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As part of a programme of work for the European Enhanced Vehicle-safety Committee (EEVC), TRL has undertaken two pieces of work for the UK Department for Transport that are both summarised in this report. The first part of this project was to evaluate the biofidelity of the latest versions of the RID3D, BioRID II and Hybrid III rear impact crash test dummies against previously defined performance requirements. This testing then formed the UK contribution to a wider programme of research carried out by the EEVC Biomechanics Working Group to evaluate those dummies. To assist with this wider programme, the second objective of this project was to collate the results from other contributors and synthesise them (together with the TRL results) into a report for the EEVC.

The information from the UK and from WG12 was then used to produce a final report on the suitability of these dummies for use in a regulatory rear impact test procedure and to make recommendations as to any further developments which may be required in order to develop a suitable dummy for such a procedure.

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‘Whiplash’ Testing - Final Report

by D Hynd and JA Carroll

PPR 333
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Executive Summary

Neck injuries, even those with a minor threat to life, are associated with huge costs for society. The cost to European society is estimated to be between €5 billion and €10 billion per year. Consequently, it is understood in most industrialised countries that whiplash injuries constitute a serious problem with implications for the individual as well as for society as a whole. At the same time, it is recognised that progress in injury mitigation could be achieved by improving the use, design and efficiency of seats and head restraints in vehicles. Various research initiatives have been undertaken in order to develop a proposal for a test procedure for neck injury protection assessment. An appropriate test procedure adopted into a standard would ensure that seat systems are optimised to reduce the risk of whiplash injury in low-severity rear-end collisions.

Realising the need for an assessment of neck injury protection, the European Enhanced Vehicle-safety Committee (EEVC) Steering Committee has initiated a new activity on neck injury protection in rear end collisions with the aim of producing a proposal for a new European regulatory test procedure. A dedicated rear-impact working group, WG20, was formed with the overall responsibility for this activity. At the same time, the EEVC Biomechanics Working Group (WG12) was given the task to assist WG20 in the selection of an appropriate crash test dummy and associated biomechanically-based criteria for this new test procedure.

As part of this programme, TRL has undertaken two pieces of work for the Department for Transport that are both summarised in this report. The first part of this project was to evaluate the biofidelity of the latest versions of the RID3D, BioRID II and Hybrid III rear impact crash test dummies against previously defined performance requirements. The particular performance requirements were volunteer response corridors generated by TRL for the Department for Transport. This testing then formed the UK contribution to a wider programme of research carried out by EEVC Working Group 12 to evaluate the latest rear impact dummies. To assist WG12 in their efforts, the second objective of this project was to collate the results from other contributors and synthesise them (together with the TRL results) into a report for EEVC WG12.

Finally, the information from the UK and from WG12 was to be used to produce a final report on the suitability of these dummies for use in a regulatory rear impact test procedure and to make recommendations as to any further developments which may be required in order to develop a suitable dummy for such a procedure. This final project report fulfils that last objective through summarising the findings of the TRL and whole EEVC test programmes.

TRL Dummy Biofidelity Evaluation Programme

A total of nine tests were conducted at TRL with three dummies, the BioRID II, RID3D and Hybrid III, recreating the conditions used for low speed rear impact tests conducted with volunteers.

The BioRID II head displacement and rotation were clearly better than those of the other dummies in the TRL test condition and it is very likely that at comparable speeds it would engage an active head restraint in the same way as a human. The RID3D head vertical motion was not sufficient at the test speed used. Other aspects of the RID3D motion were good, in terms of how well they replicated the motion of the human volunteers tested in this configuration. The Hybrid III motion was generally not human-like, especially in terms of T1 (the first thoracic vertebra) motion; in particular, the timing of its kinematics differed to those of the volunteers. Overall, the BioRID II had the most human-like head and neck displacement and rotation as well as seat back interaction, although there is still room for improvement, particularly with the seat back interaction.

The Hybrid III head restraint interaction was found to be unsuitable in that although it just made contact with the head restraint, it exerted a much smaller force compared with the volunteers. This interaction affected the Hybrid III instrumentation readings; therefore the Hybrid III should not be used for the assessment of head restraints designed to reduce the risk of WAD (Whiplash Associated Disorder) injury for this reason.

Of the injury criteria assessed, only NIC can be used with all three dummies for injury assessment at the TRL test condition, based on the results obtained. LNL should be investigated further and actual injury risk values are required for this criterion. Intercept values for the proposed injury criteria Nij and Nkm should be calculated for the RID3D and BioRID II and injury risk tolerances should be calculated for these criteria as they may have potential for assessing injury risk.

Synthesis of EEVC WG12 Dummy Evaluation and Literature Review

The analysis of the TRL tests was combined successfully with the test results and analyses from testing at other laboratories. The three candidate rear impact dummies have now been evaluated in four of the identified biofidelity assessment conditions selected by EEVC WG12 (the LAB, AZT/Chalmers, TRL and Allianz/GDV conditions). In addition, a review of the literature regarding the biofidelity of the Hybrid III dummy in low-
speed rear impact loading conditions was undertaken. The key conclusions from the dummy evaluation and literature review were:

- Proposed injury criteria for use in assessing whiplash injury risk were assessed by WG12 based on the biomechanical basis for the criterion, the applicability to dummy measurements and the availability of an injury risk function. The five criteria considered were \( N_{ij} \), \( N_{km} \), LNL, NDC and NIC. \( N_{km} \) and NIC\(_{max} \) were evaluated more thoroughly than the other criteria and these are the only two criteria with established injury risk curves.

- None of the criteria reviewed have a definite biomechanical basis and their validity in predicting the risk of injury needs to be established. None of the criteria can be recommended on a strictly biomechanical basis.

- Several of the proposed injury criteria make sense mechanically and could be evaluated further if the strict biomechanical requirement (that requires identification of the injury) is relaxed. For instance, these parameters may be suitable for use as a seat evaluation criterion, rather than an injury criterion.

- Conclusions regarding the repeatability and reproducibility of the BioRID II, RID\(^{3D} \) and Hybrid III in low-speed rear impact test conditions are expected from WG12 shortly; these may affect the recommendation regarding the most appropriate dummy to use in these test conditions.

- A review of the literature found that the poor biofidelity of the Hybrid III in low-speed rear impact conditions has the potential to reduce the effectiveness of head restraints by encouraging active head restraints to be optimised for the dummy such that they may be less effective for a human occupant. The Hybrid III is therefore not appropriate for low-speed rear impact whiplash protection testing.

- In all of the test conditions selected by WG12 for the biofidelity assessment, the Hybrid III showed performance that was further from the response corridors that define the requirements than were the RID\(^{3D} \) and BioRID II. The Hybrid III has insufficient biofidelity for it to be considered further for use as a test tool in the assessment of whiplash injury risk in low-severity rear impact testing.

- The Hybrid III seat back interaction was not human-like.

- In many parameters from the whole test programme, the BioRID II and RID\(^{3D} \) were similarly close to meeting the biofidelity requirements.

- The CORA (CORrelation and Analysis) rating system for comparing response curves with corridor requirements was used to obtain an objective interpretation of the biofidelity results. Overall scores were produced giving equal weighting to each of the five test series conducted and the seven parameters which were judged to be the most important for the assessment of biofidelity. The results ranked the Hybrid III as having the lowest biofidelity score (0.41), followed by the RID\(^{3D} \) (0.53), and with the BioRID II having the highest biofidelity rating of the dummies tested (0.59).

- The BioRID II head restraint and seat back interaction were the most human-like when assessed under the TRL test conditions.

