

Collision and injury criteria when working with collaborative robots

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There is a need for adequate protection of people from the health and safety risks associated with collaborative robot systems. Standard ISO 10218 (Parts 1 and 2) and a draft Technical Specification TS 15066 'Collaborative robots' have been developed to deal specifically with this situation. This study explored the safety, reliability and evidence for the force limits defined by the draft TS 15066, and of the methods for testing them. It also addressed whether the proposed approach in the draft TS 15066 is likely to adequately protect people from the risks. Risk assessment of potential collision scenarios, human reliability and behaviour issues, and equipment failure modes and rates are discussed, as is the adequacy of personal protective equipment against collision injuries. Collaborative robots is an subject area that is still growing.

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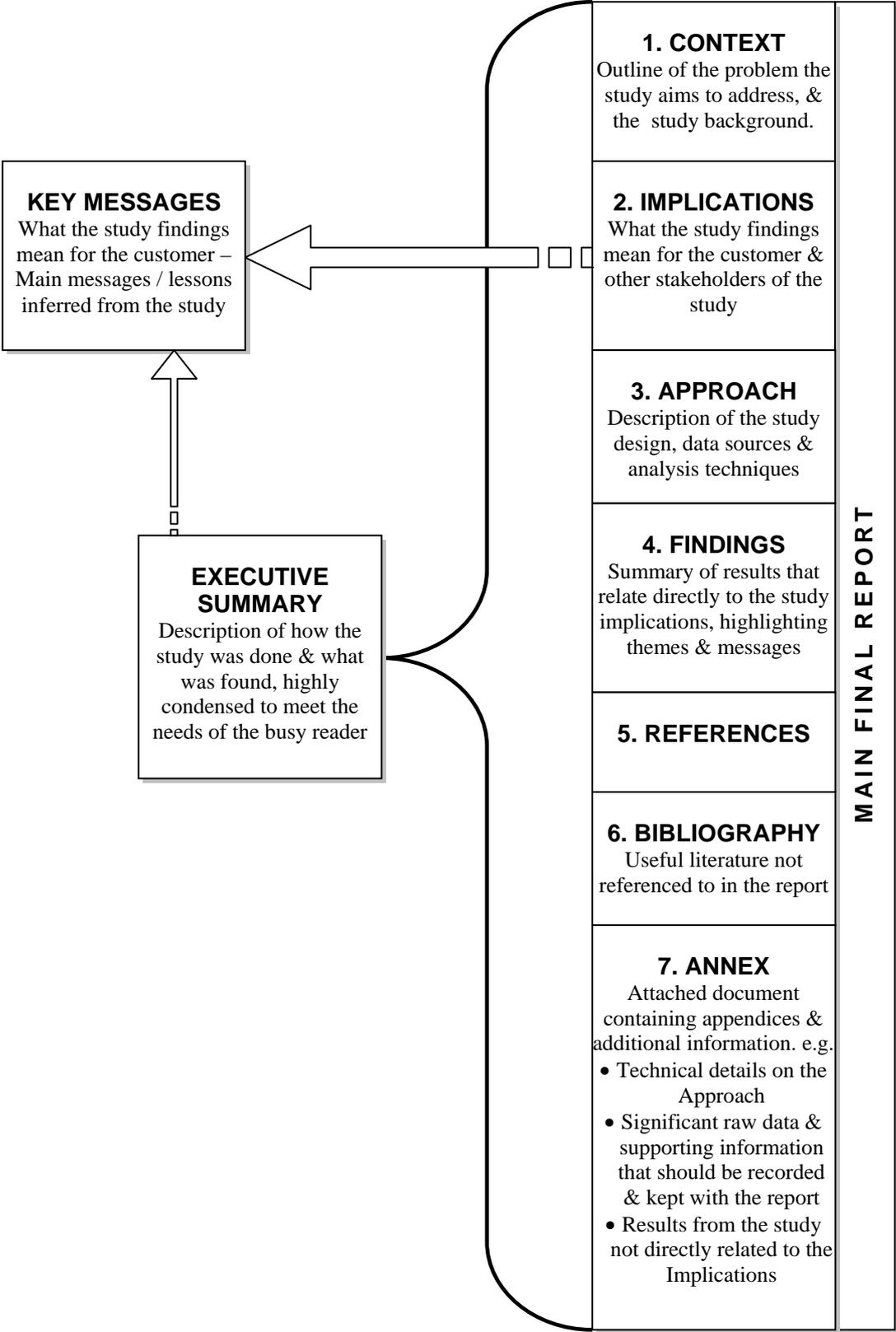
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STRUCTURE OF THIS REPORT



KEY MESSAGES

This study sought to answer the question of whether the approach adopted in the draft Technical Specification ISO/TS 15066 ‘Collaborative robots’ is likely to sufficiently and realistically protect people from the risks of working with collaborative robots, and be practical to implement.

The literature search carried out for the study revealed an extensive amount of research in the collaborative robots subject area, and was more than expected. Consequently this study was not in a position to categorically answer the questions that were posed at the outset because the amount of data that needed to be reviewed in detail was far in excess of the limits of this study, but significant steps have been made towards achieving well-informed answers by providing an initial appraisal of the research and scoping out a path to achieve more fully informed answers.

The study has brought to light a number of points, including:

- Although the force limits stated in the draft standard have been based on a review of over 200 literature sources, and seem ‘on the safe side’, issues with conducting research on human tolerance to injury and pain, along with issues of individual variability, affect the validity of the available research for determining force tolerance limits.
- Psychological, behavioural and organisational aspects affecting the level of human-robot collision risk are recognised in the literature, but not strongly represented in the draft standard at present. The effects of human movement velocities are also not represented.
- Some within the industry are of the opinion that customised injury criteria are required, rather than use of the Abbreviated Injury Scale and ICD-10 criteria.
- Currently the frequency of injury is not included in the criteria for acceptable collision limits.
- Investment in standardised instrumentation and methods is under development – discussions on the practicality and cost of development, distribution and training in use might need to take place.

An additional output from the study was a draft categorisation structure for the range of subject areas that are relevant to development of the draft ISO/TS 15066 standard. It is envisaged that this will be of benefit to managing the extensive range of research and information on collaborative robots, and to tackling the questions that are posed.

The study has some implications for potential additions to the draft ISO/TS 15066, and these have been presented for consideration in section 2.5 of the ‘Implications’ section.

There may be value in further and deeper consideration of several topic areas than was possible within the constraints of this study. These are described in section 2.6 ‘Possible next steps’.

EXECUTIVE SUMMARY

Robotic machinery and people are increasingly working in close proximity within industrial workspaces and there is a need for adequate protection of people from the health and safety risks associated with collaborative robot systems. This has led to the development of standard ISO 10218 (Parts 1 and 2) and a draft Technical Specification TS 15066 ‘Collaborative robots’ to deal specifically with this situation. The current study aims to address the following:

- a) Whether force limits defined in the draft TS 15066 are safe & realistic;
- b) Whether methods proposed in the draft TS 15066 for testing the force limits are likely to be reliable, realistic and pragmatic for risk assessment of collaborative robot systems under real circumstances;
- c) Whether the proposed approach in the draft TS 15066 is likely to adequately protect people from the risks.

Methods

The current state of research on the body’s tolerance to various applied forces was investigated by literature search, and the force tolerance values in the draft TS 15066 compared with those found in the literature. Contact with the developers of the proposed force values was made in order to establish how the force values had been derived.

The Personal Protective Equipment (PPE) specialists at the Health & Safety Laboratory (HSL), Buxton, UK were consulted as to whether it is reasonable to assume that PPE can adequately protect the ears, eyes, nose and mouth from injury when working with robots in foreseeable working scenarios.

To consider the practicality of the proposed measurement and risk assessment methods in the draft TS 15066, the availability of appropriate measurement components and devices was investigated. Consideration was given to the measurement approaches adopted in other standards, and to practical issues that could affect the validity and reliability of the testing and risk assessment methods proposed.

Whether the approach proposed in the draft TS 15066 would adequately protect people from the risks of working with collaborative robots was addressed by considering the proposed force limits in conjunction with real scenarios of human-robot collaborative working, and the potential risks. Real scenarios of collaboration and associated risks were gathered from internet sources and accident reporting.

Findings

The developers of the force limit values that are proposed in the draft TS 15066 had reviewed over 200 literature sources, providing confidence that the values are based on thorough consideration of the research available. However, it is apparent from the literature that: a) there are significant gaps in the research; b) that there are ethical issues that constrain the quality of the data that can be gathered, and; c) it is a research area that is still growing. It was not feasible to review the full range of research and data that are available in order to determine if the proposed values are safe and realistic, but literature sources were found which summarise some of the data. Compared to these sources, the force values in the draft TS 15066 were mostly lower and seemed ‘on the safe side’. Because of the complexity of potential collisions between humans and robotic machinery, and because the data available do not cover all of these potential

complex collisions, it was not possible to categorically confirm whether or not the proposed force values are safe and realistic. The developers of the force values have planned further work to investigate pain thresholds over the body, and to perform verification work on the proposed forces, which will help determine whether the values are safe and realistic.

