

Reliability of the KPSIT C50 dummy's cervical joint in cyclic tests for low-speed collisions up to 20 km/h

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Abstract

The durability and stability of the cervical joint system of the KPSIT C50 crash dummy were evaluated under low-speed impact conditions. The two-element neck module has two degrees of freedom, enabling flexion-extension and right-left rotation. The resistance torque characteristics were measured on a test bench using the point method, combining force and angular deflection measurements, and were compared with those of the Hybrid III reference dummy within the usable angular range. The durability assessment was based on 200 real low-speed crash tests carried out over a 24-month period as part of a broader programme aimed at evaluating the behaviour of individual body segments of the dummy during collision. The resistance torque characteristics were checked after every 25 crash tests. No significant parameter changes were observed up to 75 tests. From approximately 100 tests onward, the resistance torque gradually decreased, mainly in the extreme motion zones. After 200 tests, the maximum reduction reached about 15% in flexion-extension and about 12% and 10% in rotation, while the values in the central working range remained stable. A 20 km/h frontal crash test showed larger head displacements after the test programme, indicating a moderate increase in cervical joint compliance without loss of repeatability. The results confirm the suitability of the KPSIT C50 cervical joint for long-term low-speed crash test campaigns and support the need for periodic torque checks after approximately 100 crash tests.

Keywords: anthropometric dummies, joints, reliability, crash tests

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Highlights

- KPSIT C50 cervical joints were compared with the Hybrid III reference dummy.
- KPSIT C50 neck joints were evaluated for durability in low-speed crash tests.
- Results confirm functionality and durability for long crash test campaigns.
- Resistance moments were repeatable and changed after operating cycles.

1. Introduction

Injuries of the cervical spine, including ailments classified as WADs, are among the most frequently analysed consequences of relatively low-energy collisions, especially in rear impacts [1,2]. In this type of event, despite the limited deformations of the vehicle structure, the scale of load on the neck tissues is determined by the time course of the relative movement of the

head in relation to the torso and the conditions of contact between the head and the headrest. As a consequence, neck protection is now considered in parallel as a problem of injury biomechanics and a problem of seat system engineering, where even slight differences in the geometry and suitability of the seat can alter the kinematics and loads of the cervical spine [2,3].

For this reason, safety assessment programs are being developed that formalize the methodology for dynamic testing of seats and headrests in order to reduce the impact of station spread and ensure comparability of results between laboratories and test series [4–9]. In practice, this means defined sled pulses, acquisition quality requirements, and unambiguous rules for interpreting results in terms of injury criteria and kinematics of the head, neck, torso system [4,5,7]. At the same time, certification documents for rear-impact dummies emphasize the need to maintain a stable mechanical response of the neck and

thoracic components, which has a direct impact on the repeatability of assessments [9–11].

The basic tool in such research remains anthropomorphic test dummies. The dummy is required to be biofidelic and repeatable at the same time, and in low-energy tests, elements responsible for small displacements and small moments, i.e. primarily kinematic connections, are particularly sensitive to changes in parameters [12–14]. The literature indicates that differences in neck construction and adopted characteristics may lead to different time courses of head movement and head T1 relationships, and this directly affects the determined neck load measurements and the assessment of headrest operation [14–20]. This means that in parallel in the development work on neck components, it is necessary to take into account the operational requirements, parameter stability and kinematic compatibility under conditions representative of the target speed range.

This part of the paper describes the cervical joint of the KPSIT C50 dummy designed for crash tests at low speeds up to 20 km/h [21,22]. The neck design uses the separation of kinematic functions into two joints. One is responsible for turning the head right to left, while the other performs movement in the sagittal plane upwards downwards, i.e. flexion and extension. The object of this part is the joint responsible for flexion and extension, which does not allow the head to rotate. This approach facilitates the controlled shaping of the characteristics of motion resistance as a function of angle and angular velocity and reduces couplings between axes of motion, which promotes the repeatability of responses in cyclic tests [12,16,23].

The verification of the suitability of the adopted solutions was related to experimental data obtained with the participation of volunteers, in particular to head movements recorded during the crash test at a speed of 20 km/h [21]. Such a reference allows us to assess whether the kinematic response of the head-neck system in the low-velocity range is within the observed corridors and whether the behavior of the cervical joint is conducive to the reproduction of the actual course of movement in the phase of growth and inhibition of head displacement [2,21]. In the following chapters, the design assumptions of the joint, its construction and the assessment of the stability of the characteristics under cyclic loading, important for serial tests

carried out in conditions up to 20 km/h [16,21], are presented.

The volunteer-based reference data used in this study were taken from the experimental programme described in [21]. The tests involved 130 volunteers aged 18–45 years, including 80 men and 50 women. Before the crash tests, all participants were measured and weighed, and then assigned to anthropometric percentile groups on the basis of the mean value of 15 selected body dimensions. The volunteer tests were used as a kinematic reference for assessing whether the dummy reproduced the displacement pattern of the human body during a low-speed frontal impact. The comparison was focused mainly on head displacement trajectories, because the motion of the head–neck system is one of the most sensitive indicators of cervical joint response in low-speed collision conditions. In the doctoral study, the agreement between the simulation dummy, the physical dummy and the volunteers was evaluated using relative trajectory differences and displacement compatibility in the first phase of impact. For the head trajectory, the maximum difference was approximately 8% between the simulation dummy and the physical dummy, and approximately 10% between the simulation dummy and the volunteers representing the corresponding anthropometric group. These values were treated as a kinematic consistency corridor for the assessment of dummy biofidelity in low-speed frontal crash tests. The results indicate that the KPSIT C50 dummy reproduces the general form and amplitude range of volunteer head motion with sufficient accuracy for comparative low-speed impact studies.

2. Research methodology

The test methodology was developed to evaluate the cervical joint of the KPSIT C50 dummy for low-speed crash tests, assuming that the dummy can only be used in the range up to 25 km/h. This test programme has adopted a reference speed of 20 km/h, as comparative data from tests with volunteers were available for this level and it was possible to make references to the Hybrid III physical dummy. The tests concerned the cervical joint performing movement in the sagittal plane (flexion and extension, up-down). The right-left rotation of the head was structurally separated and implemented by a separate joint, while the cervical joint analyzed in this paper did not allow for head rotation.

The angular ranges of the cervical joint were defined on the basis of literature in the field of kinesitherapy and functional diagnostics and clinical data available in online sources, accepting them as reference values for determining the permissible deflections and selection of mechanical stops in the joint [24,25]. It has been assumed that in low-speed crash tests, it is crucial to faithfully reproduce the functional area of flexion-extension motion and to repeat the mechanical characteristics in subsequent tests, because even small changes in friction, pressure and clearance can significantly change the kinematics of the head.

The stiffness and damping parameters were selected on the basis of a review of the literature on the description of deformations and deformations in biomechanics and methods of quantitative motion analysis, which support the selection of nonlinear moment-angle characteristics and their interpretation under low-energy load conditions [26,27]. In addition, items organizing the issues of biomechanics and motion control, as well as works on deformation analysis based on displacement tracking methods, were used as a background for adopting the method of approximating the characteristics and selection of the form of the damping element dependent on angular velocity [28,29]. In terms of reference data for dummy properties and input parameters, a classic study including measurements of the characteristics of the Hybrid III dummy and a simulation database was also used [30]. On this basis, the working characteristics of the joint movement resistance were adopted as the sum of the angle-dependent component and the angular velocity-dependent component. The author assumed that the stiffness and damping parameters determined for a frontal collision can also remain unchanged for a rear and side collision in the same low-speed range, because they describe the internal properties of the articulation and not the directionally specific response of the vehicle structure.

The research program included two comparison tracks. The first track concerned the comparison of the cervical joint and kinematic response of the KPSIT C50 dummy with the Hybrid III reference dummy, treated as a reference standard in crash tests [12]. In this comparison, the time courses of head movements and their extreme values were analyzed, as well as the sequence and nature of the phases of movement in the event. The second track was a verification based on the head

movements of volunteers recorded during the crash test at a speed of 20 km/h, and then comparing them with the head movements of the KPSIT C50 dummy in a similar scenario [21]. The comparison with the volunteers was kinematic in nature and was limited to the analysis of displacements and trajectories during the event. The author assumed that obtaining a positive assessment of the conformity of the displacements of selected parts of the body in the frontal test justifies the use of simulation dummies for the analysis of rear and side collisions at low speed, provided that the weight, dimensions and angular ranges with the human body are consistent.

3. Innovative joints KPSIT C50 dummy

The KPSIT C50 physics dummy was developed as an anthropometric test object to reproduce human body kinematics in low-speed crash tests, with an assumed range of use up to 25 km/h (Figure 1). The design of the dummy is segmented and modular, which allows both repetitive recording of movements and interactions in selected areas of the body, as well as quick service after a series of tests. The solution assumes the separation of the body into solids corresponding to the basic anatomical segments: the head and neck as separate elements, the upper limb divided into the shoulder, forearm and hand, the lower limb into the thigh, lower leg and foot, and the torso composed of two parts (upper and lower) [31]. The C50 variant corresponds to the 50th percentile male metric, and the dimensions of the selected segments are assumed at the following levels: head 160 mm, neck 125 mm, chest with abdomen and hips 553 mm, thigh 310 mm, lower leg with foot 445 mm, arm 260 mm, forearm with hand 250 mm [31]. On the other hand, the masses of the segments (including, m.in, neck 1.0 kg, head 1,8 kg) and the total weight of the C50 dummy were selected to correspond to the mass distribution used in the reference solutions and to allow for a reliable representation of the inertia of individual parts of the body [31].

The dummy is based on a frame made of 25×25 mm steel profiles and 50 mm wide steel flat bars, which ensures appropriate geometric rigidity of the segments while maintaining the possibility of mounting joints and measuring elements. The outer geometry and protective layer were achieved by covering the structure with leather material, while the volume of the segments was supplemented with

a biodegradable filler. Such a combination of materials allows to maintain the external dimensions and reduces accidental damage to the articulated mechanisms during tests [31]. One of the key assumptions of the KPSIT C50 is the ability to quickly replace a damaged component without disassembling the entire system and the ability to adjust the resistance in the joints, which allows to fine-tune the characteristics to test requirements and anthropometric variants [31].

