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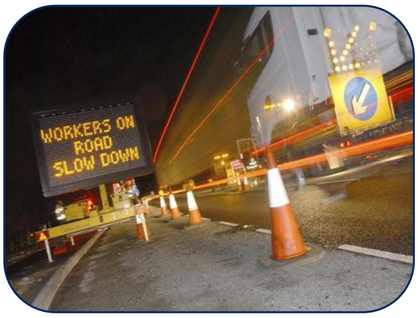

CLIENT PROJECT REPORT CPR1302

Global Impact Dummies - Application of BioRID II in UNECE Regulation No17

Final Report

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Executive Summary

Rear impact crash protection is currently legislated for in Europe by EC Directives 2005/39/EC (amending 74/408/EEC), 96/37/EC, 81/577/EEC, 78/932/EEC and 74/408/EEC, and UNECE Regulations 17 and 25. These control the height and strength of head restraints, the strength of seat backs, the energy absorbing capacity of head restraints and the rear surface of seats, as well as various other aspects of seat performance. Some, but not all, of these requirements are related to rear impact safety. Under the terms of the recently adopted General Safety Regulation, the existing Directives will be repealed and replaced by direct reference to the appropriate UNECE Regulations and their contents in 2014.

In addition to these requirements, Global Technical Regulation 7 (Head Restraints) was established on the Global Registry in 2008. GTR-7 includes static requirements on head restraint geometry, and performance requirements in a dynamic rear impact test procedure using the Hybrid III crash test dummy. Further work is on-going to update GTR-7 to include a dynamic test of seat performance using the BioRID II dummy, which has a more humanlike response than the Hybrid III dummy in low-speed rear impact loading conditions.

In the interim, the EC and Japan proposed an amendment to UNECE Regulation No.17 to incorporate a dynamic test of head restraint geometry using the BioRID II rear impact dummy. The proposal is based on a test procedure concept developed by TRL on behalf of the UK Department for Transport (DfT) as part of its contribution to the work of EEVC WG20. The test involves measuring the relative motion of the head and torso of the BioRID II dummy in a seat-back co-ordinate system, using marker tracking from high-speed film of the test.

At the time that the dynamic geometry test procedure was proposed by WG20, it was acknowledged that further validation work was required before the concept could be considered as ready for use in a regulation. In particular, the repeatability and reproducibility of the test procedure was not fully assessed and there was no performance requirement for the dynamic geometry metric. Furthermore, it was identified that a proper calibration of the marker tracking process was required to ensure that the measurement was of suitable quality. The calibration should include consideration of the camera/lens combination, depth-correction processing and the marker tracking software in combination as an instrument, and should be analogous to calibrating any load cell or accelerometer used for legislative testing.

The objectives of this project are to provide the evidence base for the use of the dynamic geometry test procedure in legislative testing, and to validate the calibration of marker tracking systems so that the dynamic geometry measurements are of equivalent, traceable robustness to conventional load cell or accelerometer measurements. The specific objectives are:

- Document the current status of the validation of the dynamic geometric test procedure and measurement criteria;
- Document any gaps in the validation of the procedure, and identify the further work that would be required to address any gaps;

- Assess the robustness of the calibration procedure for the marker tracking process (including the camera, lens, and software) that will ensure reproducible measurements from laboratory to laboratory.

The project involved a review of the literature regarding validation of the dynamic geometry metric, and a theoretical assessment of the likely effect of different types of error on the measurement of the metric using marker tracking. The reproducibility of the metric was assessed using test data from the project reported in CPR1303: ‘Global Impact Dummies - Assessment concerning BioRID II in Future Regulatory Applications’. Standards for the calibration of high-speed cameras and marker tracking systems were assessed in small-scale laboratory experiments, and the use of ISO 8721 was trialled in the main BioRID II dummy evaluation test programme as reported in CPR1303.

The conclusions of the work were:

Validation of the dynamic geometry metric

Performance requirement:

- A pass-fail threshold for the dynamic geometry metric of 52 mm has been proposed by Japan that directly relates the dynamic measurement to the equivalent static backset measurement for standard seat types. This proposal meets the original objective for the metric, which was to enable the dynamic assessment of head restraint geometry and thereby make the specification of head restraint geometry less design restrictive. The pass-fail threshold also correlated well with insurance industry whiplash ratings for seats.
- The pass-fail threshold was developed for a 15.7 km.hr^{-1} pulse, but consideration could be given to using the 17.6 km.hr^{-1} pulse proposed for the draft GTR-7 Phase 2.

Assessment of reproducibility

- In the project reported in CPR1303, tests were performed using four different BioRID II dummies in a repeatable laboratory seat. The seat was based on a production car seat, with an external mechanism to control the recline angle.
- The coefficient of variation (CV) of the dynamic geometry metric in these tests was 12%. This is close to the target CV of ≤ 10%, despite significant variations in the ramping-up behaviour of the four dummies that were tested.
- It should be noted that the dynamic geometry metric for the seat used in this study was 20 mm which is much less than the threshold proposed by Japan of 52 mm. Therefore, although the CV relative to the measured metric (i.e. 20 mm) is 12%, relative to the pass-fail threshold proposed by Japan it may be much less than 10%.

A number of issues were identified that required further validation:

- The assessment of seats with a single-sided recliner mechanism; the backs of these seats may twist during testing, which may affect the datum used for the dynamic geometry metric.

- Determination of the BioRID target backset, which is used when setting-up the dummy prior to testing. The GTR-7 Phase 2 Informal Group is working to improve the specification of the 3DH machine and HRMD to improve the reproducibility of this measurement, and it is recommended that the progress of Group is monitored.

Calibration of camera-based marker tracking systems

- A theoretical analysis of calibration requirements suggested that random measurement errors are likely to dominate over any systematic errors. As long as the data is filtered to remove some of the variation caused by the random error, the accuracy of the calculated peak dynamic geometry metric will be comparable to the accuracy of the marker position measurements.
- The ISO 8721:2010 standard was to a large extent found to be suitable for checking the accuracy of off-board camera-based marker tracking systems used to measure the dynamic geometry metric
    - Further work would be required to develop a method for applying the standard to the calibration of on-board camera systems
- In the context of measuring the dynamic geometry metric, the standard may be unnecessarily complex in some respects. Consideration should be given to referencing a sub-set of the requirements in the standard, e.g.
    - The Control Point Distribution index may be unnecessary
    - Target Size index is considered as met, provided that:
        - The markers tracked for measurement are at least as large and of the same pattern as the reference distance markers; and
        - The lighting for the markers tracked for measurement and the reference distance markers is comparable
    - The Target Detection index may be unnecessary
- A suitable accuracy index must be specified. The testing programme reported herein used a requirement of 5 mm (approximately 10% of the proposed dynamic geometry threshold), which was achievable and may be considered adequate.

1 Introduction

The EC and Japan have proposed an amendment to UNECE Regulation 17 based on a concept test procedure developed by TRL on behalf of the UK Department for Transport (DfT) as part of its contribution to the work of EEVC WG20. The concept involves measuring the motion of the BioRID II dummy head relative to the torso in a dynamic rear impact sled test. This is measured in a seat-back co-ordinate system, using marker tracking from high-speed film of the test, and is known as the dynamic geometry test procedure. The concept was proposed as an alternative to the Hybrid III test procedure contained in the first phase of Global Technical Regulation number 7 (GTR-7 Phase 1). The principal reason for the proposal is to take advantage of the much better biofidelity of the BioRID II dummy compared with the Hybrid III in low-speed rear impacts, as well as the more humanlike interaction of the BioRID II with seat structures such as those used to actuate reactive head restraints. This makes it more likely that a reactive head restraint mechanism will work with a human occupant, not just the test dummy.

At the time that the dynamic geometry test procedure was proposed by WG20, it was considered to be a very promising concept based on the initial validation work that had been undertaken at that time. However, it was acknowledged that further validation work was required before the concept could be considered ready for application in legislative testing. In particular, the repeatability and reproducibility (R&R) of the test procedure was not fully assessed, and it was identified that a proper calibration of the marker tracking process was required. This calibration should include consideration of the camera/lens combination, depth-correction processing and the marker tracking software in combination as an instrument, and should be analogous to calibrating any load cell or accelerometer used for legislative testing.

Furthermore, there were aspects of the dynamic geometry concept that were undefined at the time that it was proposed. These included the seating procedure to be used, the use of a fixed torso angle (e.g. 25°) or the manufacturer’s design angle, and so forth. More recently it has also been identified that the BioRID II dummy may not be suitable for testing seats with a torso angle less than 20°, which would complicate the use of the manufacturer’s design angle for some seats.

1.1 Project Objectives

The objectives of this project are to provide the evidence base for the use of the dynamic geometry test procedure in legislative testing, and to validate the calibration of marker tracking systems so that the dynamic geometry measurements are of equivalent, traceable robustness to conventional load cell or accelerometer measurements. The specific objectives are:

- Document the current status of the validation of the dynamic geometric test procedure and measurement criteria;
- Document any gaps in the validation of the procedure, and identify the further work that would be required to address any gaps;
- Assess the robustness of the calibration procedure for the marker tracking process (including the camera, lens, and software) that will ensure reproducible measurements from laboratory to laboratory. The calibration procedure should be

equivalent to that specified for other dummy measurements such as accelerations, including calibration of the transducer and data acquisition system.

2 Validation of the Dynamic Geometry Test Procedure

2.1 Introduction

The dynamic geometry (or ‘dynamic backset’) concept was proposed by the UK to the EEVC as part of the UK contribution on rear impact (whiplash) safety research. The concept was developed by TRL as part of a project for the UK Department for Transport that examined a number of existing and potential future options for measuring head restraint geometry in a dynamic test procedure (Hynd and Carroll, 2008). Extensive marker tracking analysis of existing films from Insurance Institute for Highway Safety (IIHS) consumer information and Euro NCAP Technical Working Group tests was undertaken. This work demonstrated the feasibility of using marker tracking to assess the rearward motion of the head relative to the torso, and that this dynamic geometry metric had reasonable repeatability and reproducibility. It also demonstrated that the dynamic geometry metric ranked four seats that had been tested by IIHS in the same order as the full IIHS test and rating procedure. This last assessment was previously used to demonstrate the suitability of the updated FMVSS 202a regulation in the US.

It was concluded that the dynamic geometry test was very promising as a way of controlling head restraint geometry in a dynamic test procedure. However, it was acknowledged that the work was subject to a number of limitations, including:

- The film analysis was performed using existing film stock primarily from tests that were not intended to provide film for detailed marker tracking analysis. In particular, the set-up and images were not controlled properly for the distance of the markers from the camera. This was likely to be an important factor given that some of the cameras were mounted on the sled (and therefore very close to the seat and dummy) and some were mounted off-board (and therefore potentially much further from the seat and dummy). This leads to different amounts of parallax error for the two camera set-ups, plus on board cameras need additional markers fixed to the sled in order to compensate for vibration of the camera during the impact.
- For most of the tests, the cameras, lenses, laboratory set-up (camera mounting, lighting etc.), and the marker tracking software were not calibrated. Without calibration, each of these components could be associated with increased uncertainty in the measurements made. The combination of these uncertainties gives an unknown inaccuracy to the results.
- No criterion (pass-fail threshold) for the dynamic geometric criterion was proposed. It was recommended that a threshold be developed based on comparison with long-term whiplash injury insurance claims for selected seats.

The proposal for a dynamic geometry metric using BioRID II as an alternative to the similar metric using Hybrid III was not taken forward in the GTR Phase 1 discussions. However, it was subsequently proposed as an update to UN Regulation No.17 by Japan and the European Commission, with the aim of providing a test for dynamic (e.g. reactive) head restraints that cannot be assessed adequately by static geometry alone. This proposal was subsequently withdrawn, following the start of this project. However, it was recognised that the dynamic geometry metric may be of interest for the GTR-7

Phase 2 Informal Group, and the investigation of camera and marker tracking calibration may be relevant to GTR-7 and other regulations. For instance, camera data is used to determine head excursion in UN Regulation No.44, but there are very limited requirements on the calibration of the camera system. This is in contrast to all of the other measurements made in this type of test procedure, where the calibration of accelerometers, load cells and other instrumentation is very tightly controlled.

A number of key parameters may need to be considered before the dynamic geometry metric could be used in a Regulation. Many of these, such as the selection of a suitable pulse, have direct parallels with decisions and on-going discussions in the Informal Group on GTR No.7 Phase 2, so a brief review of the status of these discussions is included in this report. These parameters include:

- The selection and definition of the sled acceleration pulse for dynamic geometry testing, and the use of deceleration vs. acceleration sleds
- The seating procedure for the BioRID II dummy defined in the text of the proposal, which is different to that used in consumer information testing (e.g. Euro NCAP) and is likely to be different to that used for GTR-7;
- The implications of using a fixed 25° torso angle (currently used for most BioRID II consumer information testing except JNCAP) compared with the manufacturer's design angle (typically used in UN Regulations and used in JNCAP)

Issues that may be considered specific to the dynamic geometry metric include:

- The evidence that could be used to recommend a pass-fail limit for the dynamic geometry metric
- Repeatability and reproducibility of the dynamic geometric metric;
- The effectiveness of measurements made on seats with a single recliner *cf.* a dual recliner (single recliner seats will have different seat recline angles for the left and right side of the seat);

The level of validation of the dynamic geometry test procedure in the original study by Hynd and Carroll is reviewed in Section 2.2. Section 2.3 reviews the subsequent validation of the procedure. Sections 2.4 to 2.6 consider further some of the specific issues noted above.

2.2 Validation in the Original EEVC Proposal

Limited validation of the dynamic geometry test procedure was conducted in the original EEVC study (Hynd and Carroll, 2008; see also HR-10-7 on the GRSP web site). Two aspects of the test procedure were assessed:

- Reproducibility
- Comparison of the dynamic geometry metric with other seat performance measures

2.2.1 Reproducibility

As noted in Section 2.1, the EEVC study used films of low-speed (16 km.hr^{-1}) rear impact tests at five European laboratories, with a mixture of on-board and off-board camera systems, as a preliminary assessment of reproducibility. None of the films were taken with the intention of calculating the dynamic geometry metric, so marker placement and lighting conditions were variable. Furthermore, no calibration information was available for any of the tests, so it was not known what, if any, correction had been made for lens distortion, camera orientation, or camera distance from the markers.

Nevertheless, despite the use of five dummies, from five laboratories, with two deceleration and three acceleration sleds, and two on-board and two off-board cameras, with no calibration data, and production seats, the reproducibility was encouraging. All of the seats assessed had a very similar response shape, and each of the three seats assessed had a distinctive response magnitude, with no overlap with the other seats. Given the range of variables in the assessment, and the lack of control on camera and marker set-up, this was considered to be encouraging.

2.2.2 Comparison with other Seat Performance Measures

Further to the initial assessment of reproducibility, Hynd and Carroll (2008) compared the dynamic geometry metric with insurance whiplash ratings for four seats published by IIHS. These seats were chosen because they were used by Voo *et al.* (2007) to assess the Hybrid III in low-speed rear impacts, and because the test data were available from IIHS. It was found that three seats rated ‘Good’ by IIHS had dynamic geometry measurements between 10 and 20 mm, while a seat rated ‘Acceptable’ had a dynamic geometry measurement of nearly 60 mm. The dynamic geometry metric correlated well with the insurance rating for these four seats.

Clearly, a larger study than this would be preferred. The comparison with consumer information ratings for seats assumes that the ratings are a reliable guide to whiplash injury risk. If this assumption is correct the comparison also indicates that the dynamic assessment of geometry has greater potential for reducing injury risk, while being less design restrictive than a static assessment of geometry. For instance, reactive head restraints are designed to have a larger backset in normal use, and then move forward in a rear impact (driven by the inertia of the occupant loading a mechanism in the seat back). This means that a reactive head restraint may have a larger backset in a static test, but a smaller backset during a rear impact.

Also, the original goal was to develop a geometric assessment that would be equivalent to the Hybrid III assessment used in GTR-7 Phase 1, which is a lower level of validation than comparison with dynamic seat assessments. A direct comparison between static and dynamic geometry for a range of seats may also be useful. Finally, if it was of interest to use the dynamic geometry metric as an injury assessment, rather than a simple control on head restraint geometry, it would be best to make a direct comparison with the presence or absence of injury in volunteer and PMHS tests. This is outside the scope and intention of the original proposal, but recent presentations from Japan and the US in the GTR-7 Informal Group (see presentations from the March 2012 Informal Group meeting on the UN GRSP web site; not available at the time of writing, so presentation numbers are not yet available) suggest that head-to-neck rotation and possibly head-to-neck displacement may be well correlated with injury risk in accident simulations and PMHS tests.

Finally, Hynd and Carroll compared the dynamic geometry metric for Volvo and Saab seat designs before and after the introduction of specific whiplash reduction technologies. In both cases, the dynamic geometry metric was lower in the seat that was designed to reduce whiplash. This was taken to indicate that the metric was sensitive to the design of the seat.

It should be reiterated that the goal of the original work was to propose a dynamic geometry metric that would be equivalent to the assessment of head restraint geometry made using the Hybrid III dummy in GTR-7 Phase 1. There was no intent to relate the metric directly to injury risk.

2.3 Subsequent Validation

Since the EEVC publication, there has been relatively little new work on this metric. The only work that has been identified has come from Japan, in support of the proposal to update UN Regulation 17. This has been in the form of a number of presentations to GRSP, each more recent presentation updating the information in preceding presentations. The most recent document was presented at the 44th GRSP (document number GRSP-44-24, December 2008; superseding document number GRSP-43-20, May 2008) and is reviewed below.

This presentation gives an overview of the rationale for the proposed update to UN Regulation No.17, which is to allow an alternative to the static test of head restraint geometry for seats with active, reactive and pre-active head restraints. It was noted that this could deliver the same benefits as the static test while being less design restrictive. The presentation defines 'dynamic backset', which is the same as the dynamic geometry metric defined by Hynd and Carroll.

The presentation then compared neck loads, NIC, Nkm and other parameters commonly used to assess seats in low-speed rear impacts, with static backset. It was noted that this comparison was based on a Madymo simulation study, but no further information was given. However, it was reported that the 'dynamic backset' had the best correlation with static backset in the simulation study. The R^2 value of 0.99 indicates a very good correlation with static backset and supports the original objective of the metric, which was to provide a dynamic assessment of head restraint geometry using the BioRID II dummy.

The Coefficient of Variation (CV) of the 'dynamic backset' and many other BioRID II dummy measurements was assessed. The assessment appears to have been for three dummies in three seat types: 'normal', 'passive' and 'reactive', but it is not clear how many seats of each type were used. The CV was variable for the different seat types, but the 'dynamic backset' measurement was reported to have a worst-case CV of approximately 6.5% in these tests, which is well within the target CV of 10% recommended by ISO. This was also better, and in some cases much better, than the CV for the other parameters that were assessed.

Finally, the presentation made a recommendation for a pass-fail threshold for the 'dynamic backset' metric. Two methods were used to develop the recommendation, based on tests with 31 seats, including the data presented by the EEVC (Hynd and Carroll, 2008). The seats were rated as follows by IIHS, based on the IIWPG test procedure:

- 10 rated 'Good'

- 4 rated ‘Acceptable’
- 6 rated ‘Marginal’
- 11 rated ‘Poor’

The 31 seats tested included the following seat types:

- 11 ‘Normal’ seats (with no specific whiplash mitigation technologies)
- 10 seats with ‘Reactive’ head restraints (where the inertia of the occupant forces the head restraint forward via a mechanism in the seat back)
- 9 ‘Passive’ seats (e.g. the Toyota WILS design)
- 1 ‘WHIPS’ seat (with an energy absorbing recliner mechanism)

Firstly, the ‘dynamic backset’ measurement for each seat was compared with the static backset measurement for all seats classified as ‘normal’, and a best-fit line (passing though the origin) applied to the data. Based on this best-fit line, the static backset requirement of 55 mm was equivalent to a dynamic backset of 48 mm. The scatter in the data was quite large, and no R^2-value was provided for the best-fit line. It is assumed that the best-fit was only applied to the ‘normal’ seat data, because ‘passive’ and ‘reactive’ seat types may be intended to have smaller dynamic backsets than static backsets.

Secondly, a ‘dynamic backset’ threshold of 48 mm was compared with the IIHS rating for each seat that had been tested. It was observed that a 48 mm threshold would pass all seats rated ‘Good’ by the IIHS, and fail most seats rated ‘Poor’ or ‘Marginal’; one seat rated ‘Acceptable’ would also be failed. It should be noted that a slightly lower threshold of 45 mm would fail all ‘Poor’ and ‘Marginal’ seats, while retaining all seats rated ‘Good’.

Finally, a threshold of 52 mm was proposed, comprised of the 48 mm noted above, plus a 4 mm allowance for measurement variation. The 4 mm allowance seems to be derived from the standard deviation of the ‘Normal’ seats, which was larger than that for the ‘Passive’ and ‘Reactive’ seats.

In summary, the information in document GRSP-44-24 takes the validation of the dynamic geometry metric several steps forward from the original proposal by the EEVC. The repeatability and reproducibility of the metric were assessed and found to be good, and better or much better than typical upper neck forces and moments measured in the BioRID II dummy. A proposal was also made for a pass-fail threshold to be used with the dynamic geometry metric. The threshold was reported to be equivalent to the H-point-based static backset requirement, based on tests with 11 ‘normal’ production seat types. The threshold was also reported to have a reasonable correlation with IIHS seat ratings, with all ten seats tested in the study that were rated ‘Good’ passing the proposed threshold, and most seats rated ‘Marginal’ or ‘Poor’ being failed.

The provision of information on the repeatability and reproducibility of the dynamic geometry metric and the proposal of a threshold for the metric address key limitations of the original study by Hynd and Carroll. However, there is only limited information available within the presentation. For example, the exact build-level and certification-level of the dummies used is not defined in this presentation, and the dummies may not have complied with the latest build and maintenance checklists defined by the Informal Group. More detailed information on the evaluation programme would therefore be useful.

2.4 R&R

Document GRSP-44-24 reports very encouraging information on the repeatability and reproducibility of the dynamic geometry metric, based on tests with three dummies in three seat types. Nevertheless, it was planned to conduct a review of general kinematic repeatability and reproducibility of the BioRID II dummy from information in the literature. It was anticipated that the general kinematics of the dummy, including other marker tracking measurements as well as dummy acceleration measurements, would provide supplementary evidence to support the encouraging reproducibility information reported in document GRSP-44-24. This review may be found in Appendix B.

However, since the literature review was completed, the BioRID II test programme for this project has been completed. As reported in Section 5, the reproducibility of the dynamic geometry metric is markedly better than for the head, T1 and pelvis angle data, and Z-axis displacements of the dummy (which is similar to the ramping-up of the dummy). This indicates that there is not necessarily a good correlation between different measurements in terms of their reproducibility, but it also indicates that the dynamic geometry metric is relatively insensitive to the differences between the dummies tested.

2.5 Single *vs.* Dual Recliner

The dynamic geometry metric uses the seat back as a datum. In the dynamic test, this datum rotates (and possibly translates, e.g. the Volvo WHIPS system) throughout the test. This is somewhat analogous to the static measurement, for which the backset is measured at a set seat back angle (e.g. 25°, or the manufacturer's design angle). In fact, the dynamic geometry test offers the advantage that the assessment is not so strongly related to a single seat back angle as the static measurement. The dynamic geometry measurement for a given seat design may be affected by the initial torso angle, because this could affect the effectiveness of reactive head restraint deployment, or the severity of contact between the head and the head restraint, or even the ramping-up of the dummy. However, it is likely that the static measurement is more sensitive to the seat back angle, and that the dynamic measurement offers a more representative assessment of geometry.

However, one obvious potential difficulty with using the seat back as a datum relates to the measurement in seats with a single-sided recliner mechanism. It is understood that these are not common in Europe, but they are relatively common on smaller, cheaper cars in some regions. With a dual-recliner mechanism both sides of the seat would be expected to rotate backwards by the same amount in a rear impact. However, with a single-recliner mechanism one recliner mechanism is replaced by a simple pivot, which has a lower effective stiffness than the recliner mechanism on the other side of the seat. This means that recliner side of the seat will rotate less than the pivot side. Clearly this will lead to a difference in the datum used if either the recliner or pivot side of the seat is viewed by the high-speed camera for marker tracking. If nothing else, this could lead to a reproducibility problem because different laboratories may choose to assess a different side of the seat.

One possible solution is to prescribe that the seat must be filmed from the side with the recliner. This would give the closest match with the measurement made on seats with dual recliners. However, the seat back angle at the mid-line of the dummy would be half way between the seat back angle for the two sides of a single-recliner seat. Also, some laboratories may only be able to place cameras on one side or the other of their sled, so testing some seats would not be possible for some laboratories. Another possible solution would be to film from both sides, and use the mean value, but again this may be impossible in some laboratories and is likely to lead to problems with the lighting in others.

It is possible that the seat back angle for both sides of the seat could be measured using just one camera by mounting markers for the non-visible side of the seat on wands mounted rigidly to the seat frame, somewhat like the T1 and pelvis marker wands on the BioRID II dummy. This would require access to the seat frame in order to ensure that the attachment of the marker wands was rigid, which may mean cutting the seat fabric. When the dynamic geometry metric was originally proposed, some industry commentators indicated that the markers must be attached rigidly to the seat frame in order to ensure an accurate assessment of seat back angle, while others indicated that the markers must not be attached rigidly to the seat frame, because this would require cutting the seat fabric and may therefore change the seat response. This discussion was not resolved because the proposal was not adopted in Phase 1 of the GTR.

It is recommended that the effect of single-recliner mechanisms is checked based on data using a seat that has been filmed from both sides.

2.6 Other Issues

2.6.1 Sled Pulse

The validation data presented by the EEVC and by Japan used the Euro NCAP medium severity pulse, which has a delta-*v* of 15.65 km.hr^{-1}. The EEVC recommended a delta-*v* of 20 km.hr^{-1} (EEVC WG20, 2007) for the assessment of risk of long-term whiplash injury, and the draft GTR-7 Phase 2 test procedure uses a delta-*v* of 17.6 km.hr^{-1} (GTR-7-06-10). The EEVC WG20 recommendation was for either a bi-modal pulse (with two peaks), or a triangular pulse (essentially a scaled-up version of the Euro NCAP medium severity pulse). The pulse in the draft GTR-7 Phase 2 procedure is also a scaled-up version of the Euro NCAP medium severity pulse.

As proposed, the dynamic geometry metric is intended to evaluate the geometry of the head restraint, so it was not directly correlated with injury risk. In this context the sled pulse used may not be critical, provided it is well defined – i.e. with sufficiently tight tolerances that the test results are repeatable and reproducible.

However, the threshold for a dynamic geometry metric may be related to the severity of pulse. For instance, if the head-to-head-restraint contact forces are higher in a higher severity test, then the head restraint may be pushed further rearwards, giving a higher dynamic geometry measurement. If the ‘dynamic backset’ threshold proposed in document GRSP-44-24 is adopted, then it may be important to use the pulse used in that study (the Euro NCAP medium severity pulse) in order to ensure that the metric is directly equivalent to the static assessment of head restraint geometry. If a different pulse is used, it may be necessary to adjust the threshold. It may be possible to do this by re-testing a sub-set of the 'Normal' seats tested in document GRSP 44-24 and scaling the metric as appropriate.

The results of the sled testing programme reported in Section 5, which used the draft GTR-7 Phase 2 pulse, suggest that the definition of the pulse is adequate, but all testing was performed on a single sled with a very well-controlled pulse. Ideally this would be confirmed by testing at multiple laboratories, because this would give a greater range of variations on the pulse within the tolerances allowed than testing at one laboratory.

Some deceleration sleds that have been used for rear impact seat testing with BioRID II have included an apparatus to hold the head of the dummy in position during the initial acceleration phase of the sled. The head is then released at T_0. This is not necessary for acceleration sleds, provided that there is no 'jolt' as the acceleration mechanism engages with the sled, because there is no movement of the sled prior to T_0.