The draft ISO TS 15066 appears to make the assumption that PPE will adequately protect ears, eyes, nose and mouth from robot collision injury, but it might not be appropriate to assume this. Potential problems with making this assumption are that a) selection, fitting and maintenance of PPE can be unreliable, and b) unless PPE is tested in representative human-robot collision scenarios, the protection it can offer, or even the damaging forces it might inflict, are not known.

The variety of potential collision scenarios, together with human reliability and behaviour issues and equipment failure modes and rates (both hardware and software), would appear to present a considerable risk assessment task. Probably the most significant difference between risk assessment of ‘traditional’ machinery and robotic machinery is the complexity of potential safety related equipment failure modes and the fact that the relative movement between machine and human may be more complex and variable. Additionally, robotic systems are being designed which are easy to re-program on site for different tasks, which can change their movement behaviour. There is also a potential issue with people becoming habituated to robot systems maintaining collision avoidance, and what happens when the avoidance system fails.

One potential failing of the proposed approach would seem to be that a person’s movement and body position could significantly change the collision forces, so if a robot system has been designed to meet the proposed force limits when colliding with a static person, the collision forces could be higher when colliding with a moving person, and the body injuries different.

Whether people will be adequately protected from the risks of collisions with collaborative robots will partly depend on what is considered to be adequate protection – consensus is needed about the acceptable extents of injury and also their frequency. The approach adopted in the ISO TS 15066 uses the ICD (International Classification of Diseases) and AIS (Abbreviated Injury Scale) classification systems to set what the criteria are for acceptable injury. However some within the industry feel that a customised set of criteria would be more suitable.

The draft ISO TS 15066 states that a reduction in accidents is expected with the use of collaborative robots because the defeating of safety guarding systems might be reduced. Unless technological systems are completely resistant to being circumvented by people, then defeating is most likely to be controlled by eliminating any perceived advantage from defeating rather than by technological solutions. Any perceived benefits of overriding the safety systems are likely to depend on the design and application of the collaborative robot and the collaborative task, rather than inherently because the robot is a collaborative one – this is an area that may require further consideration.

An approach to categorising the information and research was developed, adopting the following topic areas (all of which have a bearing on the questions that this study attempted to answer):

- Human-robot collision criteria (including the effects of collision forces and injury classification systems);
- Risk assessment (including measurement of potential collisions and assessment of collaborative robot scenarios);
- Risk control (including technological controls, human and organisational factors, regulation, guidance and inspection).

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1. CONTEXT

1.1 BACKGROUND TO THE STUDY

The hazards that people are exposed to from robots and machinery have traditionally been controlled by use of guarding, interlocking and cordoning off areas. However, a newer breed of 'collaborative robots' are being developed that are designed to be used with human and robot working in closer physical proximity to each other, sharing the workspace more closely. This requires new approaches to maintaining safe separation between people and robots, and setting standards for adequate protection of people from the health and safety risks of collaborative robot systems. A draft Technical Specification (TS) document is under development by the International Organisation for Standardisation (ISO) which will provide guidance on acceptable risk levels, risk assessment and counter-measures. The draft Technical Specification has raised questions about:

- a) Whether the force limits defined in the draft TS are safe & realistic;
- b) Whether proposed methods for testing the force limits can be reliable, realistic and pragmatic for real risk assessment of collaborative robot systems;
- c) Whether the proposed approach is likely to adequately protect people from the risks.

Development and application of collaborative robots is taking place in industry, with or without health and safety constraints. The Health & Safety Executive (HSE) of the UK would like to ensure it has defensible lines on the matters above that will allow it to take a proportionate stance, avoiding over prescriptive requirements while ensuring adequate levels of safety. The use of collaborative robots is seen as a likely growth area, with significant pushes expected by industry. Providing good, sound advice should allow the area to mature while avoiding significant accidents. HSE envisages that further investigative studies may be required depending on the results of this study.

1.2 DEVELOPMENT OF THE DRAFT ISO TECHNICAL SPECIFICATION

During the completion of this work a new and substantially revised version of the draft ISO Technical Specification was issued, under the title of '*Draft ISO/TS 15066. Collaborative robots*'. A substantial amount of this project report was completed based on the first draft Technical Specification titled '*Risk assessment according to mechanical hazards of workplaces with collaborative robots – Specification to safety requirements for collaborative robot operation which are defined in ISO 10218-1 and ISO 10218-2*' but every effort has been made to update the text to take into account the more recent ISO document.

1.3 DEFINITION OF COLLISION AND INJURY CRITERIA

The various body injuries that a person might sustain from collaborative robot systems, ranging from minor surface injuries to fatal injuries, can be put into a classification system. The description of the type and degree of body damage forms the criteria for classifying the injury – the injury criteria. An injury criterion, as defined in the draft ISO/TS 15066, is a 'selected biomechanical threshold which corresponds to a defined injury severity'.

Collision criteria are the properties of a human-robot collision that lead to a certain level of injury. The criteria are generally a description of the pressure, impact and shear forces acting on a body area that lead to a given type and degree of injury.

A formal definition of injury criterion is [1]:

‘An injury criterion is a mathematical relationship, based on empirical observation, which formally describes a relationship between some measurable physical parameter interacting with a test subject and the occurrence of injury that directly results from that interaction.’

A formal definition of tolerance level (in relation to injury criterion) is [1]:

‘The tolerance to injury can be defined as the value of some known injury criterion that delineates a non-injurious event from an injurious event. Or, phrased another way, the tolerance is the minimum dose associated with a specified probability of producing injury of a specified severity.’

1.4 AIMS & OBJECTIVES

The aim of this study was to examine the approach being adopted in the draft ISO/TS 15066 standard, and to gauge whether this will adequately protect people from the risks of working with collaborative robots. Various force limits for robot-human collisions are being proposed, and an assessment of whether these appear to be safe & realistic is sought. An assessment of whether the proposed measures can be practically implemented is also sought.

Objective 1: Gauge the research available on crush / pinch / shear force limits for various body parts. Provide overview of available research. Find out what research the proposed force limits are based on, including discussions with the primary originators of the first draft of the standard .

Objective 2: Examine the approach of defining body areas & force limits, given realistic foreseeable scenarios. Provide initial views on whether forces & measures proposed are safe & realistic, or what further steps are needed to establish this.

Objective 3: Carry out an initial appraisal of whether robot designers and installers are likely to be able to implement the proposed approach, given technological limits of robotics and force measurement instrumentations and costs. Consider measurement instruments available, and further steps / research required to establish realistic measurement methods. Give consideration to realistic collision scenarios, and whether the approach suggested in the draft standard is pragmatic.

2. IMPLICATIONS

2.1 BREAKING DOWN THE COLLABORATIVE ROBOTS SUBJECT AREA

A number of subject areas were encountered that relate to the safety of working with collaborative robots, and a proposal for a breakdown of these areas was developed to help meet the aims and objectives of the project. Figure 1 presents an overview of subject areas, and Figure 2 attempts to illustrate the aspects of collisions between humans and robots.

The information from the literature search was organised into the categorisation system in Figure 1, although some information sources fell into several of these topic areas. To help manage the pool of information for future reference and to help manage the addition of further information, it would be highly beneficial to employ a database system. It would also be beneficial to achieve wider consensus on a categorisation system such as in Figure 1, and to incorporate this into the database system.