- It should be noted that the biofidelity requirements are all at a relatively low impact severity compared with real-world rear impacts in which whiplash symptoms are reported.

- No inappropriate results (i.e. where suggested injury thresholds were exceeded) were found for NIC, \( N_{km} \) or \( N_{ij} \) in these biofidelity tests in which the volunteers were uninjured. The LNL threshold was exceeded and the NDC did not seem to rate injury risk appropriately for these test conditions. These results are not able to conclusively confirm or exclude any of the proposed injury criteria that were calculated.

The key recommendations from the work are:

- It is recommended that the Hybrid III has insufficient biofidelity for it to be considered further for use as a test tool in the assessment of whiplash injury risk in low-severity rear impact testing.

- It is recommended that, based on the currently available biofidelity data, the BioRID II is the most suitable dummy for use in a low-speed rear impact test procedure.

- The repeatability and reproducibility of the dummy used in such a test procedure will also be important. Therefore, to help select the most appropriate rear impact dummy for the test procedure, it is recommended that the results from the EEVC WG12 repeatability and reproducibility testing conducted at BASi be taken into consideration.
1 Introduction

1.1 Background

Neck injuries, even those with a minor threat to life, are associated with huge costs for society. Kleinberger [2000] estimated the total annual monetary cost for whiplash injuries, or Whiplash Associated Disorders (WAD), in the United States (population of 268 million) to be roughly $4.5 billion US, while O’Neill [2000] estimated the cost to be $7 billion US. Ryan and Gibson [2000] estimated the annual cost for WAD in Australia (population of 19 million) to be approximately $540 million AU. The cost to the European society is estimated to be between €5 and €10 billion per year.

Consequently, it is now understood in most industrialised countries that whiplash injuries constitute a serious problem with implications for the individual as well as for society as a whole. At the same time, it is recognised that progress in injury mitigation could be achieved by improving the use, design and efficiency of seats and head restraints in vehicles. Various research initiatives have been undertaken in order to develop a proposal for a test procedure for neck injury protection assessment, such as EC Brite Euram Whiplash I and II, Swedish national research, the UK Department for Transport Spine Project and the work by the International Insurance Whiplash Prevention Group (IIWPG). An appropriate test procedure adopted into a standard would ensure that seat systems are optimised to reduce the risk of whiplash injury in low-severity rear-end collisions.

Realising the need for an assessment of neck injury protection, the European Enhanced Vehicle-safety Committee (EEVC) Steering Committee has initiated a new activity on neck injury protection in rear-end collisions with the aim of producing a proposal for a new European regulatory test procedure. A dedicated rear-impact working group, WG20, was formed with the overall responsibility for this activity. At the same time, the EEVC Biomechanics Working Group (WG12) was given the task to assist WG20 in the selection of an appropriate crash test dummy and associated biomechanically-based criteria for this new test procedure.

The latest rear impact dummies selected by WG12 as candidates for use in a rear impact test procedure were the BioRID II, RID3D, Hybrid III and the THOR. However, there is not a final version of the THOR available currently so it was excluded from immediate consideration.

1.2 Project Objectives

The initial objective of this project was to evaluate the biofidelity of the latest versions of the RID3D, BioRID II and Hybrid III rear impact crash test dummies against previously defined performance requirements. The particular performance requirements were volunteer response corridors generated by TRL [Roberts and Carroll, 2005] for the Department for Transport funded ‘Dummy development to evaluate spine injuries’ (Spine) Project.

This testing then formed the UK contribution to a wider programme of research carried out by the EEVC Working Group 12 to evaluate the latest rear impact dummies. To assist WG12 in their efforts, the second objective of this project was to collate the results from other contributors and combine them with the TRL results to produce a report for EEVC WG12. The WG12 dummy biofidelity evaluation (undertaken at five laboratories, including TRL) is reported in Carroll et al. [2007]; the dummy repeatability and reproducibility evaluation report will be completed by BASt.

Finally, the information from the UK and from WG12 was to be used to produce a final report on the suitability of these dummies for use in a regulatory rear impact test procedure and to make recommendations as to any further developments which may be required in order to develop a suitable dummy for such a procedure. This final project report fulfils that last objective through summarising the findings of the TRL and the other EEVC test programmes. It should be noted that another report summarising the WG12 synthesis report for the EEVC Steering Committee is also expected as an output from the Working Group. This Steering Committee report will incorporate the material...
presented here. In addition it will also provide background to the requirements against which the candidate dummies have been evaluated.

Therefore the key objectives from this project were:

1. Biofidelity testing
   - The evaluation of the three candidate rear impact dummies against the TRL volunteer performance requirements

2. WG12 programme of work to evaluate dummies for low-speed rear impact testing
   - Contribution of biofidelity testing results and then the synthesis and reporting of the overall WG12 biofidelity, repeatability and reproducibility programme results

3. Final reporting
   - Conclusions on the suitability of the candidate dummies based on the UK and WG12 test results and recommended actions that may still be required to develop a suitable dummy for a rear impact test procedure
2 TRL Dummy Biofidelity Evaluation

2.1 Introduction

In order to meet the first project objective, the latest versions of the RID3D, BioRID II and Hybrid III dummies were tested under the same conditions as used in the volunteer testing reported by [Roberts and Carroll, 2005]. This dummy evaluation work has been reported to the Department for Transport in full already, as a previous deliverable from this project [Willis et al., 2007].

2.2 Method

The test configuration was designed to replicate previous pure-rear impact tests conducted at TRL in 1999 with ten male volunteers. Three tests were conducted with each of three dummies, the RID3D, BioRID II and Hybrid III, and all tests used the same set-up and pulse. Each dummy was seated on a modified UNECE Regulation 44 test seat on a ‘target’ sled, which was free to move on the rails; this was impacted by a ‘bullet’ sled of the same mass, moving at 12.5 km.hr\(^{-1}\) (~3.5 m.s\(^{-1}\)) to give a \(\Delta v\) of 7 km.hr\(^{-1}\) (~1.9 m.s\(^{-1}\)). The impact pulse (2 g) was controlled by a block of aluminium honeycomb mounted on the back of the target sled. A schematic of the test set-up is shown in Figure 2.1.

An adjustable head restraint was attached to the seat to limit gross motion of the occupant’s head. In addition to the standard instrumentation, a Tekscan® pressure mat was used to record the pressure distribution formed by each dummy’s back against the seat during the test. Previous testing with both volunteers and dummies had shown that whilst quantitative analysis of the seatback pressure was unreliable, the qualitative assessment of the distribution was very informative. Figure 2.2 is a photograph showing a dummy seated on the test bench prior to testing.

![Figure 2.1: Pure-rear impact test set-up as viewed from above](image-url)
2.3 Results

A total of nine tests were completed, three with each of the RID3D, BioRID II and Hybrid III. A few key results from these tests are shown in the following sections. Full results are contained within the Biofidelity testing report [Willis et al., 2007] and its appendices.

2.3.1 Seat-back and Head Restraint Interaction

Images from the Tekscan pressure mat, taken at regular time intervals from each impact, were compared to indicate to what extent each dummy engaged the seat. These results are shown in Appendix A of the Willis et al. report for each test. An example of the results from one test with each dummy and from two volunteers is shown in Table 2.1.