It is recommended that consideration is given to reviewing the need for such additional apparatus for deceleration sleds and, if they are found to be essential for repeatability and reproducibility, including this requirement in the text. Ideally, this would be expressed as a performance requirement, rather than a specific design of the apparatus. It is likely that such a performance requirement would have to set a tolerance on the movement of the dummy prior to T_0, and on how quickly the dummy is released (i.e. is free to move) after T_0. It should be noted that the dynamic geometry metric may be expected to be less sensitive to these issues than other BioRID II dummy-based measurements.

2.6.2 Seating Procedure

The seating procedure for the BioRID II dummy consists of the following elements:

- Setting the seat position and adjustment
    - E.g. seat height, seat cushion tilt, lumbar support
- Setting the head restraint position and adjustment
    - E.g. head restraint height and tilt
- Setting seat back angle to give the specified torso angle
    - Typically a fixed angle of 25° or the manufacturer's design angle
- Determining the BioRID target backset
    - Relative to a marked location on the head restraint
- Installing the BioRID II on the seat
    - With backset, H-points and pelvis angle within the specified tolerances

The seating procedure for the BioRID II dummy in the proposed update to UN Regulation No.17 is similar to the Euro NCAP seating procedure, but has been cut down and simplified. Detailed comments on this were provided in the Interim Report for this project (CPR 1118), particularly relating to the adjustment of the seat and the adjustment of the head restraint.

The seating procedure in the GTR-7 proposal was also slightly different to the Euro NCAP seating procedure, with some aspects such as set-up of the seat and head restraint defined in less detail in the GTR-7 draft text. It is understood that the Euro NCAP procedure has been refined based on experience with a large number of seats and seat types. For instance, it is understood that the seat and head restraint set-up procedure has been defined in increasing detail in order to ensure that each laboratory will set the seat adjustments in the same way and therefore result in exactly the same seat configuration prior to setting the seat back angle and installing the BioRID II dummy. Given the very large range of adjustments, including in some cases different mechanisms for manual and electric seats, it is understood that the extra detail in the procedure has been found to be necessary and – for current seats – sufficient. It is therefore recommended that the Euro NCAP seating procedure is used within the Regulation.

The tests studied by Hynd and Carroll (2008) used either the IIWPG or draft Euro NCAP seating procedures. Since that data was generated The Euro NCAP seating procedure has been updated in several ways:

- The seat set-up procedure has been refined with the aim of ensuring that the procedure will give a reproducible seat configuration at different laboratories
- A calibration procedure for some aspects of the geometry of the 3D H-point machine and head restraint measurement device (HRMD) has been introduced, with the aim of improving the reproducibility of backset measurements and the BioRID target backset

TRL report CPR1303 “Global Impact Dummies - Assessment concerning BioRID II in Future Regulatory Applications” identified that the BioRID II installation procedure used in their test series (Euro NCAP seating procedure v3.1, dated June, 2011) was adequate to demonstrate dummy repeatability, at least for the seat used in that test series. Data from the same test series is used in Section 5 of this report, again with good repeatability for kinematic parameters. There is, however, an on-going discussion within the GTR-7 Informal Group regarding the reproducibility of the procedure to determine the BioRID target backset (and other backset measurements), which is fundamental to achieving a reproducible seating position for the dummy, and presumably therefore to reproducible seat assessment. This was not evaluated in the tests noted above, because the focus on the repeatability and reproducibility of the dummy; therefore, the target backset was determined using a single 3DH machine and HRMD, and the same technicians.

This discussion regarding the procedure to determine the target backset in a repeatable and reproducible manner has focussed on the following issues:

- Control of the mass and dimensions of the HRMD
- Control of the combined dimensions of the HRMD and 3D H-point machine
- Control of the 3D external geometry of the seat pan and back pan of the 3D H-point machine
- Variability in the application of the test procedure between technicians

Recent discussions within the Informal Group have suggested that it would be acceptable to take on-board the experience from Euro NCAP and use a more detailed test procedure such as they have defined. In addition to this, GRSP document GTR7-04-16/Rev.1 (September, 2010) included a proposal from Japan to reduce the BioRID target backset tolerance to ±2 mm, rather than the ±5 mm previously used. This proposal was based on a sensitivity study which found that the backset was the most critical parameter for reproducibility in seat tests, followed by H-point location and pelvis angle. A tolerance of ±2 mm on the BioRID II backset compared to the target backset implicitly includes the tolerance on determining the target backset. This implies that the control on 3D H-point machine and HRMD measurements must be markedly better than ±2 mm, which may be difficult to achieve.

One option that may reduce the variability is to not use the HRMD. When the HRMD is used, two of the torso weights on the 3D H-point (3DH) machine are removed and compensated by the mass of the HRMD. The torso weights could simply be retained, and the backset measurement made using a co-ordinate measurement machine (e.g. a Faro arm). This would ensure that the seat cushion and seat back were loaded (by the 3DH machine), but would eliminate variations due to the production tolerances of the HRMD, and due to variations in the interface between the HRMD and the 3DH machine. This would remove two sources of variation, and may make a tighter tolerance on the BioRID target backset more achievable. This would also be equivalent to the proposed Annex 1 test procedure for measuring the height of the head restraint.

Finally, it should also be noted that some rear impact injury criteria or seat assessment criteria may be more sensitive to target backset than others. In the study reported in GTR7-04-16/Rev.1, the dynamic geometry metric had a variation of <5% due to a ±5 mm variation in target backset; this was better than many of the other parameters assessed, and may be considered acceptable.

2.6.3 Torso Angle

It is not stated in GRSP-44-24 whether the tests (see Section 2.3) were performed at the design torso angle, or using a fixed torso angle (e.g. 25°). However, the presentation was made in support of the proposed update to UN Regulation No.17, which states that the design torso angle should be used. Even if the design torso angle was used, it is not known what range of design torso angle was included in the test series.

The GTR-7 Informal Group has identified possible concerns with the use of the BioRID II dummy at more upright torso angles, related to the stability of the dummy in an upright seating position. The Informal Group has decided to focus its efforts on developing a test procedure that can be used to assess seats with a design torso angle greater than or equal to 20°.

If the GRSP-44-24 test series used design torso angles between 20° and 25°, then no further work on the torso angle is necessary within the context of measuring the dynamic geometry metric, because the static backset measurement in the proposed update to UN Regulation No.17 is made at the design torso angle. If the GRSP-44-24 test series used a fixed torso angle, or a very narrow range of torso angles, then additional work may be required to validate the pass-fail threshold at a range of torso angles.

2.6.4 Review of Proposal for Alignment of Regulation 17 with GTR-7

The text of the proposed update to Regulation 17 has been reviewed in detail, and comments provided within the text. Appendix A provides an overview of the main issues identified during this review.

Much of this text was proposed as a basis for the BioRID II updates in GTR-7 Phase 2 at the 6th GTR-7 Informal Group meeting in February. Many of the comments on the Regulation 17 text are therefore also relevant to the proposed GTR-7 text. The detailed comments on the proposed Regulation 17 text have therefore been used as an input to the two GTR-7 drafting meetings that have been held to date.

2.7 Conclusions

Limited validation of the repeatability and reproducibility of the dynamic geometry metric has been identified in the literature, but the information that is available indicates that the reproducibility of the metric good, and that it is better than most other metrics measured in the same test series. The BioRID II dummies used in the studies reviewed pre-date the latest BioRID II specification from the GTR-7 Phase 2 Informal Group. However, improvements in the dummy specification have been made with the intention of improving reproducibility, so the results would be expected to apply to more recent versions of the dummy.

The kinematics of the BioRID II have generally been reported to be repeatable and reproducible. As an additional check on the likely repeatability and reproducibility (R&R) of the dynamic geometry metric, a review of the kinematic R&R of the BioRID II dummy may be found in Appendix B. However, since the literature review was completed the testing BioRID II test programme for this project has been completed and the reproducibility of the dynamic geometry metric has been quantified. Further information on the reproducibility of the dynamic geometry metric from the test programme for this project may be found in Section 5.

The original EEVC WG20 dynamic geometry proposal noted the need to develop a proposal for a pass-fail threshold to be used with the test procedure. Since then, a proposal of a threshold of 52 mm has been made by Japan, based on a study of the equivalence of static and dynamic backset measurements. According to the supporting study for the proposal, this threshold would pass all the seats rated as ‘Good’ by IIHS and included in the study, and fail a proportion of seats with lower ratings. It is not known whether the seats in this study were tested at the manufacturer’s design angle (as recommended in the proposed update to UN Regulation No.17, for static and dynamic backset/geometry) or what range of torso angles were included. However, if the study did use a reasonable range of design torso angles (e.g. 20°-25°) then this threshold seems to satisfy the need for a threshold that is the dynamic equivalent of the static requirement.

The assessment of seats with a single-sided recliner mechanism may have reproducibility problems, because the recliner and non-recliner sides of the seat back may rotate by a different amount. It is recommended that the effect of single-recliner mechanisms is checked based on data using a seat that has been filmed from both sides. In particular, the use of a mean seat back angle from the left and right views should be considered.

The validation data provided by Japan, including the test programme to develop a pass-fail threshold for the dynamic geometry metric, was undertaken using the 15.7 km.hr^{-1} Euro NCAP medium severity pulse. It would be most obvious, therefore, to continue to use this pulse if the metric is adopted in regulation. However, the dynamic geometry metric is also shown to have good reproducibility at the draft GTR-7 Phase 2 17.6 km.hr^{1} pulse (see Section 5). The magnitude of the dynamic geometric metric is likely to be somewhat affected by the pulse severity, so ideally the pass-fail threshold should be validated at the pulse used. However, the difference in dynamic geometry metric between the two pulses is likely to be smaller than for other BioRID measurements, so consideration could be given to the use of either pulse.

The seating procedure for the BioRID II dummy incorporates a number of elements relating to the set-up of the seat and head restraint, measurement of the BioRID target backset, and installation of the dummy in the seat. The definition of the set-up of the seat and head restraint in the proposed update to Regulation No.17 lacks detail compared to some other seating procedures for the BioRID II dummy. It is recommended that the more detailed seat and head restraint set-up procedure defined by Euro NCAP is considered. The GTR-7 Phase 2 Informal Group is currently working on improvements to the definition of the 3D H-point machine and HRMD in order to improve the reproducibility of the definition of BioRID target backset. It is recommended that these improvements are included in any test procedures that assess the dynamic geometry metric. Finally, the results in Section 5 of this report suggest that the BioRID II installation procedure is adequately defined.

One key factor that has not been fully addressed is the calibration of the camera and marker tracking system that is used to make the dynamic geometry measurement. Further information on this can be found in Sections 3 to 5.

3 Effect of Measurement Errors on the Accuracy of the Dynamic Geometry Metric

A theoretical assessment of the effect of measurement errors on the dynamic geometry metric has been made in order to estimate the measurement accuracy that would be required in order to ensure a specified accuracy in the final dynamic geometry metric. This work is summarised in the following section.

The measurement of peak dynamic geometry metric from video analysis relies on the measurement of the x and y coordinates of four markers (see Figure 3-1), for a total of eight variables:

- Seat back upper x and y coordinates
- Seat back lower x and y coordinates
- OC pin x and y coordinates
- T1 pin x and y coordinates

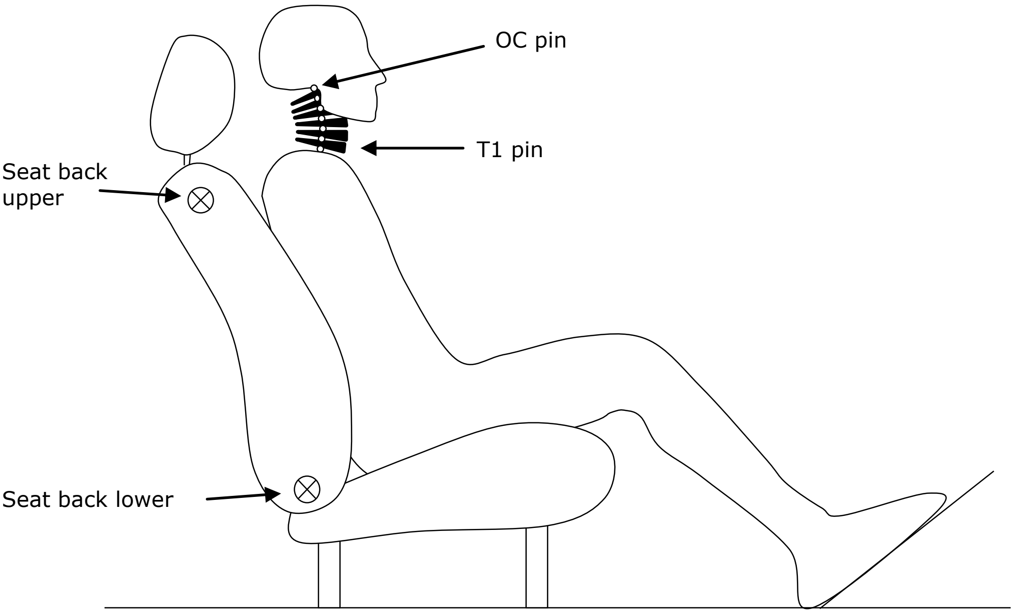

Figure 3-1: Schematic showing the four markers that have to be tracked to determine the dynamic geometry metric

This gives eight variables which could all have an associated error, either a systematic error (if the program tracks something other than the centre of the marker), or a random error (if there is a limit to the accuracy with which the program can locate the centre of the marker).

Video from a typical dummy test has been used to determine the error in the calculated peak dynamic geometry metric for different types and magnitudes of error in tracking the markers. A spreadsheet has been produced which allows systematic and random errors to be added or removed so that the effect on the calculated dynamic geometry metric can be assessed.

The original dynamic geometry metric calculated for this test, with no errors added, has the form shown in Figure 3-2. The peak dynamic geometry metric is calculated by first zeroing the metric relative to its initial value, then taking the minimum value of the zeroed metric. In this figure, the peak dynamic geometry metric is 29.5 mm.

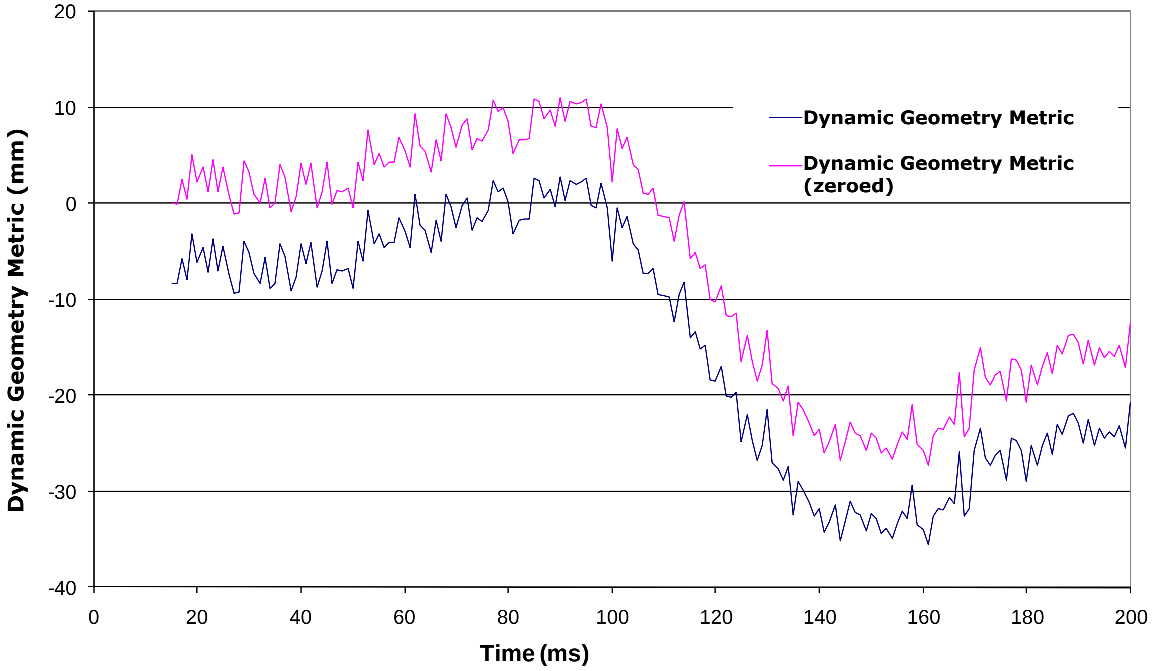

Figure 3-2: Original dynamic geometry metric, and zeroed dynamic geometry metric (for calculation of peak dynamic geometry), with no errors added

When either systematic or random errors are introduced, the dynamic geometry metric changes in some way. This altered dynamic geometry metric is zeroed using its new initial value, and the peak for the altered metric can be compared to the original peak dynamic geometry metric before any errors were introduced. The difference between the original peak dynamic geometry metric, and the peak dynamic geometry metric after the errors have been introduced, indicates the inaccuracy caused in the peak dynamic geometry metric by the errors in the coordinates of the target markers.

3.1 Systematic Errors

A systematic error is an error which causes the mean of many separate measurements to differ significantly from the actual value of the measured parameter. Possible causes of systematic errors in the location of the target markers could include the video analysis software tracking the wrong part of the target marker (such as the edge instead of the centre) or an aberration in the optical system.

The effect on peak dynamic geometry metric of a systematic error in a single variable is summarised in Figure 3-3. This suggests that for most of the eight variables, a relatively large systematic error will have a small effect on the measurement of peak dynamic geometry metric. For example, if there is a systematic error of ±10 mm in the x-axis measurement of the seat back inferior marker, this results in an error of approximately ±0.5 mm in the peak dynamic geometry metric.

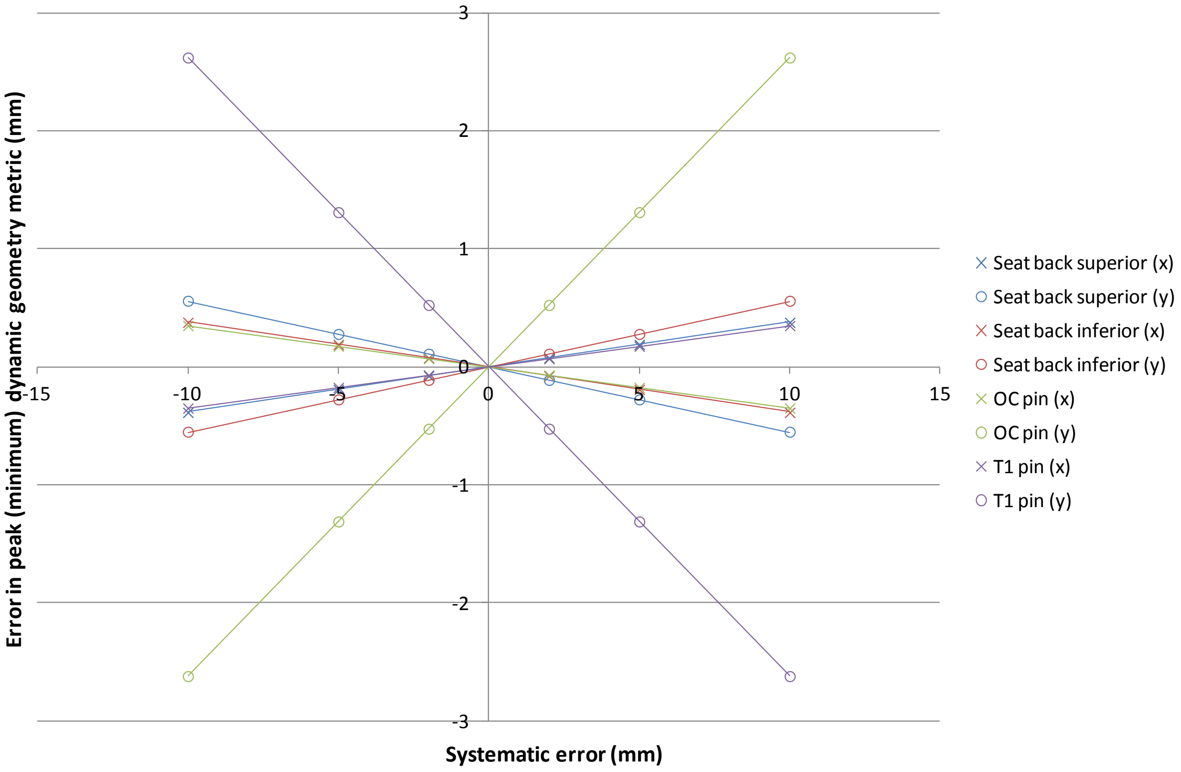

Figure 3-3: Effect of systematic error in individual variables

Systematic errors in the two dummy variables (the OC pin and T1 pin y-coordinate) have a larger effect on the peak dynamic geometry metric, but even this is relatively small. A ±10 mm systematic error in one of these variables gives a ±2.5 mm error in the peak dynamic geometry metric.

The relationship between systematic errors and the error in peak dynamic geometry metric was also investigated in reverse, to determine what systematic errors would be required for a given error in peak dynamic geometry metric. The results of this are summarised in Table 3-1. This shows the minimum systematic error which would be required in an individual variable to give an error of ±2 mm or ±5mm in peak dynamic geometry metric.

Table 3-1: Systematic error required for a given error in peak dynamic geometry metric

	Systematic error required for error in peak dynamic geometry metric (mm)			
Variable	**2**	**-2**	**5**	**-5**
Seat back superior (x)	57.7	-50.3	N/A	-124.1
Seat back superior (y)	-35.0	37.3	-85.1	99.6
Seat back inferior (x)	-57.7	50.3	N/A	124.1
Seat back inferior (y)	35.0	-37.3	85.1	-99.6
OC pin (x)	-57.2	57.2	-143.1	143.1

OC pin (y)	7.6	-7.6	19.1	-19.1
T1 pin (x)	57.2	-57.2	143.1	-143.1
T1 pin (y)	-7.6	7.6	-19.1	19.1

As suggested by Figure 3-3, very large systematic errors are required for a single variable to significantly affect the peak dynamic geometry metric measurement. For the x-coordinate of the seat back superior and inferior markers, there was no systematic error which could give an error in peak dynamic geometry metric larger than 3.6 mm.

Combinations of systematic errors do not necessarily increase the error in peak dynamic geometry metric. This can be seen in Figure 3-4, which shows the resulting error in peak dynamic geometry metric (represented by the size of the circles) given by errors in the x and y coordinate of the OC pin marker.

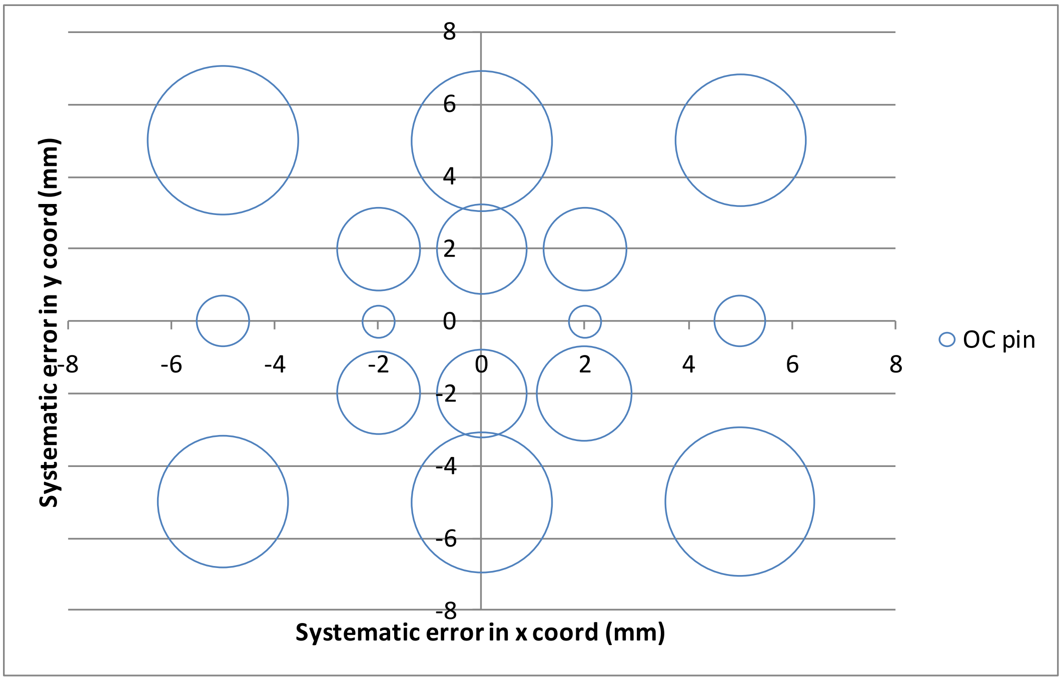

Figure 3-4: Systematic error in x and y coordinates of a marker

Although the error at (-5,5) is greater than the errors at (-5,0) and (0,5), the error at (5,5) is actually smaller than the error at (0,5). This suggests that the direction of the systematic error is important, as well as its magnitude – if there is already an error in the y-coordinate, adding a systematic error in the x-coordinate can actually reduce the resulting error in peak dynamic geometry metric, depending on the direction of the error.

Systematic errors in the coordinates of two different markers seem to interact in the same way, as shown in Figure 3-5. If there is an error in both variables, this can be more or less than the error in a single variable, depending on the direction of the error.

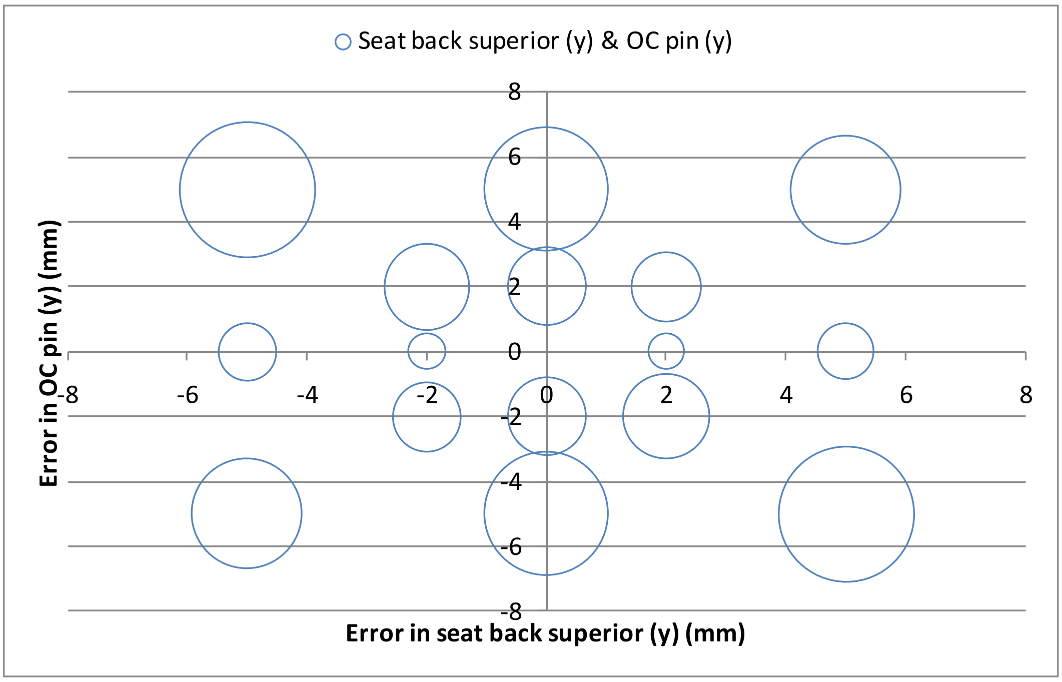

Figure 3-5: Systematic error in seat back superior (y) and OC pin (y)

The effect of a systematic error changing in time was also investigated. This could occur if the video analysis software, at some point in time, stops tracking the centre of a marker and starts tracking another point, such as the edge of the marker. Figure 3-6 shows the effect this might have on the measurement of dynamic geometry metric. The '10 mm near peak' line shows what happens when a 10 mm systematic error is introduced at 125 ms, and removed at 175 ms. The '0 mm near peak' line shows the opposite: a systematic error of 10 mm is present from the start, but is removed between 125-175 ms.