Collaborative robots safety research - subject areas

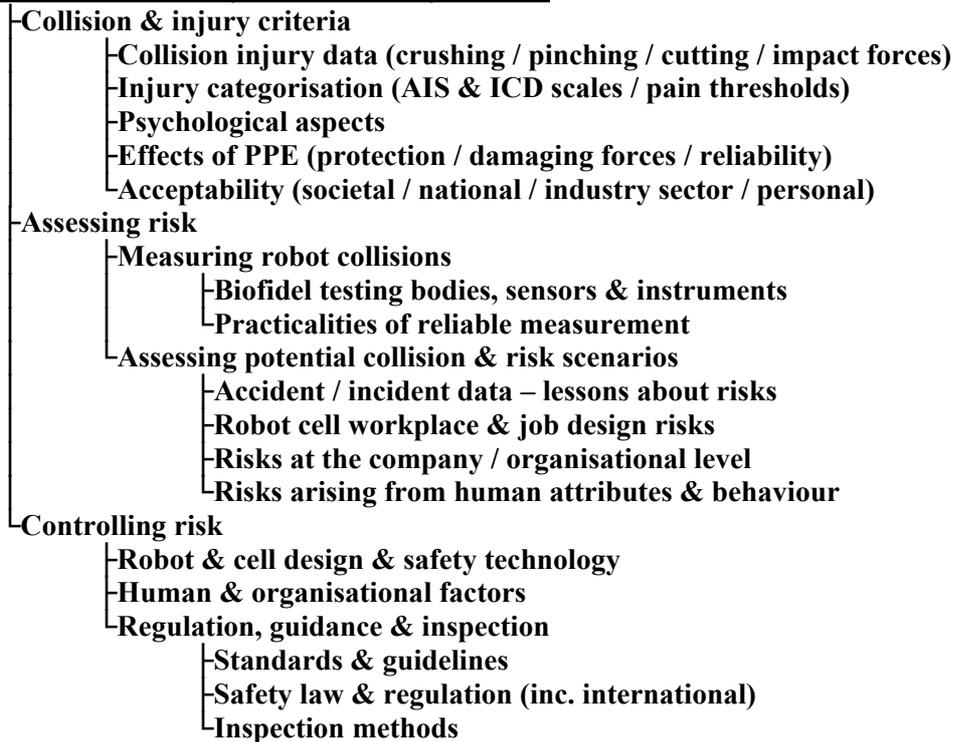


Figure 1: A draft structure for safety research on collaborative robots

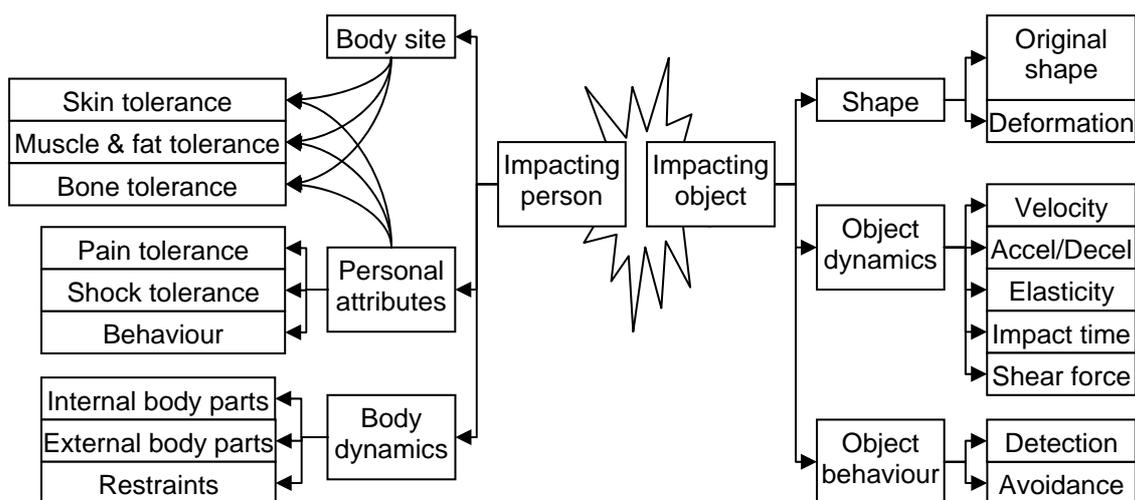


Figure 2: Aspects of human-robot collisions

2.2 ARE THE PROPOSED FORCE VALUES FOR INJURY CRITERIA WITH COLLABORATIVE ROBOTS SAFE AND REALISTIC?

The force limit values in the draft International Organisation for Standardisation Technical Specification (ISO/TS) 15066 appear to be conservative (‘on the safe side’) compared with other values found during this study, but this does not conclusively mean that the values are safe and realistic – there is a lack of research on the tolerance limits of the human body because of ethical and practical issues with obtaining good data in this field. The developers of the force limits (a research institute in Germany) have confirmed that the force values have been based on a thorough review of available data, but even if the force values will limit injury to contusions without skin breakage as suggested, there is a debate about what injury levels are acceptable for a given frequency of collisions – is one bruise a day acceptable, or one a year?

The injury limits in the draft ISO/TS 15066 have been set to not exceed Abbreviated Injury Scale (AIS) level 1, and forces must not cause skeletal damage. However it is worth noting that the AIS level 1 injury criteria includes one broken rib, so the AIS scale criteria don’t appear to be entirely suitable – this raises the question of whether a customised injury criteria and classification system would be beneficial.

Given evidence for a lack of available data for some areas of the body, and the variable quality for all body areas, there is some residual doubt over whether the suggested forces would adequately protect all areas of the body under the variety of real collision circumstances that are possible. Unless the suggested force values have been tested on a variety of real people and have covered all possible variables (for example, body impact site, impact area, impact angle, impact speed and restrained or unrestrained body) then there remains a residual risk of error in the values. Added to this there is the variability of people’s tolerance to injury and their ability to avoid collisions or falls (that is, their reaction speeds and ability to avoid becoming overbalanced), which changes the risk of the force values being suitable for certain populations. Further discussion with the developers of the force values seems essential in order to clarify exactly how the force values were derived, and ideally the developers would produce a document publicising the derivation of the values. There is recognition in the literature that there are psychological aspects to being hit by a robot, but no research was found on this area.

2.3 IS IT LIKELY TO BE PRACTICAL TO APPLY THE LIMITS TO REAL RISK ASSESSMENTS?

It is not likely to be practical to reliably apply the draft limits without investment in standardised instrumentation and testing methods. According to the draft ISO/TS 15066, standardised equipment to test robot collisions is under development. When standardised instruments do become readily available, there are other issues that need to be taken into account, such as ensuring appropriate test points in a complex human and robot movement cycle, and how to take into account human movement errors which could lead to unplanned movements and collisions.

The suggested force limits are designed to apply when the systems that should maintain a safe distance between human and robot, fail for some reason. Robotic systems are good at repeatedly and precisely following a programmed pattern of movement, whereas humans are unreliable at doing so. Lessons from incidents suggest that unpredictable human behaviour and movement are often contributing factors to incidents. For the robotic system to maintain a safe distance from the human, it will therefore need to be able to handle the potentially variable and unreliable behaviour and movement of the humans around it. If robotic systems employ collision avoidance systems to avoid human contact, this increases the variety of movements of the robot. The relative movements of human and robot appear to be potentially complex and variable, so the exact conditions in which human and robot come together in collision seem potentially complex. This appears to make valid collision measurement and risk assessment a complex task for some systems [24]. Where there are combined complexities of person and robot velocities, there may be potential to produce collision scenarios that could be difficult to predict.

Although the movement of specific robot systems is programmed and normally predictable, the variety of robot movements that can occur across different robot installations can vary enormously and therefore finding criteria and measurement approaches that can take into account this variety would seem to be a challenge. Also, some robot installations are currently programmed with a very long series of movement patterns (for example stacking onto a pallet) or are intended to be easily re-programmed frequently in the workplace so they can provide ad-hoc support with variable tasks. It has been pointed out in the literature that collaborative robots that can be easily re-programmed for different movements and tasks are being developed and are expected to be increasingly used in small-medium sized enterprises [36] which can be expected to increase the robots variety of movements in any given installation. To enable the draft ISO to deal with the diversity of current and emerging robot systems it would seem necessary to perform extensive trials with the full variety of systems and circumstances.

The automotive industry has developed injury criteria and 'biofidel' test dummies for assessment of injury risk, which has involved expense of over \$14 million USD and international collaboration to achieve. The resulting test dummies are only valid for use in car impact scenarios, as they have been tailored to gather measurements relevant to car impacts. Compared to the motoring industry, developing practical biofidel test dummies and injury criteria for the collaborative robot industry may present additional complexity because of the greater potential variety of human and robot tasks, movements and impacts which need to be catered for; the physical environment surrounding people inside a car is fairly well standardised and predictable, as is the position and limited movements of the person (for example, a car occupant who is restrained with a seatbelt and performing predictable driving tasks in collision with the seatbelt, airbag or steering wheel or other car interior parts).

In order to achieve practical risk assessment, the various potential failure scenarios of the robot and of human performance will need to be determined and weighed up. A challenge for risk assessment seems to be in determining what the failure scenarios might be, given the human – robot system complexity, and how to determine the probability & consequences of the failure.

