Development of a Hand and Forearm Impact Test Method and a Study on Influencing Factors

Magnus Björklund, Joakim Risberg, Oscar Laudon, Lotta Jakobsson

Abstract Upper extremity Injuries have not decreased to the same extent as overall injury reduction in car crashes and may result in long-term consequences. There are few tools and methods to evaluate injuries to forearm and hand/wrist. The objective of this study was to develop a method, including a novel instrumented forearm, capable of capturing possible hand and forearm injuries caused by hand impacts to vehicle interiors in frontal impacts. A Hybrid III forearm was modified to measure moment in the wrist, along with a force transducer in the middle section of the forearm. It was launched by an ejector as a free moving object.

A parametric study was performed using a generic board as an impact surface, in addition to a series of tests performed impacting a vehicle instrument panel. Thirty-one different configurations were included in the parametric study, varying stiffness, friction, impact angle and hand position. The test method was shown to be repeatable, as well as sensitive to distinguishing differences between the configurations, with potential to provide input to vehicle design. Impact surface stiffness was found to have the largest influence on the kinetic response of the arm, followed by a combination of friction and impact angle. Impacts with the hand in the flexion resulted in lower forearm forces and wrist moments compared to when in extension.

Keywords Crash test dummy arm, forearm, test method, upper extremities

I. INTRODUCTION

A continuous development in vehicle safety has reduced injury risks for car occupants. This is seen overall and irrespective of crash direction [1-2]. Studying frontal impacts during 1998–2015 in NASS-CDS, [2] reported that the AIS2+ injury risks were overall lower for restrained occupants in newer vehicles (model year 2009 and later) compared to older model years, although to a different degree per body region. Injuries to the forearm and hand/wrist were among the most common injury types and were not reduced at the same rate compared to AIS2+ injuries to other body regions. The authors highlighted forearm and hand/wrist injuries as injury types that remain to be addressed. This was also seen in the study on one vehicle brand by [3]. Comparing occupants in Volvo cars involved in crashes during mid-1990s and mid-2000s, the reduction of AIS2+ upper extremity injury risks was less than the overall MAIS2+ injury risk reduction.

Although usually not life-threatening, upper extremity injuries can result in long-term consequences. Upper extremities account for the second overall highest scoring of Permanent Medical Impairment (PMI) of degree 1% or more (PMI1+), given the event of injury/diagnosis [4]. Only lower extremities were found to have overall higher risk of PMI1+. Long-term consequences for upper extremity injuries were seen irrespectively of crash configuration, with PMI1+ ranging between 14.5-30.0%. Wraighte *et al.* [5] calculated financial costs and functional impairment of upper extremity injuries to 62 front seat occupants in frontal impacts in the UK, showing the highest average upper extremity impairment to the elbow and wrist.

Jakobsson and Lindman [3] reported that upper extremity fractures were found predominantly in frontal impacts and drivers tend to be more exposed. Fractures to the forearm, wrist and hand, in addition to the clavicula were most frequent. The main mechanisms of fractures to the wrist and the forearm were trauma to an outstretched, extended or clenched hand. Investigating upper extremity fractures in the CIREN database,

M. Björklund (+46 729 707724, magnus.v.bjorklund@volvocars.com) is a Senior Attribute Leader, J. Risberg is a Senior Measurement Engineer, O. Laudon is a Safety Analysis Engineer and L. Jakobsson is Senior Technical Leader, Injury Prevention at Volvo Cars Safety Centre, Volvo Cars, Sweden. L. Jakobsson is also Adjunct Professor in Vehicle Safety at Chalmers. All authors are associated with SAFER – Vehicle and Traffic Safety Centre at Chalmers in Sweden.

1997-2004, [6] showed that drivers and passengers had different upper extremity injury patterns and the direction of impact influenced the injury pattern. The authors identified the front vehicle interior as the most contributing injury source for forearm fractures [6]. Otte [7] studied the biomechanics of upper extremity injuries of belted car drivers and emphasized the need for car developments and dummy test work. The study demonstrated two different mechanisms for upper extremity fractures: direct impact with longitudinal and rotational load to hand, hand joint and forearm resulting in a forward movement of the forearm and rotational effects with injury risk for joints and lower forearms; and lateral collisions with load transmission to lateral parts of the forearm resulting in injuries to the whole upper extremity.

Tests have been executed investigating the injury occurrence of wrist and forearm injuries. Forman *et al.* [8] performed 15 tests where the forearm was impacted axially with the hand in extension position. They suggested that an axial reaction force of 4.3kN in the elbow corresponds to a 50% fracture risk of the forearm. Duma *et al.* [9] performed 17 tests with impact to the palm identifying forearm fractures, with axial reaction forces ranging from 1.7kN to 4.7kN with the forearm free hanging. Begeman *et al.* [10] evaluated moments in the ulna and radius during lateral three-point bending loading, suggesting fracture level at 90Nm. Saul [11] suggested 120 – 150Nm for evaluation of distal bending moment for male subjects, based on a summary of publications.

There are few tools and methods addressing the mechanism of hand and forearm injuries in vehicle safety testing. The Research forearm Injury Device (RAID) was designed in the 1990s to detect risk for injuries in frontal airbag deployment [12] although it has not attained much attention over the years. Made from an aluminium tube with double pivot attachment to allow motion along two axes, RAID was placed across the airbag module to measure hand fling velocity and moment. The Society of Automotive Engineers (SAE) instrumented forearm, also developed during the 1990s, was based on the small female sized Hybrid III (HIII) forearm and may be used on the small female sized crash test dummies (HIII and SIDIIs) for air bag interaction evaluation [13]. The forearm is instrumented with a 6-axis load cell capable of recording moments and forces in the forearm, centrally on the long bones. The midsized male HIII forearm described by [11] is designed for airbag interaction and equipped with accelerometers at elbow and wrist in combination with possibilities to record bending moments in the forearm. Except for the SAE instrumented forearm, which is used in a side airbag out-of-position test method [14], these tools are not included in standardised testing, nor are they intended to be used for direct impact to interior vehicle surfaces.

