the results demonstrate that the impact forces of a moveable PFMD are significantly lower than those of a fixed PFMD. This effect is enhanced by decreasing the total mass of the human body m_H . Furthermore, the forces obtained with the conversion method are slightly higher than those measured with the movable PFMD. In conclusion, the conversion method achieves almost the same accuracy in the results from experimental tests as from simulations.

6 Discussion

A sensitivity analysis regarding the input parameters of the conversion method is performed to study the influences of uncertainties on the overall accuracy. Of particular interest is the following part of Eq. (1)

$$c = \sqrt{\frac{m_H}{m_H + m_R^*}}. \quad (4)$$

that calculates a factor ≤ 1 to convert $\hat{F}_C$ into $\hat{F}_F$. To determine the sensitivity with respect to the input parameters the partial derivatives for m_H and m_R^* must be calculated

$$\begin{aligned} \frac{\partial c}{\partial m_H} &= \frac{m_R^*}{2(m_H + m_R^*)^2 \sqrt{\frac{m_H}{m_H + m_R^*}}} \\ \frac{\partial c}{\partial m_R^*} &= -\frac{m_H}{2(m_H + m_R^*)^2 \sqrt{\frac{m_H}{m_H + m_R^*}}}. \end{aligned} \quad (5)$$

The summation of the partial derivatives gives the total error

$$\Delta c = \frac{\partial c}{\partial m_H} \Delta m_H + \frac{\partial c}{\partial m_R^*} \Delta m_R^*. \quad (6)$$

Figure 5 shows the courses of sensitivity for each parameter. It indicates that the collision masses m_H and m_R^* have a non-linear effect on the conversion result. The absolute magnitude of the sensitivity for m_H and m_R^* decreases with increasing mass. However, the sensitivity of m_R^* with respect to c is negative denoting that an

underestimation of m_R^* will result in a higher scaling factor or higher impact force ($\Delta m_R^* < 0$ leads to $\Delta c > 0$ and then to $\Delta \hat{F}_F > 0$). Since m_H is assumed to be given, the estimation of m_R^* must be analyzed in more depth. The partial derivatives of Eq. (2) with respect to the input parameters momentum p and impact velocity v are

$$\begin{aligned}\frac{\partial m_R^*}{\partial v} &= -\frac{p}{v^2} \\ \frac{\partial m_R^*}{\partial p} &= \frac{1}{v},\end{aligned}\quad (7)$$

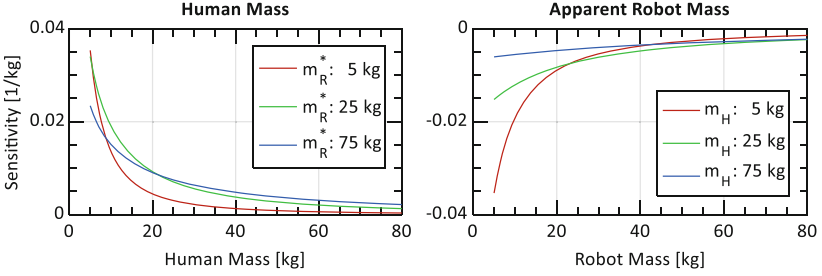


Fig. 5. Sensitivity analysis of the conversion with respect to the input parameters human mass m_H and apparent mass of the robot m_R^*

that further give the following expression for the total error

$$\Delta m_R^* = \frac{\partial m_R^*}{\partial v} \Delta v + \frac{\partial m_R^*}{\partial p} \Delta p. \quad (8)$$

Equation (7) indicates a proportional influence of p and a negative non-linear one of v . Since $\frac{\partial m_R^*}{\partial v}$ describes a hyperbolic function, the absolute magnitude of the sensitivity of m_R^* decreases with increasing v . This behavior indicates that the higher the impact velocity, the better the estimation accuracy. To study whether the sensitivity has a significant influence on the conversion method, the following relative error

$$\Delta x_{rel} = \frac{\hat{F}_{conv}}{\hat{F}_{meas}} - 1 \quad (9)$$

and absolute error

$$\Delta x_{abs} = \hat{F}_{conv} - \hat{F}_{meas} \quad (10)$$

is introduced. Both can be calculated from the converted force $\hat{F}_{conv}$, obtained with the conversion method, and the impact force $\hat{F}_{meas}$ measured with a movable PFMD. The green bars in Fig. 6 display the distribution of the errors in a histogram. It includes all data from the experimental tests, which incorporate more than 1000 individual results. The error distribution shows that 91 % of the impact forces obtained with the conversion method exceed the forces measured in tests