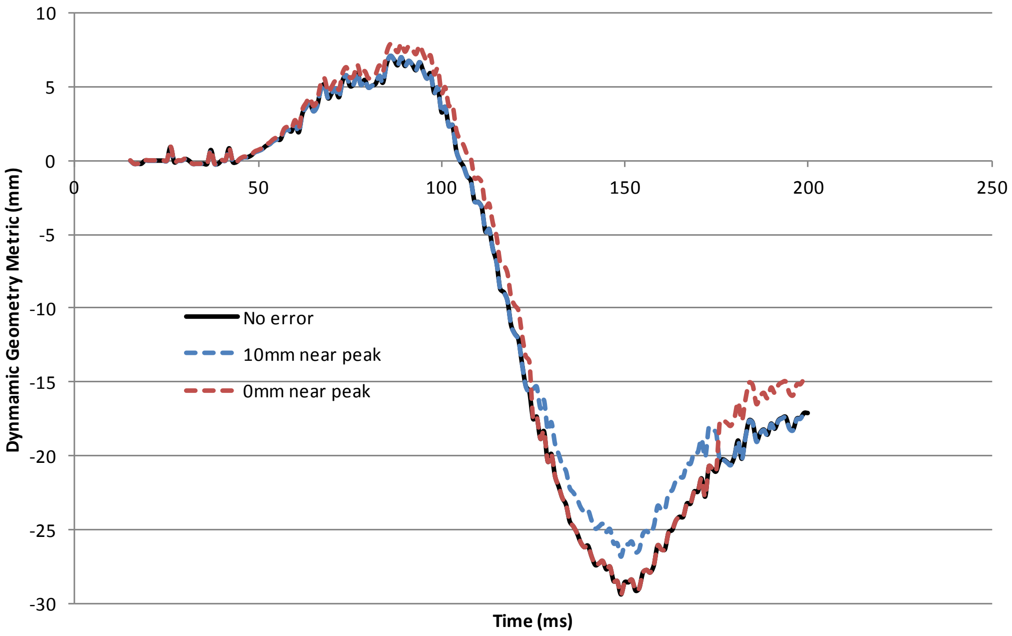

Figure 3-6: Effect on dynamic geometry metric measurement of changing systematic error with time

This shows that a systematic error only affects the dynamic geometry metric for the duration the error occurs. When an error of 10 mm is introduced after 125 ms and removed after 175 ms, the dynamic geometry metric at times outside this range matches exactly the dynamic geometry metric that was measured when there was no error. Similarly, if there is an error from the start of the impact, but this is removed near the peak, the peak dynamic geometry metric will equal the dynamic geometry metric where there was no error at all.

When measuring the peak dynamic geometry metric, systematic errors will only affect the measurement of peak dynamic geometry metric if they occur at the same time as the peak dynamic geometry metric.

3.2 Random Errors

Random errors result from the limitation on the accuracy with which the location of the target markers can be determined. This accuracy will depend on a number of factors, such as the pixel size or the quality of the optical system. For example, if the accuracy is ±2 mm, the measured position of the target markers could be 2 mm away from their true position, and the magnitude (0-2 mm) and direction of this error will vary randomly each time it is measured.

The accuracy of the peak dynamic geometry metric will be affected by these random errors. Two methods have been used to quantify the effect of this random error on the peak dynamic geometry metric. Firstly, confidence intervals have been calculated for the zeroed dynamic geometry metric based on the error in measuring the location of the target markers. In addition, a spreadsheet has been developed that allows the user to add a random error to the co-ordinates of the target markers. The magnitude of this random error, and the magnitude of the error used to calculate the confidence intervals, can be used to explore the effects of random errors on the measurement of dynamic geometry metric.

Figure 3-7 and Figure 3-8 show the effect of introducing a random error of ±1 mm and ±2 mm respectively, on the co-ordinates of all the target markers. These figures show the upper and lower confidence interval which has been calculated analytically for an error of this magnitude, using the standard method for measuring the propagation of errors in independent variables. Each graph also shows three sets of data where a random error of that magnitude has been added.

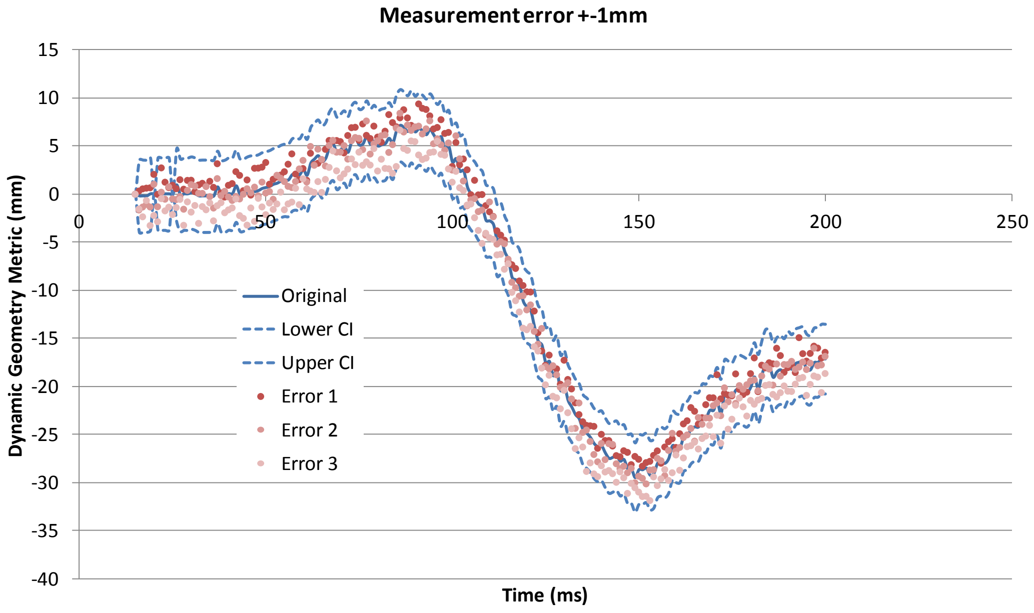

Figure 3-7: Effect on dynamic geometry metric of random error of ±1 mm on all variables

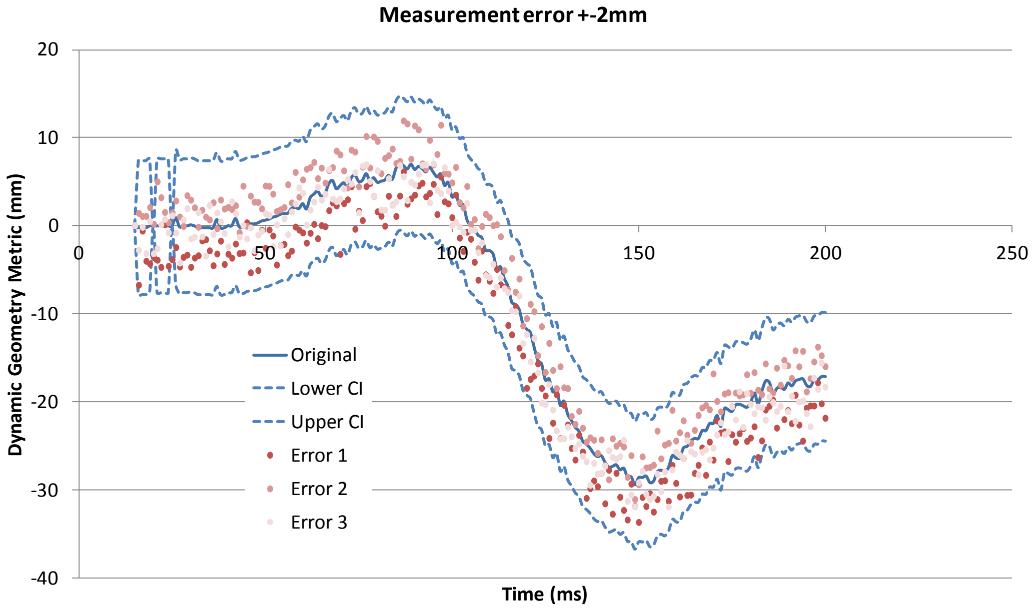

Figure 3-8: Effect on dynamic geometry metric of random error of ±2 mm on all variables

The confidence intervals shown in Figure 3-7 suggest that a random error of ±1 mm on the location of all the target markers would result in an error in peak dynamic geometry metric of approximately ±4 mm. With a random error of ±2 mm on all variables, the confidence intervals in Figure 3-8 suggest that the error in peak dynamic geometry metric would be approximately ±8 mm. The relationship between the magnitude of error in the input variables, and the width of the confidence intervals, appears to be approximately linear, and is shown in Figure 3-9. It should be noted that this graph is drawn directly from the confidence intervals, which are calculated analytically, and not from the random error distribution.

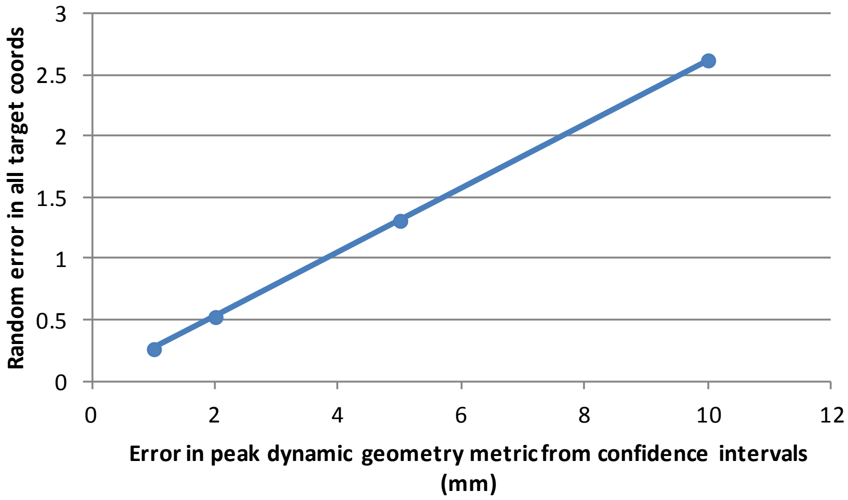

Figure 3-9: Relationship between random error on target marker co-ordinates, and error in peak dynamic geometry metric calculated from the confidence intervals

However, if the dynamic geometry metric data is filtered to reduce some of the high frequency variation caused by random errors, this may reduce the error in peak dynamic geometry metric. The effect of filtering the dynamic geometry metric data is shown in Figure 3-10. A random error of ±2 mm was applied to the co-ordinates of all the target markers, and two datasets were plotted: one where the random errors led to a general decrease in dynamic geometry metric, and one where the random errors led to an increase in dynamic geometry metric. A CFC_60 filter was then used on the two datasets, which smoothes out some of the variation caused by the random errors.

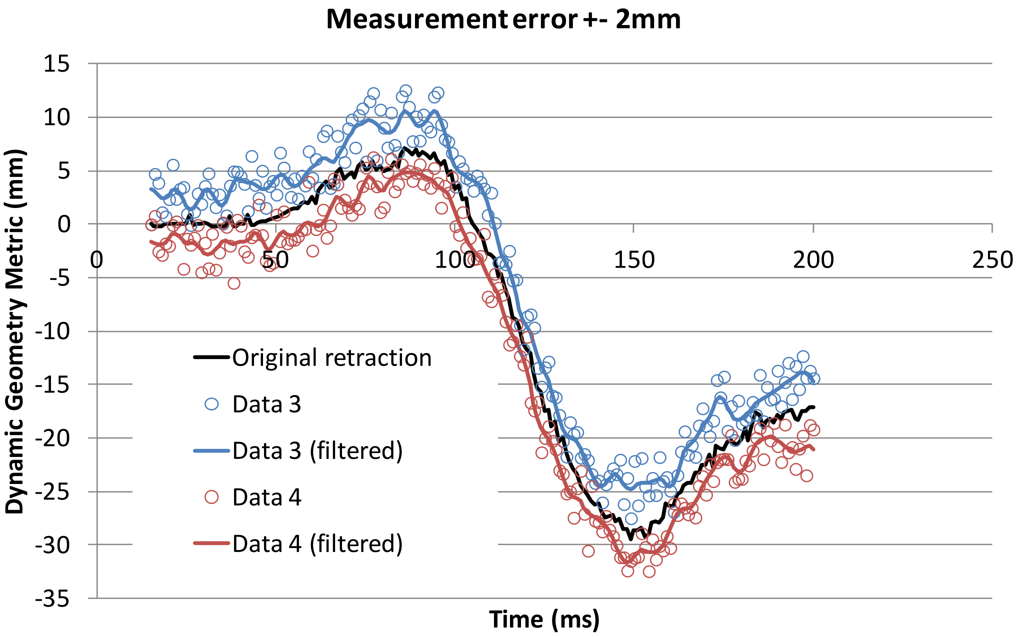

Figure 3-10: Effect of filtering the dynamic geometry metric data with a random error of ±2 mm

Before the data is filtered, the peak dynamic geometry metric of one of the random sets of data is about 5 mm greater than the dynamic geometry metric without the random error. The other dataset, although almost all the points are higher than the original dynamic geometry metric, has a similar value of peak dynamic geometry metric to the original dynamic geometry metric. When the data is filtered, one set of data has a peak dynamic geometry metric closer to the original, and the other set has peak dynamic geometry metric further away from the original.

However, after the data has been filtered, it needs to be zeroed. Once this is done on the datasets in Figure 3-10, the error in peak dynamic geometry metric is substantially reduced, as can be seen in Figure 3-11. Zeroing the data removes the reliance of the dynamic geometry metric on the error on the initial point. In the previous graphs, the error on the initial point had a strong influence on the size and direction of the error in the peak dynamic geometry metric, because the dynamic geometry metric is calculated by determining the change in position from the initial point.

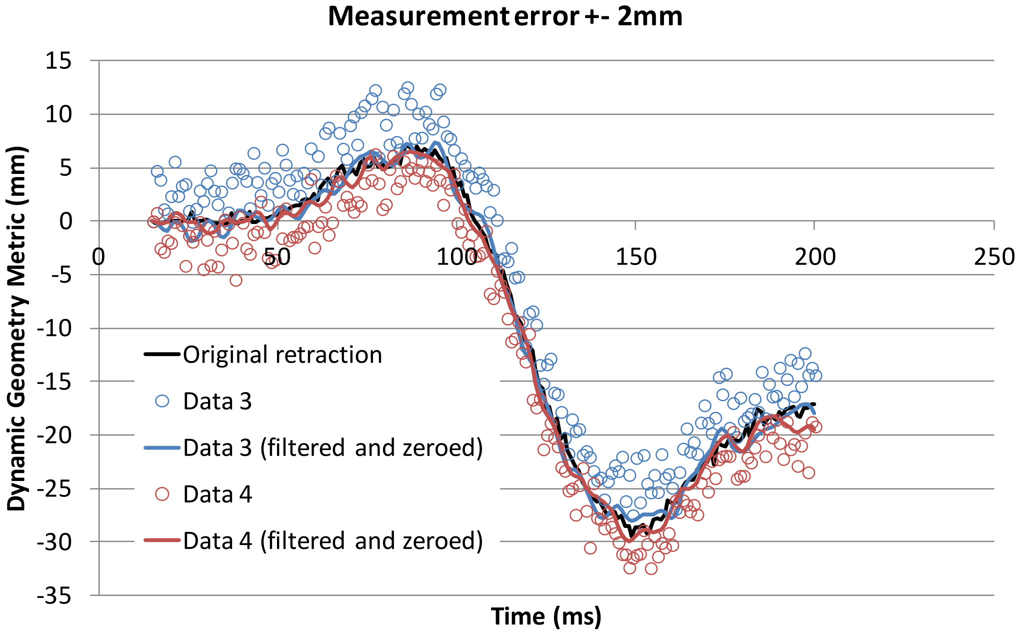

Figure 3-11: Effect of filtering and zeroing data with random errors

This comparison between filtered and unfiltered dynamic geometry metric was performed for random errors of ±1 mm, ±2 mm, ±5 mm, and ±10 mm, and the results are summarised in Figure 3-12. This shows the error in peak dynamic geometry metric calculated using the filtered and unfiltered data. Two datasets with random errors are shown for each point – one where the random error led to the dynamic geometry metric being overestimated, and another where the dynamic geometry metric was underestimated.

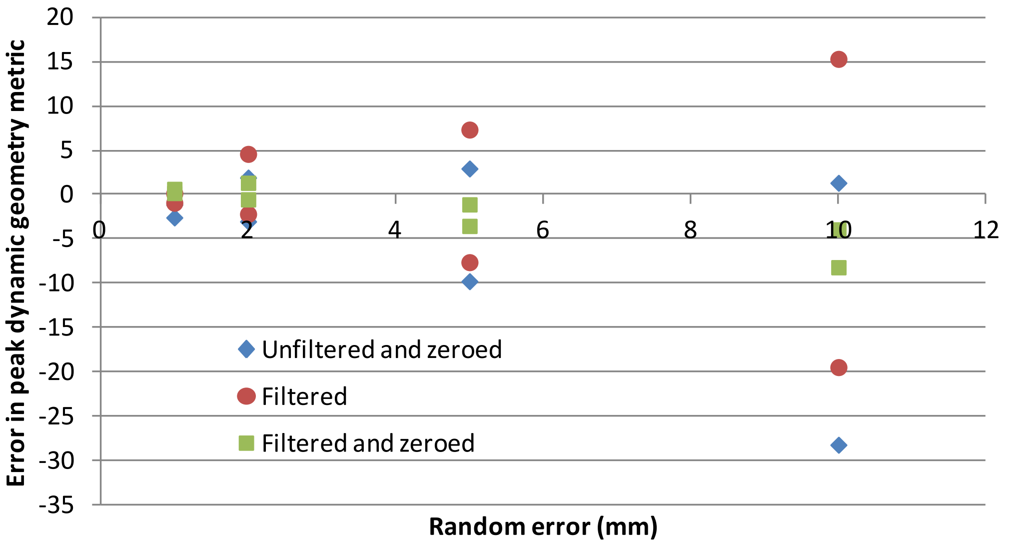

Figure 3-12: Errors in peak dynamic geometry metric for unfiltered, filtered, and filtered data with zeroing

Before filtering, the random errors lead to an error in peak dynamic geometry metric that is either a slight underestimate, or a much larger overestimate. After the dynamic geometry metric data has been filtered, the random errors can lead to a possible error in peak dynamic geometry metric that is much more symmetrical, and reduces the possible magnitude of the error. Once the filtered data has been zeroed, the error in peak dynamic geometry metric is substantially reduced, although it is still measureable: a random error of ±10 mm leads to a ~5 mm error in peak dynamic geometry metric.

It may be possible to reduce these errors even further by using a filter which removes all but the very lowest frequencies. The data from the test suggests that the variation in dynamic geometry metric has a frequency of the order of 10 Hz, while the random errors have a frequency closer to the sampling rate of 1000 Hz. The filter which has been used, CFC_60, removes frequencies above 100 Hz, but lower frequency variations caused by the random error remain. Using a filter closer to the frequency of the dynamic geometry metric may remove even more of the variation caused by random errors.

Finally, the effect of an error on the initial data point has been investigated. The dynamic geometry metric is measured relative to the initial dynamic geometry metric, so it is possible that reducing the error on the initial measurement of dynamic geometry metric may reduce the error in the peak dynamic geometry metric substantially. This is explored in Figure 3-13, which uses filtered and zeroed data to determine what difference the error on the first data point makes to the error in peak dynamic geometry metric.

Two datasets with random errors have been used. Each of these datasets had a relatively large error on the initial data point. The error on the initial data point was then removed, and the results compared to see if this resulted in a more accurate measurement of peak dynamic geometry metric.

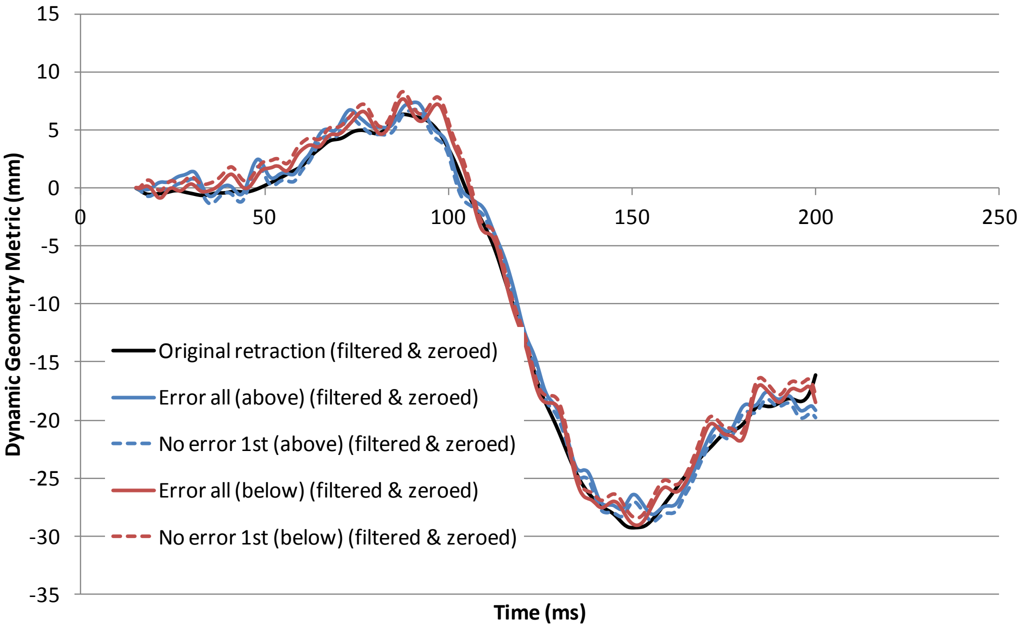

Figure 3-13: Effect of minimising the error on the initial data point

From this figure, although removing the error on the initial data point alters the peak dynamic geometry metric, it does not make it more accurate.

In order to further test the effects of an error on the initial data point, a number of datasets with random errors were generated. The error on the initial dynamic geometry metric for each dataset was noted, then the calculated dynamic geometry metric for the dataset was filtered, and zeroed. The error in peak dynamic geometry metric for the dataset was then determined. Figure 3-14 shows the resulting relationship, for all the datasets generated, between the error on the initial data point and the error in peak dynamic geometry metric.

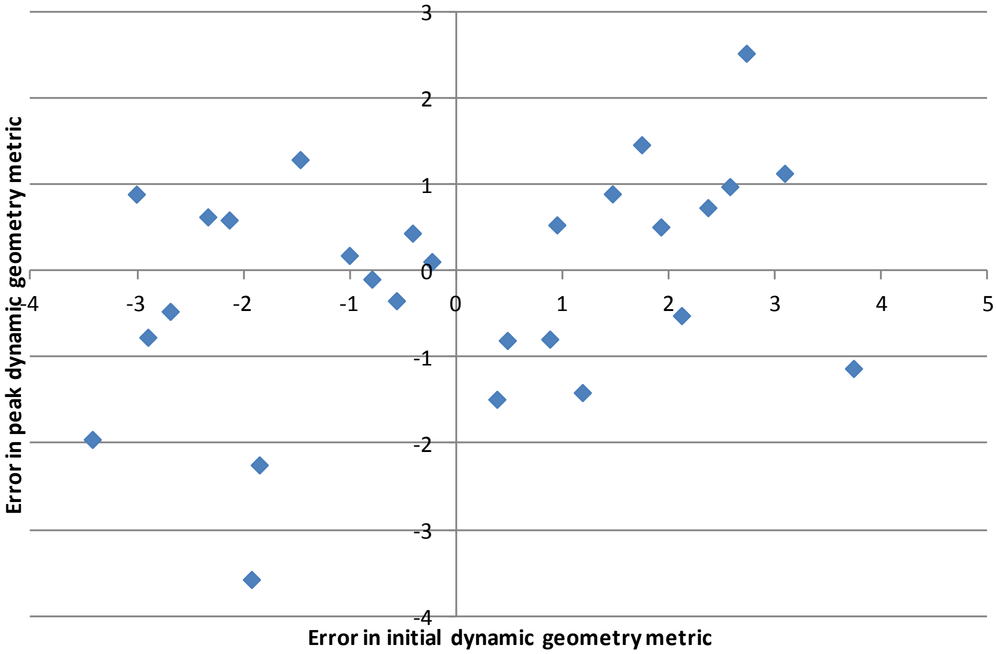

Figure 3-14: Effect of error in initial data point on the peak dynamic geometry metric

This figure suggests that there is no strong relationship between the error on the initial data point, and the error in peak dynamic geometry metric.

3.3 Definition of Performance Requirements for a Marker Tracker Calibration Scheme

The performance requirements of the marker tracker calibration scheme can be determined based on the above results, which give the relationship between the accuracy of the marker positions, and the accuracy of the dynamic geometry metric calculated from these marker positions.

The above results can be used to estimate the relationship between measurement error and the calculated peak dynamic geometry metric, for three different instances:

1. Systematic error in one variable. Figure 3-3 suggests that the error on peak dynamic geometry metric ≈ 0.25 x the systematic error in one variable.
2. Random error in all variables, zeroed but unfiltered. Figure 3-12 suggests that the error in peak dynamic geometry metric ≈ 3 x random error.
3. Random error in all variables, zeroed and filtered. Figure 3-12 suggests that the error in peak dynamic geometry metric ≈ 0.5 x random error.

These results suggest that random measurement errors are likely to dominate over any systematic error, and that as long as the data is filtered to remove some of the variation caused by the random error, the accuracy of the calculated peak dynamic geometry metric will be comparable to the accuracy of the marker position measurements.

4 Calibration of Marker Tracking Measurement Systems

4.1 Introduction

Some form of calibration is required that will control the quality of marker tracking measurements in a way that is comparable to the calibration of accelerometers, load cells and other instrumentation used in crash testing. This is particularly important if a camera-based measurement is to be used in a regulation. This section of the report documents the selection of, and initial trials with, a candidate calibration standard.

4.2 Standards for Marker Tracking Measurement Systems

A short review of available standards for marker tracking systems has been conducted. This included standards in the automotive and other fields, as well as general photogrammetric standards. The two most relevant standards that have been identified are:

- SAE J211-2:2001 – Instrumentation for Impact Test – Part 2: Photographic Instrumentation
    - Provides a method for quantifying the optical quality of the camera-lens combination, including factors such as lens distortion and lens misalignment. There is also a requirement to compare the optically measured distance between two points throughout a test with the known distance between the two points.
    - This standard provides a good foundation for establishing the accuracy of an optical measurement from a marker tracking system, but it is not sufficient to guarantee that measurements in different planes (which are a fundamental part of the dynamic geometry measurement as currently defined) are accurate. It is limited to static measurements in a single plane. Furthermore, only the error measurement method is defined – the selection of pass/fail criteria for the various metrics calculated in the standard is considered to be application-specific, and it is up to the user to determine what pass-fail criteria are necessary to ensure the required accuracy in the user's application.
- BS ISO 8721:2010 – Road vehicles – Measurement techniques in impact tests – optical instrumentation
    - The 2010 version of this standard is a very comprehensive update of ISO 8721:1987, which was less sophisticated than the SAE J211-2:2001 standard.
    - Builds on, and refers to SAE J211-2:2001. Includes additional metrics that assess: the suitability of the marker size that is used, the likelihood of markers having motion-blur due to the speed of the test object, that reference distances are provided for each plane of measurement, and the performance of 3D optical channels. The use of the J211-2 standard target pattern for assessment measurements, or alternative target patterns, is allowed.