2.4 IS THE PROPOSED APPROACH LIKELY TO ADEQUATELY PROTECT PEOPLE FROM THE COLLISION RISKS WITH ROBOTS?

In deciding whether the proposed approach will adequately protect people, there needs to be a consensus about what ‘adequate’ means, and what levels of injury are acceptable. The draft TS has proposed definitions of ‘acceptable’ injury using two injury classification systems: the superficial injuries described in the injury classification system called ‘ICD-10-GM 2006’ (<http://www.who.int/classifications/icd/en/>) and the ‘Level 1’ injuries of the Abbreviated Injury Scale (AIS) (<http://www.aaam1.org/ais/>). Examples given of ‘acceptable’ injury are contusions (bruising) and grazes. There needs to be consensus internationally about whether this is acceptable, and whether the dividing line between a bruise and a more serious injury is too fine to make any collision acceptable – how reliably can a robot limit injury to only bruising without doing more serious harm? Given that different individuals will sustain different levels of injury given the same robot impact (because of different skin, flesh and body dimension properties, for example) it would seem necessary to ensure that ‘tolerable’ bruising and grazing limits are set for the most easily injured population that will come into contact with robots. This raises the question of how this can be achieved given the lack of available scientific data.

2.5 IMPLICATIONS FOR THE DRAFT STANDARD

Potential additions to the draft ISO/TS 15066 are suggested for consideration:

- Inclusion of (or reference to) a list of research and information that has been used to develop the force limit values and the overall approach in the draft ISO document, so that it is clear what material was used to develop the current version and therefore what new research and information might be relevant when the standard is due for review;
- Inclusion of how typical movement speeds of humans within the workspace might change the nature of the forces when robots collide with humans;
- Inclusion of the frequency of potential collision and injury between robots and humans as part of the collision criteria, rather than just injury severity;
- The use of graphical flowchart roadmap for the risk assessment process.

2.6 POSSIBLE NEXT STEPS

To determine if the draft ISO/TS 15066 will provide a practical approach to assessing and controlling robot-human collision, more information is needed about how the force limits and overall approach have been developed – further and more detailed consultations with the original developers of the draft ISO in Germany and with other contributors to the draft seem necessary to achieve this.

Several topic areas were not ‘bottomed out’ during the study and there may be value in further and deeper consideration than was possible within the constraints of this study. These include:

1. Why human behaviour and human performance issues in the collaborative robot context might be different compared with the traditional machinery context – this is addressed in some of the un-reviewed literature and may be worth investigating;

2. Investigation into the reliability and failure modes of robots and their safety related systems, including the technological advances that are taking place in terms of maintaining safe distances between robots and humans, the failure modes of these and their resistance to being circumvented by people. This will need the involvement of technical specialists;
3. Consideration of whether psychological issues need to be taken into account when defining acceptable collision criteria i.e. psychological effects of being in a collision and how this might affect confidence / performance working with collaborative robots;
4. How the nature of the robot surface that might be in collision with a person (such as its surface roughness, its edges, sharpness, softness etc) affects the nature of any resulting injury to the person, and how this might impact on the draft ISO/TS 15066 standard;
5. How the angle of movement between a robot surface and a person may change the nature of any injury for a given collision force (for example, a sideways movement across the skin at a force that would be considered acceptable if applied perpendicular to the skin surface). This factor does not appear to be covered within the draft ISO/TS 15066, and little mention of it was found in the literature – IFA in Germany seem likely to be able to help on this subject;
6. What pressing / crushing forces might cause asphyxiation at various points on the body, and whether such forces have been considered in the draft ISO/TS 15066 standard (a number of fatal incidents have been from asphyxiation due to trapping);
7. Availability of appropriate force sensing equipment and sensors, and the methods used to develop the biofidel testing dummies for the car industry, and how experts in the collaborative robots industry see biofidel testing equipment developing;
8. Whether there are any other BS / EN / ISO / IEC / ANSI standards which use injury criteria or set force limit values for impacts / pressures / crushing forces on the human body, and a detailed review of the American robotics related standards;
9. Consideration of how practical risk assessment is going to be affected by the increasing prevalence of collaborative robots whose movement can be easily re-programmed in the workplace and applied to varying tasks;
10. Consideration of whether there might be more practical approaches than setting force limits for various body areas as is proposed in the draft ISO/TS 15066;
11. Quantification of the potential additional forces that human movement could add to human-robot collision scenarios, and quantification / qualification of the effects of PPE on human-robot collision scenarios.

Consideration might be given to managing the extensive range of research material, that has or might be gathered, by entering it into a reference management database. Consideration might also be given to reviewing and finalising the proposed subject categorisation system that is described in this report, and to use it to categorise the material in the database, which should help to manage all the elements of this complex and developing subject area.

3. APPROACH

3.1 SELECTION OF TOPICS TO BE INVESTIGATED

To meet the aims and objectives the following topics were selected for investigation:

- The current state of research on pressure / impact / crushing forces and their corresponding effects on body areas, and consideration of how the proposed values and measures in the draft Technical Specification have been derived;
- Whether the proposed values and measures are safe / realistic taking into account the protection afforded by PPE for the ears, eyes, mouth and nose;
- The current state of the technology for measuring forces between a planned or existing robot and areas of the human body;
- Potential collision scenarios between humans and robots, including lessons learnt from accidents;
- Practicability of applying the proposed values and measures to robot design and risk assessment.

3.2 INVESTIGATION METHODS

3.2.1 Literature search

The Google™ and Bing™ internet search engines were used to search for the initial terms:

Collaborative robot; Human Robot Interaction; Robot safety; Safety criteria; Injury criteria; Abbreviated Injury Scale; ICD.

Further searches were carried out on author names and institutions cited in texts and web sites, and on further key words from relevant literature.

3.2.2 Discussions with the Draft ISO developers

Contact was made with the developers of the first draft of the ISO standard, who are based in Germany. Questions were asked on the following:

- How the proposed force values in the draft ISO/TS 15066 were decided;
- How the force values will be applicable in a variety of real circumstances;
- Whether subjective / psychological issues have been included in determining the values;
- How the collision time period is taken into account.

3.2.3 Discussions with Personal Protective Equipment (PPE) unit at HSL

The PPE unit at HSL were consulted on:

- PPE available for facial protection against object collisions;
- Effects of PPE on transfer of impact energy to head areas;
- Body part tolerance to forces.

3.2.4 Investigation into force measurement equipment

Internet searches were carried out to find information on:

- Force sensing components available;
- Generic force sensing instruments available;
- Customised and specialist force sensing instruments;
- Instruments and components used by HSL.

3.2.5 Investigation of potential robot collision scenarios

Potential robot-human collision scenarios were considered from:

- Accident reports and accident summaries available from internet sources;
- Information on, and demonstrations of, collaborative robot usage from internet sources.

3.2.6 Investigation of other standards

Some other standards which set injury or collision criteria, or set force limit values for use by engineers, were investigated. This included a draft standard on testing body impact protection equipment (CEN/TC 162) [2], and the standard for acceptable trapping / crushing forces for powered gates and doors (BS EN 12453:2001) [12]. Internet sources of BS / EN / ISO standards were searched for any reference to crushing / squeezing / impact force limits on the human body.

4. FINDINGS

4.1 THE CURRENT STATE OF RESEARCH ON PRESSURE / IMPACT / CRUSHING FORCES AND THEIR CORRESPONDING EFFECTS ON BODY AREAS

4.1.1 Overview of research

The research available on the effects of forces on the body is very extensive and varies in quality. Within the constraints of this project it was not practical to review all the available foundation research to determine if the force values provided in the draft ISO/TS 15066 are safe and realistic. Annex 6.1 of this report serves to illustrate the extent of the research available back in 2002, which can be expected to have been considerably further developed since then. Communication with the developers of the first draft ISO in Germany [13] revealed that the force limits provided in the draft TS document were based on approximately 200 reviewed publications. A major issue is the fact that much research is based on limited sample sizes and populations, such as young fit males and cadavers, which is difficult to generalise to the wider population. However, the ‘raw’ research has been reviewed and consolidated for use in a number of projects and standards, for example:

- A draft standard on testing body impact protection equipment (CEN/TC 162) [2];
- The ‘Occupant Protection & Egress In Rail Systems’ project (OPERAS) [1];
- Determining acceptable trapping / crushing forces for powered gates and doors [12];
- The NATO injury criteria and tolerance levels [7];
- The review and development of automotive thoracic / abdominal injury criteria [10; 11];

It has been more practical for this study to compare the limit values in the draft ISO/TS 15066 with these types of sources. The draft standard for testing body protection PPE is particularly useful as it provides references for the sources used for each area of the body (consideration might be given to providing reference sources in the draft ISO/TS 15066 in the same way).