Given the relatively high frequency of upper extremity injuries, that can result in long-term consequences for car occupants of today's cars, test methods addressing this area are needed. The objective of this study is to develop a repeatable and efficient test method, including a novel instrumented forearm, capable of capturing the potential hand and forearm injuries caused by hand impacts to vehicle interiors. Specifically, the method will focus on typical kinematics occurring in frontal impacts. The method's capabilities to capture differences in impact characteristics will be investigated through a parametric study.

II. METHODS

The hand and forearm impact test method will be described, followed by a test series of five tests towards a vehicle instrument panel (IP) and a parametric study with 91 tests in 31 different configurations towards a generic test board. The purpose of the IP test series was to provide insight into its sensitivity in a vehicle-like interior impact situation as a complement to impacts to the generic flat test board. The parametric study using the generic test board was performed to evaluate factors influencing surface characteristics and impact load cases, providing input on kinetic responses targeting potential mitigation of injuries to the forearm.

The Hand and Forearm Impact Test Method

A test method with the aim of evaluating countermeasures to forearm injuries from the vehicle interior in frontal impact was developed, as shown in Figure 1a. The method comprises a novel instrumented forearm based on the midsize male HIII dummy forearm, displayed in Figure 1b. The forearm was propelled towards interior surfaces using a 6D-robot forearm at a variety of pre-set angles and speed. The method is designed to have a wide flexibility in impact angles and velocity, as well as being quick between tests, making it attractive in the vehicle development process.

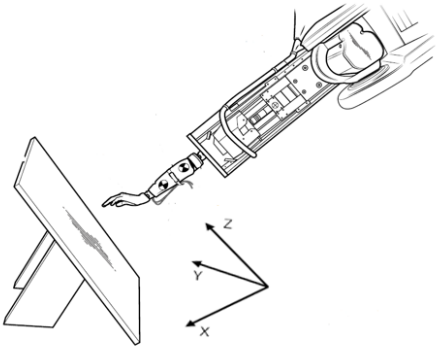


Fig. 1a. The hand and forearm impact test method.

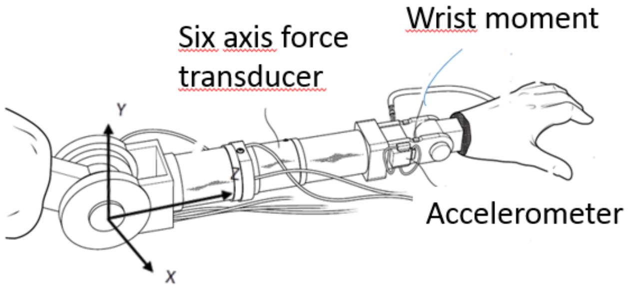


Fig. 1b. The novel instrumented forearm.

The forearm is instrumented with three sensors capturing force, acceleration and bending moment. Force is measured using a six-axis force transducer sensor in the middle section of the steel bar representing the long bones ulna and radius. For detailed instrumentation see Appendix Table A.I. A three-axis accelerometer was placed on the forearm section adjacent to the wrist joint (Figure 1b). The wrist joint was modified to implement strain gauges in a bending bridge configuration. The sensor output is the bending moment at a fork-like steel bar representing the wrist joint, referred to as wrist Mx. The modifications involve grinding out areas of the wrist to ensure high sensitivity and low crosstalk effect, i.e., influence from other force directions on the output. This study focused on the axial force in the forearm (Fz) and the moment in the wrist (Mx).

The wrist joint has a range of motion of approximately 95° flexion and 70° extension. Neutral position has been defined as a straight line through the elbow joint, the wrist and between the thumb and pointer. The wrist joint screw was tightened with a torque of 3 Nm, for most tests positioned in 30^{0} flexion or 35^{0} extension. The hand is replaceable, using either a right or a left hand. In this study the right hand was used, except in two tests in the IP test series when simulating a case with left forearm injury. An adapter in hard plastic was mounted on the elbow joint allowing attachments in multiple positions, however in this study only the straight position was used. The adapter was attached to an electro-magnetic propelled ejector (specifications, see Appendix Table A.I.) and held in place by a vacuum pump. The forearm was propelled along the direction of the ejector. Typical sequences of impact are displayed in Figures 2 and 3, for impacts in flexion and extension hand orientation, respectively.

Fig. 2. Example of trajectory with hand in initial 30^{0} flexion orientation. Left: the fingers' first contact, mid: bottoming-out of the fingers, right: flexion with a bending moment of the wrist.

Fig. 3. Example of trajectory with hand in initial 35^{0} extension orientation. Left: the fingers' first contact, mid: extension of hand, start of wrist moment, right: forearm bottoming out.

The complete weight of the novel instrumented forearm and adapter in this study is 2.42kg; whereof 2.11kg is the forearm. The weight of the adapter is to compensate for some of the weight of the lack of an upper arm. The design and the instrumentation of the novel instrumented forearm allow for use in a large variety of impact situations, including mounting on a crash test dummy during a full-scale crash test.