Figure 2.2: Pre-test photograph of a dummy (RID3D) positioned on the test bench
Table 2.1: Tekscan pressure mat results

<table>
<thead>
<tr>
<th></th>
<th>0 ms</th>
<th>24 ms</th>
<th>47 ms</th>
<th>87 ms</th>
<th>252 ms</th>
</tr>
</thead>
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<tr>
<td><strong>RID\textsuperscript{3D}</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
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<tr>
<td>58SD03</td>
<td><img src="image6.png" alt="Image" /></td>
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<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
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<tr>
<td>Hybrid III</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
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<tr>
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<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
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<td>BioRID II</td>
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<td>58SD08</td>
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<tr>
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<tr>
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</table>

Considering the images from all volunteer tests it was observed that there were differences in the way each of the volunteers loaded the seat back, but that all of them created a fairly distributed pressure over the seat back. The volunteers’ flexibility allowed them to mould themselves to the shape of the seat back and caused their spines to straighten during the test and their shoulders to be pushed back, changing the pressure profile during the impact.

In contrast, none of the dummies was able to sit against the seat back such that the pressure they exerted was as distributed as any of the volunteers, prior to testing. However, the pressure exerted by the BioRID II was more distributed than either of the other two dummies. The RID\textsuperscript{3D} back flesh caused all of its weight to be focussed in the thoracic spine area and the Hybrid III rested on its spine mainly. The BioRID II has the most flexible spine of the three dummies which gives it the most human-like back profile. During each test, the BioRID II back pressure increased in the thoracic and pelvic regions in a similar manner to that of each volunteer; the main difference was that the volunteers exerted pressure on the seat between their shoulders whilst the BioRID II pressure increase appears to have been lower down the spine. The RID\textsuperscript{3D} pressure increased and became more spread out during the impact, but the timing was different to that of the volunteers. The Hybrid III behaved...
similarly but with most of the pressure exerted along the whole of its spine, which is clearly the least like the volunteer profiles.

The head restraint was instrumented with load cells and hence the total force exerted on the head restraint by the volunteers and dummies was compared. These head restraint interaction results are shown in Appendix B of the Willis et al. report. The mean total head restraint loads for the dummies are reproduced in Figure 2.3.

![Figure 2.3: Mean total head restraint load for each dummy](image)

A comparison of the forces exerted on the head restraint showed that the BioRID II and RID3D both exerted less force (in total) on the head restraint than the volunteers, whilst the Hybrid III exerted much less. The Hybrid III exerted only a small force on the head restraint because its neck was only flexible enough to allow it just to make contact with the head restraint, not push into it at all. This is an important part of the kinematics required from a rear impact dummy and strongly suggests that the Hybrid III has insufficient biofidelity in this respect.

### 2.3.2 Head and Neck Kinematics

The dummy head and neck motion has been analysed in terms of displacements and rotations calculated from an analysis of the high-speed film results and in terms of accelerations. These were then compared with the response corridors which had been generated from the volunteer test results. These results and comparisons with the corridors form Appendices C and D of the Willis et al. report.

Head motion: None of the dummy responses fell within the corridors entirely, but the BioRID II displacements and rotations were consistently closest in terms of amplitude, timing and shape. The BioRID II responses were usually within one corridor width of the corridor, whilst the RID3D and Hybrid III responses were sometimes more than one corridor width from the volunteer response.

Head motion relative to T1: None of the dummies were able to replicate the neck elongation seen in the volunteers, but it is not known how crucial this is to the generation or prediction of whiplash injury. If vertical displacement is excluded, the BioRID II displacements and rotations usually fell within the corridors, whilst the RID3D responses had the same shape and were within one corridor width of the corridors. However, the vertical head displacements relative to T1 were negative for both...
the BioRID II and RID\textsuperscript{3D} (this is because the relative timings of the T1 and head displacement peaks were different for the dummies and volunteers; the T1 vertical displacement peaks occurred much later for the volunteer signals compared with the dummies). The Hybrid III had no vertical head displacement relative to T1, but its other head displacements and rotations were close to the corridors.

T1 motion: In terms of displacements, the RID\textsuperscript{3D} response was the closest to the corridors in amplitude and form. In terms of rotation, both the BioRID II and RID\textsuperscript{3D} responses were within one corridor width of the corridors. The Hybrid III T1 motion was the furthest from the corridors and it had no T1 rotation.

The high-speed film analysis and instrumentation results show that, in general, the results for each dummy were repeatable based on consideration of the coefficients of variation for each response.

2.3.3 Dummy Instrumentation

Where accelerations were measured for the human volunteers, the response corridors were compared with the dummy accelerations in order to gain an indication of how close the accelerations, forces and moments measured in the dummies were to those seen in a human subject. Whilst all three dummies have their limitations, the Hybrid III head fore-aft accelerations were very poor compared with the other two dummies and compared with the volunteer corridor and there was a clear difference between its pelvis acceleration responses and those of the other dummies. The Hybrid III neck moments were also very different in form, timing and amplitude compared with the other dummies. The differences in head and neck instrumentation readings can be explained by the head restraint interaction. The Hybrid III barely made contact with the head restraint, so its head was accelerated by its neck, rather than by the head restraint, resulting in the lower head fore-aft acceleration. The Hybrid III neck is also much stiffer than those of the other dummies, generating higher moments at each end.

The BioRID II and RID\textsuperscript{3D} had good head acceleration responses but the timing of the BioRID T1 acceleration was different to the volunteers and the RID\textsuperscript{3D} T1 vertical acceleration was not like those of the volunteers.

A number of injury criteria were calculated from the dummy results, primarily so that the criteria themselves could be assessed: the test conditions were completely non-injurious to the volunteer subjects and hence the results from each dummy for each injury criterion were expected to reflect this when compared with proposed injury thresholds. Although there were differences between the responses from different dummies and between volunteer and dummy responses, none of the results showed any obvious anomalies that might have made the injury criteria calculations invalid. The BioRID II upper neck responses have been excluded as these responses were found to be unreliable post-test due to use of an incorrect skull cap (that was used because none was supplied with the dummy).

2.3.4 Dummy Handling

The test set-up used was very straightforward in that there was no requirement to set the H-Point with a manikin prior to testing and no vehicle buck or seat shaping to fit the dummy into. The test set-up was also identical for each dummy. However, differences between the three dummies could be seen in terms of documentation and instrumentation.

The RID\textsuperscript{3D} requires an up-to-date user manual as it still uses the manual for the RID-2, even though it has undergone a variety of modifications since the manual was written. The positioning of this dummy was hampered by the back flesh, which can only be inserted once the dummy is in place on the sled.

The BioRID II was difficult to position initially because its documented seating procedure assumes seating in a car seat, having first recorded an H-point position with the HRMD manikin. Both rear impact dummies were more difficult to position initially than the Hybrid III due to the fact that their necks had to be protected and they could only be lifted via a harness.
The Hybrid III was more straightforward to use because of its familiarity. It was not any easier to position in the seat as it was so much stiffer than a human volunteer.

2.4 Summary of the TRL Biofidelity Testing

Each rear impact specific dummy was able to replicate different aspects of the volunteers’ motion and both had displacements and rotations which were close to those of the volunteers. The BioRID II head displacement and rotation was clearly better than those of the other dummies in this test condition and it is very likely that at comparable speeds it would engage an active head restraint in the same way as a human. The RID3D head vertical motion was not sufficient at the test speed used; but based on this one test condition, it is not known what effect an increase in speed would have on the dummy’s motion. Other aspects of the RID3D motion were good, in terms of how well they replicated the motion of the human volunteers tested in this configuration. The Hybrid III motion was generally not human-like, especially in terms of T1 motion; in particular, the timing of its kinematics differed to those of the volunteers. Overall, the BioRID II had the most human-like head and neck displacement and rotation.