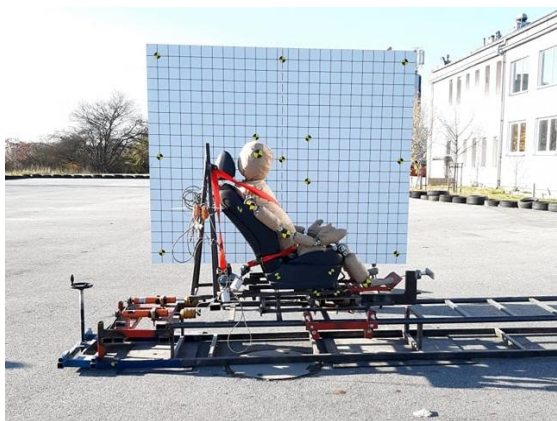


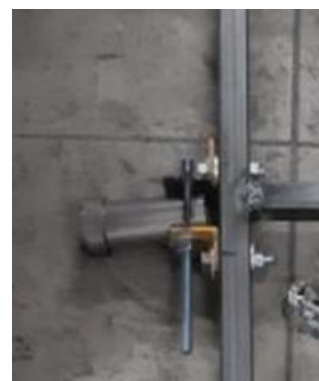
Figure 1. Still of video captured with the high-speed Digital Phantom V310 camera, showing simulations of a collision between a rear car and a permanent obstacle at 20 km/h (KPSIT C50 dummy).

An important component of the dummy is the cervical joint, designed as a two-element system with the separation of the movement function into two degrees of freedom. The upper element of the neck joint is connected to the head with two steel screws, while the lower element is attached to the body of the dummy with a steel screw that also acts as an adjusting element that affects the range of motion and the moment of resistance in the joint. In the lower connection, a compression spring is used on the mounting screw, which makes it possible to shape the stiffness characteristics by changing the pressure, and thus changing the resistance of movement in the plane of bending and extension [31]. The forward-backward movement is carried out in the lower joint (kinematically corresponding to the bending and straightening of the neck), while the right-left movement is carried out in the upper part thanks to the use of ball bearings in the upper mounting of a protective steel tube, which gives the assembly a shape similar to the human neck. Limitation of extreme deflections and stabilization of movement in the right-left direction are realized by splines cooperating with the outer sleeve, which reduces the risk of exceeding the permissible rotation and improves the

repeatability of the joint behavior in subsequent tests [31]. Figure 2 shows the cervical joint of the KPSIT C50 dummy. Figure 3 shows an adjustment spring used to shape the resistance moment characteristics in the joint that allows the head to move in the up-down direction (flexion-extension). A second spring, responsible for adjusting the resistance characteristics in the right-left direction (rotation), is located inside the steel neck body.



(a)



(b)

Figure 2. KPSIT C50 dummy neck joint: (a) neck joint mounted to the skeleton and head of the C50 dummy, (b) neck joint before mounting to the head of the C5 dummy.

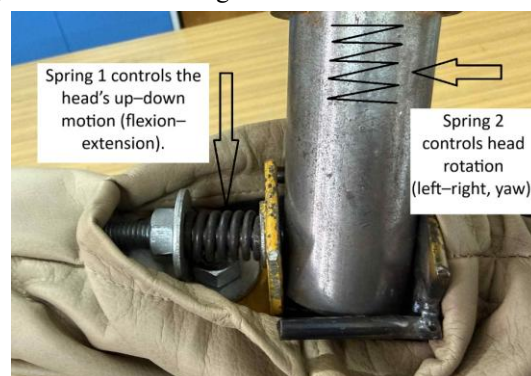


Figure 3. Resistance torque adjustment springs in the neck joints of the KPSIT C50 dummy.

The angular ranges of the cervical joint were determined and controlled by measuring with a protractor, set at the center position of the joint axis, in accordance with a uniform procedure also used for the Hybrid III reference dummy. For the degree of freedom responsible for up-down motion (flexion and extension), the range from -30° to $+45^{\circ}$ was obtained [31]. For the degree of freedom responsible for right-left movement (head rotation), the range from -90° to $+90^{\circ}$ is assumed, while in the design the limitation of this movement is implemented mechanically by a system of splines and cooperating bushings in the upper part of the joint. Such a separation of functions has interpretative consequences: in the structural point of view, the neck module contains two "sub-joints" that implement two independent directions of movement, while in the functional point of view, the entire complex is a cervical joint with two degrees of freedom, in which movements are guided and limited in a controlled manner.

The characteristics of the movement resistance in the dummy's joints were determined using the point method, combining force measurement with a strain gauge with angular deflection measurement. On this basis, the moment of drag as a function of angle was determined and then the waveforms were compared with the reference dummy. For the cervical joint, the stiffness characteristics were consistent at the level of about 95%, with the differences manifesting themselves mainly in the final deflection ranges: for positive values, the torque difference was about 5 Nm at 30° , while for negative values about 5 Nm at 40° [31]. From an operational point of view, the serviceability of the solution is also important: joint repair in the KPSIT C50 involves replacing the ball bearing or the entire bearing with the housing, and dismantling is limited to unscrewing the mounting screws. After a series of tests, a full calibration of the mechanism is not required, and the basic control activity remains to check the set of the spring pressure screw, which allows for quick detection of changes in resistance resulting from wear or damage [31].

In order to verify the anthropometric consistency of the KPSIT C50 dummy, the mass distribution of its main body segments was compared with the Hybrid III-based reference adopted during the design stage (Table 1). The physical KPSIT C50 dummy was developed as a segmented structure corresponding to the 50th percentile male crash-test

configuration. According to the design assumptions, the masses of the individual body segments were selected to correspond to the segment masses of the Hybrid III dummy. Therefore, the comparison was performed by checking the segmental mass deviation between the KPSIT C50 dummy and the Hybrid III reference and by determining the percentage contribution of each segment to the total dummy mass.

Table 1. Comparison of KPSIT C50 mass distribution with the Hybrid III reference.

Body segment / block	KPSIT C50 physical dummy mass, kg	Hybrid III reference mass adopted in design, kg	Deviation from Hybrid III, %	Share in total KPSIT C50 mass, %
Forearm	3.5	3.5	0.0	4.5
Upper arm	4.5	4.5	0.0	5.7
Hand	0.5	0.5	0.0	0.6
Lower leg	10.1	10.1	0.0	12.8
Foot	1.2	1.2	0.0	1.5
Thigh	13.8	13.8	0.0	17.6
Neck	1.0	1.0	0.0	1.3
Head	3.8	3.8	0.0	4.8
Pelvis / hips	20.5	20.5	0.0	26.1
Chest	9.7	9.7	0.0	12.3
Abdomen	10.0	10.0	0.0	12.7
Total	78.6	78.6	0.0	100.0

The results show that the KPSIT C50 dummy reproduces the adopted Hybrid III-based segmental mass distribution without measurable deviation. The total mass of the KPSIT C50 dummy is 78.6 kg, and the mass contribution of each main segment remains consistent with the reference values used during the design stage. This confirms that the dummy preserves the required mass balance between the main anatomical segments, which is important for reproducing the inertial behaviour of the body during low-speed crash tests.

4. Determination of the resistance torque characteristics in the KPSIT C50 dummy joints

The drag torque characteristics of the individual joints of the physical dummy were determined using a point-by-point procedure. For each joint, the applied force was recorded with a strain-gauge force transducer, while the corresponding joint position and range of motion were read with a protractor. The measured force values were then converted into the resisting moment about the joint axis, which made it possible to construct the moment-angle relationship for the analysed joint. In the adopted description, the resisting moment is expressed as the

sum of an angle-dependent term, a term related to angular velocity, and a constant defined by the initial conditions, as given in Equation (1) [31]. A representative example illustrating the contribution of these components for the elbow joint is presented in Figure 4 [31]. The model is written as:

$$M = M_k(\Delta\varphi) + M_c(\Delta\dot{\varphi}) + C \quad (1)$$

Where:

$M_k(\Delta\varphi)$ – a component that is a function of the joint angle,

$M_c(\Delta\dot{\varphi})$ – component that is a function of the angular velocity at the joint,

$C = M_o - M_k(\Delta\varphi_o)$ – constant selected on the basis of initial conditions,

$M_o, \Delta\varphi_o$ – torques and initial joint angles.

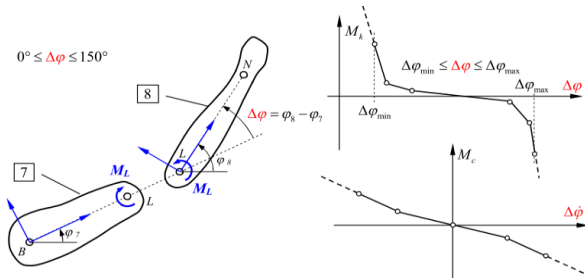


Figure 4. Sample trajectories of the components of the resistive moment at the elbow joint.

Figure 5 shows the characteristics of the up-down (flexion-extension) torque of the cervical joint resistance for the KPSIT C50 dummy compared to the Hybrid III dummy. The average drag torque difference in this range is about 3 Nm, which corresponds to about 7-8% of the maximum drag torque value of the Hybrid III dummy in this range. The maximum local deviation in the working area does not exceed approximately 5 Nm, which is approximately 12-13% of the Hybrid III reference value.

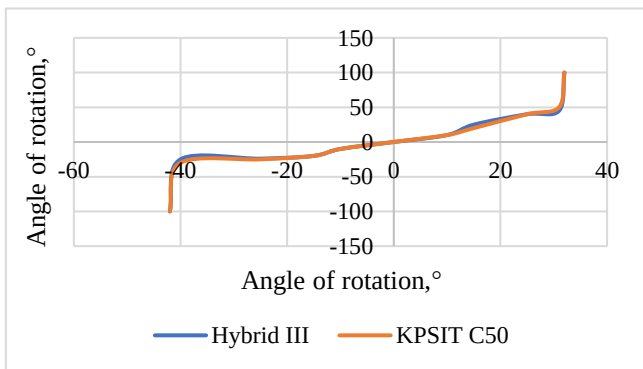


Figure 5. Characteristics of the torque of resistance of the cervical joint of the KPSIT C50 dummy in the up-down direction (flexion-extension) compared to the Hybrid III dummy.