Instrument Panel (IP) Test Series; Reconstructing Real World Crashes

A series of impact tests to a vehicle instrument panel (IP) was conducted with the main purpose of providing insight into the novel instrumented forearm's sensitivity in a vehicle-like interior impact situation. Two of the detailed accident reconstruction cases from [15], served as an inspiration source for the test set-up. The two drivers were reconstructed using a human body model in corresponding finite element vehicle models. The first case (Number 6 in [15]) involves a 67-year-old male driver exposed to a 100% overlap frontal impact with a deltaV of 77km/h. The second case (Number 10 in [15]) involves a 42-year-old male driver exposed to a 34% left overlap frontal oblique impact with a deltaV of 64km/h. Both drivers sustained distal radius fractures, in the wrists of the right and left hand, respectively. In the second case, evidence from the hand's impact was documented, see Figure 4a. Figure 4c displays the same area after the impactor test.

The reconstructions were performed with the hands initially placed in a standardized driving position; "ten-to-two o'clock". The velocities were measured in the wrist of the human body model at time of impact (Figure 4b). The point of impact and the hand and forearm trajectories were studied as input for the choice of set-up in the impactor tests. Some few variations in arm orientations and impact points were chosen to mimic the configurations seen, taking into consideration the limitations by the impactor test set-up enabling pure axial launch only, in addition to targeting some variations in impact surface.

Fig. 4a. Photo of the left hand's impact area from the real world crashed car.

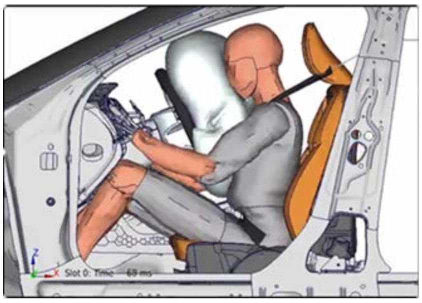
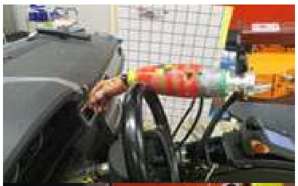


Fig. 4b. The human body model at time of hand impact; from the reconstruction of the second case.

Fig. 4c. Photo of the IP panel after test 2:1.

In total five tests were performed in the IP test series, see Table I. Three tests were performed with right hand impacts at an impact speed of 9.9m/s, related to the first case, and two with left hand impacts at impact speed 12.4m/s, related to the second case.

TABLE I
TEST MATRIX OF THE IP TEST SERIES, SPECIFYING; IMPACT VELOCITY, IMPACT POINT, HAND ORIENTATION AND THE ANGLES OF THE FOREARM ORIENTATION.
*ARM ORIENTATION X IS ACCORDING TO THE COORDINATE SYSTEM IN FIGURE 1B AND Y, Z ACCORDING TO FIGURE 1A.

Test No.	Impact velocity (m/s)	Impact point	Hand orientation	Arm orientation*	Photo
1:1	9.9	IP upper right edge, above the air vent	Flexion (30°)	X = 41° Y = 10° Z = 15°	
1:2	9.9	Air vent on the right side	Flexion (30°)	X = 41° Y = 10° Z = 15°	
1:3	9.9	IP upper right edge	Flexion (30°)	X = 41° Y = 10° Z = 5°	
2:1	12.4	Lower part of the air vent on the left side	Flexion (25°)	X = 75° Y = 10° Z = 5°	
2:2	12.4	Upper part of the air vent on the left side	Flexion (25°)	X = 75° Y = 10° Z = 5°	

Generic Test Series; Parametric Study

With the purpose of evaluating the influence of a variety of factors and repeatability, a parametric study was performed. In total 91 tests were done in 31 configurations, varying; stiffness, friction, impact angle and hand orientation. Different materials were used to create three levels of stiffness and friction; high, medium and low (Table II). The materials were chosen to achieve substantial differences in surface characteristics. Four different impact angles were used (Figure 5). The hand orientation prior to impact were extension (35°) or flexion (30°), see Figure 6a and 6b. The test matrix, with the combination of variables, is presented in Table III.

TABLE II
STIFFNESS AND FRICTION FACTORS AND CORRESPONDING TYPE OF MATERIAL

Stiffness	Material	Friction	Material
High	Hard wood	High	IP-skin
Medium	25mm thick high-density plastic foam	Medium	Smooth leather
Low	25mm thick high-density plastic foam and 50 mm soft foam material	Low	Course leather with lubrication

a) 0^{o} b) 25^{o} c) -25^{o} d) 30^{o}

Fig. 5. Impact angle variables seen in XZ-plane as in Figure 1.a.

Fig. 6a. Hand position in extension.

Fig. 6b. Hand position in flexion.

All tests were performed with an impact speed of 8.4m/s, based on an analysis of hand to IP impact velocity from 29 human body model simulations in a vehicle interior, as presented in [16].

As shown in Table III, the 31 configurations represented five different load cases of combinations of extension/flexion and impact angle. Hand orientation in extension was run in the impact angles 0^{o}, $+25^{o}$ and $+30^{o}$, and flexion in +/- 25^{o} (angle definitions see Figure 5). In total 21 configurations were performed in extension; including all variations of stiffness and friction in the angled impacts and only stiffness variations for impact angle 0^{o}. All, except two, of the configurations were tested in three repetitions.

TABLE III
TEST MATRIX FOR THE PARAMETRIC STUDY IN THE GENERIC TEST SERIES, SPECIFYING VARIABLES FOR; STIFFNESS, FRICTION, IMPACT ANGLE AND HAND ORIENTATION, IN ADDITION TO NUMBER OF REPETITIONS.