The BioRID II seat back interaction was the best of the three dummies and was the only one to produce a back pressure profile similar to that of a human throughout the test, although it could still be improved. This result is from a test conducted with a flat seat and further tests assessing seat back interaction in a standard car seat are needed to assess the other dummies’ abilities in this respect. However, the result indicates that the BioRID II was best able to adapt to the shape of the seat in the same way as a human occupant and suggest an advantage with the BioRID II over the RID3D and Hybrid III.

The RID3D head restraint interaction was as human-like as that of the BioRID II, but its interaction with the seat back was affected by its back flesh (which has been designed based on UMTRI data from in-car subjects). The RID3D back pressure profiles showed all of the weight being distributed through the back flesh, preventing the lower part of the dummy back from engaging the seat. This response may be better in a standard car seat, but it may also indicate that the dummy spine is too stiff overall and needs more flexible elements.

The Hybrid III head restraint interaction was found to be unsuitable in that although it just made contact with the head restraint, it exerted a much smaller force compared with the volunteers. This interaction affected the Hybrid III instrumentation readings. For this reason, the Hybrid III should not be used for the assessment of head restraints designed to reduce the risk of WAD injury.

None of the dummies were able to replicate the “neck stretching” seen in the volunteers, but it is not known how crucial this is in the generation or prediction of WAD injuries.

All three dummies had appropriate repeatability in this test condition for the limited number of tests conducted, given that there was no confirmation of their positioning prior to testing.

Different dummies produced more appropriate results for different injury criteria. The lack of Hybrid III head restraint interaction has affected the inputs to the injury criteria and hence the Hybrid III is not suitable for this purpose under these test conditions.

NIC had appropriately low values for all three dummies. NICmax appears to be a useful injury criterion for use in low speed rear impact (ΔV < 20 km.hr⁻¹) with both the RID3D and BioRID II dummies.

Nkm and Nij could only be calculated for the RID3D and Hybrid III due to technical problems with the BioRID which invalidated its upper neck load cell readings. Both injury criteria had suitably low values for the RID3D and when calculated with this dummy the maximum values occurred during the rebound phase of motion.

Although suitably low values of LNL resulted from calculations using outputs from the RID3D and BioRID II, clear values corresponding to actual risk of reported injury are required for this criterion.
The NDC values generated from BioRID II data do not correspond to the test severity used and the Hybrid III values fall outside the volunteer response limits. Hence it is recommended that this injury criterion not be used.

All the injury criteria calculated require dummy specific injury tolerance limits to be defined before they can be compared with different dummies and different test conditions. The NIC appears to be the most reliable for the test conditions used here.
3 Synthesis of the EEVC WG12 Dummy Biofidelity Evaluation

3.1 Introduction
A synthesis report on the combined dummy biofidelity testing programme of EEVC WG12 has been delivered to the UK Department for Transport as the second deliverable for this project [Carroll et al., 2007]. A summary of the work carried out by the Working Group and the key findings from the combined testing are reproduced in the following sections.

3.2 Test Programme
Table 3.1 below shows which WG12 partner tested the candidate dummies in which test condition. As far as possible, the programme was designed to ensure that the dummy tests against a particular requirement were conducted by the same laboratory that had generated the volunteer or PMHS data on which that requirement was based. To eliminate any possible differences in the results due to variations between different issues of the same dummy, the same three dummies were used for all tests and were recertified at appropriate points in the test programme.

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>Test Laboratory (country)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Biofidelity tests replicating Allianz/Chalmers test conditions</td>
<td>Chalmers (Sweden)</td>
</tr>
<tr>
<td>2. Biofidelity tests replicating JARI test conditions</td>
<td>JARI (Japan)</td>
</tr>
<tr>
<td>3. Biofidelity tests replicating LAB test conditions</td>
<td>LAB (France)</td>
</tr>
<tr>
<td>4. Biofidelity tests replicating TRL test conditions</td>
<td>TRL (UK)</td>
</tr>
<tr>
<td>5. Biofidelity tests replicating Allianz/GDV test conditions</td>
<td>INSIA (Spain)</td>
</tr>
</tbody>
</table>

3.3 Biofidelity Requirements
A series of five biofidelity requirements was selected by EEVC WG12 against which the candidate dummies should be assessed [Hynd et al., 2007]. The data sets were selected as priorities from a list of nineteen available data sets based on the:

- availability of data
- quality of test set-up, instrumentation and the subject quality
- reproducibility
- relevance of the test conditions, loading condition and velocity change
- distribution of subject anthropometry, gender and age
- number of tests and test subjects
The prioritised data sets include both PMHS and volunteer data and were generated on rigid as well as laboratory or ‘standard’ seats.

- **LAB data set [Bertholon et al., 2000]**
  - Six PMHS tests were conducted with three subjects; each strapped in a rigid lab seat with no head restraint and restrained using three straps across the thighs, pelvis and thorax. The sled was accelerated to 10 km.hr\(^{-1}\), using a pulse with a peak acceleration of 12 g.
  - The set-up used in the PMHS and dummy tests is shown in Figure 3.1.

- **AZT/Chalmers data set [Davidsson et al., 1998]**
  - Five volunteer tests were conducted with four subjects (all with approximately 50\(^{th}\) percentile male anthropometry) using a specially built laboratory seat, consisting of four panels and a head restraint. The stiffness characteristics of the panels and the cloth used to cover them were chosen to closely match those of the Volvo 850 seat. The seat was mounted on a target sled and each volunteer was restrained using a lap and shoulder belt, positioned as closely as possible to the arrangement in a Volvo 850. The target sled was impacted by a bullet sled to give a \(\Delta v\) of 7 km.hr\(^{-1}\) and a peak acceleration of 3.5 g.
  - A schematic of the set-up used in the AZT/Chalmers volunteer and dummy testing is shown in Figure 3.2.
• JARI data set [Ono et al., 1997]
  o This test series used two different seats, a “rigid” laboratory seat based on UNECE R16 and a standard car seat. Each of these was mounted on a sled designed to slide backwards into a damper system to give the desired rear impact pulse. Due to the fact that it is no longer possible to obtain car seats with the same properties as those used in the original test series, only the rigid seat tests have been replicated. Twelve volunteers were tested in the “rigid” seat. The volunteers were positioned in normal seating posture and were then instructed to grip a handle (positioned similarly to steering wheel) and relax. The mean $\Delta v$ for the rigid seat tests was 9.3 km.hr$^{-1}$ and mean maximum acceleration was 3.7 g.

• TRL data set [Roberts and Carroll, 2005]
  o Ten male volunteers, with approximately 50th percentile anthropometry, were tested using a dual sled impact to simulate a low-speed rear impact in a car-to-car shunt. Each volunteer was seated on a modified UNECE R44 test seat (seat back raised to 590 mm above the Cr line, head restraint added) on a target sled, which was then impacted by a second sled to give a $\Delta v$ of 7 km.hr$^{-1}$ ($\sim$1.9 m.s$^{-1}$) and a 2 g impact pulse.

• Allianz/GDV data set
  o Six rear impact tests were performed with 3 male and 3 female volunteer subjects with a $\Delta v$ of 9 km.h$^{-1}$ and a peak acceleration of 3 g.
  o The set-up used in the Allianz/GDV testing is shown by the photographs in Figure 3.3 and Figure 3.4.