Near extreme tilts, the differences increase. For negative angles close to -35° , the drag torque in the KPSIT C50 joint is about 5 Nm higher, which corresponds to about 18% of the Hybrid III's torque of drag at this point. For positive angles near $+28^\circ$, the difference is also about 5 Nm, which is about 12% of the reference value. This means that in the up-down direction, the KPSIT C50 cervical joint is very compatible with the Hybrid III in terms of usability, while in the end zones it shows slightly higher terminal stiffness and a steeper build-up of the drag torque.

Figure 6 shows the characteristics of the torque of the cervical joint in the right-left direction (rotation) for the KPSIT C50 dummy compared to the Hybrid III dummy. In the angular range of approximately -60° to $+60^\circ$, the waveforms of the characteristics are very similar, with an average torque of drag difference of about 2.5 Nm, which corresponds to about 9-10% of the maximum value of the Hybrid III torque in this range. The maximum deviation in this range is about 3.5 Nm, which is about 13-14% of the reference value. Near the neutral position (0°), the differences are the smallest and do not exceed about 1 Nm, which corresponds to about 3% of the maximum value.

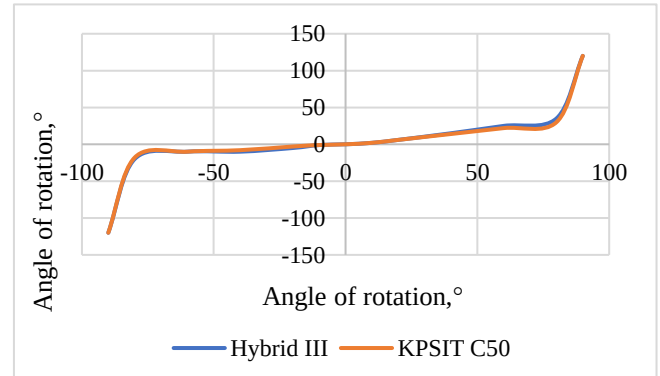


Figure 6. Characteristics of the torque of resistance of the cervical joint of the KPSIT C50 dummy in the right-left direction (rotation) compared to the Hybrid III dummy.

For larger rotation angles, above about $\pm 70^\circ$, a clear, non-linear build-up of drag torque is observed in both dummies associated with entering the zone of the range limiters. In this area, the torque of the cervical joint of the KPSIT C50 dummy is lower than that of the Hybrid III by about 5-6 Nm, which corresponds to about 12% of the maximum value of the Hybrid III torque in this range. This indicates that in the right-left direction, the KPSIT C50 cervical joint is slightly "softer" in the end zone, while maintaining a very similar course of

characteristics in the operating range.

In summary, the response of the torque resistance characteristics of the cervical joint of the KPSIT C50 dummy to the Hybrid III dummy in the usable range is approximately 90-93% for up-down movement and approximately 90-91% for right-left rotation. The largest differences, reaching 12–18%, occur near the extreme deflections and are mainly related to the different shape of the transition to the stop zone and the selection of the stiffness of the elastic elements. From the point of view of crash tests at low speeds, these differences do not significantly affect the behavior of the joint in the operating range and should be considered acceptable.

5. Dummy joints dummy KPSIT C50 joint reliability analysis

Over a period of 24 months, the KPSIT C50 physical dummy was subjected to a series of 200 crash tests. The drag torque characteristics of the joints were checked each time after a cycle of 25 crash tests. The characteristics of the drag moment in the cervical joint of the KPSIT C50 dummy, which allows head-neck movement in the up-down direction (flexion and extension), are shown in Figures 7–15. A summary of the characteristics of the drag torque in this joint, taking into account all measurement cycles from the crash tests, is presented in Figure 16.

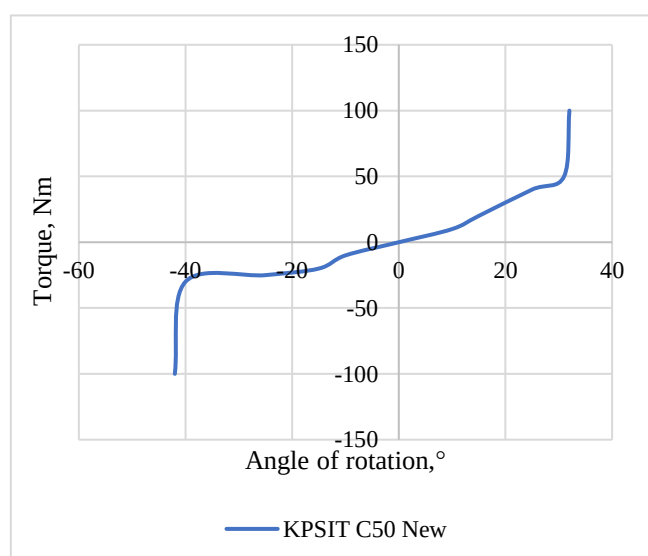


Figure 7. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy before the first crash test.

For the initial state of the KPSIT C50 New, the reference

values are 100 Nm at 32° and -100 Nm at -42°. In the intermediate range, the values are 50 Nm at 31°, 40 Nm at 25°, -30 Nm at -40° and -25 Nm at -25°, respectively, while in the middle region they remain at -20 Nm at -15°, -10 Nm at -10°, 0 Nm at 0°, 10 Nm at 10° and 20 Nm at 15°. In the further part of the description, the difference in the moment of resistance is given as the difference from the initial state, expressed numerically in Nm and as a percentage in %. After 25 crash tests, no changes in the drag torque characteristics were found in the entire angular range. This means that the difference in the moment of resistance from the initial state is 0 Nm, and the percentage difference is 0% at each point analyzed. After 50 crash tests, a similar result was obtained. The difference in the resistance moment from the initial state is 0 Nm and the percentage difference is 0% over the entire range. After 75 crash tests, the mileage remains in line with the new state. The difference in torque resistance to the initial state is still 0 Nm and the percentage difference is 0% at each measurement point, which confirms the lack of measurable degradation to 75 tests.

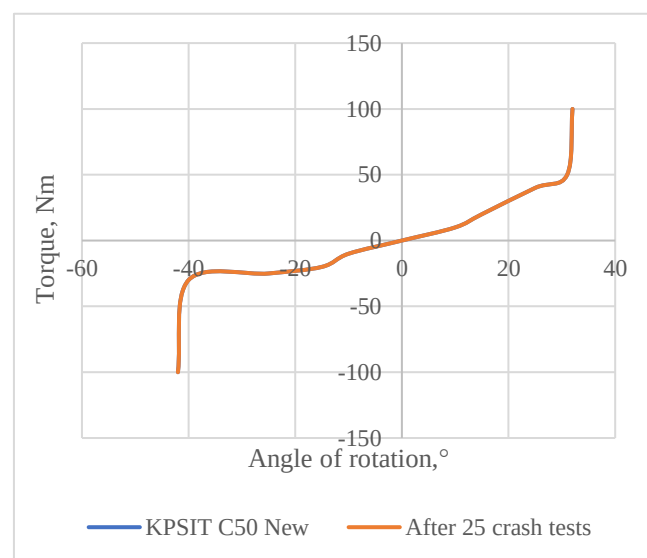


Figure 8. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy after 25 crash tests.

After 100 crash tests, the first measurable deviations appear, concentrated at the ends of the range and at the extreme points. For 32°, the torque drops from 100 Nm to 96.25 Nm, which corresponds to a drop of 3.75 Nm, or 3.75%. For 31°, the torque drops from 50 Nm to 48.5 Nm, which corresponds to a drop of 1.5 Nm, or 3.0%. For 25°, the torque drops from 40 Nm to 39.2 Nm, which corresponds to a decrease of 0.8 Nm, or 2.0%. On the negative side, for -42°, the torque changes from -100 Nm

to -96.25 Nm, which corresponds to a decrease in the absolute value of 3.75 Nm, or 3.75% . For -40° , the torque changes from -30 Nm to -29.1 Nm, which corresponds to a decrease in the absolute value of 0.9 Nm, or 3.0% . For -25° , the torque varies from -25 Nm to -24.5 Nm, which corresponds to a decrease in the absolute value of 0.5 Nm, or 2.0% . No changes were recorded in the central area from -15° to 15° , indicating degradation limited to the access zones to the stops.

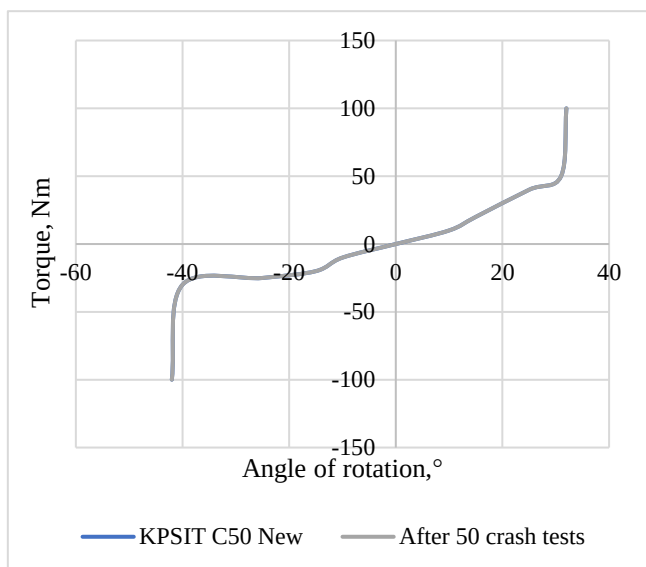


Figure 9. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy after 50 crash tests.