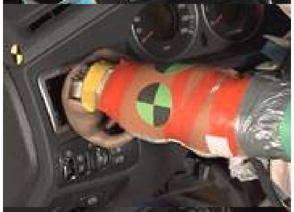
Configuration	Stiffness	Friction	Impact angle (^{o})	Hand orientation	Repetitions
1	High	Medium	0	Extension (35^o)	3
2	Medium	Medium	0	Extension (35^o)	3
3	Low	Medium	0	Extension (35^o)	3
4	Low	Medium	25	Extension (35^o)	3
5	Medium	High	25	Extension (35^o)	3
6	Medium	Medium	25	Extension (35^o)	3
7	Medium	Low	25	Extension (35^o)	3
8	Low	High	25	Extension (35^o)	3
9	Low	Low	25	Extension (35^o)	3
10	High	Low	25	Extension (35^o)	3
11	High	Medium	25	Extension (35^o)	3
12	High	High	25	Extension (35^o)	3
13	High	High	-25	Flexion (30^o)	3
14	High	Medium	-25	Flexion (30^o)	2
15	High	Low	-25	Flexion (30^o)	3
16	Low	Medium	-25	Flexion (30^o)	3
17	Low	High	-25	Flexion (30^o)	3
18	Low	Low	-25	Flexion (30^o)	2
19	Medium	Medium	30	Extension (35^o)	3
20	Medium	Low	30	Extension (35^o)	3
21	Medium	High	30	Extension (35^o)	3
22	Low	High	30	Extension (35^o)	3
23	Low	Medium	30	Extension (35^o)	3
24	Low	Low	30	Extension (35^o)	3
25	High	High	30	Extension (35^o)	3
26	High	Medium	30	Extension (35^o)	3
27	High	Low	30	Extension (35^o)	3
28	Low	Medium	25	Flexion (30^o)	3
29	Medium	Low	25	Flexion (30^o)	3
30	Medium	Medium	25	Flexion (30^o)	3
31	Medium	High	25	Flexion (30^o)	3

III. RESULTS

Instrument Panel (IP) Test Series; Reconstructing Real World Crashes

The axial force in the forearm (Fz) and the wrist moment (Mx) from the five tests in the IP test series are presented in Table IV, together with the observations and photos from time of impacts. In tests 1:1-1:3, Fz ranged between 0.8 – 2.3kN and Mx between 58 – 191Nm. For the two tests simulating the second real-world crash, 2:1 and 2:2, the moments were 102 and 210Nm, while Fz was 1.3kN in both tests. The observations of sliding and structural damage to the IP contribute to relative reductions in Fz. Irregularities in the structure contribute to relatively higher Mx responses.

TABLE IV
THE FOREARM PEAK AXIAL FORCE (FZ), PEAK WRIST MOMENT (MX), OBSERVATIONS AND PHOTOS AT TIME OF IMPACT, FOR THE TESTS IN THE IP TEST SERIES

Test No.	Forearm Fz (kN)	Wrist moment (Nm)	Observations	
1:1	0.8	58	The hand slides on the edge, unloading the forearm	
1:2	1.0	191	Minor crack on the air vent splines. Hand gets stuck on IP-edge	
1:3	2.3	63	Perpendicular impact to instrument panel edge	
2:1	1.3	210	Cracks of air vent splines, followed by sliding up towards IP edge	
2:2	1.3	102	Minor damage on air vent and deco-list. More rebound compared to test 2:1.	

Generic Test Series; Parametric Study

The peak forearm axial force Fz and peak wrist moment Mx for all the 91 tests are presented in Appendix Table A.II., in addition to the average values and standard deviation for each configuration. The relative standard deviation, measured as the standard deviation per average value, ranged 1-11% and 1-37%, for Fz and Mx, respectively. When excluding the six most deviating configurations, the relative standard deviation ranged between 2-8% for Fz and 2-7% for Mx. The Mx-outliers were mainly in configurations with soft stiffness, i.e., configurations 16, 17, 18 and 28. For the substantial deviation in configuration 28, no obvious reason could be identified.

Higher stiffness generally resulted in higher loads. The influence of stiffness was seen for all combinations of hand orientation and impact angles, especially for Fz (Figures 7-11). While for Mx, the results were shown to both increase and decrease with changed stiffness. For the perpendicular impacts (Figure 7), there was no clear increasing trend. In the non-perpendicular impacts, Mx responses were also influenced by the impact angle and friction, in addition to stiffness.

The combination of impact angle and friction influenced the responses. Generally, the hand tended to slide on the surface with increasing angle and decreasing friction. This was reflected in all the load cases (Figures 7-11), with an increased Fz with increased friction. When comparing the difference in responses for 25° and 30° impact angles in combination with extension hand orientation (Figures 8 and 10), it was seen that higher angle decreased Fz in the configurations with high stiffness. At an impact angle of 30°, the hand slid off in all tests to different extents, whereby it did not compress the impact surface as much as compared to smaller impact angles.

The impact angle influenced the forearm responses; both Fz and Mx. Comparing the tests with 25^o and -25^o impact angles with hand orientation in flexion (Figures 9 and 11), a consistent higher response could be seen for the -25^o configurations. Analysing the kinematics, it was obvious that the slide-off effect was more pronounced in 25^o than -25^o, having impact on the forces acting through the forearm. Comparing hand in extension and flexion, with the same impact angle 25^o (Figures 8 and 11), consistent lower Fz and Mx were seen with the hand in flexion.