4.1.2 Comparison of limit values

Table 1 shows a selection of values taken from the draft ISO/TS 15066 compared with values in draft CEN/TC 162 [2]. It can be seen that the values chosen for the draft ISO/TS 15066 are nearly all lower than the values suggested in CEN/TC 162, suggesting that cautious force levels have been chosen. The exception appears to be the ‘Feet / toes / joint’ category, where CEN/TC 162 provides a slightly lower minimum value for joint damage. However, it is important to realise that the body part categories used in the draft ISO/TS 15066 generally don’t have a direct equivalent in the CEN/TC 162 document, and the CEN/TC 162 tends to use only body part fracture / failure data, whereas ISO/TS 15066 takes into account pain thresholds and skin / flesh damage (which may be the reason for the lower force values that are proposed). The values in CEN/TC 162 are gathered from a range of research sources, with references provided (refer to Annex for the list of references in the standard).

Table 1: Some comparisons of force limit values from draft CEN/TC-162 and draft ISO/TS-15066

Body area	Level of injury resulting from impact force ranges (N)		
	CEN/TC-162 Severe / moderate	CEN/TC-162 Slight or no injury	ISO/TS 15066* Injury criteria
Skull top / forehead impact	600 to 11000N	<1000N	175N
Face	900 to 5500	<100	90
Neck (front/larynx)	700	<100	35
Chest / ribs	580 to 8500	<500	210
Belly / abdominal organs	1000 to 4000	800 to 2000	160
Back	2000 to 5000	<2000	250
Upper arm / elbow joint	2000 to 4000	1700	190
Lower arm / hand joint	500 to 3800	500	220
Thigh / knee	2600 to 10000	1000 to <5000	250
Lower leg	900 to 8000	<1000	170
Feet / toes / joint	130 to 1300	Not listed	160

**Level of injury is defined in ISO/TS 15066 as: 'In the established main and individual body regions according to Table 1, only those stresses on the skin and underlying connecting or muscle tissue may occur where there was no deeper skin/tissue penetration accompanied by lacerations or abrasions, fractures or other skeletal damages. ... Under no circumstances a risk for injuries with higher severity than category 1 of the Abbreviated Injury Scale (AIS1) and more severe than with the codifications for surface injuries of the ICD-10-2006 can be tolerated.'*

Some further comparisons of the draft ISO/TS 15066 limit values with tolerance values found in the report for the Occupant Protection & Egress In Rail Systems (OPERAS) project [1] are provided in Table 2. Some of the comparisons involve different units and measures of tolerance and so are only intended for qualitative comparison. For example, whereas ISO/TS 15066 might provide force values in Newtons, the OPERAS project might provide tolerance in terms of g-force or maximum physical displacement in mm. The fact that some literature sources use different measures of tolerance serves to illustrate one of the issues with attempting to develop definitive tolerance values from the range of data sources available, and the issues with attempting to deliver all tolerance values in terms of impact forces, crushing forces, surface pressing forces and a compression constant (as ISO/TS 15066 attempts to do).

Table 2: Comparisons of force limit values from Draft ISO/TS-15066 and other literature sources

<i>Value from Draft ISO/TS 15066¹</i>		<i>Value from OPERAS report</i>	
<i>Criteria description</i>	<i>Value (N)</i>	<i>Criteria description</i>	<i>Value⁴ (mixed units)</i>
Skull/Forehead CSF ²	130N	No skull fracture	<2200N
Skull/Forehead IMF ³	175N	AIS 0-1, no concussion	<55g for 3ms
Face CSF	65N	AIS 0-1, no facial injury	<250N
Chest CSF	140N	AIS 0, no rib fracture	<=58mm chest deflection
Chest IMF	210N	Minor injury, sternum	3300N
Chest IMF	210N	25% chance of AIS 4 injury	5500N
Belly CSF	110N	AIS 0, no injury	<20mm deflection
Pelvis IMF	250N	AIS 0, no fracture, lateral	<4000N
Uppr arm/Eblw joint IMF	190N	Humerus, bending, female	1710N
Lwr arm/Hand joint IMF	220N	Ulna, bending, female	810N
Lwr arm/Hand joint IMF	220N	Radius, bending, female	670N
Hand/finger IMF	180N	No hand fracture	<5m/s impact velocity
Thigh / knee IMF	250N	Femur, bending, female	2580N
Thigh / knee IMF	250N	No dislocation	<8mm lng shear displacement
Lower leg IMF	170N	Tibia, bending, female	2240N
Lower leg IMF	160N	Fibia, bending, female	300N

¹ See Table 1 for a description of the injury criteria for the ISO/TS 15066 force values;

² CSF = Clamping / squeezing force

³ IMF = Impact force

⁴ Some values are not directly comparable because of the difference in the units, but are provided for making a qualitative comparison. Even where units are the same, the exact method and site of measurement is likely to be different, which limits comparisons.

The BS/EN 12453:2001 standard for powered doors and gates [12] provides a force limit which varies over time – an initial maximum force of 400N is allowed for 0.75 seconds, after which the force must not exceed 150N for the next 5.0 seconds, falling to a static force of no more than 25N. There is added complexity to these limits in that the five second limit can be disregarded if the force never reaches 50N and the door can be pushed back. The complexity of the force limits provided in BS/EN 12453:2001 illustrates the complexity involved in defining safe force limits. This variable force limit over time applies to gaps 50 to 500mm and therefore appears to apply to most parts of the body. However, the injury criteria for these force limits was not found to be clearly defined i.e. whether the limit is design to prevent death, serious injury or minor injury.

4.1.3 Consideration of dynamic complexities

The human body as a whole can be dynamically complex during collisions. For example, a rapid rotational acceleration of the head can create damaging forces between the skull and brain even without any external impact force on the head itself. A review of injury criteria and

tolerance levels for the rail industry [1] concluded that several injury criteria are required for the head because of the complexity of the dynamic properties of the skull and brain in a collision – both skull fractures and the movements of the brain within the skull need to be considered. Although the draft ISO/TS 15066 provides impact limit values for the head, it has not been confirmed whether this takes into account any potential for damage to the brain. A NATO research project [7] concluded that damage to head and neck would occur before brain injury occurs, but other sources [for example, 1] suggest otherwise.

Another example of the dynamic complexity of the body as a whole is the forces on the neck due to rapid movement of either the head or body parts following impact with an object. For example, from impact tests performed with human crash test dummies it can be seen that the head impact forces can be transferred into the neck (video footage of these tests are available on the internet [21] and excerpts of the video are shown in section 6.3 of the Annex to this report). The dynamic complexities are well explained in work carried out by the Institute of Robotics and Mechatronics, German Aerospace Centre [22; 23]. Force measurements taken from the test dummy provided neck force values for given head impact values. This work also indicated how the constraints of surrounding objects can significantly affect the forces transferred into the neck. In conclusion, any attempt to set an acceptable impact force for the head and torso would have to include consideration of acceptable resulting knock-on forces in the neck. It hasn't been confirmed with the developers whether these type of knock-on forces are considered in the force limits within the draft ISO/TS 15066.

4.1.4 Consideration of internal joint injury

It has not been confirmed whether the draft ISO/TS 15066 takes into account the forces required to cause joint damage e.g. whiplash to the neck, or damage to shoulder or knee, which could potentially result in longer term health complications. Such injuries would appear to be above the maximum tolerable limits specified in the draft ISO/TS 15066, because the document states '*Under no circumstances a risk for injuries with higher severity than... with the codifications for surface injuries of the ICD-10-2006 can be tolerated*'. An internally damaged knee would be classified under 'S83 Dislocation, sprain and strain of joints and ligaments of knee' of the ICD-10 2006 coding system, which is a more severe injury category than just 'surface injury'. Further discussion on the ICD-10 system is provided below. Internal joint injury is an area which could be raised with experts in Germany who developed the first draft of the ISO/TS 15066, and data on the forces which could damage joints could be investigated in more detail than was possible for this current study.

4.1.5 Suitability of the AIS and ICD-10 scales for defining acceptable injury criteria

The draft ISO/TS 15066 gives the maximum allowable injury level as Abbreviated Injury Scale (AIS) category 1, or the 'surface injury' categories of the International Statistical Classification of Diseases and Related Health Problems, 10th Revision (ICD-10) [8]. The draft also states:

'Only those stresses on the skin and underlying connecting or muscle tissue may occur where there was no deeper skin / tissue penetration accompanied by lacerations or abrasions, fractures or other skeletal damages.'

The AIS injury category 1 is not an entirely suitable injury criteria because a single rib fracture is classed as a category 1, 'Minor' injury, and so it requires additional caveats in order to be

suitable for application to collaborative robot safety. Also, the AIS system may not provide appropriate full criteria for acceptable collisions as it does not include some of the complications arising later from a Level-1 injury e.g. sight damage, asphyxiation or chronic joint injury. In other words, although the Level-1 injury may be acceptable at the time of the incident, the resulting longer term health complications may not be. Some recent research [9] concluded that new injury criteria specifically designed for the field of robotics may be needed. De Santis et al (2008) [24] support the thinking that safety measures and criteria need to be revised and customised for the collaborative robot circumstances.

