

Predictive Technique for Seat Belt Submarining Injury by Triaxial Iliac Load Cell

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ABSTRACT

Submarining is one of the confirmation items in the frontal crash test, and if signs of submarining can be grasped with a single crash test, it will contribute to increasing the development efficiency of crash safety performance. This study created a prototype of a triaxial iliac load cell for an anthropomorphic test device and devised a method for calculating the position change of the acting point of the seat belt restraint load applied to the front end of the ilium, as a sign of submarining. In frontal crash sled tests that intentionally generated submarining, the acting point of the load applied to the ilium was observed to move upward from the front end of the ilium in the time zone before submarining occurred. As a result, this enabled to detect the signs prior to the occurrence of submarining.

1. Introduction

In 1992 during a period known as the “second traffic war” in Japan, there were a total of 11,452 traffic accident fatalities, of which 4,783 were vehicle occupants⁽¹⁾. Since then, however, traffic accident fatalities have trended downward^{(2), (3)}, with a total of 3,215 traffic fatalities in 2019, of which 1,083 were vehicle occupants⁽³⁾. Especially for vehicle occupants, the rate of decline is remarkable, at 77%.

This can be attributed to various factors, such as stiffer penalties for driving under the influence of alcohol, development of traffic infrastructure, popularization of safety devices such as airbags and child seats, and body frame structures with enhanced safety performance⁽²⁾. In addition, higher seat belt usage rates due to mandatory seat belt usage^{(2), (4)} can also be considered as a contributing factor.

However, there are also scattered reports of trauma in which the seat belts that should protect occupants are considered as the source of injury⁽⁵⁾. These injuries are so-called “seat belt injuries⁽⁶⁾,” and occur mainly in the thoracoabdominal region⁽⁷⁾.

Furthermore, comparison of vehicle occupant fatality rates from 2018 traffic statistics⁽⁸⁾ by main injury site excluding factors such as overall injury, asphyxiation,

and drowning reveals that abdominal injuries have the highest fatal and serious injury rates, as shown in Fig. 1. For this reason, research and study continue related to the occurrence of abdominal injury due to load input from a seat belt, with the aim of further reducing traffic accident fatalities and injuries^{(9), (10)}.

Among the phenomena that are thought to result in seat belt injury, submarining refers to the phenomenon where the lap belt that restrains the pelvic region of the

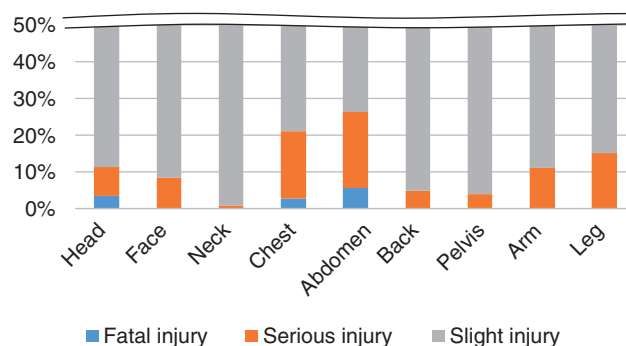


Fig. 1 Percentage of fatal, serious, and slight injuries of vehicle occupants by main injury site in Japan in 2018

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occupant moves from the intended restraint position of the recess below the anterior superior iliac spine (ASIS) to above the iliac crest, deviating from the ilium and directly compressing the occupant's abdomen, as shown in Fig. 2⁽¹¹⁾.

In the frontal crash test, an anthropomorphic test device (ATD) is used to confirm the absence of submarining. To perform this confirmation, the ATD's pelvic region has a structure that simulates the shape of the human body not only in the shape of the outer surface, but also the ilium inside. As an example of this structure, Fig. 3 shows the structure of the pelvic region of the Hybrid III 5th percentile female (H-III 5F) ATD⁽¹²⁾, which is the ATD for a small female physique. The illustration uses a finite element model made by Humanetics Innovative Solutions, Inc.⁽¹³⁾

In addition, the occurrence of submarining is detected using the time histories of iliac loads measured by the load cells built into the ATD's ilium. A total of two load cells are built into the left and right sides near the ASIS of the ilium, as shown in Fig. 3(a). During the period when the lap belt restrains the front of the ATD's ilium, a corresponding reaction force is generated as the load F_x and the moment M_y shown in Fig. 3(b). However, when submarining occurs, the lap belt no longer restrains the front of the ilium, and thus the magnitudes of F_x and M_y decrease sharply. This is used to detect the occurrence of submarining. A more detailed detection method is defined in Technical Bulletin TB-021⁽¹⁴⁾ of the Euro NCAP (European New Car Assessment Programme).