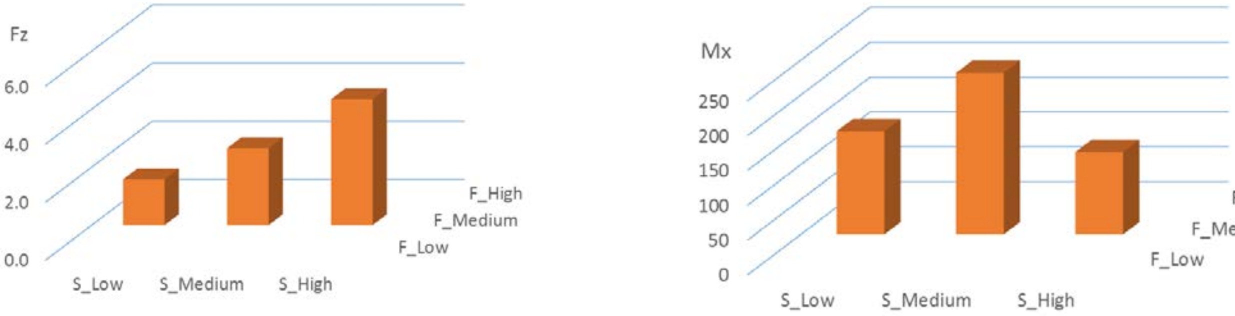


Fig. 7. Impact configurations 1-3; extension and impact angle 0°; left: forearm axial force Fz(N), right: wrist moment Mx(Nm). F=Friction, S=Stiffness.

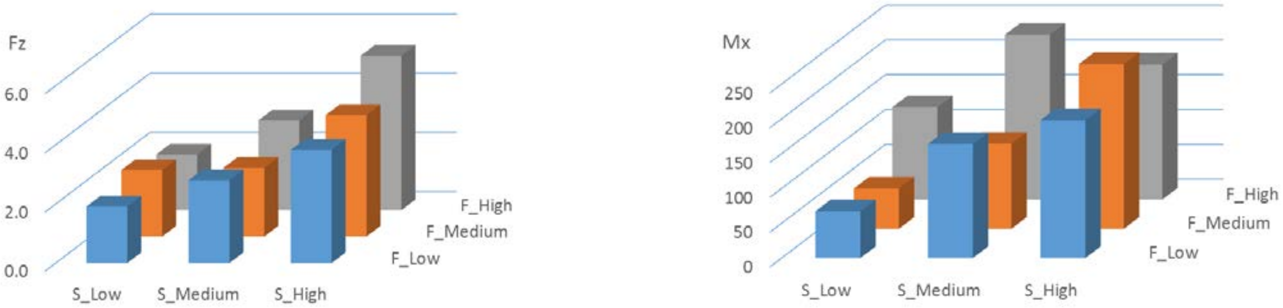


Fig. 8. Impact configurations 4-12; extension and impact angle +25°; left: forearm axial force Fz(N), right: wrist moment Mx(Nm). F=Friction, S=Stiffness.

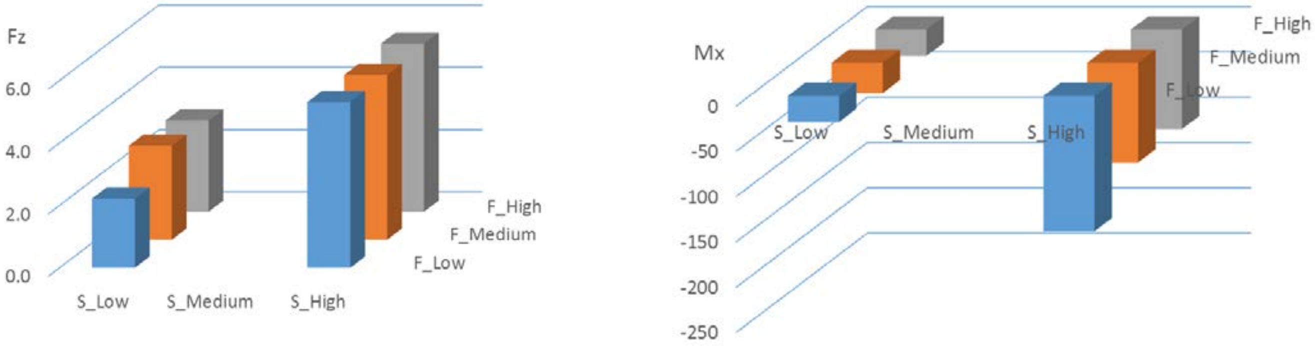


Fig. 9. Impact configurations 13-18; flexion and impact angle -25°; left: forearm axial force Fz(N), right: wrist moment Mx(Nm). F=Friction, S=Stiffness.

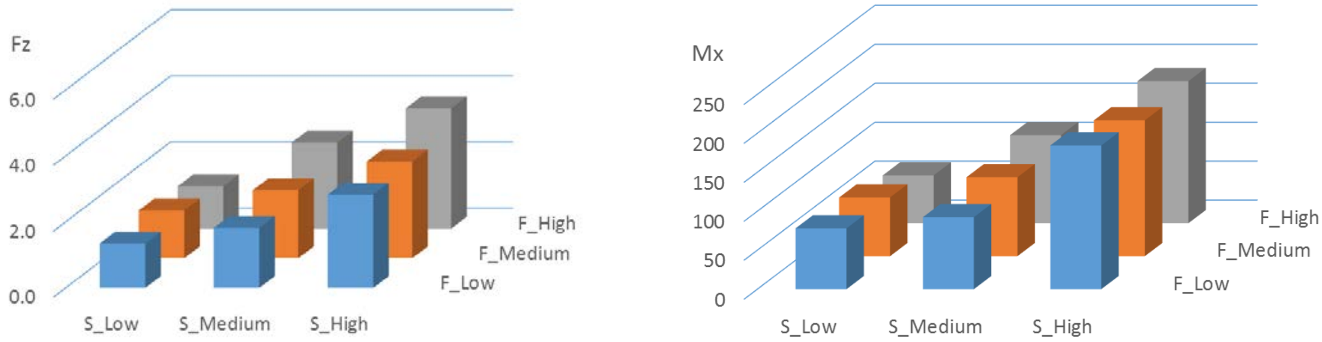


Fig. 10. Impact configurations 19-27; extension and impact angle 30°; left: forearm axial force Fz(N), right: wrist moment Mx(Nm). F=Friction, S=Stiffness.