Although there are obvious benefits to adopting standard systems such as the AIS and ICD-10, if they are not ideal for categorising collaborative robot injuries (they were developed for emergency medical treatment and clinical records use), then a customised or extended injury criteria / classification system might be something to consider. A customised criteria / classification system could, for example, take into account pain thresholds, psychological issues and the variety and extent of skin damages that can occur – these factors are difficult (or not currently possible) to cover with the AIS and ICD systems. The Occupant Protection & Egress In Rail Systems (OPERAS) project [1] provides an example of the development of custom injury criteria and tolerance levels. The system was developed to help perform assessments of the crashworthiness of train carriage designs. The injury categorisation system was based on an occupant's ability to be able to exit from the carriage after various levels of injury, and on the level of assistance they might require to exit.

4.1.6 What is acceptable injury?

Consensus may need to be sought over what the acceptable level of injury is [24], as this may vary from country to country or sector to sector. HSL has done work previously, to examine acceptable forces for finger trapping / crushing (Milnes, E ERG/05/19) [3] which used the onset of pain as the determinant of acceptable forces rather than physical damage levels. However, the pain-threshold approach might not be suitable for all areas of the body or collision types, because in some cases people can tolerate forces that lead to physical damage without subjectively unacceptable pain levels. What are considered to be subjectively acceptable collision forces is clearly a factor that is worth considering when determining acceptable collision limits. IFA / BGIA in Germany have raised the question of what is acceptable, and this is demonstrated in a workshop presentation given in 2007 [14].

4.1.7 Consideration of human variability

Because of the ethical difficulties of obtaining scientific data on what forces cause various body injuries, many data sources for force values are based on work with young and very fit population types, or cadavers, or computer models. The resulting data that is available is patchy and difficult to apply across age ranges and variations in body attributes. Research has shown that the resilience of bone and soft tissue declines significantly with age and this can vary widely (e.g. in the region of 20% reduction in resilience is possible between 20 and 80 years, which can be as much as 70% for seatbelt induced trauma type injuries) [4; 5; 6]. Because of the lack of good data, this may be partly why the values shown in the draft ISO/TS 15066 seem conservative, but the exact nature of the scientific data used in the draft TS needs to be confirmed with the developers of the draft ISO.

4.1.8 Consideration of psychological aspects

The developers of the first draft ISO, in Germany, were asked if psychological factors have been taken into account when defining the force limit values in the draft ISO/TS 15066 [13]. They stated that pain-threshold data was taken into account, but other than that psychological issues were not currently dealt with in the document, but is a subject area that they hope to incorporate at a later stage after further research work. Some mention of psychological issues was found [24], but nothing which fully considers these aspects in relation to the impacts on individuals and on workplaces e.g. would a robot-human collision in the workplace increase people's caution and stress levels around robots, and would it reduce their confidence in working with robots, which could lead to other issues – these subject areas appear to be open for new research or research applied from other areas.

4.1.9 Consideration of forces that can cause asphyxiation

Evidence from accidents [32; 33; 34; 35] shows that deaths from robot-human collisions are sometimes due to asphyxiation from trappings. This current work did not reveal information on the force limits that could lead to asphyxiation e.g. by pressing on the neck or chest. Further work to clarify whether such values are available or have been taken into account in the draft force limits of ISO/TS 15066 is suggested.

4.1.10 Limitations of the data sources

Force data is limited or absent for areas of the body such as the shoulders, elbow points, wrists, breast tissue, genitals and feet [2], which suggests that the body regions defined in the draft standard may be too limited; individual body regions that are defined in ISO/TS 15066 are:

- Head with neck: Skull/forehead; Face; Neck (front); Neck (back+sides);
- Trunk: Back/shoulders; Chest; Belly; Pelvis; Buttocks;
- Upper extremities: Upper arm/elbow joint; Lower arm/hand joint; Hand/finger;
- Lower extremities: Thigh/knee; Lower leg; Feet/toes/joint).

4.1.11 Horizon scanning: future research

The developers of the initial draft ISO, in Germany, have plans for further research [15], e.g:

- A full-body pain survey;
- Further work on the accuracy of the body region model;
- Additional compilation of medical / biomechanical injury data.

This research may have an impact on the choice of force limit values in the draft ISO/TS 15066.

4.1.12 Consideration of the probability element of the risk

The first draft of the ISO/TS 15066 did not make it clear that the primary objective must be to avoid collision and maintain a safe distance between person and robot, and that the force limits provided in ISO/TS 15066 are for when the systems designed to maintain the safe distance fail, but this appears to have been rectified in the more recent draft. It is an important point because the probability of failing to maintain a safe distance clearly affects the risk levels that human collaborators are exposed to, and affects what the acceptable injury criteria should be.

What can be considered acceptable collision forces needs to take into account the probability / frequency of the safe distance failing to be maintained and a collision occurring. For example, if collisions occur once in ten years, then the suggested force values will be more acceptable than if collisions are likely to occur on a monthly basis. Accident statistics may help in making this decision, although it will depend on the particular robot design and application. The probability element is clearly an aspect that needs to be included in the risk assessments, rather than just the collision forces themselves, but may be a difficult aspect for risk assessors of collaborative robot systems to deal with, especially as the reliability of the robot system will depend on software as well as hardware aspects. In the high-hazard industries, manufacturers need to supply designers with failure rate / mode information for their products, so that quantified risk assessment can be carried out – should robot manufacturers supply something similar? De Santis et al (2008) [24] provide an excellent discussion of the reliability issues in human-robot collaboration.

Whether or not people will be adequately protected depends to a large extent on the probability of collision, as well as the collision forces. Because of this, the management of safety in the use of collaborative robots will be an important factor in whether the values will protect people, as will the failure modes and failure rates of safety related equipment that prevents collisions. The importance of the reliability of maintaining a safe distance between robot and humans is recognised in the industry, and the systems for doing this are still under development as of 2010 [30].

4.2 CONSIDERATION OF HOW THE PROPOSED VALUES AND MEASURES IN THE DRAFT TECHNICAL SPECIFICATION HAVE BEEN DERIVED

Enquiries were made with the developers of the first draft ISO/TS 15066 about the exact methodology used to derive the force limit values that are provided. The main points from the response to those enquiries are [13]:

- The force values in the draft ISO/TS are derived from a literature study of approximately 200 publications;
- Publications included regulations for gates, doors and hatches and data from a wide spectrum of sources including pain pressure thresholds or pain tolerance levels, superficial injuries, through to heavier injuries and injuries with breaking effects of body parts;
- The acceptable injury criteria level that has been set includes only minor injuries of the outer surface of the human body;
- The injury severity is represented in a collision stress model through the combination of a force limit value and a pressure limit value;

- Only static and impulse collision types have been studied, because these are the usual collision types found in actual collaborative robot applications that the developers of the draft have been involved with.

4.3 REALISTIC COLLISION SCENARIOS BETWEEN HUMANS AND ROBOTS, AND LESSONS LEARNT FROM ACCIDENTS

Giving consideration to realistic collision scenarios was an important part of considering whether the force limit values provided in the draft ISO/TS 15066 are reasonable and can be applied in practice.

4.3.1 Consideration of the complexity of potential collisions

No research was uncovered that attempts to deal with the complexities of body impacts taking the whole body system into account. For example, although an impact of a certain force to the upper back might not cause damage to the back or the skin, it might however lead to damage to the neck due to whiplash type effects. Depending on the direction of force, impacts to the knee, for example, can result in very different damages, and it is not clear at this stage whether the draft force limits take the worst case scenario in determining the acceptable forces. A previous research review carried out by HSL [3] found that the properties of body soft tissue and support structures is understood well enough to describe their behaviour under dynamic loads, but that when in complex structures such as the human body, predicting impact behaviour, and subsequent body damage, becomes far more complex and difficult given the wide range of human body properties.

4.3.2 Movement forces of the person

Consideration may need to be given to the potential movement of the person relative to the robot, as this, combined with the robot velocity, might raise collision forces to levels which cause greater damage. It was beyond the scope of this work to determine what forces human movement might add to a collision situation. If the aim of the force limits is to limit injury to 'acceptable' injury levels, then the person's movement probably needs to be given serious consideration. The proposed collision measurement systems don't appear to take this into account – further contact with the developers of the draft ISO is recommended to confirm this, and to obtain their views on this issue. Movement of a person relative to the robot is relatively foreseeable, and the variability of human movement and the velocities involved may make risk assessment much more difficult. It is not clear if the force values provided in the draft ISO/TS 15066 allow any contingency for movement of the person. The 'traditional' machinery guarding standards provide safe distances from danger zones which take into account the movement speed of humans; ISO 13855:2010 'Safety of machinery -- Positioning of safeguards with respect to the approach speeds of parts of the human body' takes into account the approach speed of a person when considering suitable safeguarding, although this is more to do with allowing time for the machinery to stop than with the impact force that the human movement might add to the contact with the machinery. However, it is clear that the speed of human movement alters the risk levels with ordinary guarding, and so too might it affect the risk with robot collisions.