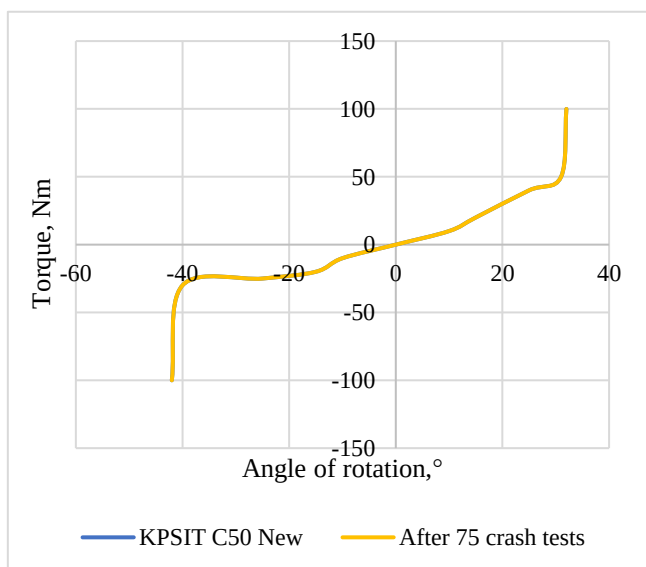


Figure 10. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy after 75 crash tests.

After 125 crash tests, the downward trend continues at the same points. For 32° , the torque is 93.25 Nm, which corresponds to a drop of 6.75 Nm, or 6.75% . For 31° , the torque

is 47.3 Nm, which corresponds to a decrease of 2.7 Nm, or 5.4% . For 25° , the torque is 38.56 Nm, which corresponds to a drop of 1.44 Nm, or 3.6% . On the negative side, -42° was obtained -93.25 Nm, which corresponds to a decrease in the absolute value of 6.75 Nm, i.e. 6.75% . For -40° , -28.38 Nm was obtained, which corresponds to a decrease in absolute value by 1.62 Nm, i.e. 5.4% . For -25° , -24.1 Nm was obtained, which corresponds to a decrease in the absolute value of 0.9 Nm, i.e. 3.6% . In the range of -15° to 15° , the values remain unchanged.

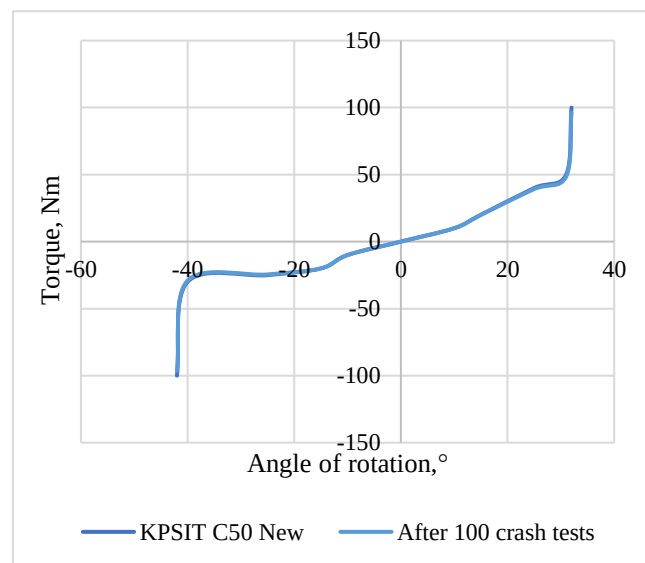


Figure 11. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy after 100 crash tests.

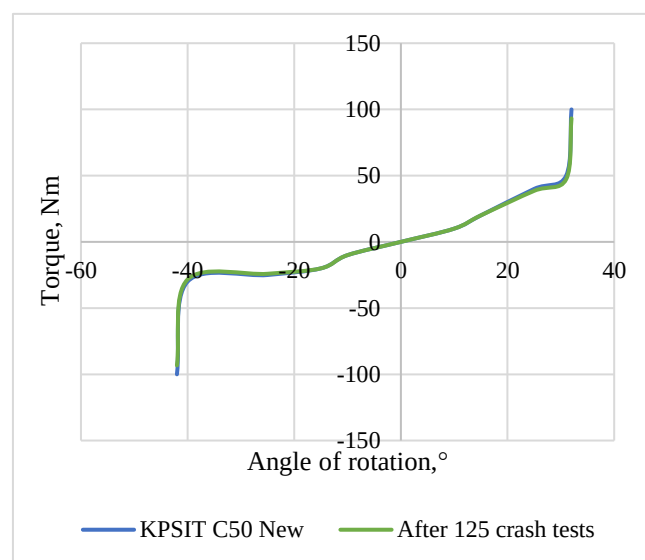


Figure 12. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy after 125 crash tests.

After 150 crash tests, the reductions are clear at the edges.

For 32°, the torque is 89.5 Nm, which corresponds to a decrease of 10.5 Nm, or 10.5%. For 31°, the torque is 45.8 Nm, which corresponds to a decrease of 4.2 Nm, or 8.4%. For 25°, the torque is 37.76 Nm, which corresponds to a decrease of 2.24 Nm, or 5.6%. On the negative side, -42° was obtained -89.5 Nm, which corresponds to a decrease in the absolute value of 10.5 Nm, i.e. 10.5%. For -40°, -27.48 Nm was obtained, which corresponds to a decrease in the absolute value of 2.52 Nm, i.e. 8.4%. For -25°, -23.6 Nm was obtained, which corresponds to a decrease in the absolute value of 1.4 Nm, i.e. 5.6%. No degradation is observed in the middle angles.

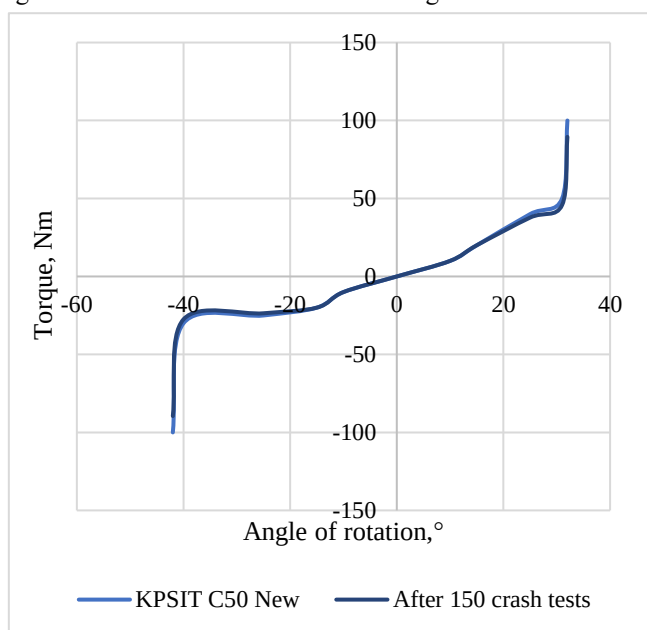


Figure 13. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy after 150 crash tests.

After 175 crash tests, the joint shows further degradation in extreme zones. For 32°, the torque is 86.5 Nm, which corresponds to a decrease of 13.5 Nm, or 13.5%. For 31°, the torque is 44.6 Nm, which corresponds to a decrease of 5.4 Nm, or 10.8%. For 25°, the torque is 37.12 Nm, which corresponds to a decrease of 2.88 Nm, or 7.2%. On the negative side, -86.5 Nm was obtained for -42°, which corresponds to a decrease in the absolute value of 13.5 Nm, i.e. 13.5%. For -40°, -26.76 Nm was obtained, which corresponds to a reduction in absolute value by 3.24 Nm, or 10.8%. For -25°, -23.2 Nm was obtained, which corresponds to a reduction in the absolute value of 1.8 Nm, i.e. 7.2%. The range of -15° to 15° remains stable.

After 200 crash tests, the maximum accepted level of changes in the end zones has been reached. For 32°, the torque

is 85 Nm instead of 100 Nm, which corresponds to a drop of 15 Nm, or 15%. For 31°, the torque is 44 Nm instead of 50 Nm, which corresponds to a decrease of 6 Nm, or 12%. For 25°, the torque is 36.8 Nm instead of 40 Nm, which corresponds to a drop of 3.2 Nm, or 8%. On the negative side, -42° was obtained -85 Nm instead of -100 Nm, which corresponds to a reduction in the absolute value of 15 Nm, i.e. 15%. For -40°, -26.4 Nm was obtained instead of -30 Nm, which corresponds to a reduction in absolute value by 3.6 Nm, i.e. 12%. For -25°, -23 Nm was obtained instead of -25 Nm, which corresponds to a decrease in the absolute value by 2 Nm, i.e. by 8%. In other characteristic points, the values remain unchanged.

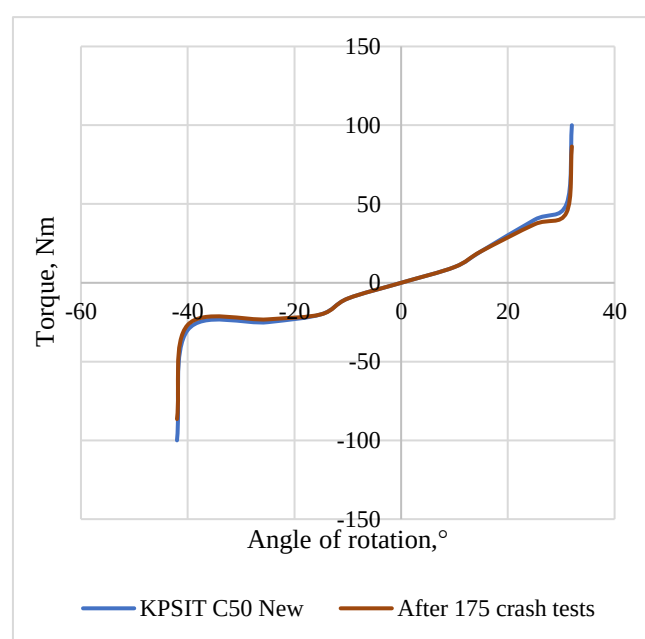


Figure 14. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy after 175 crash tests.

Based on the data collected, the degree of wear of the up-down cervical joint can be assessed as moderate and localized. No changes to 75 tests indicate high resistance in the initial phase of operation, while from 100 tests there is a systematic decrease in the drag torque limited to the limit zones, which is consistent with the wear mechanism of the components responsible for final stiffness and operation near the stops. Susceptibility to damage in the operating range from -15° to 15° is low, but susceptibility to damage increases at extreme positions, where after 200 tests the reduction of drag torque reaches up to 15% at 32° and -42°, indicating an increased risk of further degradation under conditions of subsequent shock

loads near the ends of the range.