  - This standard constitutes a useful enhancement to SAE J211-2, although many of the additional metrics are simply checks that specification of the optical system and marker array are expected to be adequate, not a verification that the resulting film and marker tracking are of sufficient accuracy.

Both of these standards rely on a standard target pattern that is filmed to determine the camera/lens quality, and a check that the distance between two markers (in each plane for ISO 8721) is accurate. ISO 8721:2010 shows the most promise for being able to assess the accuracy of the marker tracking system, provided that the target markers on the dummy are of comparable size and similarly lit to the reference markers in each plane.

It should be noted that the use of the SAE J211 target pattern is precluded for most applications, because the standard limits the maximum size of the target pattern to 750 mm. The target pattern must be exposed ‘full frame’, which implies that the target pattern must be very close to the lens. This would require the lens to be refocused, which would invalidate any calibration of the camera/lens system performed within the marker tracking software. There is no obvious reason why a larger-scale target pattern could not be used, provided that it is fabricated to a suitable accuracy. However, technically the J211 standard cannot be used for checking the calibration of a marker tracking system for measuring the dynamic geometry metric.

ISO 8721:2010 notes that the use of the SAE J211 target pattern is ‘possible’, but allows the use of any suitable target pattern. This is helpful, because some marker tracking software applications expect the use of a particular, non-SAE, target pattern. Provided that the ISO 8721 performance indices are met, there is no obvious reason why one particular target pattern should be specified.

Also, most marker tracking software will give the mean and maximum residuals following calibration of lens distortion, so provided that the calibration performed covers the whole of the field of view of the camera, this information should be adequate. This assumes that the calibration length checks in each plane of measurement defined by ISO 8721 are performed and that the requirements of these checks are met.

4.3 ISO Standard 8721

ISO standard 8721 “Road vehicles – Measurement techniques in impact tests – Optical instrumentation” defines performance and accuracy indices for 2D and 3D camera systems used to make measurements in impact tests. The 2D method is sufficient for the measurement of the dynamic geometry metric.

In order for the optical system to meet the required standard, it must pass each of 13 performance indexes and three other measurements of accuracy. These are summarised in Table 4-1.

Table 4-1: Summary of the ISO 8721 process

Name	Inputs	Purpose
Focal length index	If camera perpendicular to movement plane, and reference distances available in each movement plane, index is met Otherwise: Focal length Distance between object and camera Accuracy of focal length Desired accuracy of measurements	Determines whether the accuracy of the focal length is good enough
Distortion index	Focal length Distance between object and camera Distortion accuracy Cell size of image Desired accuracy of measurements	Determines the influence of incorrect distortion parameters Measurement based on 'worst target'
Target detection index	Focal length Distance between object and camera Target detection accuracy Cell size of image Desired accuracy of measurements	Determines the influence of the target detection accuracy
Target size index	Focal length Distance between object and camera Required target diameter Cell size of image Real target diameter	Compares the current and required target diameter
Motion blur index	Object speed Exposure time Desired accuracy of measurements	Determines whether the exposure time is short enough to avoid motion blur affecting the accuracy
Point motion index	Object speed Frame rate Allowed point motion between two images	Determines whether the frame rate is high enough
Control point distribution index	If camera perpendicular to movement plane, index is met Otherwise: Presence of targets in defined image sections Width of the image Height of the image Area formed by the control points	Determines whether the distribution of control points in the image is adequate
Time base index	Frame rate Object speed Time interval of test Accuracy of frame rate Desired accuracy of measurements	Determines whether the measurement of time is accurate enough

Name	Inputs	Purpose
Time origin identification index	Frame rate Object speed Time difference between t_0-image and t_0-signal Desired accuracy of measurements	Determines whether the measurement of t_0 is accurate enough
Camera set-up index	Type of camera set-up Focal length index Control point distribution index	Determines whether the set-up of the camera with respect to the movement plane will permit reliable analysis
Plane scale index	Number of planes of motion Reference distance in plane of motion Distance to plane of motion	Determines whether the scale can be measured in each movement plane
Camera position calculation index	Type of position determination Maximum displacement in image space Cell size of image Fix point distance Focal length Desired accuracy of measurements	Determines whether the accuracy determined from one time step is representative of the entire sequence
Scale index	Presence of reference distances	Determines whether there are enough reference distances to control the system scale
Performance value of optical data channel	Focal length index Distortion index Target detection index Target size index Motion blur index Point motion index Control point distribution index Time base index Time origin identification index Camera set-up index Plane scale index	A measure of the performance of the optical data channel
Length measurement error	Measured reference length Calibrated reference length	Determines the error in measuring the reference lengths
Accuracy	Camera position calculation index Length measurement error Calibrated reference length	Determines the accuracy of the optical data channel

Based on the values in Table 4-1, and the required measurement accuracy, ISO 8721 determines whether the optical data channel meets the required standard.

4.4 Preliminary Trials with ISO 8721

Preliminary trials were performed to evaluate the likely suitability of ISO 8721 for calibrating the marker tracker system for dynamic geometry measurements, prior to full testing with the BioRID II dummy (see Section 5). Marker tracking was performed using Tema software (Image Systems AB, Sweden). The trials used the mini-sled (Phase 1 trials) and main sled (Phase 2 trials) at TRL in order to:

- Evaluate the ISO 8721 marker tracking calibration method
- Evaluate different designs of calibration object, in order to be able to integrate the design with the design of the seat and spring-damper recliner mechanism to be used in the main BioRID II dummy test programme
- Evaluate options for improving the camera calibration or camera set-up in order to improve the ISO 8721 assessment

4.4.1 Phase 1 Trials

Initial trials on the mini-sled highlighted a number of points, the most important of which was that the tracked lengths of the calibration marker triads was strongly linked to the angle of the camera with respect to the plane of motion of the sled. In the initial tests, the camera was placed approximately perpendicular to the plane of movement by eye. Because the camera was not perfectly perpendicular, the result was that as the calibration lengths moved through the field of view, their measured length increased. This effect is shown for four marker triads (sets of three markers in each of four parallel measurement planes, each describing a vertical and a horizontal calibration length) in Figure 4-1. The figure shows data after lens distortion correction had been applied.

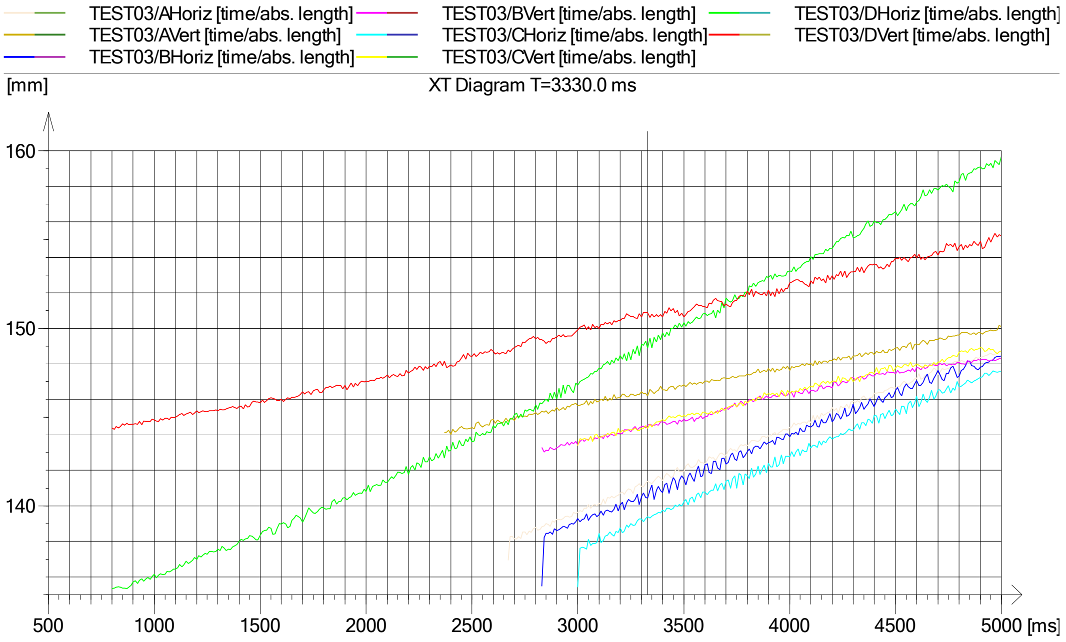

Figure 4-1: Measured length of 150 mm calibration lengths as the calibration object moved through the field of view of the camera

In the test shown in Figure 4-1, the calibrated lengths were 150 mm. In the worst case, the measured length of the calibration object (i.e. measured using the marker tracking system) varied from 136 mm to 160 mm as the calibration object moved through the field of view of the camera. This is too much variation to get reliable measurements of the dynamic geometry metric. Unfortunately, it is very difficult to measure the angle of the camera in a large laboratory space to the required accuracy. Therefore an alternative approach to determining the orientation of the camera was required. This was achieved using the 3D package in the TEMA marker tracking software, using the process as follows:

- Use a co-ordinate measuring machine (CMM) to measure the co-ordinates of all of the fixed markers on the sled in the co-ordinate system defined for the sled, including
    - All marker triads used for ISO 8721
    - Markers on fixed points on the seat and spring-damper mechanism
    - Additional marker triads placed at the far edge of the sled to provide information at a greater range of distances from the camera
- Enter the co-ordinates of all of these markers into TEMA as 'reference points'
- Use the 'Static Camera Orientation / 3D camera position' function in TEMA to calculate the position and orientation (about three axes) of the camera relative to the CMM co-ordinate system defined for the sled
- Apply this position and orientation information to the 2D tracking set-up, using the 'Skewed' motion plane option

This process corrects for camera alignment in the 2D tracking, using the camera orientation calculated by the 3D tracking module. Obviously, this approach will incorporate errors, e.g. those due to residual distortion of the camera lens following calibration. This approach considerably improved the ISO 8721 calibration in the trial tests, such that the measured lengths were 150 mm +3 / -0.5 mm. This process was therefore very successful, but required the use of 3D marker tracking software. Typically, 3D marker tracking is a cost-option not included in basic marker tracking packages, so this may not be available at all laboratories.

Although the calibration lengths were measured to be approximately equal (within ±1 mm of each other), the lengths measured by the software generally varied more than this. This was partially due to the camera not being perpendicular to the plane of motion, and partially because the calibration lengths themselves were not exactly parallel to the plane of motion of the sled. In future testing, in order to get as accurate measurements as are possible, it is important to ensure that the calibration lengths are positioned parallel to the plane of motion, or their position are adjusted for using the software.

4.4.2 Phase 2 Trials

For these trials, a Tema calibration object was produced that was just over half the width and height of the field of view of the camera at the centre-line of the sled. This enabled calibration of the whole field of view by placing the calibration object at each corner of the camera view in separate image frames, with some overlap between the image frames. That is, four calibration images can be used to cover the entire field of view.

The required size of the calibration pattern was 1250 x 1058 mm. This was printed using professional printers who quoted an accuracy of 0.1%. The Tema manual specifies that the size of the squares should be accurate to about 0.5%. In addition, the actual size of the squares can entered into the software to improve the accuracy of the calibration.

The print was attached to a flat MDF board to ensure that the pattern was flat at all times, and handles were attached so that the pattern could be moved around in the field of view. The resulting calibration board was large, but manageable, and was sufficient to calibrate the field of view both for these trials and for the main BioRID II test programme. Calibration of a larger field of view using this method would be difficult, and a different approach may be required.

As well as the calibration pattern, a series of calibration lengths were required as part of ISO 8721. The standard defines that the length of these must be known to 10 times the accuracy required for the measurements taken in the test, and that there must be two calibration lengths in each plane of motion. In addition, each pair of calibration lengths must be approximately perpendicular to each other. A frame was constructed to hold five L-shaped marker arrays, each with three markers attached (described as marker triads).

The ISO 8721 standard was applied to the data from these tests using the following user-defined values:

- Location accuracy = 5 mm (i.e. absolute accuracy required from measurements)
- Accuracy value limit = 0.025 (i.e. fractional accuracy required from measurements, equivalent to 5 mm absolute accuracy for a 200 mm calibration length)

The following results were achieved for each ISO 8721 performance index and accuracy index, using the ‘offline procedure’ option:

Performance Indices:

- **Focal length index**: Technically, because the camera was set up nominally perpendicular to the plane of motion, and there was a reference distance available in each plane of motion, this index was automatically met. However, no tolerance on ‘perpendicular’ is defined in ISO 8721. As a check the full index was calculated and was met easily for a desired location accuracy of 5 mm.
- **Distortion index**: This index was met easily for a desired location accuracy of 5 mm.
- **Target detection index**: The test set-up did not comply with this index. This seems to be because of the target detection accuracy – this was determined to be 4.4 pixels for the test set-up, but an accuracy of about 3 pixels was required to meet this index – and is further clarified in the discussion below.
- **Target size index**: This index was met – just. This index requires knowledge of the target diameter required by the software for reliable tracking – which is not known for the TEMA software used in this study, and which would be highly dependent on variables such as lighting, lens quality and so forth. A value was

used based on the smallest target that was known to have been reliably tracked using this software and lighting set-up.

- **Motion blur index**: This index was met easily. This highlighted the fact that any laboratory performing this test would have to be able to film with a shutter speed of 0.57 ms, in order to meet the standard (assuming a maximum marker velocity equal to the delta-*v* of the sled).
- **Point motion index**: This index was met easily.
- **Control point distribution index**: This index was met automatically because the camera set-up was nominally perpendicular to the plane of motion.
- **Time base index**: The important factor seems to be the frame rate accuracy – but it is not entirely certain how this is measured. According to Olympus, the manufacturers of the camera used in the testing: "The camera is run off a 80 MHz crystal that is accurate to 50 parts per million. So at 1000 fps it could be plus or minus 0.05 Hz out." Taking the frame rate accuracy as 50 ppm, the index was met easily.
- **Time origin identification index**: This index was met easily.
- **Camera set-up index:** This index was met automatically because the camera set-up was perpendicular.
- **Plane scale index**: This index was met because there were two calibration lengths present in each plane of motion.
- **Camera position calculation index**: This index was met easily, but it required a stationary marker to be visible at all times during the test, at a known distance from the camera – in this case attached to the wall behind the sled.
- **Scale index**: This index was met because the calibration lengths were present.

Accuracy Indices:

- **Performance value of optical data channel**: the requirement that Q should be greater than 0.7 was passed (Q = 0.9).
- **Length measurement error**: the length measurement error was 3 mm. This was less than the location accuracy of 5 mm that had been defined for the tests, so this performance criterion was met.
- **Accuracy**: the accuracy was 0.02. This was less than the desired accuracy value limit of 0.025 (equivalent to the length accuracy of ≤ 5mm defined for these tests), so the test set-up failed the standard. This performance criterion was met.

4.5 Discussion

ISO 8721:2010 has a number of advantages over SAE J211-2:2001. The Target Size and Motion Blur indices are useful additional checks that the marker tracking performance with real data is likely to be comparable to the rather idealised calibration conditions. It is also provides a check of marker tracking accuracy in multiple planes of motion, and allows for calibration objects that are large enough to cover the field of view of the camera without refocusing, which would invalidate any lens distortion correction applied by the marker tracking software. It is therefore recommended that ISO 8721:2010 is used in preference to the SAE standard.

Several of the ISO 8721 indices are automatically met if the camera is set-up perpendicular to the movement plane. However, the ISO 8721 standard does not define a tolerance for how perpendicular the camera needs to be, and in the testing it was found that what looked like a perpendicular setup actually was not – and significant errors were introduced despite having a 'nominally perpendicular' camera set-up. In the initial trials, these errors were enough to cause the set-up to fail the Length Measurement Error and Accuracy metrics in the standard by a factor of three. This demonstrates the utility of the standard, and indicates that the tolerance on perpendicular is not critical: if the camera is perpendicular (or if a correction is made for the angle of the camera, if this is possible in the marker tracking software) the final performance indices will be acceptable; if the camera is not sufficiently perpendicular (or corrected) the system will not meet the ISO 8721 requirements.

For the BioRID II tests, the position and orientation of the camera was calculated using the 3D marker tracking option in the marker tracking software. This involved tracking the positions of a large number of markers for which the co-ordinates had been measured in a sled co-ordinate system using a co-ordinate measuring machine. The position and orientation of the camera was then re-constructed by the software. This worked well, but will not be possible with some 2D-only software. In this case, an alternative method of aligning the camera in pitch and yaw would be required.

Obviously, the requirement to have two calibration lengths (i.e. a marker triad) in each measurement plane is very demanding if measurements in lots of planes are required. For example, in the BioRID II tests a marker triad could be required at each of the following planes:

- Centre-line of the dummy (T1 and pelvis wand)
- OC and T1 pins (if these are measured directly; not required if these are reconstructed from the head and T1 wand markers)
- Side of the head
- Side of the head restraint
- Side of the seat

This means that five calibration marker triads may have to be fitted on to the sled such that there is sufficient separation between all the markers that none are obscured during a test, or confused for another marker during tracking. During trials with the full seat rig for the BioRID II testing, it was found that a full set of marker triads could not be fitted into the available space, because the spring-damper mechanism supporting the seat back in the TRL seat was bulky and occupied much of the available space to the rear of the seat. It was also not possible to place the marker triads sufficiently far in front of the dummy that interaction between the marker triads or their supports and the dummy could be ensured. This would be easier for tests with a production car seat, which would occupy less space on the sled. However, there may be risk of damage to the marker triads or the dummy if the seat back were to collapse and allow interaction with the marker triads or their support structure.

Because of the constraints on available space, marker triads were included on the following planes for the main test programme with the BioRID II dummy:

- Centre-line of the dummy (T1 and pelvis wand)
- OC and T1 pins
- Side of the head
- Side of the seat

This arrangement covered the range of marker planes from nearest the camera to furthest from the camera, and all the marker planes used for calculating the dynamic geometry metric. This is not fully compliant with ISO 8721 if other measurements need to be made from the marker tracking. However, if the nearest and furthest marker planes meet the calibration requirements in ISO 8721, and the distance between these planes is small (as it is for this type of test), it seems reasonable to assume that interim marker planes would also comply if they were to be checked. It is possible that a regulatory text using the dynamic geometry test procedure could define the use of ISO 8721 with calibration lengths only on the nearest and further planes of motion, which would be the side of the seat and the centre-line of the dummy.

The ISO 8721 standard was found to be unnecessarily complex in some regards, and insufficiently well defined in others. For instance, the Control Point Distribution index is automatically met for a 2D analysis if the camera is set up perpendicular to the movement plane. However, as noted above, no tolerance is defined for ‘perpendicular’. If the camera is not perpendicular, the index requires control points in three out of four of the corners of the field of view of the camera such that at least 10% of the area of the image is enclosed within the control points. However, there are no requirements on the accuracy of the control points and they are not subsequently used in a 2D analysis. This parameter therefore seems to be redundant in the context of measuring the dynamic geometry metric.

The objective of the Target Size index is to ensure that the markers tracked for measurement are large enough for reliable tracking, because the markers used for the reference distances may be larger and therefore easier to track. That is, if there is no check on the size of the markers tracked for measurement it is possible that the reference distance markers would be tracked satisfactorily, but the markers tracked for measurement would not be tracked at all, or would be tracked inaccurately. However, this index requires knowledge of the minimum size of marker that can be tracked reliably by the marker tracking software. The standard implies that this should be provided by the developer of the marker tracking software, but this is generally not specified because it depends on the marker type, lens quality, lighting set-up, motion blur and so forth. It is suggested that this index is considered as met, provided that:

- The markers tracked for measurement are at least as large and of the same pattern as the reference distance markers; and
- The lighting for the markers tracked for measurement and the reference distance markers is comparable.

Despite failing the Target Detection index, the final performance requirements were met for this trial camera set-up. In the context of measuring the dynamic geometry metric, this index therefore appears to be overly stringent.

Based on these trials, the design and arrangement of the marker triad calibration lengths was finalised, including only marker triads in the plane of markers critical to the calculation of the dynamic geometry metric. It was expected that this would enable the calibration of the camera system for the BioRID II tests to be undertaken to an accuracy of better than 5 mm for the distance between the OC and T1 markers.

5 BioRID II Validation Testing

5.1 Introduction

Marker tracking analysis was performed for selected tests from the main BioRID II repeatability and reproducibility test programme reported in CPR 1303 "Global Impact Dummies - Assessment concerning BioRID II in Future Regulatory Applications". The BioRID II tests were filmed using either and off-board or on-board camera. Prior to analysis, a comparison of the results from compressed (using the Indeo video 5.10 codec, set to the highest quality setting with file sizes of approximately 80 Mb) and uncompressed (with file sizes of 2 Gb) films was made (see Appendix C). It was found that the differences were not significant, so compressed films were used throughout.

The lens distortion and camera orientation correction method recommended in Section 4 was applied to the camera configuration for the main BioRID II sled test programme, and the camera and marker tracking system was assessed using ISO 8721.

Off-board camera:

The off-board camera was positioned approximately 3 m from the sled, with a lens selected to give a field of view that covered the whole seat and dummy throughout the rear impact event. ISO 8721 calibration lengths (known as marker triads) were rigidly attached to the frame of the spring damper system at the rear of the sled. These were initially outside the field of view of the camera; therefore, the recording time was extended to one second to ensure that the calibration lengths moved throughout the field of view of the camera. Figure 5-1 shows the off-board camera view just after T_0. Lens distortion and camera orientation corrections were applied to the film prior to analysis.

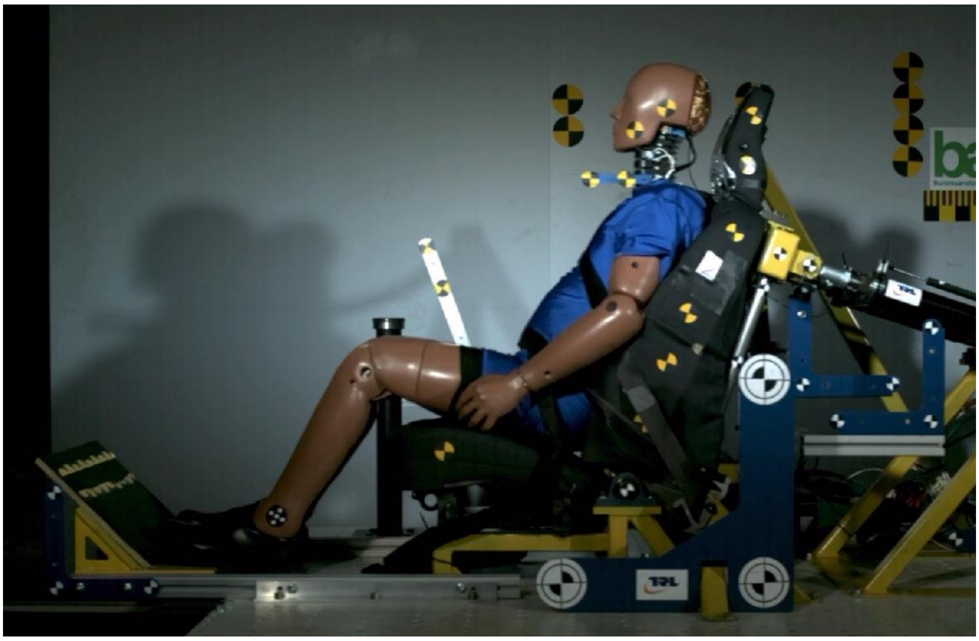

Figure 5-1: Off-board camera view

On-board camera:

The on-board camera was mounted on a framework at the side of the sled. This necessitated the use of a very wide angle lens, as shown in Figure 5-2. Again, lens distortion and camera orientation corrections were applied to the film prior to analysis.

Figure 5-2: On-board camera view

Marker tracking:

The positions of the large black and white datum markers (labelled O1, O2 and O3) in the video files were used to construct a dynamic co-ordinate system so that the tracked data indicated the positions of the markers relative to the large datum on the x-axis. The OC and T1 pin positions were calculated using a virtual marker. For instance, the OC pin position was calculated based on the known relationship between the head CoG and chin markers, and the OC pin, which was measured prior to each test using a co-ordinate measuring machine. This was found to be easier than tracking the OC pin directly. The T1 pin generally became obscured by the t-shirt during the test, so the T1 pin had to be tracked using a virtual marker.

All tracked marker data was filtered using a CFC_20 filter. Figure 5-3 shows the seat and dummy markers that were tracked. All markers on the calibration marker triads (not shown in Figure 5-3) were also tracked.

The marker tracking set-up was calibrated according to ISO 8721:2010, and the results are shown in Appendix D. The off-board camera set-up (just) failed one of the 13 indices (the Target Size index), which related to a maximum error throughout the field of view of the camera of 5 mm in the X-axis, and 7 mm in the Z-axis. The error in the middle portion of the field of view, where the measurements were made, would be expected to be lower. For the on-board camera set-up, the maximum error was 7.2 mm, although it should be noted that this value was only an estimate.

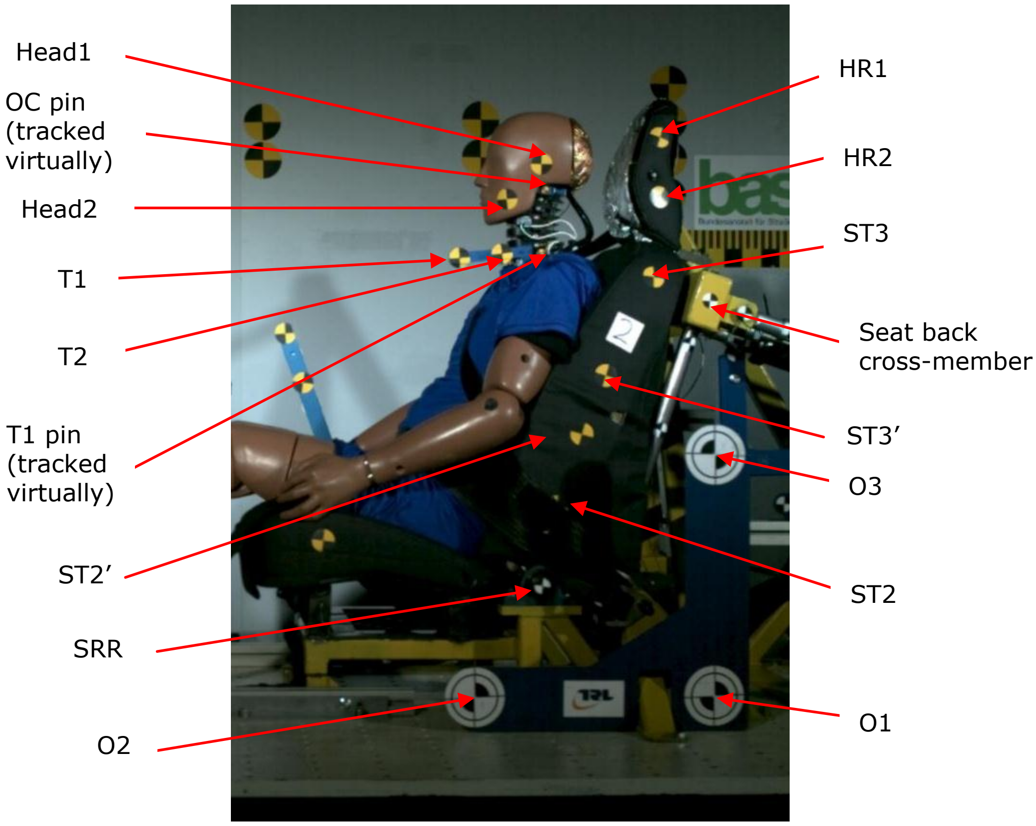

Figure 5-3: Position of markers tracked in TEMA for neck dynamic geometry metric analysis (off-board view)

5.2 BioRID II Kinematic Measurements

5.2.1 Dynamic Geometry Metric with Off-board Camera

The dynamic geometry metric was calculated for up to four tests with each of dummies number 028, 068, 077 and 100. The first test with dummy 100 was not used, because the head restraint moved during this test. Furthermore, film from two of the tests with dummy 028 was not available.