The occurrence of submarining and the instant of occurrence can be identified from these measured loads and detection method. In cases without submarining, however, it is a challenge to quantitatively detect signs preceding the occurrence, i.e., margins left before

occurrence, as physical quantities. Therefore, repeated crash tests are needed to help ensure with certainty that submarining will not occur. If a method can be devised for quantitatively detecting signs of submarining with a single crash test, it would enable increased development efficiency of crash safety performance.

Serra et al.⁽¹⁵⁾ proposed use of the value obtained by dividing the moment M_y by the load F_x (both measured by a biaxial iliac load cell) as an index for evaluating the risk of submarining occurrence. In this method, however, the calculated value is a physical quantity representing the length dimension, but there is insufficient mechanical explanation of what length it specifically indicates. Serra et al.⁽¹⁵⁾ also applied the created index to six cases of crash test results to confirm whether it matched the submarining occurrence results, but there is no indication whether there was any sign in cases with submarining. This calls for a method capable of quantitatively detecting these signs.

In the relative motion of the pelvic region and the lap belt immediately before submarining occurs, the lap belt moves to above the ASIS as described above. Accordingly, the hypothesis can be considered that the position of the acting point of the load applied by the lap belt to the pelvic region will also be observed to move to above the ASIS.

Existing ATDs are not equipped with a device that directly measures the position of this acting point, and thus a method was devised for alternatively calculating it using the iliac load cell measurements. The horizontal component F_x , vertical component F_z , and moment M_y of the lap belt restraint load received by the ASIS shown in Fig. 4 and described hereafter are needed for this calculation. However, the current iliac load cell is a biaxial load cell that measures the load F_x component and the moment M_y , as shown in Fig. 3(b), and is unable to measure the F_z component.

Therefore, this study prototyped a pair of triaxial iliac load cells that added measurement of the load F_z component to the conventional iliac load cell. In addition, frontal crash sled tests that intentionally generated