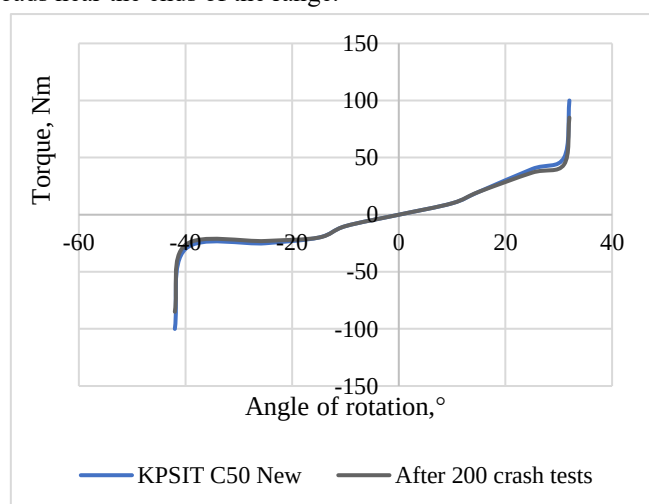


Figure 15. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy after 200 crash tests.

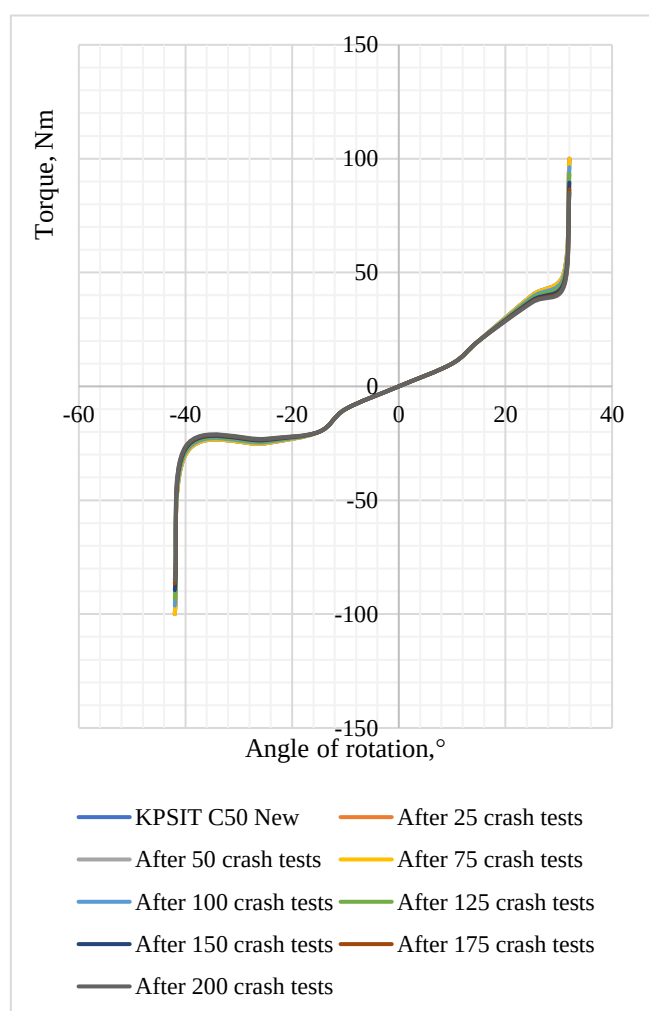


Figure 16. Summary of the resistance torque characteristics in the cervical spine joint of the KPSIT C50 dummy in the sagittal plane as a function of rotation angle after subsequent crash tests.

The resistance torque characteristics of the cervical spine joint of the KPSIT C50 dummy in the transverse direction, corresponding to right-left head rotation, are shown in Figures 17–25. A summary of the resistance torque characteristics in this direction, including all measurement cycles from the crash tests, is presented in Figure 26. The KPSIT C50 New waveform was taken as a reference state, for which the extreme values are 120 Nm at 90° and -120 Nm at -90°, while at the intermediate points 30 Nm at 80°, 22 Nm at 60°, 14 Nm at 40° and on the negative side -18 Nm at -80°, -10 Nm at -60° and -8 Nm at -40°, with no changes in the middle area from -20° to 20°. In the following part, the difference in the moment of resistance is described verbally as a decrease in torque from the initial state, expressed in Nm and in %.

After 25 crash tests, the characteristics do not change over the entire angular range; the difference in torque of resistance to the initial state is 0 Nm (0%) at all points. After 50 crash tests, the mileage remains as new; the difference in drag moment is 0 Nm (0%) over the entire range. After 75 crash tests, no measurable deviations are still observed; the resistance torque difference is 0 Nm (0%), which indicates stable joint operation for up to 75 tests.

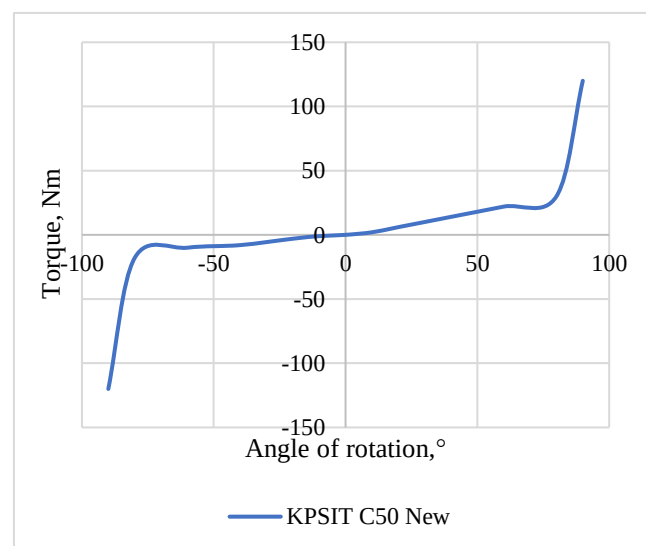


Figure 17. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction before the first crash test.

After 100 crash tests, the first measurable drops appear, concentrated in the extreme and extreme zones. For the positive side, at 90°, the torque decreases from 120 Nm to 116.40 Nm, i.e. by 3.60 Nm (3.0%), and at 80° from 30 Nm to 29.55 Nm,

i.e. by 0.45 Nm (1.5%); at 60° the drop is from 22 Nm to 21.84 Nm, or 0.16 Nm (0.73%), and at 40° from 14 Nm to 13.97 Nm, or 0.03 Nm (0.21%). For the negative side, at -90°, the absolute torque value decreases from 120 Nm to 117.00 Nm, i.e. by 3.00 Nm (2.5%), at -80° from 18 Nm to 17.82 Nm, i.e. by 0.18 Nm (1.0%), at -60° from 10 Nm to 9.95 Nm, i.e. by 0.05 Nm (0.50%), and at -40° from 8 Nm to 7.98 Nm, i.e. by 0.02 Nm (0.25%). In the middle range of -20° to 20°, no changes occur, confirming the location of degradation near the ends of the range.

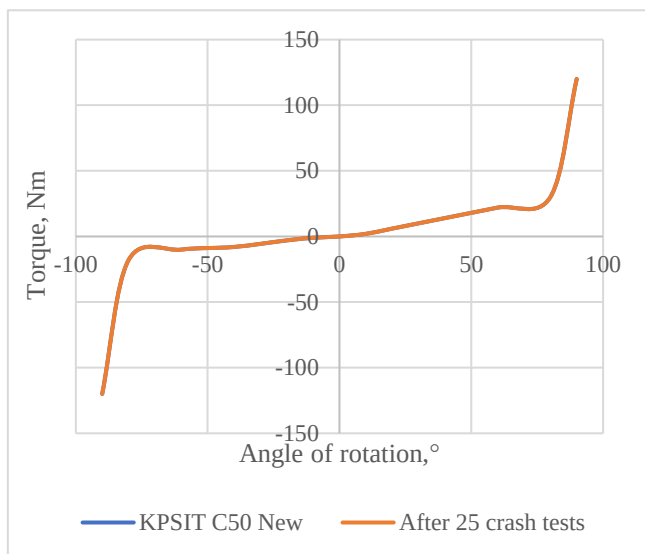


Figure 18. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction after 25 crash tests.

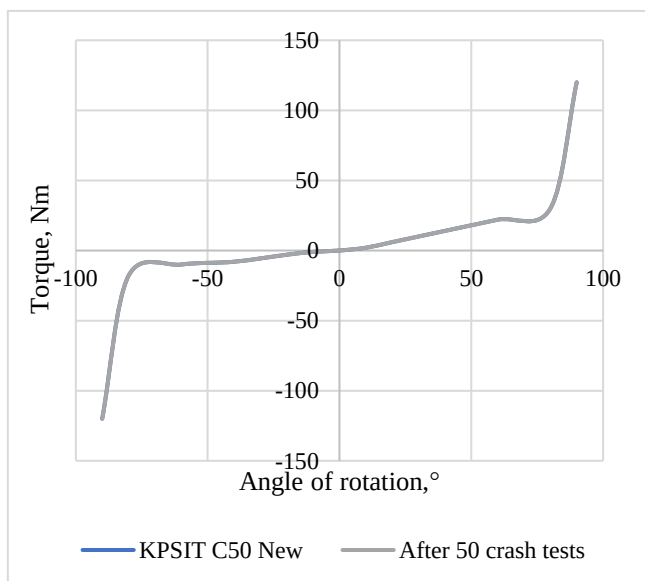


Figure 19. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction after 50 crash tests.