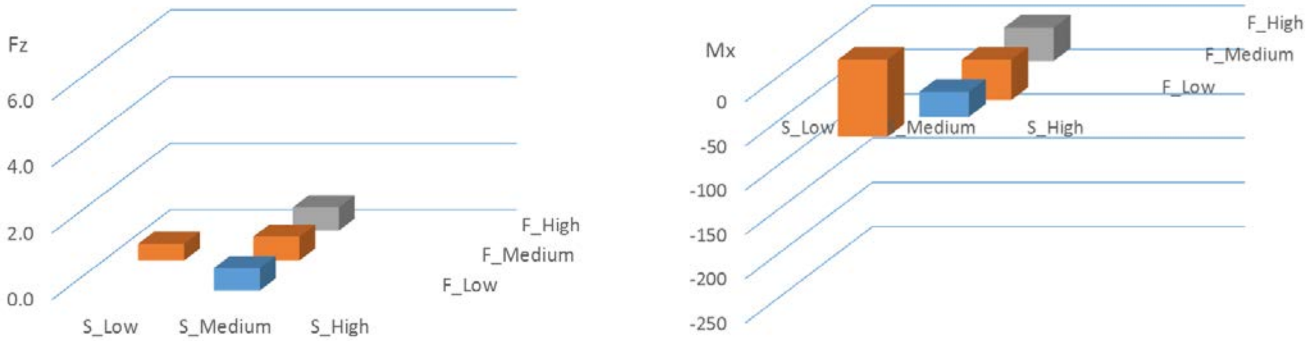


Fig. 11. Impact configurations 28-31; flexion and impact angle +25°; left: forearm axial force Fz(N), right: wrist moment Mx(Nm). F=Friction, S=Stiffness.

IV. DISCUSSIONS

The novel hand and forearm impact test method was designed to help evaluate injuries to the wrist and distal part of the ulnar and radius (forearm). The IP impact test series provided insights into its capabilities to interact with the instrument panel, a common impact area in real world crashes (exemplified in Figure 4). The responses was found to be sensible to the irregular surface of the impacting structure, as well as to cracks and other structural damage lowering the loads through the forearm. The variations in results when slightly varying the test set-up supported the need of an easy-to-use component test method for vehicle development. The IP test series provided support for the capability of the method to be used when evaluating hand impacts towards vehicle interior in frontal impacts. No effort was made to correlate the loadings from the tests and the injuries in the real-world cases. There are several reasons for this, such as lack of injury details from the real-world cases, unconfirmed assumptions in the reconstructions and the lack of correlation studies between published human tolerance data and dummy arms.

The parametric study using the generic test board provided some insight into the influence of a selection of factors to potential mitigation of injuries to the forearm. However, it also showed the complex interplay between the factors. Stiffness was found the single most influencing surface characteristics factor; increased Fz with increased stiffness. Friction influenced as well, although more in combination with other factors such as impact angle and stiffness. At certain combinations of friction and stiffness, the hand slid-off or bottomed-out for which friction seemed to be most influential on the reduction of Fz and Mx.

At comparable impact angle, consistent lower Fz and Mx could be seen with the hand in flexion at time of impact, as compared to extension. Comparing kinematics, it was obvious that the hand's angle towards the surface differed, which was a result of a different range of motion in extension versus flexion. Additionally, the rubber flesh being thicker on the palm side was likely influencing by its load distributing and therefore increasing the friction.

The hand and forearm impact test method was shown to be repeatable, reporting relative standard deviations within 2-8% for a majority of the configurations, for both Fz and Mx. Generally, the repeatability was higher for hard impacts and lower for soft impacts. During the test series it was found that the tightening torque of the wrist bolt played an important role. In some tests, but not all, the tightening torque loosened early in the test or was further tightened during loading. This may be one explanation to why the moment had a larger deviation in impacts against softer material. When in flexion, the hand tended to increase the tightening torque, while the opposite was seen in extension. Preliminary investigations using a solution with a spring washer controlling the tightening torque was shown to improve the result with a reduced relative standard deviation.

Overall, the method was sensible and capable of capturing design changes and discriminating between different configurations in the generic test series as well as the IP test series, shown by the variations in results. The flexibility in the method allowed efficient test series with 15-30 minutes between tests. Improvement areas mainly include design and specifications of the hand and wrist. For the proposed test method, the range of motion in the wrist for extension and flexion characteristics was important. The current design is based on the HIII-arm with its range of motion and damping characteristics and could be improved to better represent human characteristics. Additionally, the shape and movements of the fingers likely influence the interaction with the test object. A standardized and representative finger design would be even more important if hand bone injuries would be targeted. The existing wrist joint does not allow ulnar and radial abduction. Inclusion of this movement may be needed for certain impact configurations and could enhance biofidelity further.

The ejector used in the present study was mounted on the robot arm allowing propelling along the longitudinal axis only. In addition, the forearm was not supported by the body mass, although some compensation for the upper arm weight was included. These aspects are shared with most component tests, such as head impactor test methods. Nevertheless, it limits the possibility to completely capture the whole-body kinematics. To enable other initial rotations of the forearm than in line with the ejector, a different adapter design may be used. The novel instrumented forearm is suitable for mounting on the midsize male HIII and THOR crash test dummies and is thereby capable of taking part in full scale or sled crash tests, in addition to static tests to evaluate airbag interactions and similar. In such situations the novel forearms capability to measure 6DOF forces in the forearm and accelerations in the wrist plays a more important role than in a free moving situation. When used on a crash test dummy, the limitations of the dummy design will influence the kinematics and responses of the novel instrumented forearm. It is encouraged to then improve the dummy elbow and shoulder joints to better reflect those of humans.