The positions of the large datum markers (O1, O2 and O3) in the video files were used to construct a dynamic co-ordinate system so that the tracked data indicated the positions of the markers relative to the large datum on the X-axis. To assess how the dynamic geometry metric differs between dummies, the data were adjusted to be representative of a seat-back co-ordinate system, based on the superior and inferior/recliner markers on the seat. A further analysis comparing the selection of markers on the seat to use has also been conducted based on the following seat-back co-ordinate systems:

1. 'Hard markers', using the markers located on metal framework as close to the seat as possible. The markers selected for this were 'SRR' and 'Seat-back cross-member', as shown in Figure 5-3.

2. ‘Markers on fabric’, using the markers on the seat to form a co-ordinate system. ST2’ and ST3 were selected for this, because marker ST2 was obscured by the seat-belt and the dummy’s arm during the tests and therefore could not be tracked reliably.
3. ‘Mixed markers, using SRR (hard) and ST3 (fabric) to create an axis based on the entire length of the seat.

During the tracking process for both the on-board and off-board cameras, it was observed that the ‘hard markers used for the seat were easier to track than the triads on the seat itself as the markers on the seat were more susceptible to glare from the lighting and could be lost in some frames.

Figure 5-4 to Figure 5-6 show the dynamic geometry metric calculated for the three different seat-back co-ordinate systems using the off-board camera. The figures indicate a peak (negative) dynamic geometry metric ranging between -10 and -20 mm. Dummy 028 appears to be the least consistent in each of the seat-back co-ordinate systems, with an apparent large range in peak dynamic geometry metric values between the tests. There is less variation between the curves for all dummies when hard points are used in the seat-back co-ordinate system, potentially as a result of movement of the fabric-based markers due to movement of the fabric relative to the seat frame.

Dummies 077 and 100 produce similar dynamic geometry metric curves. It is unknown why two of the dummy 068 curves appear to be consistent outliers when compared with data from tests with other dummies.

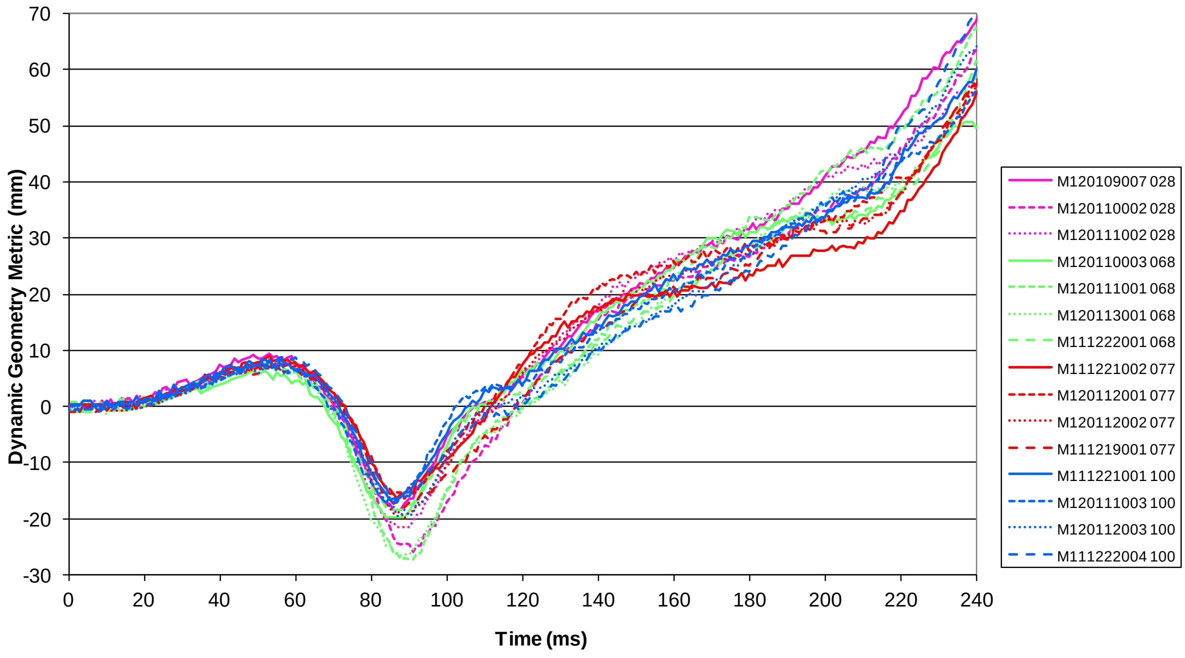

Figure 5-4: Dynamic geometry metric using a seat-back co-ordinate system based on ‘hard’ marker locations (SRR and seat-back cross-member)

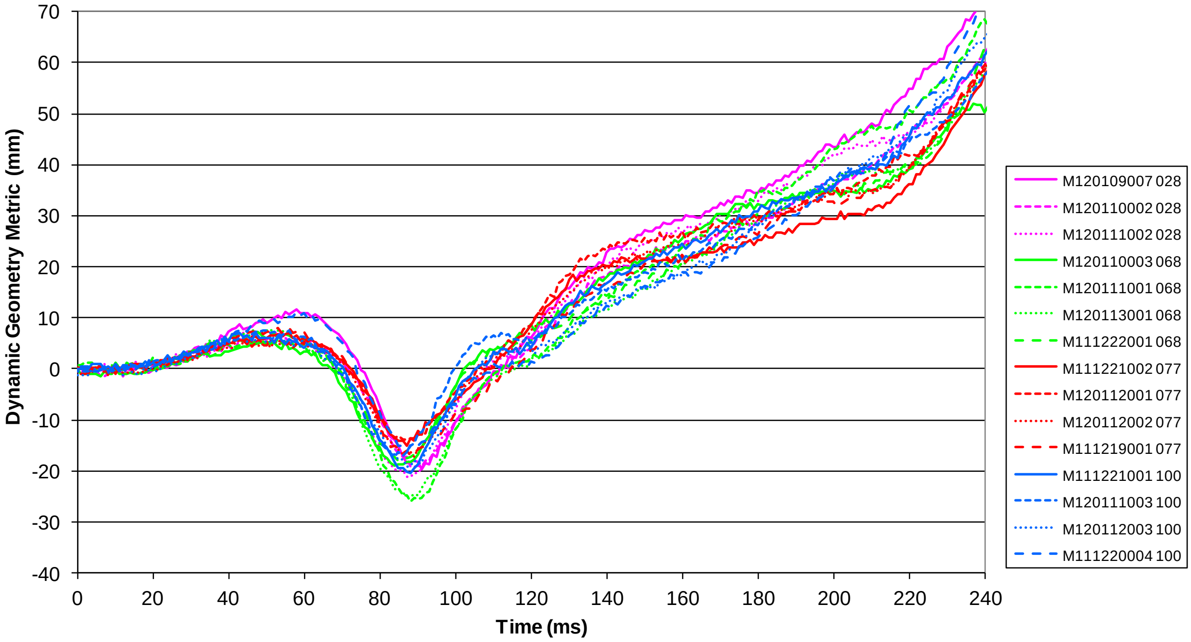

Figure 5-5: Dynamic geometry metric using a seat-back co-ordinate system based on markers on the seat fabric (ST2' and ST3)

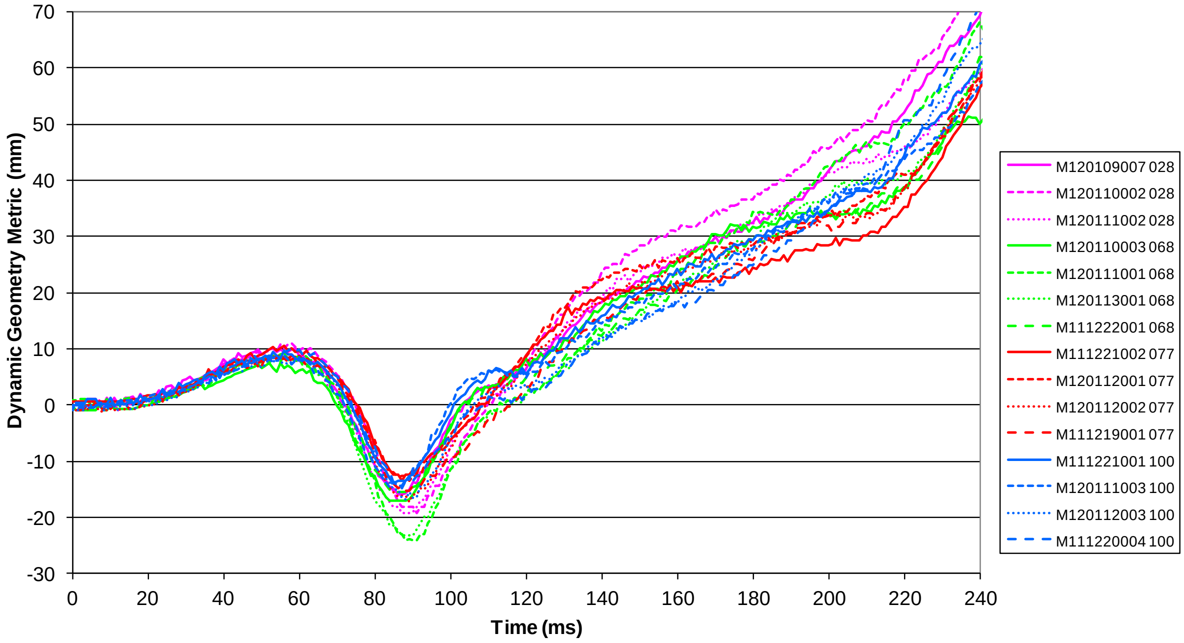

Figure 5-6: Dynamic geometry metric using a seat-back coordinate system based on one 'hard' marker and one marker on the seat fabric (SRR and ST3)

The peak dynamic geometry metric for each of the tests is indicated in Table 5-1. The average peak value for each dummy is fairly consistent, varying by up to 3 mm across the seat-back co-ordinate systems.

Table 5-1: Peak dynamic geometry metric for each seat-back co-ordinate system

Test date and dummy	Hard markers		Seat fabric markers		Mixed markers	
	Peak dynamic geometry metric (mm)	Average peak (mm)	Peak dynamic geometry metric (mm)	Average peak (mm)	Peak dynamic geometry metric (mm)	Average peak (mm)
M120110003 068	-19.8	-23.1	-17.1	-20.1	-18.9	-22.0
M120111001 068	-27.3		-24.1		-25.9	
M120113001 068	-26.5		-23.3		-25.0	
M111222001 068	-18.6		-15.7		-18.1	
M111221002 077	-16.4	-17.7	-13.5	-14.9	-15.1	-15.8
M120112001 077	-16.4		-13.6		-14.1	
M120112002 077	-20.0		-17.3		-17.1	
M111219001 077	-18.1		-15.4		-17.1	
M111221001 100	-16.5	-17.6	-13.9	-15.0	-20.5	-18.3
M120111003 100	-17.3		-14.6		-17.2	
M120112003 100	-19.6		-16.8		-19.1	
M111220004 100	-17.0		-14.9		-16.2	
M120109007 028	-18.4	-21.9	-16.0	-18.2	-19.6	-20.0
M120110002 028	-25.8		-19.2		-19.3	
M120111002 028	-21.6		-19.3		-21.0	

The coefficient of variation (reproducibility) for these tests was 12% using markers attached to hard points on the structure of the seat, which is slightly greater than the target CV of 10% for dummy reproducibility.

5.2.2 *Other Kinematic Measurements with Off-board Camera*

Although the primary goal of this work was to assess the reproducibility of the dynamic geometry metric, and the suitability of camera calibration systems determining the metric from marker tracking data, various other dummy kinematic parameters that could be derived from the marker tracking data were plotted as an input to the BioRID TEG meetings. The following kinematic parameters are discussed:

- The rotation angles of the head, T1 wand and pelvis relative to the sled
- The rotation angle of the head relative to the T1 wand
- The vertical displacement of OC pin, T1 pin and lowest pelvis marker

The rotation angles of the head, T1 wand and pelvis relative to the sled are shown in Figure 5-7 to Figure 5-9. The data was adjusted so that the rotation angles relative to the sled were 0 degrees at T_0. The head angle relative to T1 is shown in Figure 5-10.

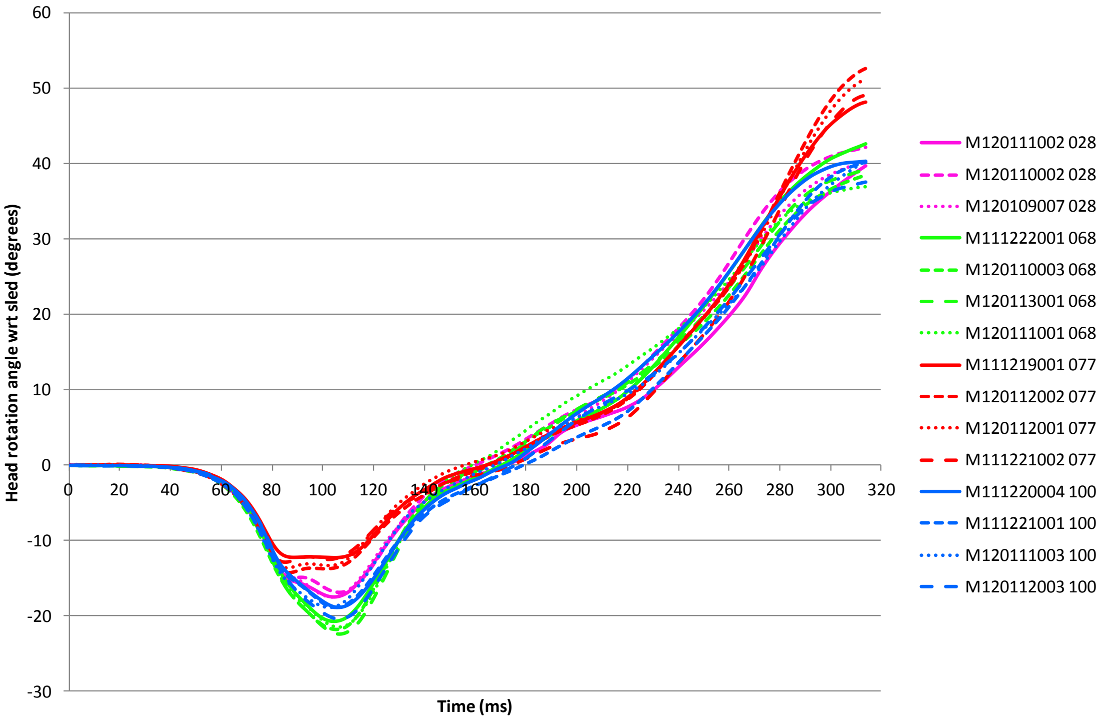

Figure 5-7: Head rotation angle with respect to the sled co-ordinate system, baseline dummy tests

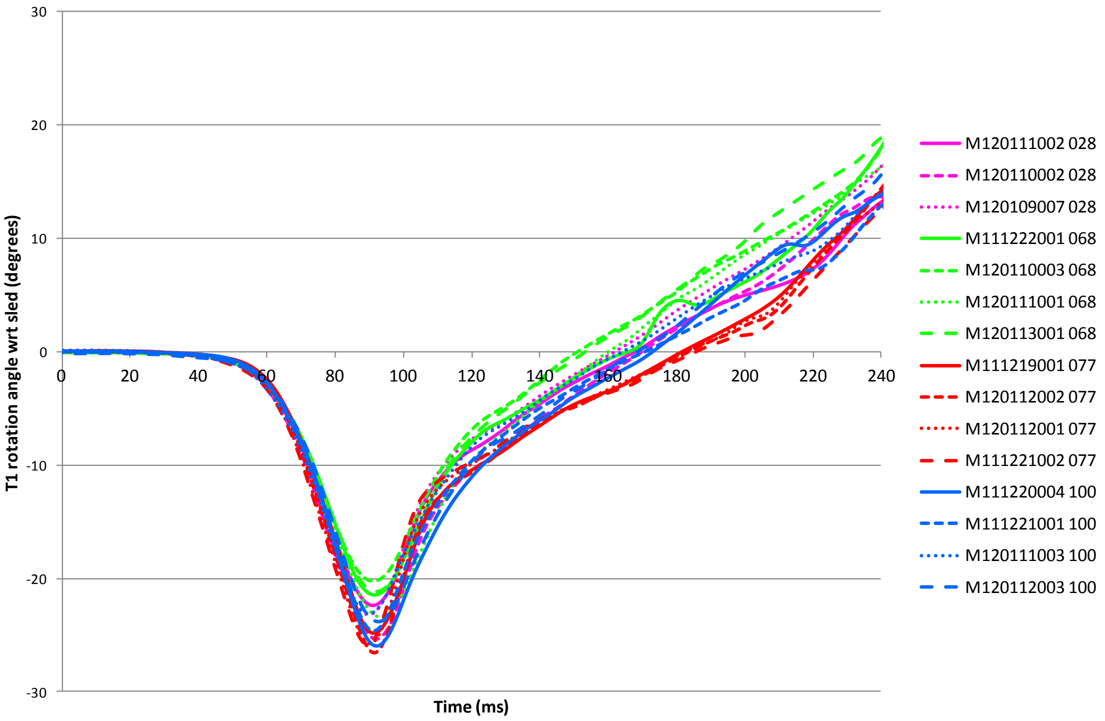

Figure 5-8: T1 rotation angle with respect to the sled co-ordinate system, baseline dummy tests

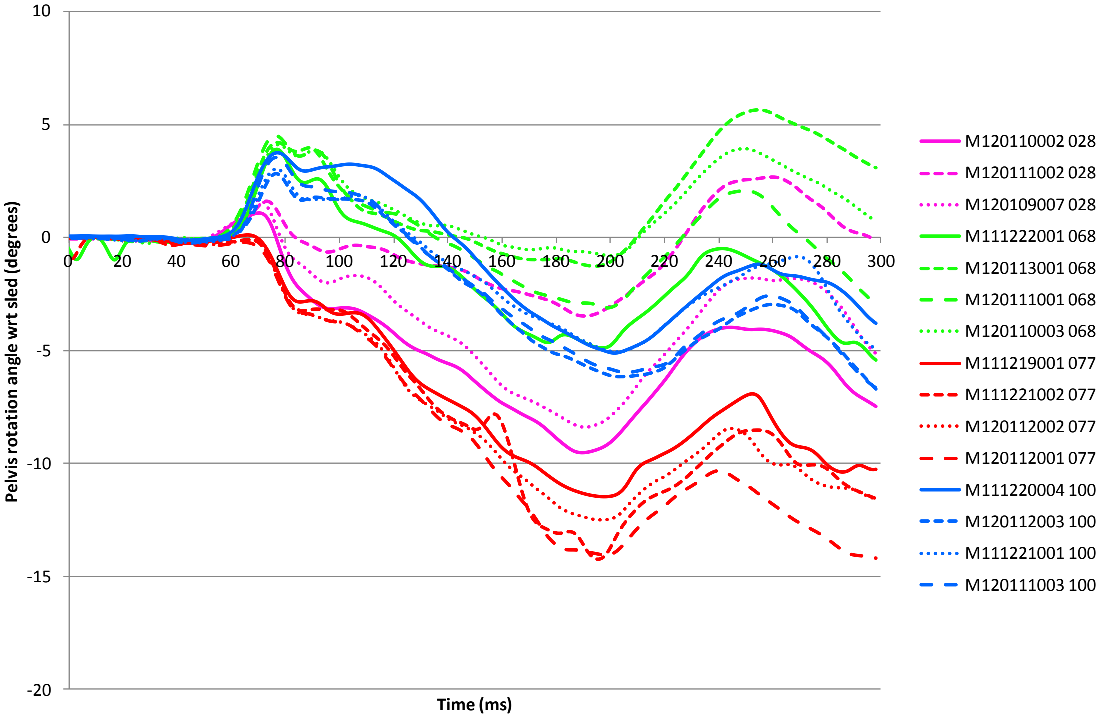

Figure 5-9: Pelvis rotation angle with respect to the sled co-ordinate system, baseline dummy tests

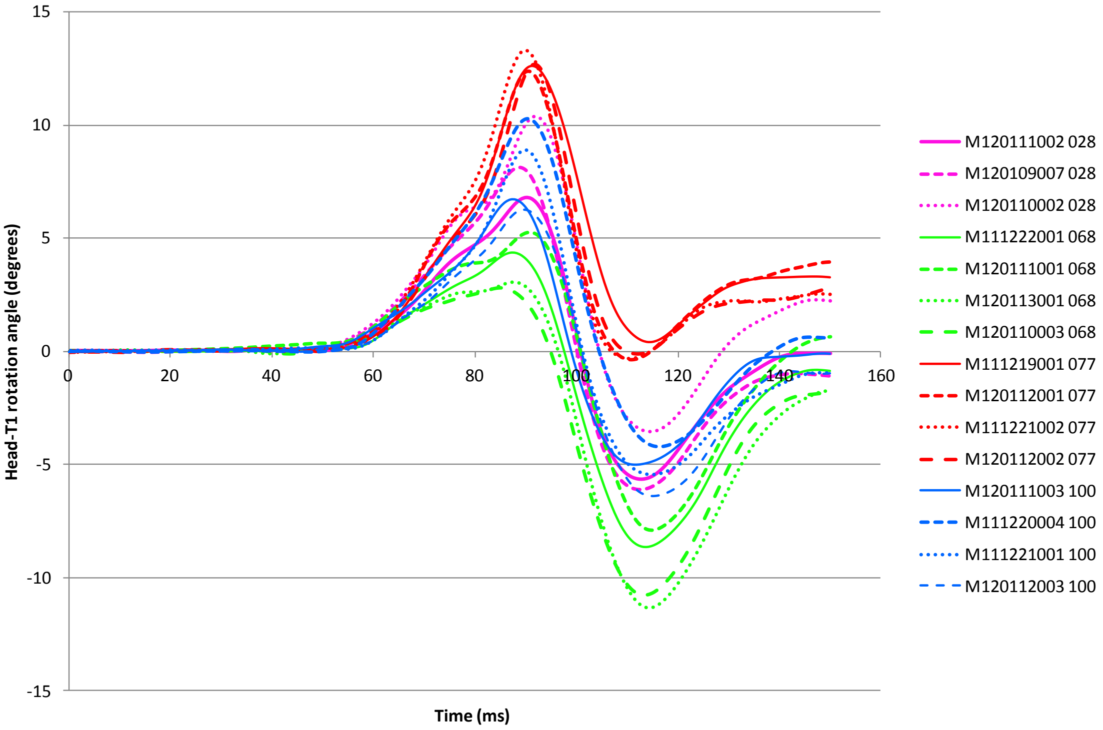

Figure 5-10: Head rotation angle with respect to T1, baseline dummy tests

Figure 5-7 and Figure 5-8 suggest that the rotation angle of the head and the T1 wand relative to the sled is repeatable as very similar behaviour is exhibited for each of the tests conducted with the same dummy. However, the reproducibility was poor, with dummy 077 producing a peak head rotation angle 10° smaller than dummy 068.

The pelvis rotation angle also had reasonable repeatability, but again the reproducibility was poor. The angles are relatively small, but the peak pelvis rotation angle relative to the sled varied by approximately 5° between dummies. Furthermore, dummies 068 and 100 had an initial positive rotation, whereas dummy 077 only shows a negative rotation throughout the rear impact event.

The head rotation relative to T1 was reasonably repeatable, but not reproducible. There was a difference in rotation of approximately 10° between dummy 068 and dummy 077 throughout the head restraint contact phase of the test.

The vertical displacement of the OC pin, T1 pin and lowest pelvis wand marker have also been calculated. These are shown in Figure 5-11 to Figure 5-13 respectively. The curves indicating the displacement of the OC pin and T1 pin show good repeatability but poor reproducibility, with dummy 077 producing the smallest displacement and dummy 068 producing the largest displacement for both components of the dummy. The difference in Z-axis motion of the dummies exceeds 20 mm during the head restraint contact phase of the rear impact test.