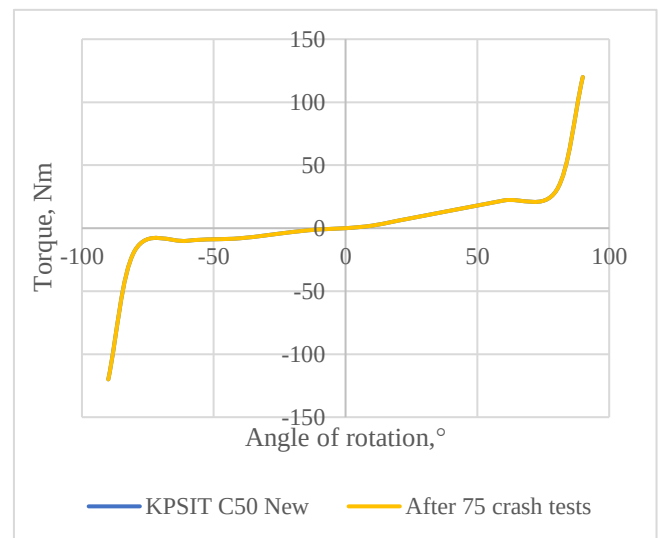


Figure 20. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction after 75 crash tests.

After 125 crash tests, the downward trend is increasing. For 90°, the torque decreases from 120 Nm to 113.52 Nm, or by 6.48 Nm (5.4%), and for 80° from 30 Nm to 29.19 Nm, or by 0.81 Nm (2.7%); for 60° from 22 Nm to 21.70 Nm, i.e. by 0.30 Nm (1.36%), and for 40° from 14 Nm to 13.94 Nm, i.e. by 0.06 Nm (0.43%). On the negative side, at -90°, the absolute value decreases from 120 Nm to 114.60 Nm, or 5.40 Nm (4.5%), at -80° from 18 Nm to 17.68 Nm, or 0.32 Nm (1.78%), at -60° from 10 Nm to 9.91 Nm, or 0.09 Nm (0.90%), and at -40° from 8 Nm to 7.96 Nm, or 0.04 Nm (0.50%). The range of -20° to 20° remains stable.

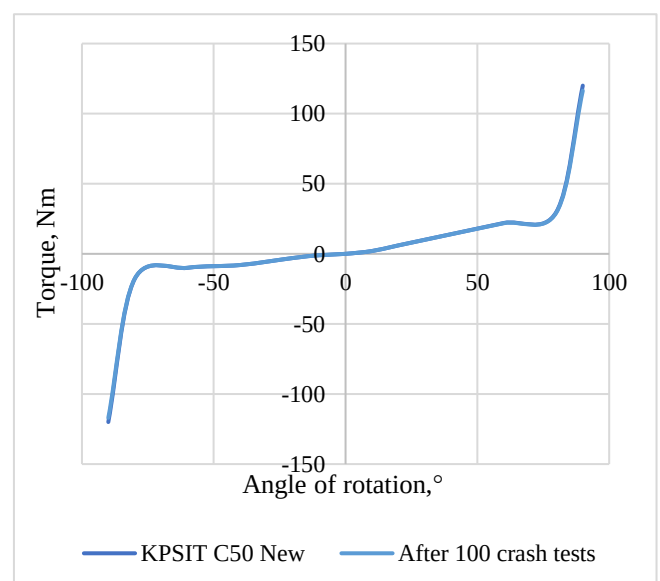


Figure 21. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction after 100 crash tests.

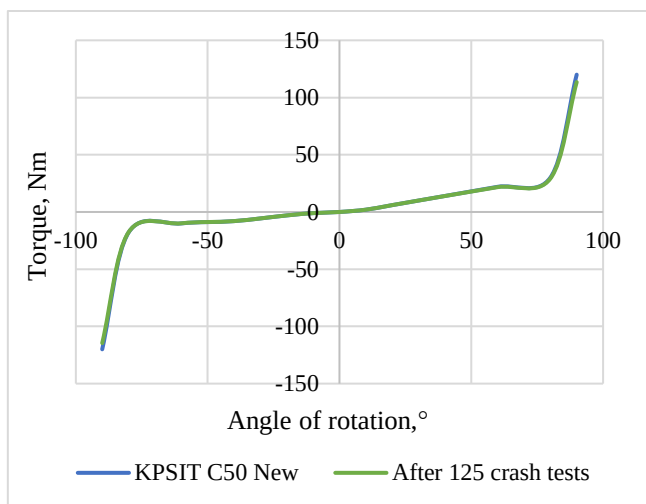


Figure 22. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction after 125 crash tests.

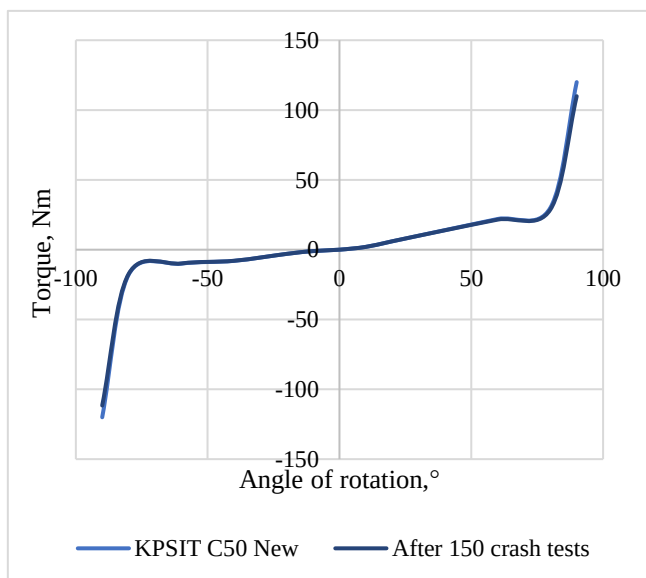


Figure 23. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction after 150 crash tests.

After 150 crash tests, the reduction in final stiffness is more pronounced, especially for the positive end. For 90°, the torque drops from 120 Nm to 109.92 Nm, or 10.08 Nm (8.4%), and for 80° from 30 Nm to 28.74 Nm, or 1.26 Nm (4.2%); for 60° from 22 Nm to 21.54 Nm, i.e. by 0.46 Nm (2.09%), and for 40° from 14 Nm to 13.90 Nm, i.e. by 0.10 Nm (0.71%). On the negative side, at -90°, the absolute value decreases from 120 Nm to 111.60 Nm, or by 8.40 Nm (7.0%), at -80° from 18 Nm to 17.50 Nm, or by 0.50 Nm (2.78%), at -60° from 10 Nm to 9.86 Nm, or by 0.14 Nm (1.4%), and at -40° from 8 Nm to 7.94 Nm, or 0.06 Nm (0.75%). No changes in the center of the characteristics persist.

After 175 crash tests, the degradation continues to progress and remains asymmetrical, with a larger drop on the positive side. For 90°, torque decreases from 120 Nm to 107.04 Nm, or 12.96 Nm (10.8%), for 80° from 30 Nm to 28.38 Nm, or by 1.62 Nm (5.4%), for 60° from 22 Nm to 21.41 Nm, or 0.59 Nm (2.68%), and for 40° from 14 Nm to 13.87 Nm, or 0.13 Nm (0.93%). On the negative side, at -90°, the absolute value decreases from 120 Nm to 109.20 Nm, or by 10.80 Nm (9.0%), at -80° from 18 Nm to 17.35 Nm, or by 0.65 Nm (3.61%), at -60° from 10 Nm to 9.82 Nm, or by 0.18 Nm (1.8%), and at -40° from 8 Nm to 7.93 Nm, or by 0.07 Nm (0.88%).

After 200 crash tests, the maximum level of change assumed in the assumptions was achieved, still concentrated at the ends. For 90°, torque decreases from 120 Nm to 105.60 Nm, or 14.40 Nm (12.0%), for 80° from 30 Nm to 28.20 Nm, or by 1.80 Nm (6.0%), for 60° from 22 Nm to 21.34 Nm, or 0.66 Nm (3.0%), and for 40° from 14 Nm to 13.86 Nm, or 0.14 Nm (1.0%). On the negative side, at -90°, the absolute value decreases from 120 Nm to 108.00 Nm, i.e. by 12.00 Nm (10.0%), at -80° from 18 Nm to 17.28 Nm, i.e. by 0.72 Nm (4.0%), at -60° from 10 Nm to 9.80 Nm, i.e. by 0.20 Nm (2.0%), and at -40° from 8 Nm to 7.92 Nm, i.e. by 0.08 Nm (1.0%). At the same time, the range of -20° to 20° remains unchanged, which means that degradation does not affect the "core" of the characteristic, but mainly concerns the final stiffness.

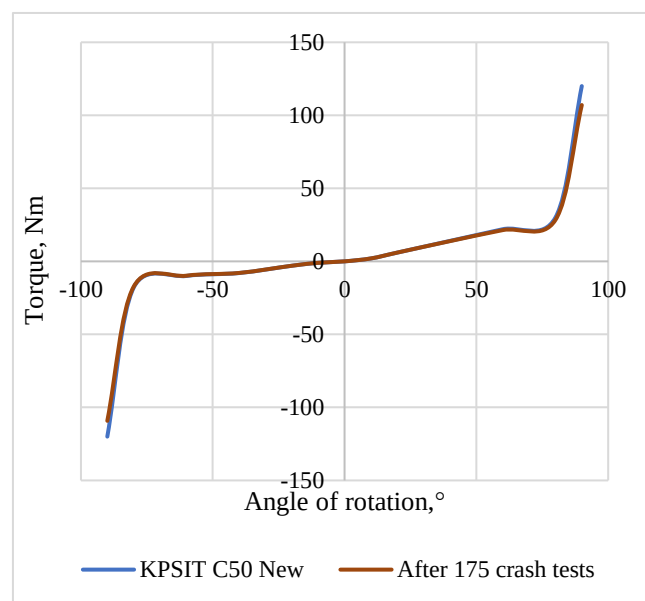


Figure 24. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction after 175 crash tests.

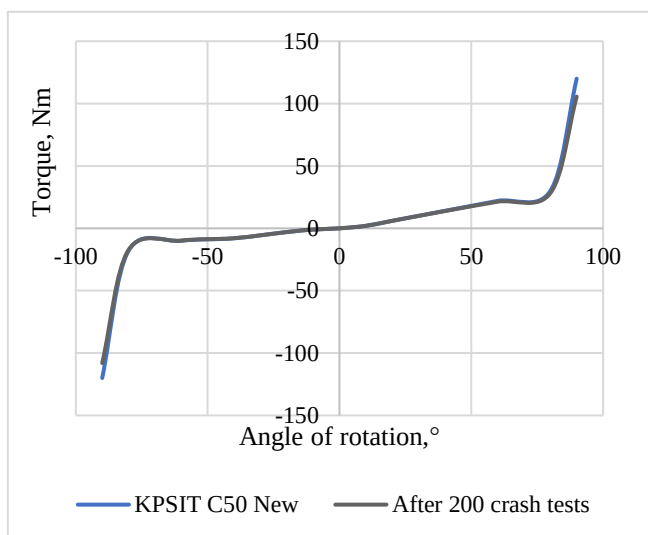


Figure 25. Characteristics of the resistance torque in the cervical spine joint of the KPSIT C50 dummy in the transverse direction after 200 crash tests.