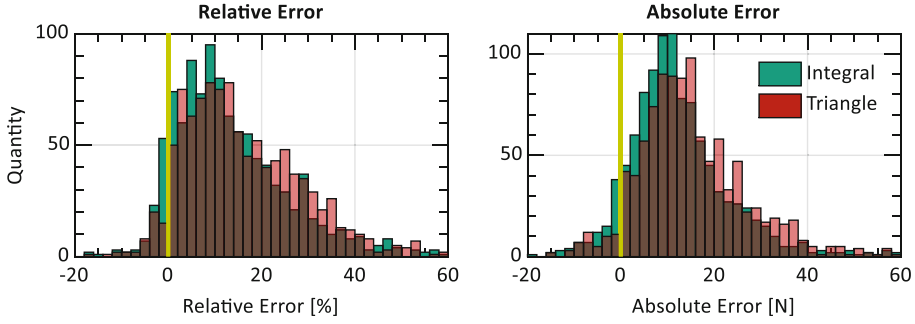


Fig. 6. Distribution of the relative and absolute error of the conversion method for different approaches to calculate the apparent mass m_R^* (the green bars use Eq. (2), the red bars Eq. (11) to calculate m_R^* ; the yellow line indicates 100 % accuracy; each error on the right hand-side of the yellow line indicates that the conversion method yields to conservative and, thus, safer results)

with the movable PFMD. The mean errors are $\Delta x_{rel} = 13.4\%$ and $\Delta x_{abs} = 12.2\text{ N}$. Considering this tendency, it can be concluded that the conversion method yields to slightly increased impact forces. Consequently, the conversion method can be considered as conservative as higher forces ultimately result in lower but safer robot velocities. The observations confirm that the parameters with positive influence on Δc dominate. Since $\hat{F}_C$ and m_H can be considered as accurately known or given, the conservative tendency of the converted values must be caused by a systematic underestimation of m_R^* . Consequently, the technique to estimate m_R^* results in too small values, which derive from $\Delta v > 0$ or $\Delta p < 0$ originating from Eq. (8). We assume that the calculation of p tends to yield smaller values, since the exact time of initial contact t_0 is difficult to detect. Considering this result, it must be highlighted that the conversion method can underestimate the impact forces even though the probability of this effect is very low with 10 %. An evaluation of the dataset shows that a safety factor of $S = 1.1$ multiplied with $\hat{F}_{conv}$ is sufficient to reduce the probability of underestimations to less than 1 %. This safety factor additionally leads to lower velocities of about 9 % for the conversion method.

7 Simplification of the Conversion Method

The error analysis has shown that underestimations of p lead to conservative estimates and lower robot velocities. This finding can be used to further simplify the estimation of the apparent robot mass m_R^* . Especially for end-users who do not have direct access to the measurement data or the knowledge to apply Eq. (2), it might be difficult to obtain p . An approximation of the integral can be obtained when considering p_{app} as the area of a triangle

$$p_{app} = \frac{1}{2}(t_{max} - t_0)\hat{F}_C, \quad (11)$$

where $\hat{F}_C$ is the maximum contact force at time t_{max} . Figure 7 compares the triangle approximation to the exact integral. The area of the triangle always cor-

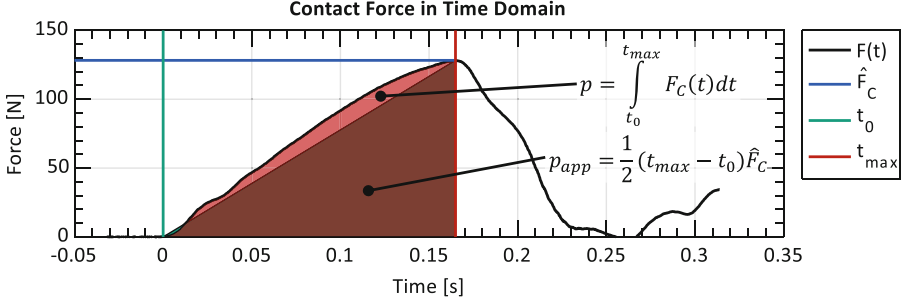


Fig. 7. Approximation of the momentum using the area of a triangle (Force signal of a UR10e robot with a payload of 66 % at an impact velocity of 150 mm s^{-1} colliding with a fixed measurement device with Spring 10 N mm^{-1} and Damper SH10)

responds to a slightly smaller momentum Δp . According to Eq. (7), a negative momentum error $\Delta p < 0$ leads to an underestimation of m_R^* , consequently to higher collision forces $\hat{F}_F$ (see Eq. (5)) and ultimately to lower, but safe robot velocities. The simplified conversion method that considers p_{app} was applied to all experimental results to calculate m_R^* . The errors compared to the measurements with the movable PFMDs are shown as red bars in Fig. 6. As expected, the simplified conversion method provides a higher relative $\Delta x_{rel} = 15.9 \%$ and absolute mean error $\Delta x_{abs} = 15.1 \text{ N}$, whereas the shape of the error distribution remains almost identical.