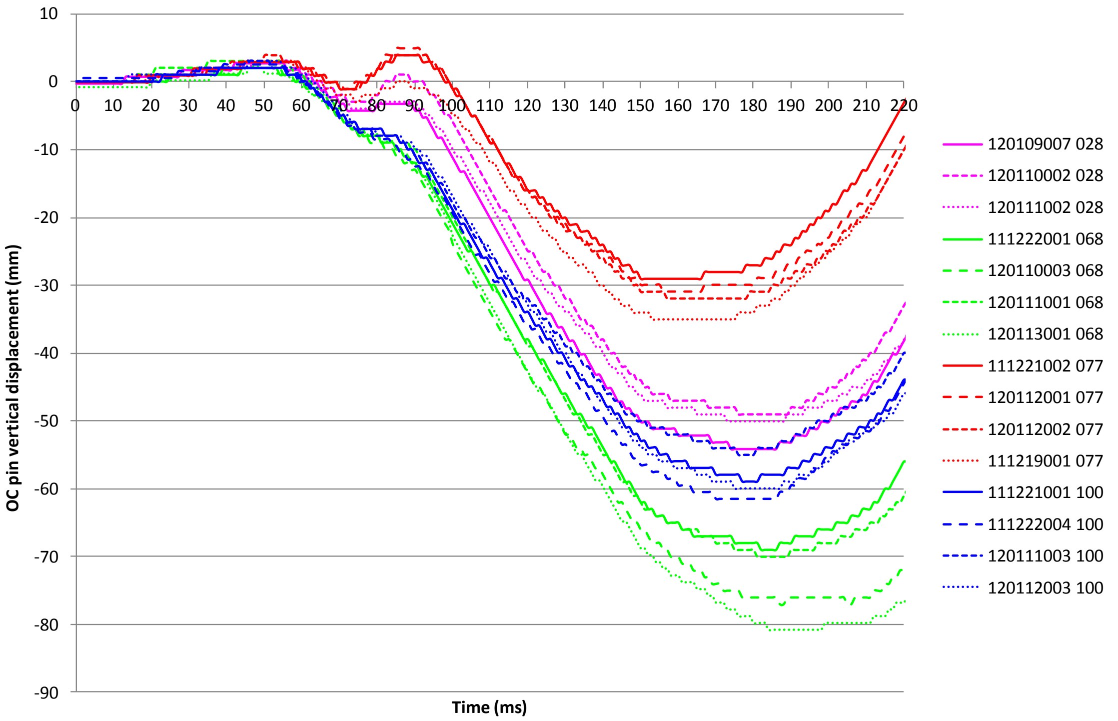

Figure 5-11: Vertical (Z-axis) displacement of the OC pin

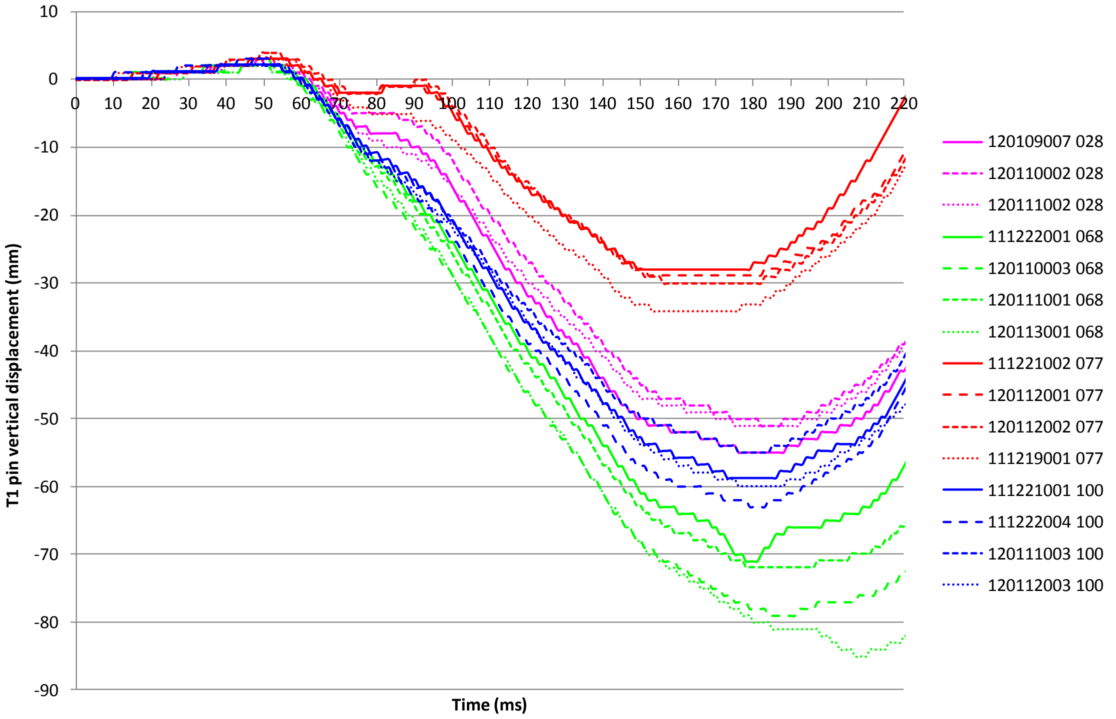

Figure 5-12: Vertical (Z-axis) displacement of the T1 pin

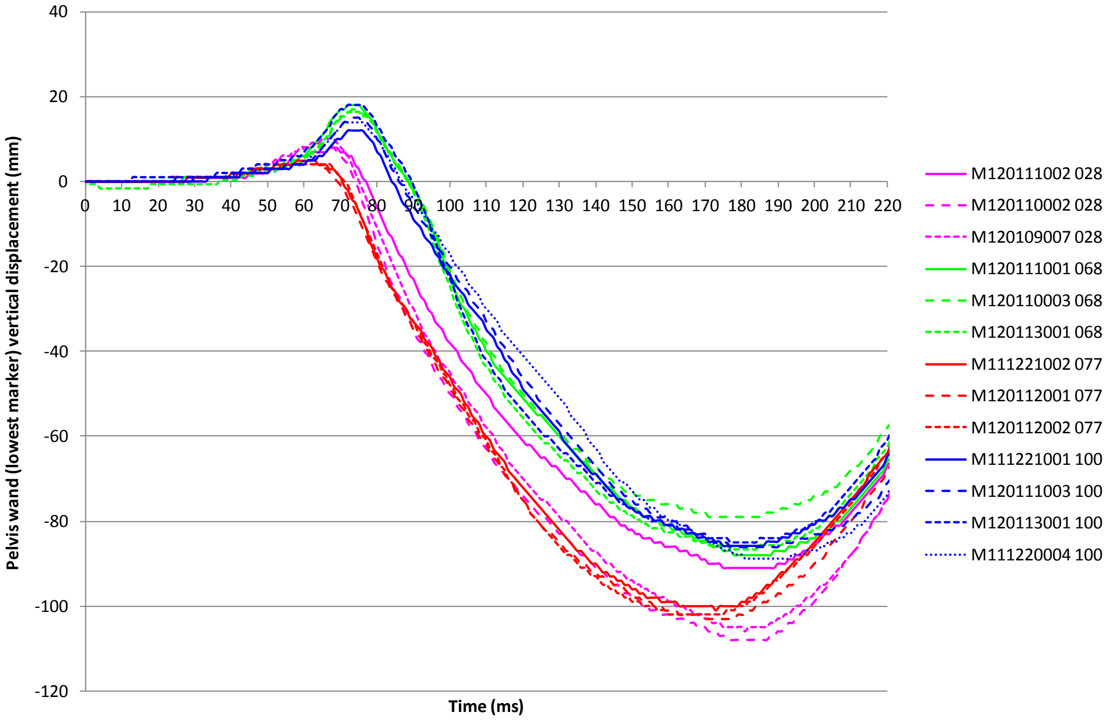

Figure 5-13: Vertical (Z-axis) displacement of the lower pelvis wand marker

5.2.3 Dynamic Geometry Metric with On-board Camera

For the on-board tests, the dynamic geometry metric was calculated using two head restraint positions, corresponding to BioRID target backsets of approximately 75 mm and 35 mm respectively. Three tests were performed at each head restraint position, using dummy 100 for all tests. Figure 5-14 to Figure 5-16 show the dynamic geometry metric calculated for the three different seat-back co-ordinate systems using the on-board camera. The tests with the 35 mm target backset are shown in red, and with the 75 mm backset in blue.

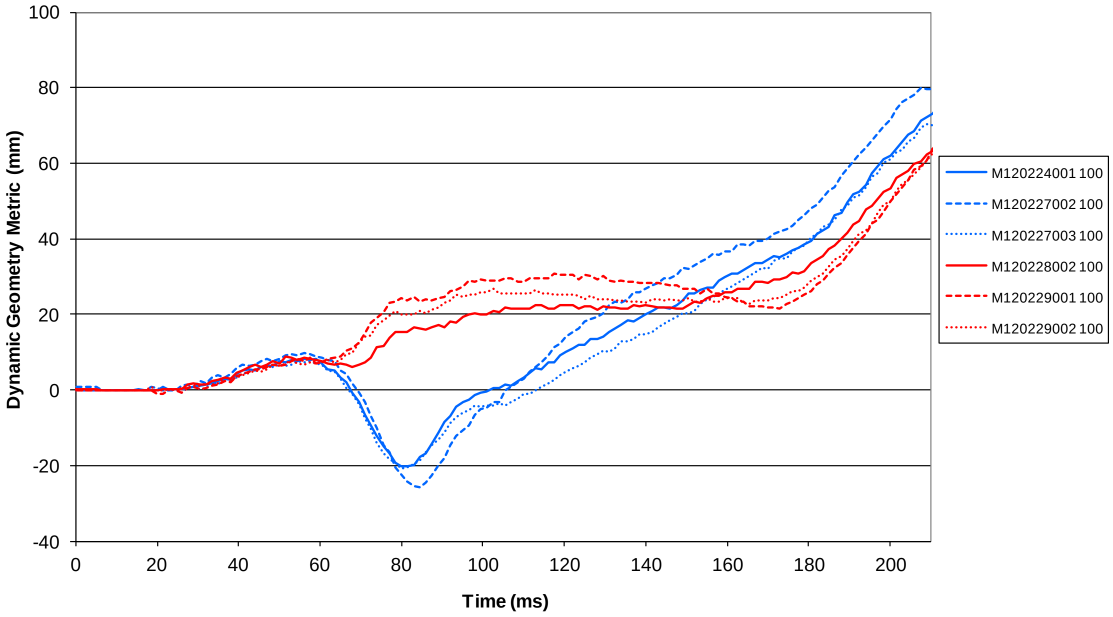

Figure 5-14: Dynamic geometry metric using a seat-back co-ordinate system based on 'hard' marker locations (SRR and seatback cross-member)

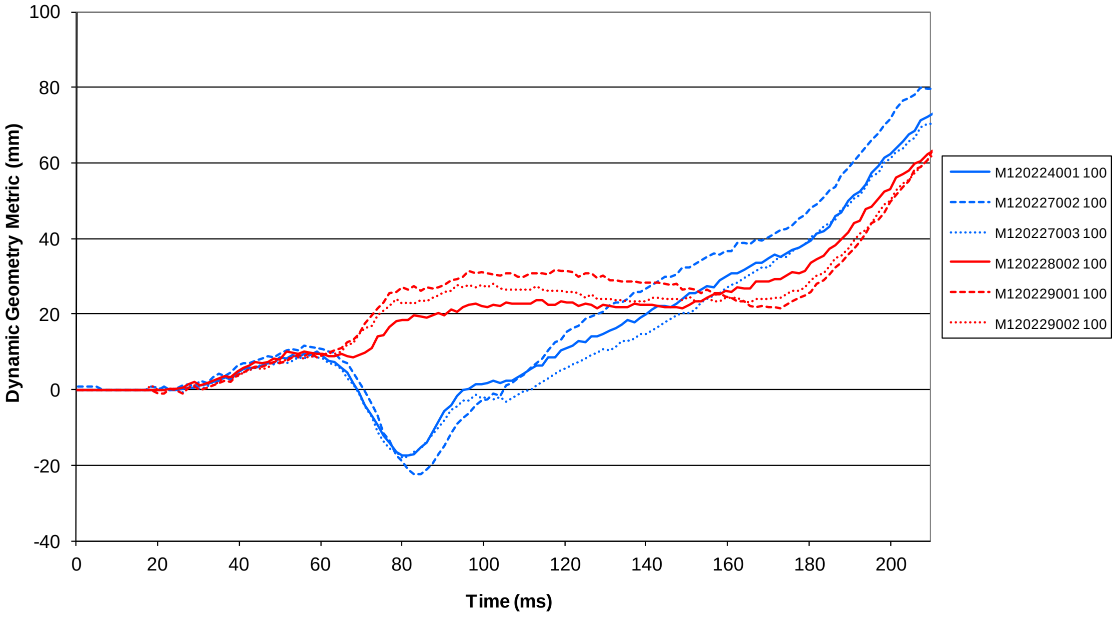

Figure 5-15: Dynamic geometry metric using a seat-back co-ordinate system based on one 'hard' marker and one marker on the seat fabric (SRR and ST3)

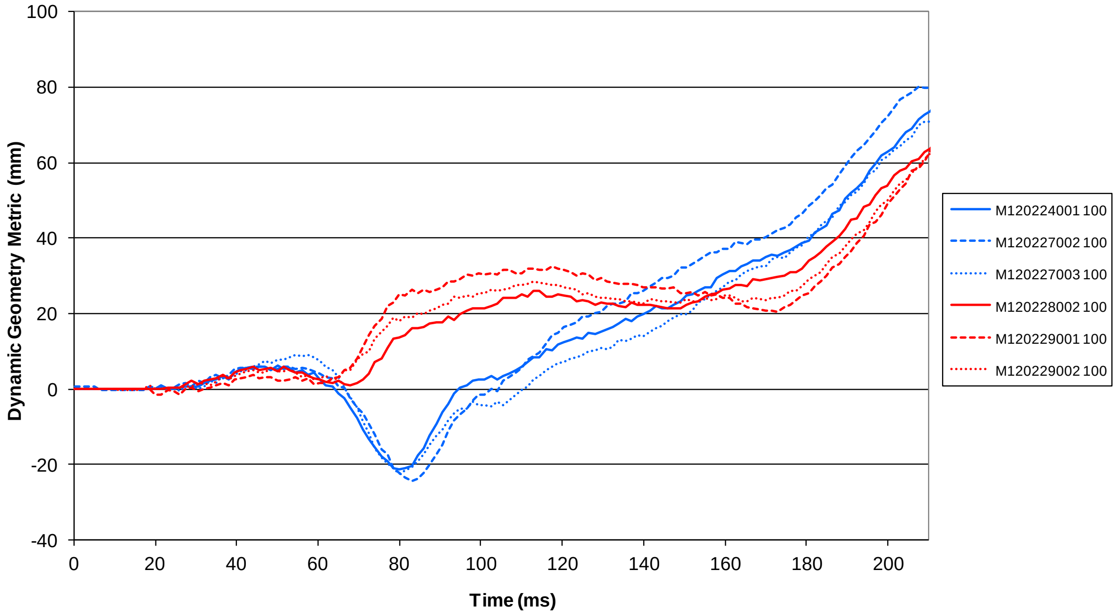

Figure 5-16: Dynamic geometry metric using a seat-back co-ordinate system based on markers located on the seat fabric (ST2' and ST3)

It can be seen from Figure 5-14 to Figure 5-16 that the dynamic geometry metric was repeatable for both head restraint conditions. The difference in the dynamic geometry metric for the two head restraint positions was approximately 40 mm (-20 mm for the far head restraint, and +20 mm for the near head restraint position). This corresponds very well with the static measurement of head restraint position for these tests, which had a range of 40 mm. It also indicates that at 35 mm static backset, the head restraint effectively pushed the OC forward 20 mm relative to the T1, which may not be desirable.

5.2.4 Other Kinematic Measurements with On-board Camera

The rotation angles of the head, T1 wand and pelvis relative to the sled are shown in Figure 5-17 to Figure 5-19. The data were adjusted so that the rotation angles relative to the sled were 0° at 0 ms. Again, the tests with the 35 mm target backset are shown in red, and with the 75 mm backset in blue.

The curves in Figure 5-17 suggest that the tests were repeatable for each dummy and test configuration as the variation between tests is small. The same small variations are evident in Figure 5-18 for the T1 rotation angle relative to the sled, where the angle appears to be nearly identical for tests conducted with the smaller backset. The peak pelvis angle at 70 ms was quite repeatable, but not repeatable or reproducible after this time.

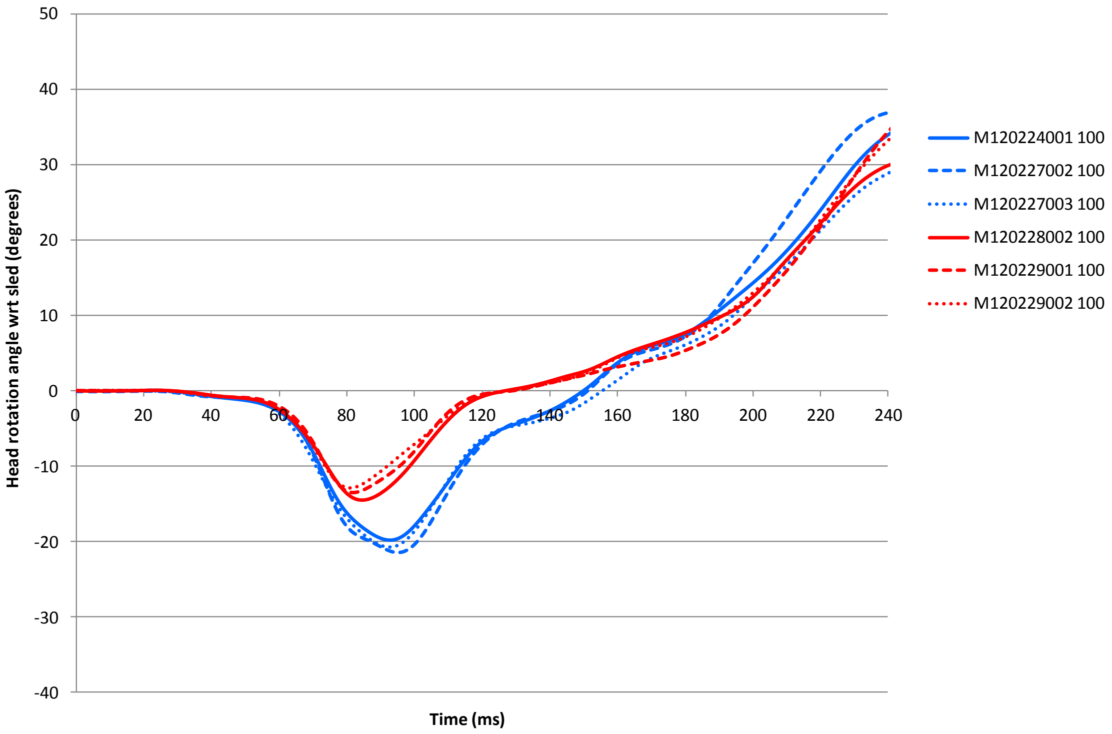

Figure 5-17: Head rotation angle with respect to the sled co-ordinate system, baseline dummy tests

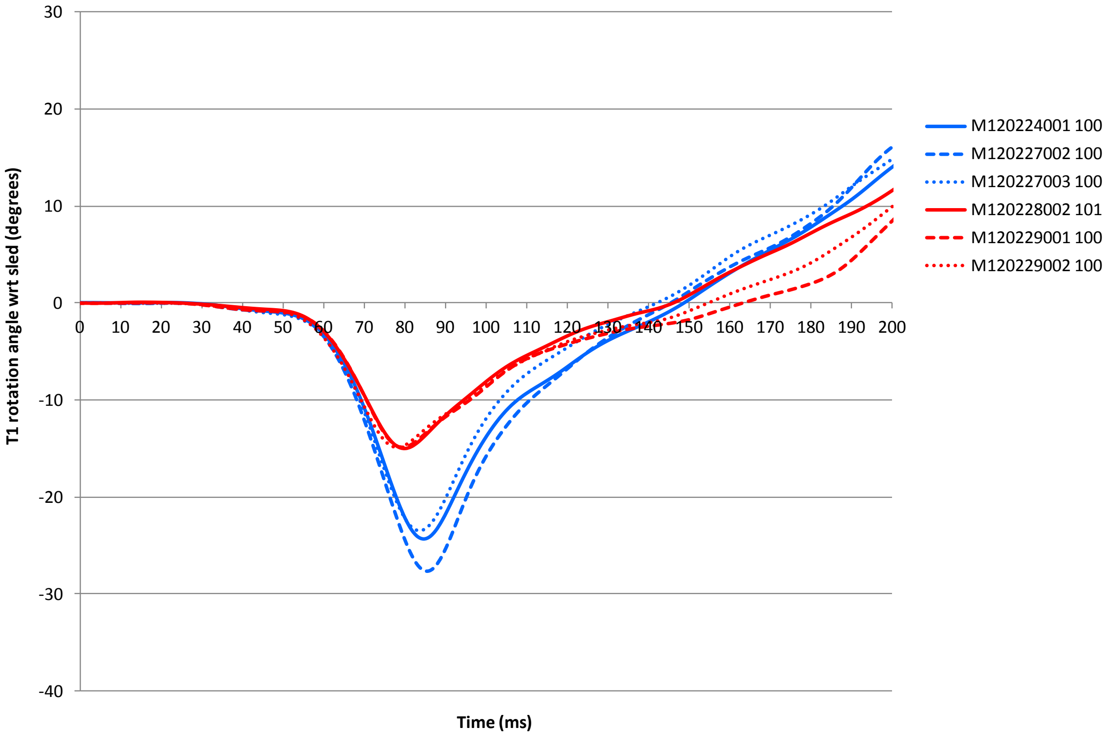

Figure 5-18: T1 rotation angle with respect to the sled co-ordinate system, baseline dummy tests

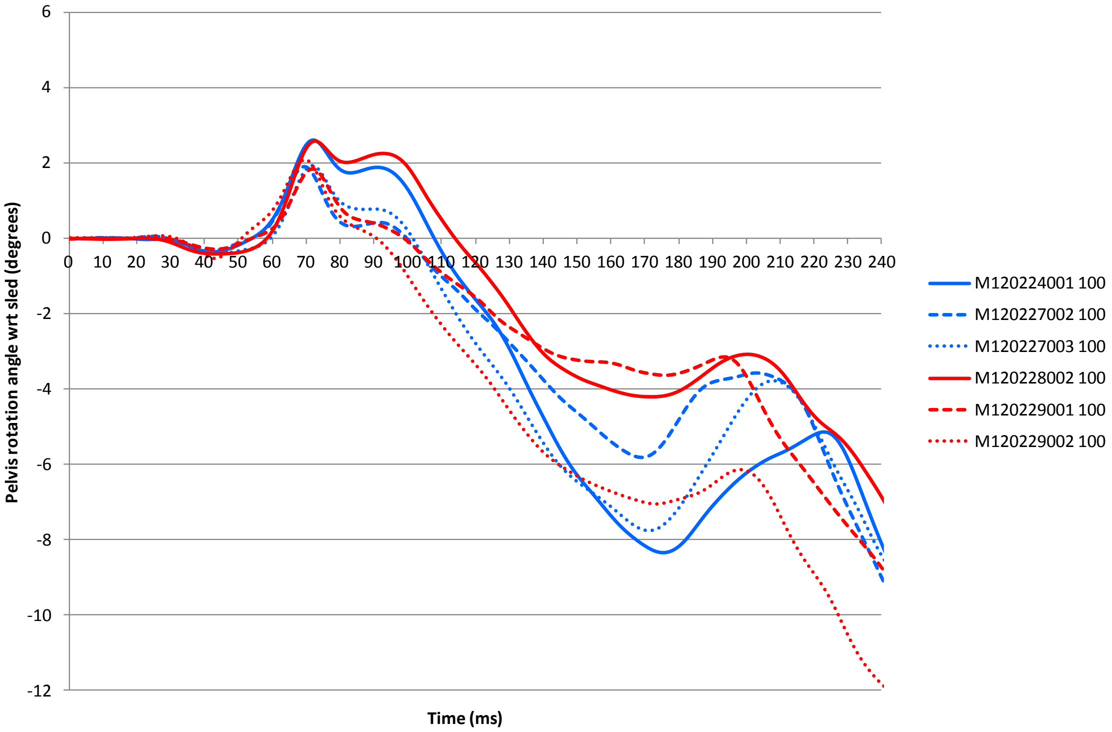

Figure 5-19: Pelvis rotation angle with respect to the sled co-ordinate system, baseline dummy tests

Figure 5-20 depicts the head rotation angle relative to the T1 wand. The amplitude of the peak rotation angles is smaller for the tests conducted with the smaller backset, and the tests appear to be more consistent than those for the head restraint adjusted to the larger backset.

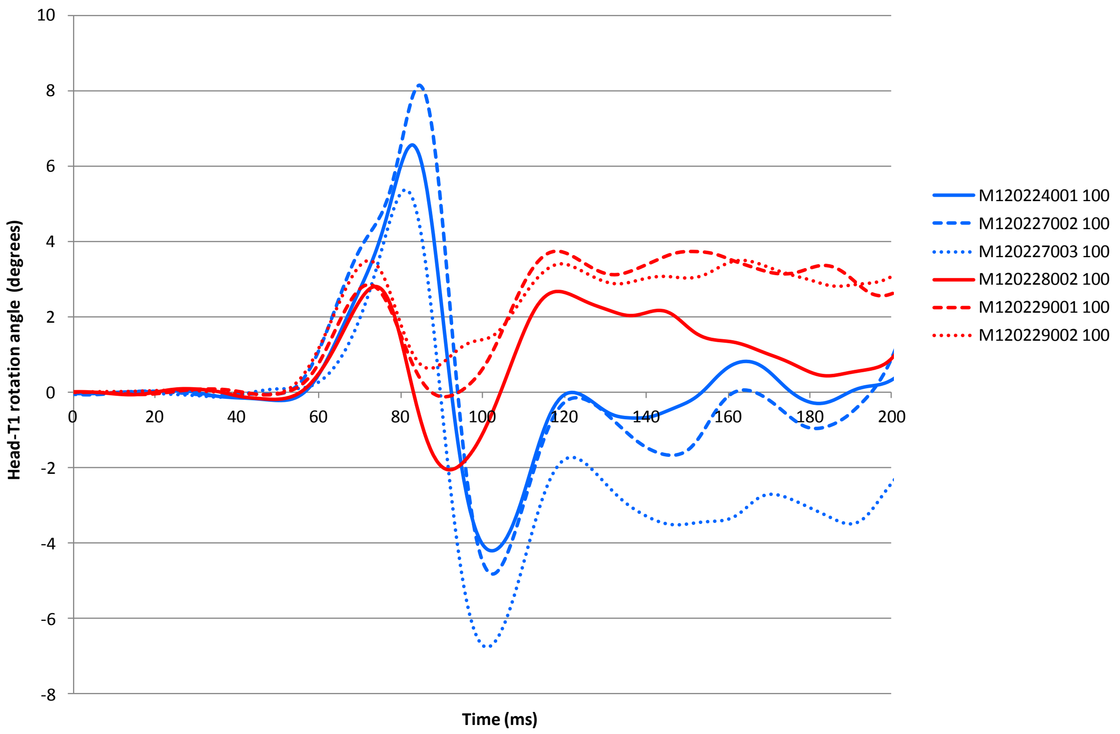

Figure 5-20: Head rotation angle with respect to T1, baseline dummy tests

The vertical displacement of the OC pin, T1 pin and the lowest pelvis marker was calculated in TEMA and the change in vertical displacement with time for each of these markers is shown in Figure 5-21 to Figure 5-23. These results show similar responses for both head restraint positions until approximately 110 ms; thereafter the repeatability of the result is not as good, although this is after the time of the key peak dummy force, moment and acceleration measurements.