A summary of the test conditions used in the biofidelity testing is shown in Table 3.2.
### Table 3.2: Summary of test conditions for each biofidelity requirement

<table>
<thead>
<tr>
<th>Test Set-up</th>
<th>Head Restraint?</th>
<th>$\Delta v$ (m.s$^{-1}$; km.hr$^{-1}$)</th>
<th>Peak/Mean Acceleration (g)</th>
<th>Seat Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAB - PMHS</td>
<td>None</td>
<td>3; 10.8</td>
<td>12</td>
<td>“Rigid”</td>
</tr>
<tr>
<td>LAB - Dummies</td>
<td>None</td>
<td>3; 10.8</td>
<td>10.5 / 7</td>
<td>“Rigid”</td>
</tr>
<tr>
<td>Chalmers - Volunteers</td>
<td>Yes, with 80 to 120 mm backset</td>
<td>1.9; 7</td>
<td>3.5 / 2.7</td>
<td>~11kN.m$^{-1}$</td>
</tr>
<tr>
<td>Chalmers - Dummies</td>
<td>Yes, with 88 to 89 mm backset</td>
<td>1.9; 7</td>
<td>4 / 2.7</td>
<td>~11kN.m$^{-1}$</td>
</tr>
<tr>
<td>JARI</td>
<td>None</td>
<td>2.6; 9.3</td>
<td>3.7 / ~2</td>
<td>“Rigid”</td>
</tr>
<tr>
<td>JARI</td>
<td>None</td>
<td>2.6; 9.3</td>
<td>3.7 / ~2</td>
<td>“Rigid”</td>
</tr>
<tr>
<td>TRL - Volunteers</td>
<td>Yes, with 50 to 75 mm backset</td>
<td>1.9; 7</td>
<td>2 / 1.8</td>
<td>~70kN.m$^{-1}$</td>
</tr>
<tr>
<td>TRL - Dummies</td>
<td>Yes, with 50 mm backset</td>
<td>1.9; 7</td>
<td>2 / 1.8</td>
<td>~70kN.m$^{-1}$</td>
</tr>
<tr>
<td>Allianz/GDV - Volunteers</td>
<td>Yes with 40 to 75 mm backset</td>
<td>2.6; 9.2</td>
<td>3.5 / 2.8</td>
<td>~11kN.m$^{-1}$</td>
</tr>
<tr>
<td>Allianz/GDV - Dummies</td>
<td>Yes, with 70 to 130 mm backset (BioRID 70mm, RID$^{10}$ 100mm, Hybrid III 130mm)</td>
<td>2.6; 9.2</td>
<td>3.5 / 2.8</td>
<td>~11kN.m$^{-1}$</td>
</tr>
</tbody>
</table>

### 3.3.1 Target Corridors

To compare the biofidelity of the rear impact dummies, it was first important to collate the requirements set at each test condition. In each case, the requirements were defined in terms of simple straight line corridors for the displacements of the test subject, based on the method used by EEVC WG9 [Roberts et al., 1991]. The straight line corridors were drawn in the same way for each parameter from each data set; based on the mean plus or minus one standard deviation of the human subject test responses. An example corridor is shown in Figure 3.5.

![Figure 3.5: Head fore and aft displacement response requirement for the TRL testing](chart.jpg)
3.3.2 **Key Biofidelity Targets**

Due to the large number of reported parameters for each of the volunteer and PMHS test series, the WG12 members decided on a list of seven key parameters measured in all conditions that would be used in the main biofidelity assessments. This list is as follows:

- T1 angle with respect to the sled
- T1 x-axis displacement with respect to the sled
- T1 x-axis acceleration
- Head rotation with respect to T1
- Head centre of gravity x-axis displacement with respect to T1
- Head rotation with respect to the sled
- Head centre of gravity x-axis displacement with respect to the sled

3.4 **Summary of EEVC WG12 Dummy Biofidelity Results**

Detailed results and discussion can be found in [Carroll et al., 2007]. The response of each dummy compared with the seven key criteria and other measured parameters was assessed subjectively by the experts of EEVC WG12.

3.4.1 **Hybrid III**

Considering horizontal displacements relative to the sled, the Hybrid III performed reasonably well against the GDV and Chalmers requirements (soft seat), but less well against the harder seats as used by TRL, JARI and LAB (stiff seat and rigid seat, respectively). Its behaviour was different to that of the other dummies in terms of head z-displacement for all test conditions. The Hybrid III had too much head rotation relative to some corridors and not enough relative to others. The LAB criterion, with a rigid seat and no head restraint, shows this limitation (Figure 3.6). In general, the Hybrid III was not able to put the head in the correct position in any of the test conditions and therefore it would not interact with the head restraint in a human-like manner in a regulatory or consumer test.

The Hybrid III T1 x-displacement was good relative to the Chalmers and GDV criteria, probably due to the compliant seats used in these tests, but poor compared with the TRL, JARI and LAB requirements. T1 z displacement was poor compared with all requirements; regardless of test severity or seat compliance; the dummy showed no sign of ‘ramping up’ the seat, which is seen in volunteer and PMHS tests. Its T1 rotation was similarly poor and in general its T1 motion was not human-like (Figure 3.7 shows T1 rotation results from the JARI testing). This implies that the Hybrid III does not engage the seat back in the same way as a human and has implications for the measurement of injury criteria, since these are usually concerned with some measure of the relative motion of the head and T1. The Hybrid III head acceleration was also poor compared with all criteria.

Based on these results the Hybrid III is unsuitable for the assessment of whiplash prevention car seats and for use in a regulatory test designed to assess WAD injury potential.
Figure 3.6: Head rotation with respect to the sled (LAB testing)

Figure 3.7: T1 angle with respect to the sled (JARI testing)
3.4.2 RID3D

The RID3D head displacement responses were similar to those of the BioRID II. In some cases the RID3D responses were closer to the performance corridors and in other cases the BioRID responses were closer. In general it appears that the RID3D performs better at higher accelerations and is more able to position the head correctly under these conditions. The test conditions that will be used in a regulatory test are likely to be more severe than those used for the volunteer tests, but probably similar in severity to the LAB PMHS tests, so the performance of the RID3D may be more suitable. However, it appears to be less able to perform well in a soft, compliant seat compared with one that is more rigid and all the seats will be tested are likely to be quite soft.

The RID3D had good T1 x-displacements relative to the Chalmers, JARI and GDV criteria and was closest to the corridors for both the TRL and LAB requirements. Its z-displacement was not very close to any of the corridors and there were significant differences between its response to the Chalmers tests and to the GDV tests – this is likely to be due to initial position. The T1 rotation was good relative to the Chalmers requirement and just outside the LAB and TRL corridors.

The RID3D head x and z-displacements relative to T1 were good with respect to the LAB requirement and poor with respect to those of the other tests (although the z-axis displacement was also reasonable in the JARI tests and the x-axis displacement was good in the Chalmers tests). Its head rotation about T1 was quite good.

The RID3D head acceleration was as good as that of the BioRID II if the differences in backset (head to head restraint horizontal displacement) for the INSIA tests are taken into account.

3.4.3 BioRID II

The BioRID II performed well against the head x-displacement requirements. Its z-displacement was too small but closest to the TRL and LAB requirements. It should be noted that these tests used laboratory seats and not the soft, shaped car seats for which the BioRID II has been designed. Its head rotation was good against all criteria and overall it put the head closest to the correct position in more of the test conditions than either of the other dummies.

The BioRID II had good T1 x-displacement relative to Chalmers and GDV criteria (soft seat), but insufficient displacement relative to the TRL requirement and too much relative to the LAB and JARI requirements. Its T1 z-displacements did not meet any of the requirements.