The real-world data shows that injuries to upper extremities are important, both from the perspective of frequency in modern vehicles and with respect to long-term consequences. As [2] pointed out, the challenge in mitigating upper extremity injuries lies with the potential chaotic nature of their causation; including a wide range of potential contact points and loading mechanisms that may contribute. This was emphasized by [3], combining statistical data analysis and in-depth studies, also pointing out that the injury mechanisms recreated in the current study being frequent in real world crashes. More in-depth studies are encouraged to provide further insights into impact mechanisms and influencing factors. Additionally, more studies on establishing injury criteria and performance characteristics for test tools, in addition to creating injury risk curves are needed. Although several studies on forearm injury tolerance values have been performed [8-11], there seems to be a lack of biomechanical data on wrist injury occurrence in the axial hand-to-vehicle interior loading, such as recreated in this study. Acknowledging the lack of data to quantify risk of injury when using the component method, it would nevertheless be reasonable to anticipate that increased forces and moments could correspond to increased risk of injury.

One main challenge of hand and forearm injuries in real-world crashes is the spread of possible combinations of impact area and forearm trajectories, due to the large variety of occupant characteristics, sitting postures and crash configurations. To address this spread, a component test method, as presented in this study, can provide support for vehicle safety development and evaluation. Obviously, substantial efforts are needed to adopt a method of this kind for standardized testing, if ever relevant. The present study could serve as a starting point for discussions on whether a component method like this could be one way forward addressing the wide-spread and increasingly important area of upper extremity injuries, also learning from the principles of head impact component test methods. Meanwhile, it can possibly help to guide the design of interior structures towards more impact friendly.

V. CONCLUSIONS

The hand and forearm impact test method, comprising a novel instrumented forearm, was shown repeatable and capable to effectively handling a large variety of hand impacts, resembling potential hand and forearm injuries caused in real-world crashes. As demonstrated by the parametric study, the method could discriminate and evaluate the effect of different impact configurations on hand and forearm loadings recreating hand impacts towards the vehicle interior in frontal impacts. As an example, it was shown that stiffness had the largest influence on forearm axial force and wrist moment, and a combined effect for friction and impact angle was seen. Impacts with the hand in flexion position resulted in lower forearm forces and wrist moments compared to when in extension. This method has potential to provide input to vehicle design, targeting the relatively increasing share of upper extremity injuries in frontal impacts, although at this stage accompanied with uncertainty in the assumed relationship of the measured parameters and risk of injury.

VI. ACKNOWLEDGEMENT

The project was carried out at SAFER – Vehicle and Traffic Safety Centre at Chalmers, Sweden, and financed by Strategic Vehicle Research and Innovation (FFI), by VINNOVA, the Swedish Transport Administration, Swedish Energy Agency and industrial partners. The authors would like to thank our peer researchers within the project, especially: Bengt Pipkorn and Victor Alvarez from Autoliv Research, Svein Kleiven and Madelen Fahlsten from KTH and Helena Stigson from Folksam. Acknowledgments to Tobias Johansson and Jacob Svensson at Volvo Cars for valuable input on wrist design and data analysis.

VII. REFERENCES

[1] Klinich, K.D., Bowman, P., Flannagan, C.A. and Rupp, J.D. (2016) University of Michigan Transportation Research Institute (UMTRI). *Injury patterns in motor-vehicle crashes in the United States: 1998-2014*, Ann Arbor, MI, USA

[2] Forman, J., Poplin, G.S., Shaw, C.G., McMurry, T.L., Schmidt, K., Ash, J. and Sunnevang, C. (2019) Automobile injury trends in the contemporary fleet: Belted occupants in frontal collisions. *Traffic Injury Prevention*, **20**(6): pp.607-612

[3] Jakobsson, L. and Lindman, M. (2010) Upper extremity fractures in car accidents. *Proceedings of IRCOBI Conference*, 2010, Hannover, Germany

[4] Stigson, H., Gustafsson, M., Sunnevång, C., Krafft, M. and Kullgren, A. (2015) Differences in long-term medical consequences Depending on impact direction involving passenger cars. *Traffic Injury Prevention,* **16**(Suppl 1): pp.133-139

[5] Wraighte, P.J., Manning, G., Wallace, W.A. and Hynd, D. (2007) Upper extremity injuries in road traffic accidents. *ESV Conference,* Paper No. 07-0239, 2007, Lyon, France.

[6] Conroy, C., Schwartz, A., Hoyt, D., Eastman, A.B., Pacyna, S., Holbrook, T., Vaughan, T., Sise, M., Kennedy, F., Velky, T. and Erwin, S. (2007) Upper extremity fracture patterns following motor vehicle crashes differ for drivers and passengers. *Injury*, **38**(3): pp.350-357.

[7] Otte, D. (1998) Biomechanics of upper limb injuries of belted car drivers and assessment of avoidance. *Proceedings of IRCOBI Conference*, 1998, Gothenburg, Sweden.

[8] Forman, J., Perry, B., Alai, A., Frelich, A., Salzar, R. and Walilko, T. (2014) Injury tolerance of the wrist and distal forearm to impact loading onto outstretched hands. *The Journal of Trauma Acute Care Surgery,* **77**(3 Suppl 2): pp.176-183

[9] Duma, S., Boggess, B., Crandall, J. and MacMahon, C. (2003) Injury risk function for the small female wrist in axial loading. *Accident Analysis & Prevention*, **35**(6): pp.869-875.

[10] Begeman, P.C., Pratima, K. and Prasad, P. (1999) Bending strength of the human cadaveric forearm due to lateral loads. *Proceedings of 43rd Stapp Car Crash Conference,* SAE-99SC24, 1999, San Diego, California, USA.