People are able to cause injury simply from impacts with stationary objects due to their own movement forces alone (empirically we know this, for example, from knocking our head or shin against something by accident), so when combined with movement of the robot, the increase in injury level could be significant. Collision with stationary objects e.g. overhead metal structures, is very different because responsibility for avoiding collision can be given to the person, and they can achieve this because the object isn't moving – it is less practical to expect a person to avoid colliding with an object moving in 3D space, and therefore there is a case for making it the responsibility of the machine designer to take into account the movement of a person, and reduce the risk accordingly. Static objects can be risk assessed relatively reliably, the potential impacts easily foreseen and measures taken to reduce the risk by controlling human behaviour and movement near the hazard. On the other hand a collision with a variably moving object is much harder to assess and it would not be reliable to control the risk entirely by controlling human movement and behaviour. If the force limit values in the draft don't take account of relative movement of the person, then the testing methods might need to include the relative dynamic movement of a person, so that the robot design can still achieve the force limits with a moving person.

If the force values in the draft standard assume a static person in the collision, and don't incorporate the potential for movement, then people may not be adequately protected from the collision risks in real scenarios, where they are likely to be moving.

4.3.3 Consideration of force times

The standard for power operated doors BS EN 12453:2001 takes into account the forces applied over time when specifying acceptable forces. This appears to be at least partly to take into account engineering practicalities so that the force specifications are pragmatic. While this makes the force specification more complex, the standard has adopted a more simplified approach than the draft ISO/TS 15066 in terms of considering different forces for different body areas i.e. it doesn't distinguish the various body areas.

4.3.4 Consideration of body loading and restraint

From the literature there is evidence that loading on bones significantly reduces strength e.g. body standing weight on the tibia reduces dynamic bending strength by 17%. Whether the body is unrestrained, restrained or partly restrained also has a significant effect on the subsequent forces to the body from collisions. For example, a collision with an upper arm that is holding onto an object is likely to result in heavier forces transferred to the arm than a free arm. This clearly makes risk assessment of collaborative human-robot collisions more complex. It would be useful to establish whether the force limits in the draft standard take into account the worse case scenarios of conceivable collisions.

4.3.5 Lessons learnt

Incidents provide useful data on robot-human accident scenarios [32, 33, 34, 35] and insights into human behaviour affecting risk [16, 17]. From some investigation reports it appears that deaths are often happening from trappings between a robot and another object. This is normally due to the robot stalling and not being able to be moved away from the trapped person manually. Another key issue appears to be human performance failure and risk-taking

behaviour, and there is some evidence that human failure causes a high percentage of robot accidents [36]. Unforeseen human behaviour may create risks that are difficult to assess in the workplace without the appropriate training and insight..

4.3.6 Human behaviour and reliability

A common theme that appears from robot related accident investigations is that the position of the colliding robot part takes the injured person by surprise [32], even though they are aware they are within the robot working zone and aware of the robot movements. This is perhaps unsurprising, but it maybe indicates that human failure to stay in a safe 3-dimensional zone is predictable and needs to be built into the risk assessments. This perhaps also impacts on the choice of acceptable injury levels for human-robot collisions because it is foreseeable that people will make mistakes when collaborating with robots – variable and unreliable human behaviour needs to be accounted for.

Given the unreliability of humans to perform the way machinery designers might expect / want them to, illustrated by the prevalence of defeating machinery guards [16] and failure to carry out risk-reducing actions when dealing with machinery [17], robot designers and risk assessors need to consider undesirable human behaviour and performance as foreseeable – the collision and injury criteria in the draft ISO/TS 15066 would therefore need to take account of this. It may be easier, harder, more obvious or less obvious when a collaborative robot protection system is circumvented – this may need further consideration. Whether human behaviour / performance is likely to be more or less of an issue with collaborative robot systems than conventional machinery would need further consideration. Recent work suggests that human-robot interactions do present additional complications [18; 19] and the solutions are currently either academic or under development, but not ready for industrial applications.

Another aspect of human behaviour is the fact that people will develop habitual expectations of, and reliance on, robot movement and avoidance systems – consideration needs to be given to what potential scenarios this might lead to when collision avoidance and safety systems (such as the examples given in ISO/TS 15066) fail.

High hazard industries use quantitative risk assessment methods, taking into account the reliability of equipment alongside the reliability of human performance, to gauge the risk within the system as a whole – whether collaborative robot systems will need more attention to human reliability than conventional machinery is something that needs further consideration.

De Santis et al (2008) [24] include behavioural aspects in their ‘Atlas of physical human–robot interaction’, supporting the stance that the variability, and reliability, of human behaviour and performance is a significant issue in the safety of collaborative robots.

The draft ISO TS 15066 states that a reduction in accidents is expected with the use of collaborative robots because the defeating of guarding might be reduced. Defeating of guarding is a human performance failure, termed a ‘violation’. Violations are most often committed with ‘good’ intentions (for example to get the job done for an employer) rather than for any malicious reasons such as sabotage. Violations are most likely to be controlled by eliminating any advantage from committing violations rather than by technological solutions to prevent them, unless the technology is impossible to circumvent. Whether or not a person sees any benefits to circumventing the safety systems, and commits a violation, is likely to depend on the design and application of the collaborative robot, the collaborative task design and the organisational culture, rather than just because the robot is a collaborative one – this is an area that may require further consideration.

4.4 PRACTICABILITY OF APPLYING THE PROPOSED VALUES AND MEASURES TO ROBOT DESIGN

The collision forces that a robot might inflict can be influenced by:

- The relative velocity at the moment of collision;
- The shape, area and hardness of the contacting part;
- The speed of collision detection;
- The mass of the robot part, and how quickly its movement / force can be braked;
- The software programming of the robot.

Adjusting collision forces would therefore involve adjusting the parameters above, and relies on there being sufficient range of adjustment available to reduce collision forces to those that have been suggested in the draft ISO/TS. Because robot installations vary to such a wide degree, we would suggest that the practicality of applying the proposed force limits should be discussed amongst industry experts.

4.4.1 Potential for confusion over whether the standards apply to older equipment

ISO 10218 Part-1 (which applies to robot machines on their own) states the standard "is not applicable to robots which were manufactured prior to its publication date." However, ISO 10218 Part-2 (which applies to robot machines installed in a robot system) does not give any exclusion dates. This indicates that Part-2 does apply to old robots being re-sold and re-applied into new robot systems i.e. Part-2 would apply to new robot systems even if they include older robots manufactured before the release of Part-1. This is a point which seems to need clarifying within the standards. Due to Part-1 being read first, there is a possibility that this could mislead people into thinking that Part-2 does not apply to older robots in new systems / cells. People may not be adequately protected from risk if risk assessors and those commissioning systems believe that 10218 and the draft TS do not apply to older robotic equipment in new robot systems.

4.4.2 Complexity of assessment

There is a danger that people will not be adequately protected because of the complexity of applying the draft TS i.e. measuring forces and movements of people, and taking into account individual differences. There appears to be a great deal of scope for the risk assessments to be poorly done, although this can only be measured through user trials of the draft TS and ISO standards, which may be a way in the future. Also, dealing with the force limits should not detract from the need to maintain a safe distance in the first place. Kabe and Kimura (2010) [27] illustrate some of the complexities of risk assessment of human-robot interaction (HRI) and make it clear that risk assessment must start at the early design stages in order to most effectively assess and control risk. In an internet article, the United States National Institute of Standards and Technology (NIST) state of collaborate robot systems 'The concept is simple, the realization less so.' [28].

The use of graphic interpretations of the risk assessment process in the draft TS might help to explain the section on the ‘Course of action for the application of this Technical Specification’. Graphics have been used in ISO 14121 and ISO 12100:2010 which helps to visualise the steps involved in risk assessment. A simplified graphic developed by the Toyota Motor Corporation was found during the literature search [31] and is available at: <http://www.robocasa.net/workshop/2007/pdf/toyota.pdf>.