The BioRID II head x-displacement relative to T1 was generally good although it was not within the corridor for the GDV or JARI requirements. Its z-displacement was quite good and only came close to the corridor in the LAB condition, in which the RID3D response was within the corridor. Its head rotation about T1 was generally good.

The BioRID II head acceleration was quite good compared with most criteria.

3.4.4 Overall Subjective Evaluation

The BioRID II positioned the head the closest to most of the requirements, although the RID3D responses were also good in this respect.

Neither of the rear impact dummies has the correct T1 z-displacement. For a soft-seat, BioRID II appears to have the most human-like behaviour overall.

Overall the BioRID comes closest to achieving human-like head displacement relative to T1.

The Hybrid III had very poor responses in most test conditions. In particular, its T1 motion is very poor and it is not capable of engaging the seat back and head restraint in the same way as a human. It should not be used for low-speed rear impact testing.
3.5 Objective Biofidelity Assessment

To make the biofidelity assessment less subjective, more quantitative and more reproducible, a standard numerical means of interpreting the results was sought. It was decided to use the CORA software (CORrelation and Analysis), which has been developed on behalf of PDB (the Partnership for Dummy technology and Biomechanics). The software was used to compare a dummy response with an inner and outer corridor; as defined from the human subject data. The rating produced a result between 0 and 1, where 0 is commensurate with no correlation between the response and the corridor and 1 is a perfect match. In practice this is defined as the response scoring 1 if it is entirely within the inner corridor for the selected time duration, and scoring 0 when the response is entirely outside of the outer corridor. The dummy responses were evaluated between 30 and 180 ms, which was the longest period where consistent data was available from each laboratory for all parameters.

The corridors were defined on a similar basis to that used in the subjective analysis. The inner corridor was set to be the mean human subject response plus or minus one standard deviation. The outer corridor was set to be plus or minus two standard deviations.

Each of the seven key parameters from each of the five prioritised data sets were assessed in this manner for each of the three candidate dummies tested. It should be noted that it is possible to obtain misleading results from such automated interpretations of data. For instance a response just on the outside of the corridor might receive a lower score than one which bears no relation to the shape of the corridor but happens to cross through it a few times during the evaluation period. This was found to occur for several responses across the testing, but generally the biofidelity scores for each response were reasonable and correlated well with the subjective assessment. The overall CORA results for each dummy are shown in Table 3.3. Note that each biofidelity requirement was weighted equally for the purposes of this assessment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RID\textsuperscript{3D}</th>
<th>Hybrid III</th>
<th>BioRID II</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1 angle w.r.t. the sled</td>
<td>0.55</td>
<td>0.38</td>
<td>0.77</td>
</tr>
<tr>
<td>T1 x-axis displacement</td>
<td>0.53</td>
<td>0.50</td>
<td>0.47</td>
</tr>
<tr>
<td>T1 x-axis acceleration</td>
<td>0.56</td>
<td>0.48</td>
<td>0.60</td>
</tr>
<tr>
<td>Head rotation w.r.t. T1</td>
<td>0.45</td>
<td>0.28</td>
<td>0.59</td>
</tr>
<tr>
<td>Head C of G x-axis displacement w.r.t. T1</td>
<td>0.49</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>Head rotation w.r.t. the sled</td>
<td>0.49</td>
<td>0.29</td>
<td>0.62</td>
</tr>
<tr>
<td>Head C of G x-axis displacement w.r.t. the sled</td>
<td>0.62</td>
<td>0.43</td>
<td>0.46</td>
</tr>
<tr>
<td>Overall</td>
<td><strong>0.53</strong></td>
<td><strong>0.41</strong></td>
<td><strong>0.59</strong></td>
</tr>
</tbody>
</table>

The subjective observations have been supported by the results from the objective CORA rating of the biofidelity responses. The overall mean scores from the seven parameters in each of the five data sets show that the Hybrid III had the lowest score (0.41) and the RID\textsuperscript{3D} had the second highest score (0.53). The BioRID II that had the highest score according to the CORA biofidelity assessment, at 0.59.

3.6 Injury Criteria Results

Where possible, the selected injury criteria (NIC, \textit{N}_{km}, \textit{N}_{ip}, LNL and NDC) have been calculated for each dummy and test series. The test series’ replicate testing with volunteers, and with PMHS in the case of the LAB tests. During the volunteer testing no injuries to the subjects were observed or
recorded (other than some discomfort for one subject from the JARI testing). Therefore one would expect the measured criteria values to be below the threshold levels, particularly for the test series other than the LAB testing.

The injury threshold levels that were used for each of the criteria are as follows:

NIC \( 15 \, \text{m}^2\cdot\text{s}^{-2} \)

\( N_{km} \) 1.0

\( N_{ij} \) 1.0

LNL 3.0

NDC corridors with acceptance limits for different dummies

No inappropriate results were found for NIC, \( N_{km} \) or \( N_{ij} \). The LNL threshold was exceeded and the NDC did not seem to rate injury risk appropriately for these test conditions. These results are not able to conclusively confirm or exclude any of the proposed injury criteria that were calculated.

3.7 Summary of Biofidelity Results

- In all of the test conditions selected by WG12 for the biofidelity assessment, the Hybrid III showed performance that was further from the response corridors that define the requirements than the RID\(^{3D}\) and BioRID II. The Hybrid III has insufficient biofidelity for it to be considered further for use as a test tool in the assessment of whiplash injury risk in low-severity rear impact testing.
  - The Hybrid III neck was too stiff.
  - The Hybrid III seat back interaction was not human-like.
  - The Hybrid III responses were often far from the biofidelity corridors and had a different form, especially in the LAB test conditions, which are the closest to any likely regulation test in terms of acceleration pulse severity.

- In many parameters from the whole test programme, the BioRID II and RID\(^{3D}\) were similarly close to meeting the biofidelity requirements.

- The CORA rating system for comparing response curves with corridor requirements was used to obtain an objective interpretation of the biofidelity results. Overall scores were produced giving equal weighting to each of the five test series conducted and the seven parameters which were judged to be the most important for the assessment of biofidelity. The results ranked the Hybrid III as having the lowest biofidelity score (0.41). Whilst the results for the BioRID II and RID\(^{3D}\) were close, it was the BioRID II that had the highest score according to the CORA rating, at 0.59. The RID\(^{3D}\) had an overall score of 0.53 from the seven key parameters assessed in the five test series.

- The BioRID II head restraint and seat back interaction were the most human-like when assessed under the TRL test conditions.

- It is recommended that, based on the currently available biofidelity data, the BioRID II is the most suitable dummy for use in a rear impact test procedure.

- No inappropriate results (i.e. where suggested injury thresholds were exceeded) were found for NIC, \( N_{km} \) or \( N_{ij} \) in these biofidelity tests in which the volunteers were uninjured. The LNL threshold was exceeded and the NDC did not seem to rate injury risk appropriately for these test conditions. These results are not able to conclusively confirm or exclude any of the proposed injury criteria that were calculated.
4 Summary of Literature Review of Hybrid III Biofidelity

The Hybrid III dummy was developed by General Motors Corporation in the 1970s, and the development of the dummy is summarised in Backaitis and Mertz [1994]. It is a high-speed front impact dummy that has been used in front impact regulations (e.g. FMVSS 208 and ECE Reg 94) and consumer testing (e.g. NCAP) world-wide for many years. The neck design requirements for the Hybrid III included rear impact, with a torque-angle performance target for hyper extension [Mertz and Patrick, 1971].