8 Conclusion and Outlook

This article presents a new method to convert impact forces recorded with a fixed Pressure and Force Measurement Device (PFMD) into such that would occur in a free collision. The technique has been validated with three different collaborative robots and two different PFMDs. The results obtained from the simulation and experiments show a significant increase of the allowable robot velocities. The findings of this study have a decisive contribution to increase the overall productivity of collaborative robots without compromising their ability to reduce the risk of human injuries. Another contribution of the conversion method to the robot community is the opportunity to evaluate unconstrained human-robot collisions of any direction even in confined spaces. Both advantages outweigh the slightly lower, but more conservative allowable robot velocity that the conversion method provides.

The moveable PFMD intends to represent a free collision between a robot and a part of the human body. One limitation is that it cannot reproduce the exact human behavior since it only has one Degree of Freedom (DoF), while the human body is a multi-body system with several DoFs. However, the short impact duration of free collisions (30 . . . 200 ms) and the elasticity of the human joints suggest that the affected human body part initially behaves like a one DoF system of specific apparent mass.

Further work will focus on the estimation of the robots velocity, which is necessary to calculate the apparent mass m_R^* . In fact, the translational velocity of

the robot must be assumed as unknown, especially if the robot executes Point-to-Point movements or if the collision point is not at the end-effector. However, it is always possible to use the velocity threshold as it is configured in the safety controller, since a safety-rated function will always ensure that the robot is never exceeding this value.

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References

1. 7th International Conference Safety of Industrial Automated Systems, Montreal, Canada, October 2012
2. Albu-Schäffer, A., Fischer, M., Schreiber, G., Schoeppe, F., Hirzinger, G.: Soft robotics: what Cartesian stiffness can obtain with passively compliant, uncoupled joints? In: Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Sendai, Japan, February 2004, vol. 4, pp. 3295–3301 (2004). <https://doi.org/10.1109/IROS.2004.1389925>
3. Behrens, R., Saenz, J., Vogel, C., Elkmann, N.: Upcoming technologies and fundamentals for safeguarding all forms of human-robot collaboration. In: Proceedings of the 8th International Conference on the Safety of Industrial Automated Systems, pp. 18–23, Königswinter, Germany, November 2015
4. Bicchi, A., Tonietti, G.: Fast and soft-arm tactics. IEEE Rob. Autom. Mag. **11**(2), 22–33 (2004). ISSN 1070-9932. <https://doi.org/10.1109/MRA.2004.1310939>
5. Falco, J., Marvel, J., Norcross, R.: Collaborative robotics: measuring blunt force impacts on humans. In: Proceedings of the 7th International Conference on the Safety of Industrial Automated Systems (2012)
6. Haddadin, S., Krieger, K., Mansfeld, N., Albu-Schäffer, A.: On impact decoupling properties of elastic robots and time optimal velocity maximization on joint level. In: Proceedings, pp. 5089–5096, Vilamoura, Portugal, October 2012. <https://doi.org/10.1109/IROS.2012.6385913>
7. Huelke, H.-J., Ottersbach, M.: 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 SIA, pp. 5089–5096 (2012)
8. Khatib, O.: A unified approach for motion and force control of robot manipulators: the operational space formulation. IEEE J. Rob. Autom. **3**(1), 43–53 (1987). <https://doi.org/10.1109/JRA.1987.1087068>
9. Khatib, O.: Inertial properties in robotic manipulation: an object-level framework. Int. J. Rob. Res. **14**(1), 19–36 (1995). ISSN: 0278-3649. <https://doi.org/10.1177/027836499501400103>
10. Oberer-Treitz, S.: Abschaetzung der Kollisionsfolgen von Robotern zur Bewertung des sicheren Einsatzes in der Mensch-Roboter-Kooperation. Dissertation, Universitaet Stuttgart (2017)
11. Salisbury, J.-K.: Active stiffness control of a manipulator in Cartesian coordinates (1980)
12. Fachbereich Holz und Metall der DGUV. Dguv-information - collaborative robot systems: design of systems with power and force limiting function (2017)