4.5 CURRENT STATE OF THE TECHNOLOGY FOR MEASURING CRUSH / PINCH / SHEAR FORCES BETWEEN A PLANNED / ACTUAL ROBOT AND AREAS OF THE HUMAN BODY

Testing technology. Currently most of the impact testing being carried out is done in specialist facilities in universities and laboratories. The draft ISO/TS 15066 states that there is currently no instrumentation available to perform the full testing that is specified, although it is under development. This presumably includes the ‘biofidel testing body’ equipment referred to by IFA in Germany [20]. The automotive industry has developed injury criteria and ‘biofidel’ test dummies for assessment of injury risk. However the instrumentation appears to be simpler than what might be required to test robot collisions, because automotive injury scenarios are less variable and more predictable (e.g. a car occupant in rear, front or side collision restrained in a seat performing a predictable task). Compared to the motoring industry, assessing robot collisions with biofidel test dummies may be considerably more complex with lower validity because of the greater complexity of collision scenarios, due to a great variety of robot and task designs, robot movements and humans movements.

It seems that it has already been decided that the proposed testing instruments in the draft TS (that are under development) are the correct way to test robot collisions. However it would seem that if these will form a critical part of this standard then they should also be subjected to international agreement before being committed to being part of the standard. Questions might need to be asked about the complexity, reliability, availability, distribution, training in use, calibration, and cost of the proposed instruments. For comparison, the development of biofidel testing bodies for the automotive industry [25] has involved international collaboration, budgets of over (USD) \$14 million, and extensive testing, validation and documentation [26].

The National Institute of Standards and Technology (NIST) Intelligent Systems Division in the USA is working with industry to find appropriate technology for risk assessment and control in collaborative robot systems, and have a collaborative robot test bed [29]. In Europe, the German Aerospace Centre (DLR) and the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA) [20] have facilities and instruments established or under development for experimental measurements with collaborative robots.

Logistics of testing. Given the predicted increase in the application of collaborative robot technology, and it’s flexibility to be re-programmed on site, it seems sensible to look ahead at the potential logistical issues of testing or re-testing a large number of installations. If testing is complex and there is potential for it to be done incorrectly, then the availability of competent assessors / testers and calibrated equipment needs consideration. If each installation will need testing because of variations in the programming and cell design, then consideration needs to be given to the quantity of testing that will need to take place, and what the practicalities will be.

4.6 WHETHER THE PROPOSED VALUES AND MEASURES ARE SAFE / REALISTIC TAKING INTO ACCOUNT THE PROTECTION AFFORDED BY PPE TO THE EARS, EYES, MOUTH AND NOSE

From discussion with the Personal Protective Equipment section at HSL, it seems that PPE probably adds another level of complexity to measuring and risk assessing collisions with robots, and the idea that PPE will automatically provide protection to ears, eyes nose and mouth probably needs to be reconsidered. At the very least, the specification of PPE that will provide the level of protection that is being suggested, needs to be clearly specified. PPE needs further consideration for two reasons:

- 1) We don't know exactly how the collision forces applied to various PPE transfer to the person, and;
- 2) We don't know how effectively the wearing of PPE around a robot can be enforced (in comparison to other machinery and job designs).

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6. ANNEX

6.1 REFERENCE LIST FROM DRAFT CEN/TC 162 / WG 5 N 657

The full reference list from CEN/TC 162 / WG 5 N 657 (DRAFT) 'Protective clothing and protective equipment - Mechanical properties Test method for measuring the impact protection provided by materials and protectors' is available by request only, and subject to permission being given by the document owners. The following is a selection of 20% of the references (formatting is as extracted from the original document).

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6.2 EXAMPLES FOUND OF COLLABORATIVE ROBOT APPLICATIONS

The following sources provide examples of some robot applications which were used to gain an idea of potential risks and accident scenarios.

6.2.1 Examples from <http://www.smerobot.org/>

The following links provide examples of collaborative robot applications, and are taken from marketing and publicising materials on the <http://www.smerobot.org/> web site.

http://www.smerobot.org/press/texts/Automatica08_exhibits/Exhibits_01-13/02_SMErobot_SMART_robot.pdf

http://www.smerobot.org/14_automatica/

http://www.smerobot.org/04_demonstrations/

6.2.2 Examples from various internet sites

6.2.2.1 www.robots.com

<http://www.robots.com/movies.php>

Examples:

Palletising robot – items are manually handled onto the desk where the robot moves them to the pallet and stacks them (note that the robot movement varies as the pallet fills).

Robot welding cell – operator exchanges the part while robot welds another part.

Operator monitoring robot welding – monitoring in close proximity to robot.

6.2.2.2 www.robotics.org

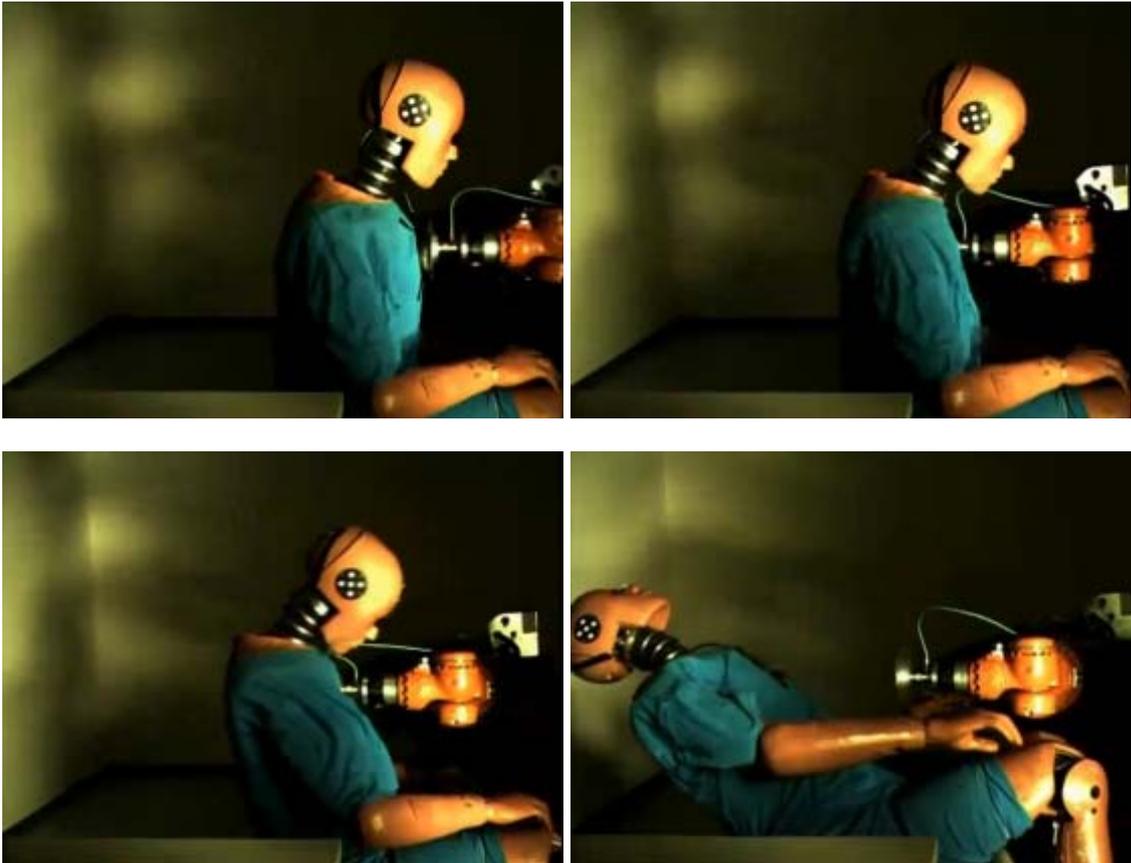
<http://www.robotics.org/company-profile-detail.cfm/Motoman-Robotics/Feature-Article/company/376/tab/3>

<http://www.robotics.org/info-center.cfm>

6.3 ROBOT-TEST DUMMY IMPACT TEST

The following sequence of images were taken from a video of impact tests carried out by the Institute of Robotics and Mechatronics, DLR German Aerospace Centre <http://www.youtube.com/watch?v=R5Gx8jpwyQ0>. They are provided to illustrate the transfer of impact forces from the site of collision to other parts of the body (in this case, the neck).

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Collision and injury criteria when working with collaborative robots

There is a need for adequate protection of people from the health and safety risks associated with collaborative robot systems. Standard ISO 10218 (Parts 1 and 2) and a draft Technical Specification TS 15066 'Collaborative robots' have been developed to deal specifically with this situation. This study explored the safety, reliability and evidence for the force limits defined by the draft TS 15066, and of the methods for testing them. It also addressed whether the proposed approach in the draft TS 15066 is likely to adequately protect people from the risks. Risk assessment of potential collision scenarios, human reliability and behaviour issues, and equipment failure modes and rates are discussed, as is the adequacy of personal protective equipment against collision injuries. Collaborative robots is an subject area that is still growing.

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