The dummy has a flexible (steel cable and rubber) lumbar spine (the lower part of the back), a rigid steel thoracic spine (the main, upper part of the back) and a flexible neck. In an effort to improve the low-speed rear impact response of the Hybrid III several new necks were developed (the RID neck [Svensson and Lövsund, 1992] and the TRID neck [Thunnissen et al., 1996]).

One study [Prasad et al., 1997] found that the Hybrid III met the original rear impact neck design target from Mertz and Patrick [1971], which was based on dynamic tests with one volunteer and with two PMHS at two speeds, plus quasi-static volunteer tests. However this requirement is limited to head rotations only, which is not an adequate measure for the neck kinematics themselves. Viano and Davidsson [2002] found that both the BioRID P3 (an early version of the BioRID II dummy) and the Hybrid III closely simulated the neck kinematics relative to T1. Given the poor T1 rotation biofidelity of the Hybrid III identified by Davidsson et al. [Davidsson et al., 1999a; Davidsson et al., 1999b], this implies that the overall biofidelity of the Hybrid III is inadequate when interaction with the seat is considered.

The remainder of the evidence reviewed (nearly 20 publications) showed that the Hybrid III is not biofidelic in low-speed rear impacts and should not be used to test seats in these conditions. For some seat designs, some head-neck motion and force parameters are reasonably good compared with a human occupant, but this is dependent on the particular interaction between the Hybrid III back (the shoulders and/or the thoracic spine) and the seat back. All studies that have specifically examined the interaction between the Hybrid III and the seat back have found that the interaction is not at all human-like due to the rigid thoracic spine of the dummy. In order to ensure that the dummy interacts with the seat in the same way as a human in a low-speed rear impact, and thereby to ensure that the assessment of the seat is reliable and the prediction of injury savings is robust, the dummy used should have a more flexible spine than the Hybrid III.

In a joint report [Hynd, 2007], WG12 and WG20 noted that the primary benefit of a dynamic test of head restraint geometry is that reactive head restraint systems can be fairly and adequately assessed. These restraints are actuated by the inertia of the occupant loading the seat back and pushing an arrangement of levers that move the head restraint forwards and, typically, upwards. This moves the head restraint from an unfavourable geometry to a favourable geometry before head contact occurs. In order for such a dynamic test to be meaningful, the dummy must load the seat back (and therefore load the reactive part of the head restraint mechanism) in a manner equivalent to a human occupant. The relevant biofidelity studies all show that the interaction of the rigid thoracic spine of the Hybrid III with the seat back is not humanlike. As a result, there is a very real risk that a reactive head restraint would deploy less effectively for a human occupant than when tested with the Hybrid III, or even not deploy at all.

There is evidence that it is possible to design a better seat using the Hybrid III - some seats that have been developed with the Hybrid III have been shown to reduce whiplash insurance claims. However, developing an effective seat using the Hybrid III requires an understanding of the limitations of the dummy in low-speed rear impact loading conditions and compensation for these limitations in the design process. It is not possible, in a regulatory test procedure, to ensure that appropriate compensation is made. It is therefore possible to design a seat that meets a given regulatory requirement based on the Hybrid III measurements that will have no real-world benefit for some or all occupants. In addition, the literature reviewed indicates that it would even be possible to develop an active head restraint that would be disbeneficial to a real-world occupant compared with a good static geometry. For instance, protection could rely on a reactive head restraint that is actuated quickly and moves forward and upwards by a large amount when loaded by the rigid spine of the Hybrid III.
dummy, but which may move to a lesser extent and later in the impact event when loaded by a human occupant with a flexible spine. Test data showing inadequate activation of a reactive head restraint when the seat is occupied by a more biofidelic dummy (BioRID II) have been published [Minne, 2006]; the same seat shows very efficient activation of the reactive head restraint when the Hybrid III dummy is used in the test.

It was concluded that the poor biofidelity of the Hybrid III in low-speed rear impact conditions could send head restraint design in the wrong direction and reduce the level of whiplash protection offered to car occupants. The Hybrid III is therefore not appropriate for whiplash protection testing.
5 Summary of Findings

5.1 TRL Biofidelity Testing

A total of nine tests were conducted at TRL, three with each of the BioRID II, RID3D and Hybrid III, recreating the conditions used for low speed rear impact tests conducted previously with volunteers. A comparison of the sled acceleration pulses suggests that the volunteer test conditions were recreated well with each of the three dummies.

5.1.1 Dummy Biofidelity

- The BioRID II head displacement and rotation were clearly better than those of the other dummies in this test condition and it is very likely that at comparable speeds it would engage an active head restraint in the same way as a human.
- The BioRID II seat back interaction was the best of the three dummies, although it could still be improved.
- The RID3D head vertical motion was not sufficient at the test speed used, but it is not known what effect an increase in speed would have on the dummy’s motion. Other aspects of the RID3D motion were good, in terms of how well they replicated the motion of the human volunteers tested in this configuration.
- The Hybrid III motion was generally not human-like, especially in terms of T1 motion; in particular, the timing of its kinematics differed to those of the volunteers.
- The Hybrid III head restraint interaction was found to be unsuitable in that although it just made contact with the head restraint, it exerted a much smaller force compared with the volunteers. This interaction affected the Hybrid III instrumentation readings; therefore the Hybrid III should not be used for the assessment of head restraints designed to reduce the risk of WAD injuries.
- None of the dummies were able to replicate the vertical head relative to T1 motion (neck stretching) seen in the volunteers but it is not known how crucial this is in the generation or prediction of WAD injuries.
- Of the injury criteria assessed, only NIC can be used with all three dummies for injury assessment for the TRL test speed, based on the results obtained. LNL should be investigated further and actual injury risk values are required for this criterion. Intercept values for \( N_{ij} \) and \( N_{km} \) should be calculated for the RID3D and BioRID II and injury risk tolerances should be calculated for these criteria as they may have potential for assessing injury risk due to neck motion during the rebound phase of an impact.

5.1.2 Dummy Repeatability

- The BioRID II and RID3D dummies had appropriate repeatability for the limited number of tests conducted.

5.1.3 Dummy Handling

- The rear impact specific dummies were more difficult to use and position than the Hybrid III, in that they could only be lifted by a suitable harness and needed suitable neck protection in place.
- Both rear impact dummies were relatively easy to instrument.
- The RID3D requires an updated users’ manual and the BioRID II requires a clearly defined and documented positioning procedure.
The RID\(^{3D}\) back flesh is a particular problem in that it must be removed and allowed to recover between tests and then put back into position before the dummy can be put in place for testing.

5.2 EEVC WG12 Biofidelity Evaluation Programme

The analysis of the TRL tests has been combined successfully with the test results and analyses from testing at other laboratories, on behalf of the European Enhanced Vehicle-safety Committee Biomechanics (EEVC WG12). The three candidate rear impact dummies have been evaluated in all five of the identified biofidelity assessment conditions selected by EEVC WG12.