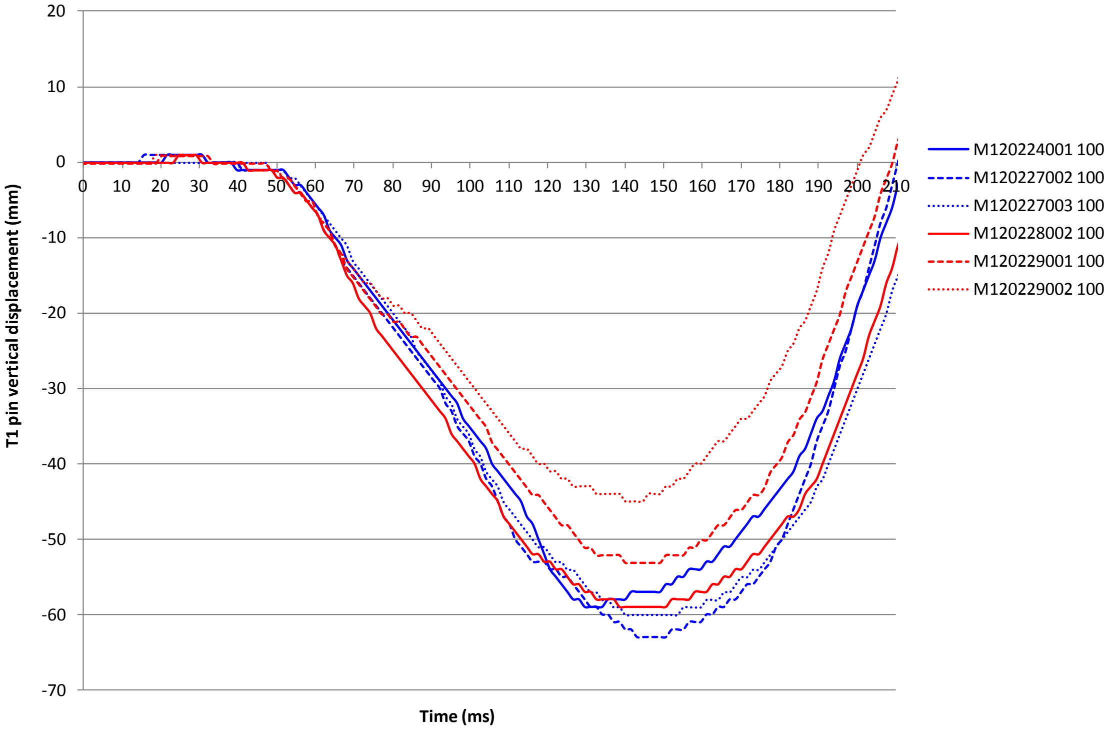

Figure 5-21: Vertical (z-axis) displacement of the T1 pin

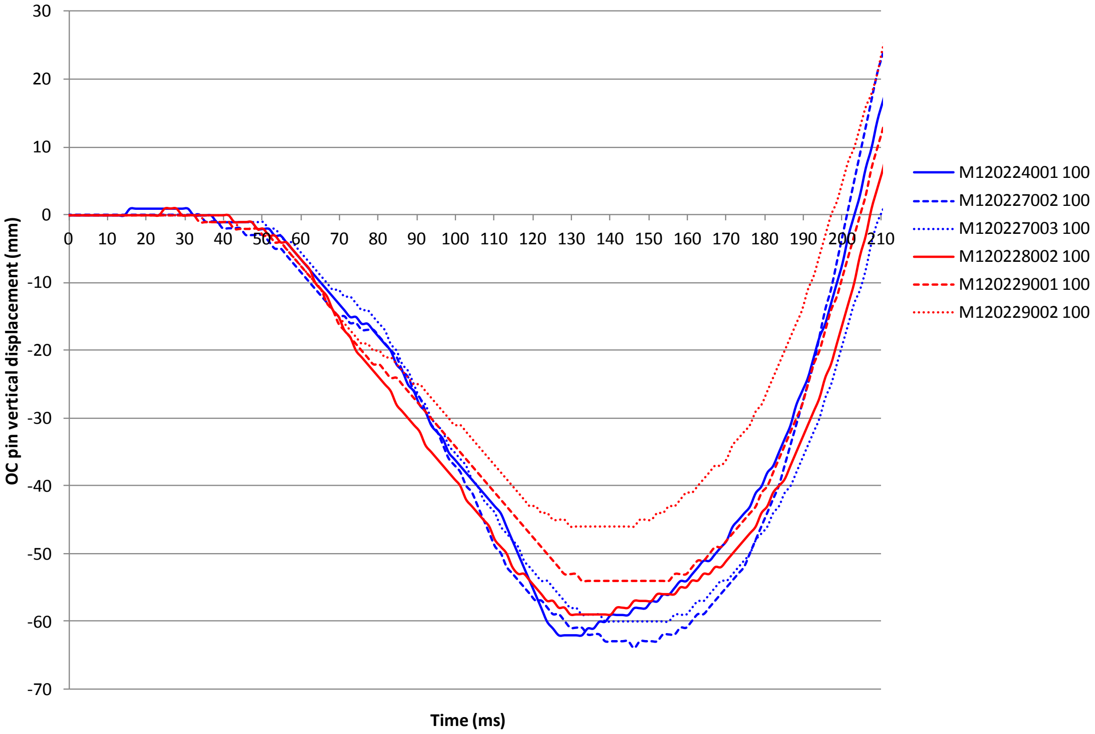

Figure 5-22: Vertical (z-axis) displacement of the OC pin

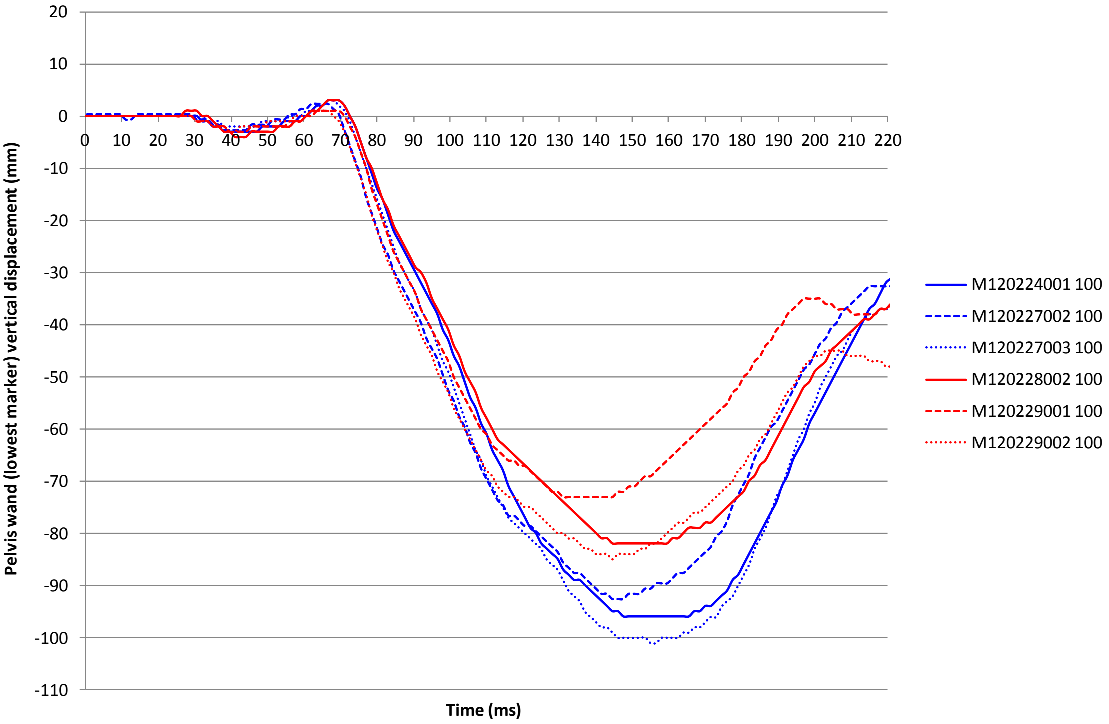

Figure 5-23: Vertical (z-axis) displacement of the pelvis wand (lowest marker)

5.3 Conclusions and Recommendations

The difference in marker tracking results between compressed and uncompressed films was found to be negligible, at least for the films and compression codec used in this study. Therefore, compressed films were used throughout the analysis.

The off-board camera was calibrated according to ISO 8721:2010, except for compliance with the target detection index. The off-board set-up would require small improvements in order to be fully compliant with the standard. Nevertheless, the results clearly show repeatable kinematic parameters for the dummies, and poor reproducibility for measurements except for the dynamic geometry.

The coefficient of variation (reproducibility) for the dynamic geometry metric in these tests was 12% using markers attached to hard points on the structure of the seat, which is slightly greater than the target CV of 10% for dummy reproducibility. The dynamic geometry metric for the seat used in this study was 20 mm, which is much less than the threshold of 52 mm proposed by Japan. Hence although the CV relative to the measured metric (i.e. 20 mm) is 12% relative to the pass-fail threshold proposed by Japan it may be much less than 10%.

The reproducibility of the dynamic geometry metric is clearly better than the upper neck My, upper neck Fz, T1 Fz measurements reported in CPR1303 "Global Impact Dummies - Assessment concerning BioRID II in Future Regulatory Applications". The reproducibility of the dynamic geometry metric may also improve if the variation in ramping-up behaviour between dummies is reduced.

On-board camera tests were undertaken for two head restraint positions. The on-board camera could not be fully calibrated to ISO 8721:2010 using the marker set-up used in these tests because the calibration markers did not move through the field of view of the camera. Instead similar checks were made based on the known distance between pairs of markers on the dummy (measured using a co-ordinate measuring machine) were made and the results were comparable with the on-board camera results.

In on-board camera tests, the dynamic geometry metric was repeatable for both head restraint positions. The difference in dynamic geometry metric with the two head restraint positions was approximately 40 mm (-20 mm for the far head restraint, and +20 mm for the near head restraint position). This corresponds very well with the static measurement of head restraint position for these tests. It also indicates that at 35 mm backset, the head restraint effectively pushed the OC forward 20 mm relative to the T1, which may not be desirable.

6 Conclusions and Recommendations

6.1 Validation of the Dynamic Geometry Metric

Development of a pass-fail threshold:

- A pass-fail threshold for the dynamic geometry metric has been proposed by Japan that directly relates the dynamic measurement to the equivalent static backset measurement for standard seat types.
- The recommended pass-fail threshold was 52 mm, which included a 4 mm allowance for the standard deviation of the dummy responses.
- The pass-fail threshold was developed for a 15.7 $km.hr^{-1}$ pulse, but consideration could be given to using the 17.6 $km.hr^{-1}$ pulse proposed for the draft GTR-7 Phase 2
- The pass-fail threshold also correlated well with IIWPG whiplash ratings for the seats.

Assessment of reproducibility:

- From the literature, good reproducibility was shown in tests with three seat types and three BioRID II dummies (the specification of the dummies used in these tests pre-dated the current Informal Group specification).
- A coefficient of variation (CV) of 12% was found for the dynamic geometry metric in BioRID II tests in the present study. This is close to the target CV of ≤ 10%, despite significant variations in the ramping-up behaviour of the four dummies that were tested.
- It should be noted that the dynamic geometry metric for the seat used in this study was 20 mm which is much less than the threshold proposed by Japan of 52 mm. Therefore, although the CV relative to the measured metric (i.e. 20 mm) is 12%, relative to the pass-fail threshold proposed by Japan it may be much less than 10%.

Issues requiring further validation:

- The assessment of seats with a single-sided recliner mechanism may have reproducibility problems, because the recliner and non-recliner sides of the seat back may rotate by a different amount. It is recommended that the effect of single-recliner mechanisms is checked based on data using a seat that has been filmed from both sides. In particular, the use of a mean seat back angle from the left and right views should be considered.
- Determination of the BioRID Target Backset, particularly relating to the reproducibility of the 3D H-point machine and HRMD. The GTR-7 Phase 2 Informal Group is working to improve the specification of the 3DH machine and HRMD to improve the reproducibility of this measurement, and it is recommended that the progress of Group is monitored.

6.2 Calibration of Camera-based Marker Tracking Systems

- A theoretical analysis of calibration requirements suggested that random measurement errors are likely to dominate over any systematic error, and that as long as the data is filtered to remove some of the variation caused by the random error, the accuracy of the calculated peak dynamic geometry metric will be comparable to the accuracy of the marker position measurements
- The ISO 8721:2010 standard was to a large extent found to be suitable for checking the accuracy of off-board camera-based marker tracking systems used to measure the dynamic geometry metric
    - Further work would be required to develop a method for applying the standard to the calibration of on-board camera systems
- In the context of measuring the dynamic geometry metric, the standard may be unnecessarily complex in some respects. Consideration should be given to referencing a sub-set of the requirements in the standard, e.g.
    - The Control Point Distribution index may be unnecessary
    - Target Size index is considered as met, provided that:
        - The markers tracked for measurement are at least as large and of the same pattern as the reference distance markers; and
        - The lighting for the markers tracked for measurement and the reference distance markers is comparable
    - The Target Detection index may be unnecessary
- A suitable accuracy index must be specified. The testing programme reported herein used a requirement of 5 mm (approximately 10% of the proposed dynamic geometry threshold), which was achievable and may be considered adequate

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Appendix A Review of ECE-TRANS-WP29-GRSP-2009-07 Japan Proposal for Alignment of Regulation 17 with GTR-7

This appendix summarises the key points arising from a review of the proposed amendment to Regulation 17 (including proposed amendments relevant to the dynamic geometric test procedure). A summary of the topics reviewed, their status and the implications of their status is given under the following headings.

Definitions

There are a number of terms used in the proposed text that are either not defined, or have an ambiguous definition. For example:

- The definition of ‘backset’ is not clear and appears to define a quantity different from that intended. See comments and diagram in Section 2.7 of the attachment.
- Two different definitions of ‘backset’ are required when using the H-point machine and HRMD: one for the static backset of the head restraint using the H-point method (Annex 4, Section 2); and a different definition of backset used to set up the BioRID II dummy (sometimes called the ‘BioRID Reference Backset’). (The definition of backset in Annex 4, Section 3 for the R-point method is clear.) See comments and diagram in Section 2.7 of the attachment.

Torso Angle

The proposed text states that the seat should be tested at the manufacturer’s design angle.

- No provision is made for what to do if this specification is not available from the manufacturer. UNECE Regulation 17.07 uses a default of 25° *unless* a design torso angle is provided by the manufacturer.
- As discussed in recent BioRID Technical Evaluation Group (TEG) and GTR-7 meetings, the BioRID IIg dummy is not suitable for use in seats with a design torso angle <20°. No guidance is given in the text regarding how such seats should be tested. Work on the use of the BioRID II at design torso angles <20° in GTR-7 Phase 2 has been deferred until a later phase of the work.
    - For seats where structures behind the seat may support the seat, these structures should be replicated for the test (by using a body in white in the current text – see comments in ‘Body in White’ section below). For such seats it may not be possible to set the seat to an angle greater than 20°.

References to BioRID II

Annex 9 requires the use of BioRID II(g) 50th percentile male test dummy, including a description of the dummy, the seating procedure, spine curvature, and reference to dynamic certification requirements available from the manufacturer of the dummy.

- Currently the text should be updated to refer to the BioRID II documents on the UNECE web site (www.unece.org/trans/main/wp29/wp29_dummyspec.html) once these documents are finalised. The documents are likely to include the drawing package, design checklist, maintenance checklist and certification procedures. Ultimately, this text will need to refer to whatever document storage system is approved by WP.29.

Body in White

Annex 9, paragraph 2.2 notes that a vehicle body in white should be used when additional support is provided to the seat by the vehicle body structures.

- It is clear that any supporting structures could significantly influence seat performance, e.g. the firewall behind the seats in a rear-engined two-seater car. However, the support provided may vary depending on the seat fore-aft adjustment position. It is recommended that consideration should be given to testing with the seat in the rearmost and forwardmost positions. The seat should pass the requirements in both positions.
- The use of a complete body in white is very likely to obscure some of the markers that have to be tracked, e.g. if the B-pillar comes between the upper seat marker and the camera. It is recommended that consideration should be given to alternatives that would provide the same support as the vehicle structures, but allow the camera to see all markers throughout the whole impact event.
- The authors are not aware of any evidence that the pulses usually used for seat testing with BioRID II can be achieved with a body in white on the sled; the feasibility of this should be demonstrated before including this option in the regulatory text.

Acceleration and Deceleration Sleds

Annex 9, paragraph 3.1 requires the use of an acceleration or deceleration sled.

- Some deceleration sleds that have been used for rear impact seat testing with BioRID II have included an apparatus to hold the head of the dummy in position during the initial acceleration phase of the head. The head is then released at t_0. It is recommended that consideration is given to reviewing the need for such additional apparatus for deceleration sleds and, if they are found to be essential for repeatability and reproducibility, including this requirement in the text. Ideally, this would be expressed as a performance requirement, rather than a specific design of the apparatus.

Marker Placement

The dynamic geometric metric is calculated based on tracking markers placed on the dummy and the seat back.

- The text requires that markers be placed on the head and T1 bracket, from which the position of the OC and T1 of the dummy can be calculated. However, in some previous work, the OC and T1 pins were tracked directly. It is recommended that consideration be given to allowing this option, provided that the required measurement can be demonstrated.
- The text requires a bracket be fitted to the upper seat back, so that the marker at this location is rigidly connected to the seat. While this is preferable from a measurement perspective, concerns have previously been expressed that this would require modifications to the seat that may affect its performance.

- The text requires that a marker is placed at the seat recliner. No guidance is given on alternatives if this part of the seat is not visible to the camera.
- It may be necessary to include additional scale markers on the sled depending on the marker tracking system and the marker tracking calibration that is used. If the ISO 8721:2010 procedure is used, three orthogonal markers of known relative displacements must be placed in each plane of measurement (i.e. in the seat back and OC-T1 measurement planes).
- Seats with a single recliner may have a different recline angle on the left and right sides. It is not defined which side should be markers be placed for seats with a single recliner.

Seat Adjustment

- The design torso angle of the seat is confirmed by the tests described in Annex 4. Section 4.2 of Annex 9 sets the seat back to this angle and *then* adjusts the position of the seat. This is likely to result in the actual torso angle changing, particularly when the seat cushion height and lumbar support are adjusted.
- Backset is measured with the seat fore-aft adjustment set to the 95th percentile occupant seating position defined by the manufacturer. The seat position is then adjusted to the test position as noted in the bullet point above. The BioRID target backset is not re-measured in the new position, which may mean that the BioRID set-up described in the text is not achievable.
- In Annex 9, paragraph 4.2.3 the highest H-point must be achieved, but it is not clear how this should be verified. This could be quite complex for seats with a large number of adjustments, particularly those where the order of adjustment affects the resulting position of the seat.
- Seats may have many more adjustments than are described in Annex 9, Section 4.2, and that the order of adjustment may be important in determining the final position of the seat. Both of these factors are considered to affect the BioRID II test results. Euro NCAP therefore has a much more detailed seat adjustment procedure, and it is recommended that consideration be given to adopting a similarly detailed seat adjustment procedure in the text. Furthermore, much of the dynamic geometric validation data that has been presented has been derived from tests that used a seat adjustment and seating procedure similar to that defined by Euro NCAP. It is not clear what the repeatability and reproducibility of the test procedure would be with a simplified seat adjustment procedure.

Head Restraint Adjustment

- There is no provision for head restraints that automatically adjust their position depending on the stature of the seated occupant.
- Head restraint 'tilt' is undefined. Other procedures define it as the position that gives the largest backset, which requires setting the tilt with the H-point machine and HRMD installed on the seat. This also implies that this may be important for the backset definition, for which Annex 13 paragraph 3.3 specifies the seat position, but not the head restraint position (other than the generic statement for all seat adjustments - apart from fore-aft seat track position – to use 'the position specified by the manufacturer'). NB the Euro NCAP procedure is far more detailed in order to try and ensure a reproducible head restraint position for testing.

Sled Pulse

- Paragraph 5.1 of Annex 9 refers to a figure and table containing the definition of a sled pulse with a delta-*v* of 16 km/h. This is a pulse typically used in consumer information testing, and is typically considered to target short-term injury. EEVC WG20 recommended a sled delta-*v* of 20 km/h to target long-term injury, and the GTR-7 Informal Group ToR focus on lower speed (e.g. 16 km/h) injuries. No formal decision has been made on the magnitude of pulse for dynamic geometric testing, although the standard 16 km/h pulse seems reasonable.
- The definition of the process for zeroing the sled pulse data in paragraph 5.1 of Annex 9 is not clear.
- The peak dynamic geometric measurements reported in TRL report PPR 471 at 115-155 ms after t_0, which is during the final ±1 *g* part of the sled pulse, or even after the pulse definition ends. As a minimum, the ±1 g part of the sled pulse definition should be extended to 160 ms.
- The tolerance on pulse delta-*v*, mean acceleration and peak acceleration are ±5%, ±8% and ±10% respectively. The ±1 g part of the sled pulse, where the maximum dummy measurements typically occur, is ±10% of the peak acceleration. This may affect the level of repeatability and reproducibility (R&R) that is likely to be achievable between different laboratories, even if the dummy R&R is good.

Appendix B Review of BioRID II Kinematic Repeatability and Reproducibility

This section reviews the existing evidence of the repeatability and reproducibility of the BioRID IIg dummy. This is based on information from journal papers, conference papers, published reports, and presentations to meetings (including the Technical Evaluation Group on Rear Impact Dummy Harmonization, Informal Group on GTR No. 7 (Head restraints), and Global BioRID II User's Meeting). Measurements which are related to the kinematics of the dummy (position, angle, acceleration, velocity, and time) are presented, as these are most closely related to the dynamic geometry.

B.1 Quantifying Repeatability and Reproducibility

In order to compare results from different studies, the repeatability and reproducibility of the dummies must be quantified in the same way. Many of the studies reviewed use the 'Coefficient of Variation' (CV) to quantify both repeatability and reproducibility.

The Coefficient of Variation for testing the repeatability of a single dummy is defined as follows:

$$C.V. = \frac{S_d}{\bar{X}} 100\%$$

where S_d is the standard deviation for a single dummy, and $\bar{X}$ is the mean value for a single dummy.

The Coefficient of Variation for testing the reproducibility between dummies is defined as follows (Asada *et al*., 2009):

$$C.V. = \frac{S_B}{\bar{X}_G} 100\%$$

Where:

$$S_B = \left[\frac{MSB - MSW}{n}\right]^{1/2}$$

$\bar{X}_G$ is the mean value for the dummies tested

MSB is the mean square between dummies

MSW is the mean square of each dummy

n is the number of repetitions of each test.

The Coefficient of Variation can be used to compare the results from different tests and different authors. Although it does not define strict limits for what is acceptable variation, Table B-1 shows the criteria which have been used by previous authors (such as Ministry of Land, Transport and Maritime Affairs, 2009) to give an indication of what may be considered acceptable and what may not.

Table B-1: Coefficient of variation criteria

CV ≤ 3%	Good
3 < CV ≤ 7%	Acceptable
7 < CV ≤ 10%	Marginal
CV > 10%	Not acceptable

It should be noted there are some limitations to the Coefficient of Variation. In the majority of studies (although not all) the CV only considers the variation in the peak value of any measure. However, this is generally the most important parameter for vehicle assessment. The CV values are also likely to be larger when measuring variables with smaller values.

It should also be noted that these guidelines were originally applied to the repeatability and reproducibility of a dummy in certification loading conditions, which are typically very well controlled and often involve loading to only one part of the dummy. With the BioRID II dummy, the standard sled-based certification procedure is more complex than - for instance – a pendulum impactor test, and would be expected to have greater inherent test-to-test variability. This puts greater demands on the repeatability and reproducibility of the dummy than has usually been the case for other dummies. Furthermore, the studies reviewed here typically concern whole-dummy sled tests, which are considerably more complex than traditional certification testing. It is not clear that the use of the certification-type CV guidelines for whole-dummy sled tests is appropriate when assessing the repeatability and reproducibility *of a dummy design*. It seems more appropriate to consider this as the CV of the *test procedure*, and higher CV values would be expected for this.

There are two studies by Eriksson (2007, 2008) which use the 'Objective Rating Method' (ORM) to quantify variation. This correlates a number of values for a test, including criteria, peak values, peak value occurrence times, and curve shapes. Similar to the CV, this method outputs a percentage value which represents the similarity between two sets of results. Eriksson suggests that an ORM greater than 65% represents high repeatability or reproducibility, based on tests of a Hybrid-III. Similarly, NHTSA have developed their Biofidelity Ranking System (Bio Rank - Rhule, 2009). Methods like ORM and Bio Rank are much better than CV for assessing biofidelity, where the shape and magnitude of the whole curve is of interest.

B.2 Summary of Evidence

The tables in sections B.2.1 and B.2.2 summarise the repeatability and reproducibility of the BioRID II dummy respectively, for the studies which either reported the CV, or where enough information was given that the CV could be calculated. Each column gives the results of a different study – the key to which study is which is given in Section B.2.3, which also gives details of the individual studies.

The headers for each table also show the type of seat used for each study:

- Production seats - usually one seat per test

- A non-reclining laboratory seat - the same seat re-used for every test
- A reclining laboratory seat - where the recline movement was controlled more repeatably than for typical production seats, often with an additional spring-damper system, with the same seat re-used for every test

Clearly, repeatability and reproducibility studies that used production seats would include seat-to-seat variation within the reported CV values. All of the tests reviewed would include variation due to the seating procedure, which would increase the variation in results compared to typical certification-type test procedures.

It should be noted that some studies do not explicitly state the version of the dummy that was used. However, based on the dates the tests were performed, it is likely that all these studies used version IIg of the BioRID dummy. It is also, therefore, unknown what certification procedures were used with each dummy.

Some studies report the variation for different axes on an accelerometer, or do not specify which axis the results refer to. This information has been included in the tables; for example, for "T1 (x)[z] acceleration", numbers in () are for the x direction, numbers in [] are for the z direction, numbers with no brackets are the resultant acceleration, and numbers followed by "$^+$" did not specify a direction.

Where the coefficient of varaition is reported, it is coloured to correspond with the criteria in table Table B-1.

B.2.1 Repeatability

Table B-2 and Table B-3 summarise the repeatability of the BioRID II dummy, measured using the coefficient of variation. Table B-2 gives the repeatability of position and angle measurements, and Table B-3 gives the repeatability of acceleration, velocity, and time measurements.

Of the position and angle measurements, there are two variables where there is evidence that they are not acceptably repeatable. These are the head rotation with respect to T1, and the head z-axis displacement. The head rotation with respect to T1 was reported to have particularly poor reproducibility in tests with car seats, with CVs of 24% and 117% in the two studies reviewed. However, in tests with laboratory seats that exclude significant seat-to-seat variation the CVs for this parameter varied between 2.3% and 12%. This is reasonable given that the BioRID dummies used will not all have been compliant with the GTR-7 Informal Group requirements on build level and certification.

The head z-axis displacement was only reported in one study, and with a CV of 19% was well above the recommended repeatability of CV lower than 10%. This study reported extensive other displacement and rotation kinematic parameters and these all had a CV of less than 10%. However, this study used a hard, non-reclining laboratory seat that is not representative of typical car seats.

All of the other displacement and rotation kinematic parameters for which information was available had a CV less than 10%.

Table B-2: Repeatability of position and angle measurements

Study	**J***	**D**	**E**	**L**	**M(b)**	**A**	**G**	**K**	**M(a)**
Controlled Recliner Laboratory Seat	✓								
Non-reclining Laboratory Seat		✓	✓	✓	✓				
Production Seats						✓	✓	✓	✓
Head z displacement	-	-	-	19	-	-	-	-	-
Head-T1 x displacement	-	-	-	6.8	-	-	-	-	-
Head-T1 z displacement	-	-	-	0	-	-	-	-	-
Head CoG x displacement wrt sled	0.8-2.3	-	-	5.3	-	-	-	-	-
T1 x displacement	-	-	-	5.6	6.1	-	-	-	2.1
T1 z displacement	-	-	-	7.1	6.3	-	-	-	4.8
T1 angle wrt sled	1.2-1.3	-	-	5.7	2.7	-	-	-	2.9
Head rotation wrt sled	3.8-4.8	-	-	4.9	-	-	-	-	-
Pelvis rotation	5.4-8.5	-	-	-	-	-	-	-	-
Dynamic backset (OC-T1)	-	-	-	-	-	4-6	3-8	-	-
Peak rearward translation of the OC pin with respect to the T1 joint axis	-	-	-	-	-	-	-	0.9-2.9	-
Head rotation wrt T1	5.9-11.7-	8-12	6-11	6.3	2.3	-	-	6.9-24.4	116.7

*value of CV at peak (reference also gives time averaged values)

Table B-3: Repeatability of acceleration, velocity, and time measurements

Study	**J***	**D**	**E**	**L**	**Mb**	**A**	**F**	**G**	**H**	**I**	**K**	**Ma**	**B**	**C**
Controlled Recliner Lab. Seat	✓													
Non-reclining Laboratory Seat		✓	✓	✓	✓									
Production Seats						✓	✓	✓	✓	✓	✓	✓		
H(x)[z] acceleration	8.4-8.9	(2-4)	-	(0.9) [2.8]	(3.7)	(1-4)	(4-5)	-	(0-3)	(3-4)	-	(3.1)	(4-6)	-
T1-Right acceleration	-	-	-	-	-	1-5	3-8	-		2-8	-	-	-	-
T1-Left acceleration	-	-	-	-	-	1-5	4-8	-		4-12	-	-	-	-
T1 (x)[z] acceleration	9.1-17.9 (7.5-17.4)	5^{+}-8^{+}	(5-9)	(5.7) [4.5]	(8.4)	-	-	(3-6)	(0-2)	-	-	(4.6)	(2-7)	(1-5)
NIC	-	-	-	-	-	-	-	1-14	4-10	6-16	1.8-6.7	-	4-9	9-14
NIC-Right	-	-	-	-	-	-	4-15	-		-	-	-	-	-
NIC-Left	-	-	-	-	-	-	5-17	-		-	-	-	-	-
T8 (x) acceleration	2.1-11	-	-	-	-	-	-	-		-	-	-	(3-5)	-
Pelvis (x) acceleration	11.3-14	-	-	-	-	-	-	-	(2-4)	-	-	-	(6-10)	-
Rebound velocity	-	-	-	-	-	-	-	-		-	-	-	-	1-3
Head contact time	1.2-2.3	-	-	-	-	-	1-4	-		-	-	-	-	4-9
L1 (x) acceleration	8-8.5	-	-	-	-	-	-	-	(2-4)	-	-	-	-	-
HIC	3.8-13.3	-	-	-	-	-	-	-	-	-	-	-	-	-

*value of CV at peak (reference also gives time averaged values)

$^{+}$Does not record whether this is the resultant acceleration

Head accelerations had a reported CV less than 10% in all studies reviewed, as did T1 acceleration except for one value at 12% in tests using a production seat (only on the left side of the dummy – the right side had a maximum CV of 8%), and some values with a laboratory seat in study J (NHTSA). NIC values, which are derived from the head and T1 accelerations were generally less repeatable, with CVs ranging from 2% to 17%. Pelvis x-axis accelerations were also slightly greater than 10% in study J (NHTSA).

This data indicates that the basic kinematic parameters such as head and neck displacements and rotations have acceptable repeatability, and generally better than the accelerations measured on the dummy and criteria derived from these accelerations.

B.2.2 Reproducibility

Table B-4 and Table B-5 summarise the reproducibility of the BioRID II dummy, measured using the coefficient of variation. Table B-4 gives the reproducibility of position and angle measurements, and Table B-5 gives the reproducibility of acceleration, velocity, and time measurements.