[11] Saul, R., Backaitis, S., Beebe, M. and Ore, L. (1996) Hybrid III dummy instrumentation and assessment of forearm injuries during air bag deployment. *Proceedings of 40rd Stapp Car Crash Conference,* SAE- 962417, 1996, Albuquerque, New Mexico, USA.

[12] Kuppa, S., Olson, M., Yeiser, C., Taylor, L., Morgan, R. and Eppinger, R. (1997) RAID - An investigative tool to study air bag/upper extremity interactions. *SAE Technical Paper 970399*, 1997, Detroit, Michigan, USA.

[13] SAE International. (2017) SAE International, *SAE Instrumented forearm User's Manual*, USA.

[14]Lund, A.K. (2003) The Side Airbag Out-of-Position Injury Technical Working Group (A joint project of Alliance, AIAM, AORC, and IIHS). *Recommended procedures for evaluating occupant injury risk from deploying side airbags – First Revision*. USA.

[15]Pipkorn, B., Iraeus, J., Björklund, M., Bunketorp, O. and Jakobsson, L. (2019) Multi-scale validation of a rib fracture prediction method for human body models. *Proceedings of IRCOBI Conference,* IRC-19-34, 2019, Florence, Italy.

[16] Harryson, M. and Cyrén, O. (2016) Biomechanical Engineering Human, Halmstad University. *Development of methods and guidelines for upper extremity injury in car accidents*. Halmstad, Sweden.

VIII. APPENDIX

Table A.I.
Instrumentation specifications

Type of equipment	Manufacturer and model	Specification	Signal filtering
Amplifier and logger	MiniDau	16 bits, 20kHz sampling frequency	
Force transducer	Denton 2432	6 DOF transducer	CFC180
Accelerometer	Endevco 7264B-500T	±500g	CFC600
Moment transducer	Volvo Cars	Strain gauge bridge	
Ejector	Frontone E-liner HEAD	Electro-magnetic propulsion	

Table A.II.
Forearm axial force (Fz) and wrist moment (Mx); each repetition and average values, including standard deviation (std. dev) and relative standard deviation (rel. std. dev) in the generic test series.

	Repetition 1		Repetition 2		Repetition 3		Average forearm axial force			Average wrist moment		
Config.	Fz (kN)	Mx (Nm)	Fz (kN)	Mx (Nm)	Fz (kN)	Mx (Nm)	Fz (kN)	std. dev	rel. std. dev	Mx (Nm)	std. dev	rel. std. dev
1	3.9	93	4.5	125	4.6	137	4.3	0.31	7%	118	18.6	16%
2	2.7	237	2.6	228	2.6	230	2.7	0.03	1%	232	3.9	2%
3	1.5	142	1.6	150	1.6	152	1.6	0.06	4%	148	4.3	3%
4	2.4	61	2.2	55	2.2	58	2.3	0.07	3%	58	2.5	4%
5	3.1	136	3.1	138	3.0	131	3.0	0.06	2%	135	2.9	2%
6	2.2	118	2.3	122	2.4	126	2.3	0.1	4%	122	3.3	3%
7	2.7	174	2.8	153	3.0	164	2.8	0.12	4%	164	8.6	5%
8	1.9	53	2.1	57	2.1	63	2.0	0.09	4%	58	4.1	7%
9	2.0	66	2.0	67	1.7	68	1.9	0.16	8%	67	0.8	1%
10	4.2	198	3.7	195	3.6	201	3.8	0.27	7%	198	2.5	1%
11	4.5	183	4.4	200	4.5	201	4.5	0.04	1%	195	8.3	4%
12	5.2	188	5.3	200	5.2	194	5.2	0.08	1%	194	4.9	3%
13	4.6	-92	5.7	-118	5.9	-120	5.4	0.6	11%	-110	12.8	-12%
14	5.2	-106	5.4	-114	No test	No test	5.3	0.11	2%	-110	4.0	-4%
15	5.2	-144	5.3	-151	5.5	-154	5.3	0.11	2%	-150	4.2	-3%
16	3.3	-43	2.6	-28	3.1	-30	3.0	0.29	10%	-34	6.7	-20%
17	2.5	-23	3.1	-32	3.2	-32	2.9	0.31	11%	-29	4.2	-15%
18	2.0	-24	2.4	-33	No test	No test	2.2	0.22	10%	-29	4.5	-16%
19	2.0	91	1.8	95	1.7	91	1.8	0.1	6%	92	1.9	2%
20	2.1	108	1.9	95	2.1	101	2.1	0.08	4%	101	5.3	5%
21	2.6	112	2.6	111	2.6	116	2.6	0.02	1%	113	2.2	2%
22	1.4	82	1.4	82	1.2	70	1.4	0.1	8%	78	5.7	7%
23	1.4	72	1.4	75	1.5	79	1.5	0.05	4%	75	2.9	4%
24	1.4	62	1.4	64	1.1	58	1.3	0.16	12%	61	2.5	4%
25	2.7	178	2.7	179	3.0	196	2.8	0.14	5%	184	8.3	4%
26	2.9	170	3.12	186	2.8	167	2.9	0.13	5%	174	8.3	5%
27	3.6	185	3.83	193	3.5	169	3.6	0.14	4%	182	10.0	5%
28	0.5	-127	0.52	-85	0.5	-49	0.5	0.02	4%	-87	31.9	-37%
29	0.7	-26	0.63	-30	0.7	-29	0.7	0.03	5%	-28	1.7	-6%
30	0.7	-48	0.72	-45	0.7	-44	0.7	0.02	3%	-46	1.7	-4%
31	0.7	-40	0.71	-36	0.7	-37	0.7	0.03	4%	-38	1.7	-5%