- In all of the test conditions selected by WG12 for the biofidelity assessment, the Hybrid III showed performance that was further from the response corridors that define the requirements than the RID\(^{3D}\) and BioRID II. The Hybrid III has insufficient biofidelity for it to be considered further for use as a test tool in the assessment of whiplash injury risk in low-severity rear impact testing.
- The Hybrid III seat back interaction was not human-like.
- The Hybrid III responses were often far from the biofidelity corridors and had a different form, especially in the LAB test conditions, which are the closest to any likely regulation test in terms of acceleration pulse severity.
- In many parameters from the whole test programme, the BioRID II and RID\(^{3D}\) were similarly close to meeting the biofidelity requirements.
- The CORA rating system for comparing response curves with corridor requirements was used to obtain an objective interpretation of the biofidelity results. Overall scores were produced giving equal weighting to each of the five test series conducted and the seven parameters which were judged to be the most important for the assessment of biofidelity. The results ranked the Hybrid III as having the lowest biofidelity score (0.41), followed by the RID\(^{3D}\) (0.53), and with the BioRID II having the highest biofidelity rating of the dummies tested (0.59).
- The BioRID II head restraint and seat back interaction were the most human-like when assessed under the TRL test conditions.
- None of the dummies has been able to replicate the T1 vertical motion seen in the human volunteers in any of the test conditions assessed so far.
- It should be noted that the biofidelity requirements are all at a relatively low impact severity compared with real-world rear impacts in which whiplash symptoms are reported.
- No inappropriate results (i.e. where suggested injury thresholds were exceeded) were found for NIC, N\(_{km}\), or N\(_{ij}\) in these biofidelity tests in which the volunteers were uninjured. The LNL threshold was exceeded and the NDC did not seem to rate injury risk appropriately for these test conditions. These results are not able to conclusively confirm or exclude any of the proposed injury criteria that were calculated.

5.3 Other EEVC WG12 Conclusions

- General requirements for a rear impact dummy were proposed by EEVC WG20 and were reviewed by WG12. The requirements include suggestions for anthropometry, likely test severities, temperature sensitivity, and repeatability and reproducibility.
- Proposed injury criteria for use in assessing whiplash injury risk were assessed by WG12 based on the biomechanical basis for the criterion, the applicability to dummy measurements and the availability of an injury risk function. The five criteria considered were N\(_{ij}\), N\(_{km}\), LNL, NDC and NIC. N\(_{km}\) and NIC\(_{\text{max}}\) were evaluated more thoroughly than the other criteria and these are the only two criteria with established injury risk curves.
None of the criteria reviewed have a definite biomechanical basis and their validity in predicting the risk of injury needs to be established. None of the criteria can be recommended on a strictly biomechanical basis.

Several of the proposed injury criteria make sense mechanically and could be evaluated further if the strict biomechanical requirement (that requires identification of the injury) is relaxed. For instance, these parameters may be suitable for use as a seat evaluation criterion, rather than an injury criterion.

Conclusions regarding the repeatability and reproducibility of the BioRID II, RID3D and Hybrid III in low-speed rear impact test conditions are expected from WG12 shortly; these may affect the recommendation regarding the most appropriate dummy to use in these test conditions.

A review of the literature found that the poor biofidelity of the Hybrid III in low-speed rear impact conditions has the potential to reduce the effectiveness of head restraints by encouraging active head restraints to be optimised for the dummy such that they may be less effective for a human occupant. The Hybrid III is therefore not appropriate for low-speed rear impact whiplash protection testing.
6 Conclusions

- The results of the TRL testing, the EEVC research and the literature review all agreed that the Hybrid III was not sufficiently biofidelic to be used effectively as a tool in a rear impact test. In particular, its poor representation of seat back loading could encourage inappropriate designs of active head restraint to be used which could potentially have an adverse effect on the level of whiplash protection offered.

- Although the biofidelity performance of the RID$^{3D}$ and BioRID II dummies was relatively close and there was some variation between the results in different tests, overall the combined data from the TRL and EEVC tests tended to suggest that the BioRID II dummy was the most suitable based on biofidelity considerations.
7 Recommendations

- It is recommended that the Hybrid III has insufficient biofidelity for it to be considered further for use as a test tool in the assessment of whiplash injury risk in low-severity rear impact testing.

- It is recommended that, based on the currently available biofidelity data, the BioRID II is the most suitable dummy for use in a low-speed rear impact test procedure. However, it should be noted that the BioRID II T1 vertical motion could be improved upon and this may have a direct effect on its ability to detect injury potential (i.e. the BioRID II lower spine may be too stiff, whilst the neck behaves as if it is too soft under certain loading conditions; modifications to these areas should produce a more human-like response).

- The biofidelity of the BioRID II and RID\textsuperscript{3D} may be similar at the conditions selected for the rear impact test procedure(s) as chosen by EEVC WG20. The repeatability and reproducibility of the dummy used in such a test procedure will also be important. Therefore, to help select the most appropriate rear impact dummy for the test procedure, it is recommended that the results from the EEVC WG12 repeatability and reproducibility testing conducted at BASt be taken into consideration.

- It was found that the BioRID II showed a more human-like seat back pressure distribution on the TRL test bench. However to increase the relevance of these findings for the WG12 dummy selection, it is recommended that pressure profile investigations are extended to include standard car seats, such as may be assessed in the test procedure for which the rear impact dummy is being selected.
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References


Abstract

Neck injuries, even those with a minor threat to life, are associated with huge costs for society. The cost to European society is estimated to be between € 5 billion and € 10 billion per year. Consequently, it is understood in most industrialised countries that whiplash injuries constitute a serious problem with implications for the individual as well as for society as a whole. At the same time, it is recognised that progress in injury mitigation could be achieved by improving the use, design and efficiency of seats and head restraints in vehicles. An appropriate test procedure adopted into a standard would ensure that seat systems are optimised to reduce the risk of whiplash injury in low-severity rear-end collisions.

As part of a programme of work for the European Enhanced Vehicle-safety Committee (EEVC), TRL has undertaken two pieces of work for the UK Department for Transport that are both summarised in this report. The first part of this project was to evaluate the biofidelity of the latest versions of the RID3D, BioRID II and Hybrid III rear impact crash test dummies against previously defined performance requirements. This testing then formed the UK contribution to a wider programme of research carried out by the EEVC Biomechanics Working Group to evaluate those dummies. To assist with this wider programme, the second objective of this project was to collate the results from other contributors and synthesise them (together with the TRL results) into a report for the EEVC.

The information from the UK and from WG12 was then used to produce a final report on the suitability of these dummies for use in a regulatory rear impact test procedure and to make recommendations as to any further developments which may be required in order to develop a suitable dummy for such a procedure.

The key conclusions from the dummy evaluation were, that:

- A review of the literature found that the poor biofidelity of the Hybrid III in low-speed rear impact conditions has the potential to reduce the effectiveness of head restraints by encouraging active head restraints to be optimised for the dummy such that they may be less effective for a human occupant.
- In all of the test conditions selected by WG12 for the biofidelity assessment, the Hybrid III showed performance that was further from the response corridors that define the requirements than were the RID3D and BioRID II.
- In many parameters from the whole test programme, the BioRID II and RID3D were similarly close to meeting the biofidelity requirements.
- The BioRID II head restraint and seat back interaction were the most human-like when assessed under the TRL test conditions.

The key recommendations from the work are, that:

- The Hybrid III has insufficient biofidelity for it to be considered further for use as a test tool in the assessment of whiplash injury risk in low-severity rear impact testing.
- Based on the currently available biofidelity data, the BioRID II is the most suitable dummy for use in a low-speed rear impact test procedure.
Evaluation of dummies for low-speed rear impact ‘Whiplash’ testing - Final report

Neck injuries, even those with a minor threat to life, are associated with huge costs for society. The cost to European society is estimated to be between €5 billion and €10 billion per year. Consequently, it is understood in most industrialised countries that whiplash injuries constitute a serious problem with implications for the individual as well as for society as a whole. At the same time, it is recognised that progress in injury mitigation could be achieved by improving the use, design and efficiency of seats and head restraints in vehicles. An appropriate test procedure adopted into a standard would ensure that seat systems are optimised to reduce the risk of whiplash injury in low severity rear-end collisions.

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