Relatively few studies were identified which quantified the reproducibility of kinematic parameters of the BioRID II dummy. Of the studies that reported the reproducibility of displacements and angles, the head-to-T1 displacement had a CV < 10% in one study with production seats, and head rotation relative to T1 had a CV of 11% in another study with a non-reclining laboratory seat.

Several studies also reported acceleration data, with rather mixed results. The CV for head x-axis acceleration reproducibility varied from 0.4% to 5% in tests with production seats, to 15.6% in on test series with a non-reclining laboratory seat. This may suggest that the rigid laboratory seat was more likely to expose differences between dummies than a standard production seat, or it may be due to the particular dummies used including possible variations in build level, certification and so forth.

As with repeatability, under different conditions the measured reproducibility can vary greatly. For example, Asada (2009) used three seats with different types of whiplash prevention: a normal seat, a passive seat, and a reactive seat. These gave a reproducibility of the T1-R acceleration of 11 (not acceptable), 3 (good), and 16 (not acceptable) respectively. This suggests that, at least for this study, it may be more the reproducibility of the seats rather than the reproducibility of the dummy that is being evaluated.

Table B-4: Reproducibility of position and angle measurements

Study	**D**	**A**
Controlled Recliner Lab. Seat		
Non-reclining Laboratory Seat	✓	
Production Seats		✓
Head z displacement	-	-
Head-T1 x displacement	-	-
Head-T1 z displacement	-	-
Head CoG x displacement wrt sled	-	-
T1 x displacement	-	-
T1 z displacement	-	-
Head rotation wrt sled	-	-
T1 angle wrt sled	-	-
Pelvis rotation	-	-
Dynamic backset (OC-T1)	-	4-7
Peak rearward translation of the OC pin with respect to the T1 joint axis	-	-
Head rotation wrt T1	10.8	-

*value of CV at peak (reference also gives time averaged values)

Table B-5: Reproducibility of acceleration, velocity, and time measurements

Study	**D**	**A**	**I**	**B**
Controlled Recliner Lab. Seat				
Non-reclining Laboratory Seat	✓			
Production Seats		✓	✓	
H(x)[z] acceleration	(15.6)	(0.5-4)	(4)	(5)
T1-R acceleration	-	3-16	4	-
T1-L acceleration	-	5-16	2	-
NIC	-	-	3	8
NIC-R	-	-	-	-
NIC-L	-	-	-	-
T8 (x) acceleration	-	-	-	(6)
T1 (x)[z] acceleration	6.3+	-	-	(9)
Pelvis (x) acceleration	-	-	-	(11)
Rebound velocity	-	-	-	-
Head contact time	-	-	-	-
L1 (x) acceleration	-	-	-	-
HIC	-	-	-	-

+Does not record whether this is the resultant acceleration

B.2.3 Details of Studies

The following sections summarise some of the important details of each study which provided information on repeatability or reproducibility in terms of the coefficient of variation. Further details are also provided in Appendix B. A brief written summary of each study is given in Section B.2.3.1 to B.2.3.13, which also includes studies which used a method other than the coefficient of variation to quantify the repeatability or reproducibility.

It should be noted that some studies do not explicitly state the version of the dummy that was used. However, based on the dates the tests were performed, it is likely that all these studies used version IIg of the BioRID.

B.2.3.1 Study A: Asada et al. (2009)

This study used three different BioRID IIg dummies, and three different types of seat, to explore the repeatability and reproducibility of the dummies, and determine whether they could distinguish between the different types of seat. One of the seats was a normal seat, one had passive whiplash protection, and the third had active whiplash protection.

B.2.3.2 Study B: Bortenschlager et al. (2009)

This study was designed to quantify the repeatability and reproducibility of the BioRID IIg dummy. A total of eight different dummies were used, each of which was checked and certified before and after the tests. The dummies were seated in four hard bucket seats, to avoid the variation present in production car seats affecting the results. In total there were 12 tests of each of the eight dummies, including tests in all four seats. The crash pulse used was different to many of the other studies: a trapezoid pulse, with a delta-v of 16 kph and a maximum acceleration of 5g.

B.2.3.3 Study C: Bortenschlager et al. (2007)

This study performed multiple tests on the same BioRID IIg dummy, enabling the repeatability to be estimated. One model of production car seat was used for all the tests, and a new seat was used for each test. The seat had a head restraint, but no other whiplash protection. Three different crash pulses were used: two trapezoid (with delta-v of 16 kph and 24 kph), and one triangular pulse with a delta-v of 16 kph. The dummy was certified before and after the series of tests, and no differences were found that would explain any variation over time.

B.2.3.4 Study D: Ishii et al. (2006)

This study compared the repeatability of the BioRID II and Hybrid III dummies. Three BioRID II dummies were tested, and all of the dummies were seated in the same rigid seat with a head restraint. A triangular 16 kph pulse was used.

B.2.3.5 Study E: Japan MLIT (2006)

This study tested three different BioRID II dummies (and three Hybrid III dummies) in the same conditions, and calculated the repeatability. Two of the BioRID II dummies underwent the standard calibration procedure before the test series, but the other was not calibrated. Because the dummies had different levels of calibration they could not be directly compared, so the reproducibility was not measured. A rigid seat with a head restraint was used to reduce the variation caused by the seat.

B.2.3.6 Study F: JASIC/Japan (2009)

This study reports the 16 kph tests performed in Asada et al. (2009), but also gives details of tests performed with a 20 kph pulse, and compared the repeatability for the dummy in the different pulses. The test setup was the same as in Asada – three different types of seat were used (normal, passive, and reactive).

B.2.3.7 Study G: Levallois et al. (2010)

This study reports the repeatability of two different BioRID IIg dummies, using the 16 kph triangular pulse. The dummies were seated in nine identical production car driver seats. Although the paper does not report the coefficient of variation for the repeatability, there is enough data presented to calculate it.

B.2.3.8 Study H: Locke (2011)

This study was designed to measure the BioRID IIg response to three different types of seatback comfort system: static suspension, horizontal lumbar, and vertical lumbar. Two tests were performed for each type of seat and for each of three seat back angles, and the repeatability of the dummy in each position and seat was calculated. The same triangular 16 kph pulse was used for each test.

B.2.3.9 Study I: MLTM, Korea (2009)

This study used three different BioRID IIg dummies in three different seating positions, and calculated the repeatability and reproducibility. The tests were performed on two different sites. The dummies were calibrated before the tests, and the triangular 16 kph crash pulse was used in each test. The seats used were production car seats with a head restraint.

B.2.3.10 Study J: Moorhouse and Donnelly (2010), Moorhouse and Yang (2011)

The repeatability of three different dummies was tested: a BioRID II, a Hybrid III, and a RID-3D. Two different triangular pulses were used – a 16.7 kph pulse, and a 24 kph pulse. The tests were performed in a yielding seatback with 30° rotation. These studies calculated the coefficient of variation for the peak values recorded (which can be compared to most of the other studies in the literature), and also calculated a time averaged value of C.V. for the upper 50% of any output.

B.2.3.11 Study K: Siegmund et al. (2005)

This study subjected a single BioRID II dummy six times to each of 15 different collision pulses, with a delta-v ranging from 3-11 kph – less severe than the majority of studies reviewed here. The 15 pulses included square, triangular, and sine waves. The seat used was a front passenger seat from a 1991 Honda Accord.

B.2.3.12 Study L: Willis et al. (2008)

A BioRID II, Hybrid III, and RID-3D were all tested using the same set-up. Three tests were performed on each dummy. The dummies were positioned on the target sled on a modified R44 test seat with a head restraint. This sled was impacted by a bullet sled, giving a crash pulse with a delta-v of 7 kph and a maximum acceleration of 2g.

B.2.3.13 Study M: Yamazaki et al. (2008)

This is another study which compares the repeatability of the BioRID IIg, Hybrid III, and RID-3D. Two series of tests were performed, using an acceleration sled and a deceleration sled. For the tests on the acceleration sled (a), the dummies were seated in a production car seat with a head restraint. For the tests on the deceleration sled (b), the dummies were seated in a rigid wooden seat without a head restraint. All the tests used an 8 kph crash pulse.

The following tables summarise some of the important details of each study which provided information on repeatability or reproducibility in terms of the coefficient of variation.

Description	**A: Asada (2009)**	**B: Bortenschlager (2009)**	**C: Bortenschlager (2007)**
Pulse	EuroNCAP / IIWPG 16 kph	Trapezoid	Low (trapezoid), medium (triangular), high (trapezoid)
Delta-v	16 kph	16 kph	16, 16, 24 kph
Max acceleration	10 g	5 g	5, 10, 7.5 g
Sled type	Unknown	HyperG220 acceleration	HyperG220 acceleration
Seat type	3 seats used: normal, dynamic, passive (from mass-production vehicles, with head restraint)	Hard bucket seats, with head restraint	"Current car seat model from high volume manufacturer", with head restraint
Seating procedure	Same as EuroNCAP, except seatback angle = design reference angle	Unknown	IIWPG procedure
Seat back angle	Design reference angle	Unknown	25±0.2º
Backset tolerance	±2mm	64-69 mm	57-60 mm
Dummy version	IIg (with new jacket)	IIg	IIg
Certification procedure	Unknown	Before and after tests by manufacturer.	Before and after tests.
No. of different dummies	3 (one with new spine damper, 2 with old spine damper)	8	1
Repititions of each test	3	12	6
Date of tests	>May 2008	≤2009	≤2007
Notes		Pelvis foam stiffness found to differ befween dummies, but no influence on R&R. Some friction based problems (e.g. cables) had minor influence.	

Description	**D:Ishii (2006)**	**E:Japan MLIT (2006)**	**F:JASIC/Japan(2009)**	**G: Levallois (2010)**
Pulse	IIWPG	Triangular	Triangular	IIWPG
Delta-v	16 kph	16 kph	20 kph	16 kph
Max acceleration	10 g	10 g	11.7 g	10 g?
Sled type	HYGE	Unknown	Unknown	2 sleds: acceleration, deceleration
Seat type	Rigid, with head restraint	Rigid, with head restraint	1 normal, 2 passive, 2 reactive, with head restraint	9 identical front driver seats from same serial production batch (with head restraint?)
Seating procedure	Unknown	Unknown	Design seat position	Unknown
Seat back angle	Unknown	Unknown	Design angle	Unknown
Backset tolerance	Unknown	Unknown	Unknown	25 mm for all tests
Dummy version	Unknown	Unknown	IIg (with new jacket and spine damper)	IIg
Certification procedure	Unknown	One dummy without callibration, two with standard calibration	Unknown	"Old" callibration procedures
No. of different dummies	3	3	1	2
Repititions of each test	5	5	Unknown	3
Date of tests	≤2006	≤ Jan 2006	≤ Feb 2009	End of 2008
Notes				

Description	**H: Locke (2011)**	**I: MLTM, Korea (2009)**	**J: Moorhouse (2010 & 2011)**
Pulse	IIWPG triangular	Korean/Euro NCAP	Low and mid-speed
Delta-v	16 kph	16 kph	16.7, 24 kph
Max acceleration	10 g	10 g	8.5, 10.5 g
Sled type	Unknown	Unknown	Unknown
Seat type	Seats with rotation stiffness of 7, 10, 15°, with head restraint, and 3 different seatback comfort systems. With head restraint.	Normal car seat, with head restraint	Yielding seatback with 30° rotation. Padding of 1999 Toyota Camry. With head restraint.
Seating procedure	Unknown	Same as Korean/Euro NCAP	Unknown
Seat back angle	Unknown	Unknown	Unknown
Backset tolerance	Unknown	15 ±5 mm	Unknown
Dummy version	IIg	IIg	Unknown
Certification procedure	Unknown	Calibrated before the test	Unknown
No. of different dummies	1	3	1
Repititions of each test	2	3	3-4
Date of tests	≤ Feb 2011	≤ Dec 2009	≤ Sep 2009
Notes			

Description	**K: Siegmund (2005)**	**L: Willis (2008)**	**Ma/b: Yamazaki (2008)**
Pulse	15 different pulses	Square pulse	Triangular pulse
Delta-v	3-11 kph	7 kph	8 kph
Max acceleration	1.3-4.4 g	2 g	3.8 g
Sled type	Feedback-controlled linear sled	Target sled impacted by bullet sled	2 sleds: acceleration and deceleration
Seat type	Seat from 1991 Honda Accord with head restraint	Modified R44 test seat (with padding), with adjustable head restraint	Acceleration sled: mass-produced seat with head restraint (a). Deceleration sled: rigid wooden seat without head restraint (b)
Seating procedure	Unknown	Unknown	Skull cup horizontal, upper torso pushed back against seat, hands put on handle/knees
Seat back angle	27°	20°	Unknown
Backset tolerance	80 mm ±?	50 ± 2 mm	Unknown
Dummy version	Unknown	Unknown	IIg
Certification procedure	Unknown	Unknown	Unknown
No. of different dummies	1	1	1
Repititions of each test	6	3	5
Date of tests	≤ Mar 2003	≤ Jan 2008	≤ Sep 2008
Notes			

B.2.4 Other Studies

Some other potentially useful studies were identified which have not been included in the comparison tables above, for various reasons. Those studies are summarised briefly here.

Aylor and Zuby (2011) performed a series of impact tests to determine the effect of crash pulse differences caused by the vehicle structure. Two BioRID IIg dummies were used, one in the driver's seat and one in the front passenger seat. The seating procedures were identical, with the exception that the front seat passenger had the head restraint placed in the lowest position. Because different cars were used which gave different crash pulses, and the driver and front seat passenger had different head restraint positions, these tests could not be used to calculate repeatability or reproducibility.

Basilautzkis (2010) looked at the effect of adjusting the hip joint of the BioRID II. The hip joint was adjusted in three ways, and two impact tests were performed at each adjustment, giving data which could be used to quantify repeatability. This was not quantified using the coefficient of variation; however, this could be calculated using the data provided. The dummy was seated in a production car seat with a head restraint, and the pulse used had a delta-v of 14 kph.

Beebe and Schmitt (2010) report on improvements made to the certification tests. This suggested that the stiffness of the dummy jacket could affect repeatability, and recommended a dynamic stiffness test of the jackets. Both this study and Beebe and Schmitt (2009) report that the certification tests are able to show differences between dummies.

Davidsson and Kullgren (2011) performed a series of sled tests using the EuroNCAP 16 kph pulse, and both BioRID IIe and IIg dummies. The focus of this paper was comparing the results for similar seats available in insurance claim data, to determine how closely related the dummy response is to the risk of injury. There was no investigation of the repeatability or reproducibility of the dummy.

Depinet (2010) lists some variables which have been confirmed to have an influence on variation between dummies. These include the jacket stiffness, the head type (skull cap load cell versus standard cap), lateral tilt adjustment of OC plate, and the head skin (which was found to create a load path around the upper neck load cell).

Nakajima et al. (2011) explored the variation of the BioRID II dummy using numerical simulation. This study first simulated the calibration procedure, and altered one of three different variables in order to give a dummy response within the defined certification corridors. The study then concentrated on the variation introduced by calibrating the dummy using each of these three methods. Although a sled test with the Euro NCAP 16 kph pulse was simulated, the results have not been used here because this study did not use the physical dummy, and because three different methods of calibration were used.

Eriksson and Zellmer (2007) and *Eriksson (2008)* both use the objective rating method (ORM) to quantify the repeatability and reproducibility of the BioRID IIg dummy. Three test pulses were used: a triangular 16 kph pulse, a trapezoid 16 kph pulse, and a trapezoid 24 kph pulse. The tests were performed at two different test sites, with five different seats, and four different BioRID IIg dummies. The seats were standard production car seats, although some had added, altered, or removed safety systems. Eriksson suggests that an ORM value over 65% indicates high correlation, i.e. acceptable or better variation. The vast majority of the tests give an ORM value above 65%, but it is not clear how this 65% value compares with a C.V. of 10%. Because these ORM studies do not use the coefficient of variation to quantify the variation, they cannot be compared to other studies; however, they do suggest which measurements are more repeatable, or more reproducible, than others.

B.3 16 kph Triangular Pulse

The majority of these studies use the triangular 16 kph pulse, although there are some which use a different pulse, or compare the repeatability and reproducibility for tests with different pulses. The triangular pulse has a delta-v of 16 kph, a maximum acceleration of about 10 *g*, and a duration of approximately 90 ms. This pulse has been scaled-up slightly to give the pulse proposed for the draft GTR-7 Phase 2 in document GTR7-06-10, so these are more likely to be relevant to the use of the dummy in the GTR. Table B-6, Table B-7, Table B-8, and Table B-9 summarise the results including only the tests which were performed using the 16 kph triangular pulse.

Once the studies are narrowed down to those which used only the 16 kph triangular pulse, all of the displacement and rotation parameters with a reported repeatability CV value have a CV of less than 10%, except for head rotation with respect to T1 which had a CV of up to 12% (in tests with production or non-reclining laboratory seats). The dynamic backset (T1 and OC relative displacement) had a CV of 4-8% in two studies with production seats.

There were only two studies of the reproducibility of the displacement and rotation kinematic variables. Ishii (2006) found that the reproducibility of the head rearward inclination angle was not acceptable. Asada (2009) found that the reproducibility of the dynamic backset was either acceptable or marginal (CV = 4-7%), depending on the type of seat – a seat with passive whiplash protection gave acceptable reproducibility, and a normal seat resulted in marginal reproducibility. The reproducibility of head rotation relative to T1 was reported in only one study, using a non-reclining laboratory seat, with a CV of 11%.

Table B-6: Repeatability of position and angle measurements – 16 kph triangular pulse only

Study	**J***	**D**	**E**	**A**	**G**
Controlled Recliner Laboratory Seat	✓				
Non-reclining Laboratory Seat		✓	✓		
Production Seats				✓	✓
Head z displacement	-	-	-	-	-
Head-T1 x displacement	-	-	-	-	-
Head-T1 z displacement	-	-	-	-	-
Head CoG x displacement wrt sled	0.8-2.3	-	-	-	-
T1 x displacement	-	-	-	-	-
T1 z displacement	-	-	-	-	-
T1 angle wrt sled	1.2-1.3	-	-	-	-
Head rotation wrt sled	3.8-4.8	-	-	-	-
Pelvis rotation	5.4-8.5	-	-	-	-
Dynamic backset (OC-T1)	-	-	-	4-6	3-8
Peak rearward translation of the OC pin with respect to the T1 joint axis	-	-	-	-	-
Head rotation wrt T1	5.9-11.7-	8-12	6-11	-	-

*value of CV at peak (reference also gives time averaged values)

Table B-7: Repeatability of acceleration, velocity, and time measurements – 16 kph triangular pulse only

Study	**J***	**D**	**E**	**A**	**G**	**H**	**I**	**C**
Controlled Recliner Lab. Seat	✓							
Non-reclining Laboratory Seat		✓	✓					
Production Seats				✓	✓	✓	✓	
H(x)[z] acceleration	8.4-8.9	(2-4)	-	(1-4)	-	(0-3)	(3-4)	-
T1-Right acceleration	-	-	-	1-5	-		2-8	-
T1-Left acceleration	-	-	-	1-5	-		4-12	-
T1 (x)[z] acceleration	9.1-17.9 (7.5-17.4)	5$^+$-8$^+$	(5-9)	-	(3-6)	(0-2)	-	(1-5)
NIC	-	-	-	-	1-14	4-10	6-16	9-14
NIC-Right	-	-	-	-	-		-	-
NIC-Left	-	-	-	-	-		-	-
T8 (x) acceleration	2.1-11	-	-	-	-		-	-
Pelvis (x) acceleration	11.3-14	-	-	-	-	(2-4)	-	-
Rebound velocity	-	-	-	-	-		-	1-3
Head contact time	1.2-2.3	-	-	-	-		-	4-9
L1 (x) acceleration	8-8.5	-	-	-	-	(2-4)	-	-
HIC	3.8-13.3	-	-	-	-	-	-	-

*value of CV at peak (reference also gives time averaged values)

$^+$Does not record whether this is the resultant acceleration

Table B-8: Reproducibility of position and angle measurements – 16 kph triangular pulse only

Study	**D**	**A**
Controlled Recliner Lab. Seat		
Non-reclining Laboratory Seat	✓	
Production Seats		✓
Head z displacement	-	-
Head-T1 x displacement	-	-
Head-T1 z displacement	-	-
Head CoG x displacement wrt sled	-	-
T1 x displacement	-	-
T1 z displacement	-	-
Head rotation wrt sled	-	-
T1 angle wrt sled	-	-
Pelvis rotation	-	-
Dynamic backset (OC-T1)	-	4-7
Peak rearward translation of the OC pin with respect to the T1 joint axis	-	-
Head rotation wrt T1	10.8	-

*value of CV at peak (reference also gives time averaged values)

Table B-9: Reproducibility of acceleration, velocity, and time measurements – 16 kph triangular pulse only

Study	**D**	**A**	**I**
Controlled Recliner Lab. Seat			
Non-reclining Laboratory Seat	✓		
Production Seats		✓	✓
H(x)[z] acceleration	(15.6)	(0.5-4)	(4)
T1-R acceleration	-	3-16	4
T1-L acceleration	-	5-16	2
NIC	-	-	3
NIC-R	-	-	-
NIC-L	-	-	-
T8 (x) acceleration	-	-	-
T1 (x)[z] acceleration	6.3$^+$	-	-
Pelvis (x) acceleration	-	-	-
Rebound velocity	-	-	-
Head contact time	-	-	-
L1 (x) acceleration	-	-	-
HIC	-	-	-

$^+$Does not record whether this is the resultant acceleration

Of the acceleration, velocity, and time measurements, the x head acceleration, rebound velocity, head contact time, and resultant L1 acceleration were all found to have good or acceptable repeatability. The L1 x acceleration, the T1 acceleration, and the resultant head acceleration were all found to have marginal repeatability, and the NIC, HIC, and T8 resultant acceleration were all reported to have a CV greater than 10% (up to a maximum of 6-16% for NIC in one study).

Both the T1-L and the resultant pelvis acceleration were found to have either good repeatability, or unnaceptable repeatability, depending on the study. Similarly the T1-R acceleration was found to be marginal or good in different studies.

A simlar variation between studies was seen for the reproducibility of the acceleration, velocity, and time measurements. The head acceleration, T1-L acceleration, and T1-R acceleration were found in at least one study to have good reproducibility, yet were found in another study to have unnacceptable reprodducibility. The reproducibility of NIC and T1 acceleration was each only calculated in one study, but was found to be good and acceptable respectively.

B.4 Overall Summary of Kinematic Repeatability and Reproducibility

There have been a large number of studies evaluating the repeatability and reproducibility of the BioRID II dummy, but with a wide variation in the parameters assessed. Within these studies, only eight reported on the repeatability of the head-neck displacements or rotations, and only two on the reproducibility. This included only one study that examined the dynamic geometry metric, which reported that the CV for reproducibility was 4-7%. Repeatability of displacements and rotations was better than CV of 10%, except for head-to-T1 relative rotation which had a CV of up to 12%.

A number of parameters have quite different repeatability or reproducibility CVs in different studies. This may reflect the range of performance of the different dummies that were assessed in these studies (i.e. some groups of dummies may just have a more consistent performance than others. However, it may also be that the repeatability and reproducibility assessment is sensitive to the seating procedure, sled pulse, seat type and so forth, which were very varied. In particular, studies using production seats will include the seat-to-seat variability in the repeatability and reproducibility measures.

There were three studies where rigid seats with head restraints were used, but only two of these used the same triangular crash pulse of 16 kph (Ishii, 2006 and Japan MLIT, 2006). These two studies both measured the repeatability of the head rearward inclination angle, but each used three different BioRID dummies with different calibrations and different states of maintenance, making the results difficult to compare. However, the two dummies which used the standard calibration procedure in the Japan MLIT study had CVs of 8.4% and 11.1% for the backward tilting angle of the head, which is within or close to the desired reproducibility.

The other study which used nominally-rigid seats with head restraints was Bortenschlager (2009), which used eight different BioRID dummies all of which were checked and certified by the manufacturer before and after the tests. This study used a 16 kph trapezoid pulse. If the variation of the seat response is important, this study would be expected to give lower CV values for repeatability and reproducibility than the other studies. However, this was not necessarily the case; the Bortenschlager study generally gives values of repeatability and reproducibility which are between those reported in the other studies. More recent testing with the same seats indicated that the upper seat back and head restraint were not particularly rigid in these tests, although seat-to-seat variation was assessed by the authors and found not to be an issue compared with dummy-to-dummy variation.

Appendix C Assessment of the Effect of Compressing the Video Files on Marker Tracking Data

Before tracking the markers to assess neck and pelvis movement, it was necessary to compare the performance of marker tracking using compressed and uncompressed video files. The use of compressed video files offered the advantage of quicker video playback and tracking in TEMA, and smaller file sizes for archive, compared with the uncompressed footage.

The differences between the two files were assessed by calculating the difference in co-ordinate position and absolute values of distances for a set of tracked points and distances for each frame that the points (and distances) could be viewed. This analysis was performed using compressed and uncompressed version of the film from test number M111221001, and by applying different combinations of camera distortion and orientation corrections (both, neither, distortion only, orientation only). Comparison of absolute position and relative distances between compressed and uncompressed film showed that for all calibration options , 95% the measurements from compressed and uncompressed data were within 1 mm of each other (except for results with camera orientation correction only).

Some points or distances had a difference between compressed and uncompressed data of 5 mm of more. However, this was generally associated with point instability due to partial obscuration of the marker by another object or by glare from the lights. Overall, for clearly visible markers the results of marker tracking with compressed and uncompressed files were considered sufficiently similar, and compressed files were therefore used for the rest of the analysis.

Appendix D ISO 8721:2010 Calibration for BioRID II Sled Tests

The ISO 8721:2010 indices, as described in Section 4.3, were calculated for the off-board camera configuration used in the BioRID sled tests performed at BASt and are shown in Table C.10.

Table C.10: Indices for off-board camera

Index		Index value	Requirement
1	Focal length index	1	>=1
2	Distortion index	6.4	>=1
3	Target detection index	1.2	>=1
4	Target size index	0.77259977	>=1
5	Motion blur index	2.5	>=1
6	Point motion index	250	>=1
7	Control point distribution index	1.3	>=1
8	Time base index	416.6	>=1
9	Time origin identification index	2448	>=1
10	Camera set-up index	2.3	>=1
11	Plane scale index	1	>=1
12	Camera position calculation index	1	=1
13	Scale index	3	>=2

The results show that for the test with the off-board camera, the camera set-up passes 12 of the 13 indices. The index which fails is the target size index. This index uses focal length, the object distance, the required target diameter, the cell size, and the current target diameter to calculate the result. It is understood that this index is intended to ensure that the measurement markers are sufficiently large that they can be tracked, so that the results from the calibration markers can be assumed to be applicable to the measurement markers. Despite failing this index, there was no difficulty tracking the measurement markers in these tests.

In the initial results, the distortion index also failed due to a maximum residual error following lens distortion calibration. However, this was traced to an incorrect calibration result; when this was corrected the index was passed.

It was not possible to calculate these indices for the on-board camera configuration because the calibration lengths were not visible. Further work would be required to determine how the ISO 8721:2010 standard could be applied to on-board camera systems.

The results for the accuracy of the measurements as assessed by the ISO 8721:2010 standard are shown in Table 11. The results show that the worst case accuracy for the off-board camera was 5 mm in the X-axis and 7 mm in the Z-axis. For the on-board camera the worst case accuracy was slightly larger at 7.2 mm, although the calculation of this was not fully to ISO 8721 specification because the initial indices could not be calculated.

Table 11: Accuracy results for off-board and on-board camera setups

	Absolute difference (mm)	Percentage difference
Off-board X	5.0	2.5%
Off-board Z	7.0	3.5%
On-board resultant	7.2	8.2%