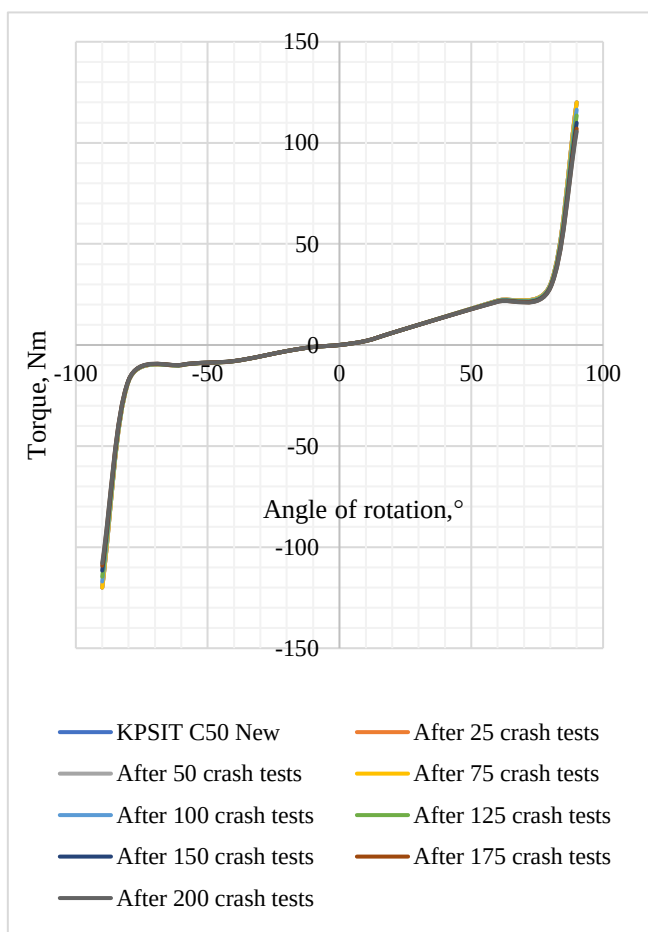


Figure 26. Summary of the resistance torque characteristics in the cervical spine joint of the KPSIT C50 dummy in the transverse direction as a function of rotation angle after subsequent crash tests.

Based on the data collected, the degree of wear of the right-left cervical joint can be assessed as moderate and localized. No

changes to 75 tests indicate high resistance in the initial phase of operation, while from 100 tests there is a systematic decrease in the drag torque in the extreme zones, typical of wear of contacts/stops and a decrease in final stiffness. Susceptibility to damage in the operating range around 0° is low, while susceptibility to further degradation increases near the edges, especially on the positive side, where after 200 tests the drop reaches 12.0% at 90° , which should be considered as the most sensitive area for further shock loads.

The summary torque-angle characteristics presented in Figures 16 and 26 were obtained from three repeated measurements performed for each angular position under the same test-bench conditions. The statistical summary is presented in Table 2. Figure 16 presents the averaged resistance torque characteristics of the cervical spine joint in the sagittal plane, while Figure 26 presents the averaged resistance torque characteristics in the transverse direction. Therefore, both summary curves represent mean values calculated from three measurement trials, rather than single measurements.

To assess the repeatability of the measurement procedure, selected diagnostic angular positions from both summary characteristics were analysed using standard deviation, repeatability error and coefficient of variation. The repeatability error was defined as the maximum absolute deviation of an individual measurement from the mean value. The coefficient of variation was calculated only for non-zero mean torque values. The statistical parameters were determined for the new state and for the states after 100 and 200 crash tests, because these stages represent the initial condition, the beginning of measurable degradation and the final condition after the full test programme.

The statistical analysis confirmed good repeatability of the resistance torque measurements used to construct the summary characteristics in Figures 16 and 26. For the sagittal plane, the standard deviation ranged from 0.78 Nm to 1.08 Nm, while the repeatability error did not exceed 1.23 Nm. For the transverse direction, the standard deviation ranged from 0.78 Nm to 1.10 Nm, and the repeatability error did not exceed 1.25 Nm. In both cases, the coefficient of variation remained low, not exceeding 1.08% for the sagittal plane and 1.04% for the transverse direction. These values are significantly lower than the torque reductions observed after long-term operation of the cervical

spine joint. In the sagittal plane, the resistance torque at 32° decreased from 100.00 Nm in the new state to 85.00 Nm after 200 crash tests, which corresponds to a reduction of 15.00 Nm, whereas the repeatability error at this point was 0.89 Nm. In the transverse direction, the resistance torque at 90° decreased from 120.00 Nm to 105.60 Nm, corresponding to a reduction of 14.40 Nm, while the repeatability error was 1.25 Nm. This confirms that the observed decrease in resistance torque was caused by progressive operational degradation of the cervical spine joint rather than by random measurement scatter.

Table 2. Statistical parameters of repeated resistance torque measurements for the summary characteristics shown in Figures 16 and 26.

Motion direction	Number of crash tests	Angle, °	Mean torque, Nm	SD, Nm	Repeatability error, Nm	CV, %
Sagittal plane, flexion-extension	0	-42	-	1.08	1.23	1.08
	0	32	100.00	0.90	1.04	0.90
	100	-42	-96.25	1.02	1.07	1.05
	100	32	96.25	0.93	1.07	0.96
	200	-42	-85.00	0.79	0.89	0.93
	200	32	85.00	0.78	0.89	0.92
Transverse direction, right-left rotation	0	-90	-	1.10	1.25	0.92
	0	90	120.00	0.94	1.07	0.78
	100	-90	-	1.07	1.12	0.91
	100	90	116.40	0.78	0.87	0.67
	200	-90	-	0.94	1.06	0.87
	200	90	105.60	1.10	1.25	1.04

Figures 27 and 28 show the X-axis and Z-axis head displacement curves for the KPSIT C50 dummy in its new condition and after 200 crash tests (frontal collision, 20 km/h). In both directions, the shape of the temporal response is maintained, while after 200 tests, local differences in amplitude and slight changes in the course are visible in selected time intervals, which indicates moderate wear and tear of elements affecting the susceptibility of the cervical system.

In the X-axis direction, the displacement build-up phase to approx. 0.10 s is comparable for both states, and the differences are mainly apparent in the maximum zone. For the new state, the maximum displacement is approx. 0.46 m and occurs in approx. 0.14–0.15 s, while after 200 tests the maximum increases to approx. 0.51 m, which corresponds to an increase in amplitude by approx. 0.05 m, i.e. by approx. 11%. This means an increase in the system's X-direction in the heaviest load phase. Later in the course, after passing through the vicinity of zero (approx. 0.23–0.25 s), a negative displacement of

a reflection nature is observed. In the new state, the negative minimum is about -0.16 m in about 0.29–0.31 s, while after 200 tests the minimum is shallower (less negative), about -0.14 m, which is a change of 10–12% compared to the amplitude of the new state. In practice, this means that after 200 tests, the system shows a greater "peak response" in the positive phase, with a slightly altered rebound character (less negative displacement).

In the direction of the Z-axis, the waveform is predominantly negative in the main phase (collapse), and the differences between the new state and after 200 tests are concentrated in the minimum region. For the new state, the minimum is approx. -0.17 m and occurs in approx. 0.13–0.15 s, while after 200 tests the minimum deepens to approx. -0.19 m. The change in amplitude is approx. 0.02 m, which corresponds to approx. 11–12% increase in the absolute value of the minimum. After the minimum phase, both waveforms return to zero in a similar time interval, and in the region of 0.28–0.35 s, a small positive correction/oscillation of small amplitude is visible; After 200 tests, its shape is slightly changed, but without a significant change in trend (the waveforms remain close to each other).

Overall, the results indicate that after 200 tests, there was a moderate degradation of the effective stiffness of the cervical system, manifested by an increase in the amplitude of displacements at key moments of dynamic response: in the X axis, an increase in the maximum by approx. 11%, and in the Z-axis, a minimum deepening of approx. 11–12%. At the same time, the general form of the waveforms and the times of occurrence of extremes are preserved, which suggests that wear is in the nature of a progressive change in susceptibility (e.g. friction/backlash/change in properties of susceptible elements) without a rapid loss of functionality, while the phases corresponding to extreme displacements are the most sensitive.



Figure 27. Comparison of the head displacement of the KPSIT C50 dummy towards the X-axis during a frontal collision at 20 km/h for the new state and after 200 crash tests.

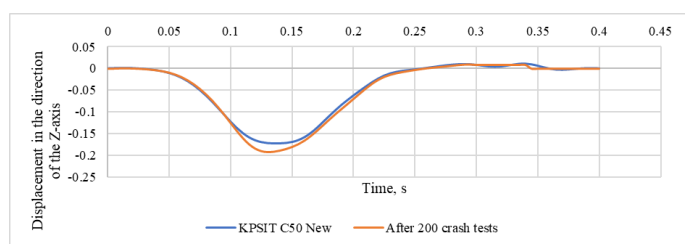


Figure 28. Comparison of the head displacement of the KPSIT C50 dummy in the direction of the Z-axis during a frontal collision at a speed of 20 km/h for the new state and after 200 crash tests.

In order to translate the obtained durability results into practical maintenance recommendations, a diagnostic inspection procedure was defined for the KPSIT C50 cervical spine joint. The inspection should be performed after approximately 100 crash tests and then repeated after every subsequent 25 crash tests or whenever visible clearance, unstable head motion or abnormal resistance of the joint is observed.

The inspection should include measurement of the resistance torque characteristics in both motion directions of the cervical spine joint: flexion-extension in the sagittal plane and right-left rotation in the transverse direction. The joint should be mounted on the same test bench as that used for the initial torque-angle characterization. The measurement should be carried out using a strain-gauge force transducer or calibrated force gauge, a fixed lever arm, and an angular measuring device such as a protractor or digital inclinometer. The resistance torque should be calculated from the measured force and lever arm length. For each diagnostic angular position, three repeated measurements should be performed, and the arithmetic mean should be used as the inspection result.

For the sagittal plane, the recommended diagnostic angular positions are -42° , -40° , -25° , 0° , 25° , 31° and 32° . Particular attention should be paid to the extreme positions -42° and 32° , because the largest torque reduction was observed in these regions. For the transverse direction, the recommended diagnostic angular positions are -90° , -80° , -60° , 0° , 60° , 80° and 90° , with special attention to -90° and 90° . The central angular range should be used mainly to verify repeatability and the absence of excessive clearance, whereas the extreme angular regions should be treated as the primary indicators of operational wear.

The reference values for inspection should be the resistance torque values measured for the new joint condition. If the mean resistance torque decreases by more than 5% in the extreme angular regions, the joint should be marked for increased monitoring during subsequent tests. If the decrease exceeds 10% in any diagnostic extreme position, the spring preload and fixing screw setting should be checked and adjusted. If the decrease reaches or exceeds 15%, or if visible damage, excessive backlash, unstable return to the neutral position or non-repeatable torque readings are observed, the joint should be disassembled and the worn components, especially the bearing, housing or preload elements, should be replaced.

This criterion is consistent with the degradation trend observed during the 200-crash-test programme. The first measurable changes appeared after approximately 100 crash tests, while after 200 tests the maximum torque reduction reached about 15% in the sagittal plane and about 10–12% in the transverse direction. Therefore, a 10% decrease in resistance torque is proposed as the maintenance threshold, while a 15% decrease is proposed as the replacement threshold.

6. Discussion

The obtained results indicate that the cervical joint of the KPSIT C50 dummy retains its suitability for low-speed crash tests, but its mechanical properties do not remain completely unchanged under conditions of long-term operation. In this study, it was shown that up to about 75 crash tests, the characteristics of the drag moment did not change significantly, while after exceeding about 100 tests, there was a systematic decrease in the drag moment, visible mainly in the extreme zones of the range of motion. After 200 attempts, this reduction reached about 15% for up-down movement and about 10–12% for right-left rotation, while maintaining the relative stability of the central operating range. This means that the degradation of the tested element is not of a rapid or global nature, but primarily concerns the areas of work related to access to the stops and the change of the final stiffness. Similar conclusions have also been presented in other papers, in which it was emphasized that in the assessment of the head-neck system, not only the value of maximum loads is crucial, but also the preservation of the correct form of dynamic response and repetition of movement in subsequent attempts [32].

In the presented results, after 200 trials, an increase in the maximum displacement of the head in the X-axis from about 0.46 m to about 0.51 m and a deepening of the minimum displacement in the Z-axis from about -0.17 m to about -0.19 m, while maintaining similar times of occurrence of extremes and similar shape of time courses. This indicates that cervical joint wear leads primarily to an increase in the susceptibility of the system, and not to a complete loss of its ability to reproduce the basic character of head movement during a collision. This is consistent with the observations presented in other studies, which indicated that even with the overall biofidelity of the model, amplitude differences may appear along with the change in the properties of susceptible elements, not necessarily associated with a fundamental change in the course of the temporal response [33]. From a practical point of view, this means that the analyzed joint can still be used in experimental studies, but its operating history should be taken into account when interpreting the results of long test series.

The results of this study are also consistent with reports indicating that the dynamic response of the head-neck system is strongly dependent on the conditions of restriction of movement, the geometry of the test bench and the cooperation of the cervical joint with other elements of the safety system [34]. Other studies have shown that changing the position of the seat belt, the type of belt arrangement or the design of the seat leads to marked changes in the trajectory of head and torso movement, as well as changes in the dynamic values of loads. Against this background, the increase in head displacement observed after 200 trials should be considered a moderate effect, but methodologically significant, as it may overlap with the influence of other experimental variables, such as backrest positioning, seat geometry or the way the seat belt is guided. This means that even a local change in the characteristics of the cervical joint can affect the final assessment of the dummy's behavior in a crash test.

It is also important that other works devoted to the safety of vehicle occupants have pointed out the need to analyze the entire system: the seat, seat belts, available space and kinematics of the dummy [35]. It was emphasized that changes in the kinematics of the head and neck can translate not only into displacement values, but also into the level of dynamic loads and the values of injury indicators. With regard to the own

results, this means that the observed decrease in the torque of resistance of the cervical joint, concentrated mainly in the vicinity of extreme deflections, may lead not only to a higher amplitude of head movement in further operation, but also to a change in the values of the parameters used in the safety assessment. For this reason, the control of the characteristics of the joint after exceeding about 100 tests seems justified both for operational reasons and from the point of view of maintaining the biomechanical reliability of the results.

To sum up, the conducted research confirmed that the cervical joint of the KPSIT C50 dummy can be used in long low-speed crash-test campaigns, but with the increase in the number of trials, there is a gradual decrease in the final stiffness and an increase in the susceptibility of the system. This phenomenon does not eliminate the investigated solution from experimental applications, but indicates the need for periodic monitoring of the characteristics of the moment of resistance and taking into account the degree of wear of the joint when analyzing the results. In the light of comparisons with other works, it can be concluded that maintaining the stability of the response in the central operating range is of fundamental importance for the usability of the dummy, while changes occurring in the end zones are the first signal of deterioration of the biomechanical compatibility of the system and may affect the final safety assessment over time [32–35].

7. Conclusion

In these studies, the durability and reliability of the cervical joint of the KPSIT C50 dummy, designed for crash tests at low speeds (up to 20 km/h), were evaluated. The design of the neck module is designed as a two-element system with the separation of kinematic functions into two degrees of freedom: one joint is responsible for movement in the up-down sagittal plane (flexion-extension), and the other performs right-left rotation, which reduces coupling between axes and promotes repeatability of responses in cyclic tests. The range of motion was determined and controlled according to a uniform procedure (also for the Hybrid III reference dummy): for up-down, from -30° to +45°, and for right-left, from -90° to +90°, with mechanical restriction of movement in the upper part of the joint.

The observed decrease in resistance torque is consistent with

a progressive wear mechanism affecting the contact surfaces, preload elements and stop regions of the cervical spine joint. Although the present study assessed wear indirectly through torque–angle characteristics and kinematic response, future work may include additional diagnostic methods used in tribology and condition monitoring. In particular, monitoring of wear particles, analysis of friction-related degradation products, and microfluidic or sensor-based detection methods could be considered as complementary tools for assessing the technical condition of dummy joints after long crash-test campaigns. Such methods may improve early detection of local wear before measurable changes in global joint torque characteristics occur.

The drag torque characteristics were determined using the point method, combining force measurement with a strain gauge sensor with angular deflection measurement, and then the waveforms were compared with the Hybrid III dummy. In terms of operation, the mileage remained very similar. For right-left rotation in the range of about -60° to $+60^\circ$, the average torque difference was about 2.5 Nm (max. approx. 3.5 Nm), while above about $\pm 70^\circ$, the KPSIT C50 joint was "softer" than the Hybrid III by approx. 5–6 Nm (~12% in this zone). Overall, compliance in terms of use was estimated at about 90–93% for up–down and about 90–91% for right–left.

The durability assessment was carried out in a long series of 200 crash tests carried out over a period of 24 months, and the joint was checked cyclically every 25 tests (angular ranges and resistance moment characteristics were checked as indicators of degradation: friction changes, downforce decrease, clearance increase, limiter adjustment). Up to 75 tests did not change the up–down joint; The first measurable deviations appeared after 100 tests and were concentrated in the end and edge zones, while the operating range remained stable. After 200 tests, the drop at the extreme points reached its maximum: for example, for 32° the torque decreased from 100 Nm to 85 Nm (–15%), and for the -42° torque from –100 Nm to –85 Nm (–15% of the absolute value), with no change in the other characteristic points.

An analogous, local character of degradation was observed for the right-left joint: up to 75 tests, the characteristics did not change, and from 100 tests there was a systematic decrease in the moment of drag concentrated at the ends of the range. After

200 tests for 90° , the torque decreased from 120 Nm to 105.6 Nm (–12%), and for -90° the absolute value dropped from 120 Nm to 108 Nm (–10%), while maintaining the "core" of the characteristics in the range from -20° to $+20^\circ$. This means that the wear is primarily related to the final stiffness/stop area, while in the typical operating range, the joint maintains stable parameters.

Kinematic verification in a frontal collision of 20 km/h (new vs after 200 tests) confirmed the preservation of the general shape of the temporal response and the similar times of occurrence of extremes, with a simultaneous increase in amplitudes indicating a moderate increase in the vulnerability of the cervical system. In the X axis, the maximum displacement increased from approx. 0.46 m to approx. 0.51 m (approx. +11%), and in the Z axis, the minimum deepened from approx. –0.17 m to approx. –0.19 m (approx. +11–12% of the absolute value). Overall, the KPSIT C50 cervical joints remain functional after 200 tests, and the observed degradation is moderate and located mainly in the marginal zones; From a practical point of view, it is reasonable to carry out regular monitoring of the characteristics after about 100 tests, with particular emphasis on maintaining the moment of resistance near the limiters, because this is where wear trends are revealed most quickly.

Based on the obtained results, periodic inspection of the KPSIT C50 cervical spine joint is recommended after approximately 100 crash tests and subsequently after every 25 crash tests. The inspection should include repeated resistance torque measurements in the sagittal and transverse directions at selected diagnostic angular positions, especially in the extreme motion zones. A decrease in resistance torque greater than 5% should be treated as an indication for increased monitoring, a decrease greater than 10% should require adjustment of the spring preload and fixing screw setting, and a decrease of 15% or visible mechanical damage should require disassembly and replacement of worn components. The added raw measurement data and inspection procedure improve the reproducibility of the results and provide practical engineering guidance for long-term use of the KPSIT C50 dummy in low-speed crash-test campaigns.

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