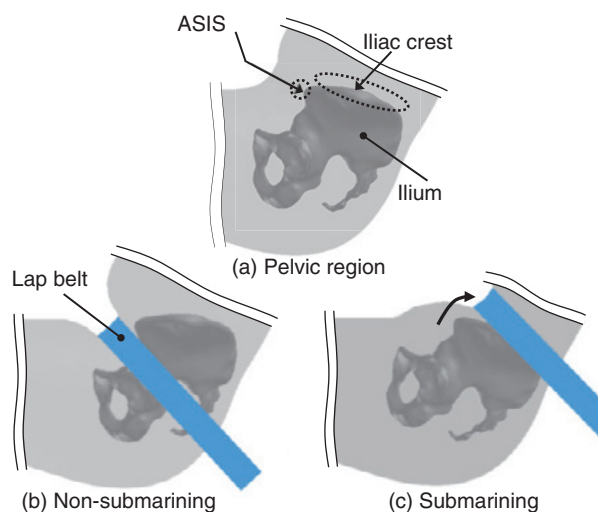


Fig. 2 Non-submarining and submarining

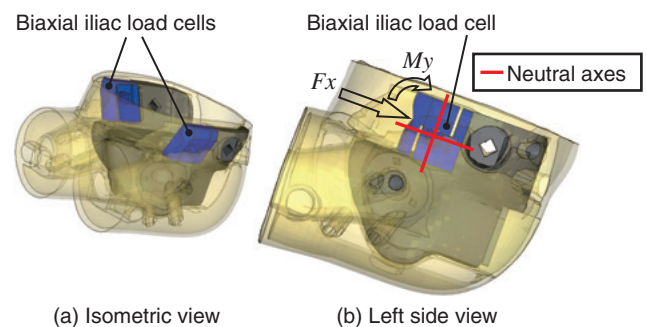


Fig. 3 Pelvis surface and pelvic bone of H-III 5F

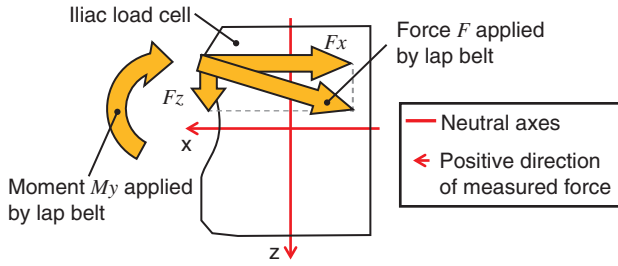


Fig. 4 Force and moment applied to iliac load cell by lap belt

submarining were conducted, the position change of the acting point of the lap belt restraint load applied to the ASIS was calculated, and it was verified whether signs of submarining could be quantitatively evaluated.

2. Principle of Measurement and Verification Method

2.1. Selection of ATD Type

This study selected the H-III 5F ATD, which simulates a small female. The reason is that it has been reported that submarining occurs more easily with the smaller 5F ATD⁽¹⁶⁾, and a smaller physique results in a lower ASIS height relative to the lap belt height, and thus submarining is thought to occur more easily.

2.2. Triaxial Iliac Load Cell

Creation of a prototype triaxial iliac load cell for the H-III 5F ATD was commissioned to Kistler Japan Co., Ltd. Figure 5 shows the front view and left side view of the triaxial iliac load cell for the right side. This load cell can be installed in place of the biaxial iliac load cell equipped as standard in the H-III 5F ATD. The red lines in the figure indicate the load measurement axes, and the

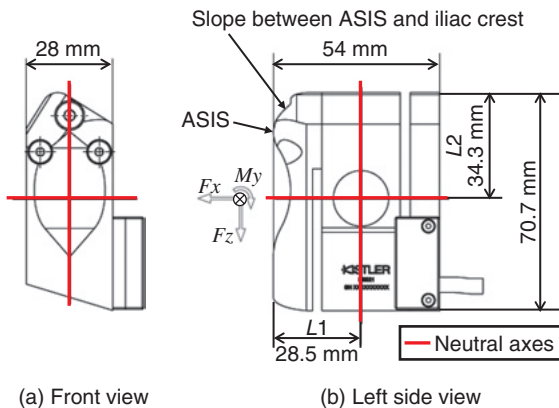


Fig. 5 Triaxial iliac load cell for right side

intersection of the red lines indicates the measurement point of load.

2.3. Principle of Calculating the Acting Point of the Lap Belt Restraint Load

Figure 6 shows a schematic drawing of the vector and the position of the acting point of the lap belt restraint load received by the triaxial iliac load cell. F_x and F_z are respectively the x -axis and z -axis components of the load measured by the load cell, and F is the total force of F_x and F_z . L_x and L_z are respectively the x -axis and z -axis components of the position of the acting point as viewed from the measurement point of load.

The premises when calculating the position of the acting point of the lap belt restraint load were that the load measured by the triaxial iliac load cell is entirely the restraining force of the lap belt, and the impact of inertial force due to motion of the load cell can be ignored. At this time, the components F_x and F_z and the moment M_y of the load measured by the triaxial iliac load cell have the relationship described by Eq. (1).

$$M_y = -L_z F_x + L_x F_z \quad (1)$$

The acting point of the lap belt restraint load is positioned on the front surface of the iliac load cell. When the acting point moves on this surface, there is little change in L_x , and thus it can be thought simply that the acting point is on the imaginary plane shown in Fig. 7. Thus, L_x is fixed to the dimension $L1$ in Fig. 5(b), and L_z , that is to say the height of the acting point of the seat belt restraint load, is obtained using Eq. (2).

$$L_z = \frac{L_x F_z - M_y}{F_x} = \frac{L1 F_z - M_y}{F_x} \quad (2)$$

The lap belt restrains the front surface of the iliac load cell, and thus the obtained acting point height L_z does not exceed the dimension $L2$ in Fig. 5(b). In addition, the lap belt restraint position is thought to move upward in cases with submarining. Therefore, it was assumed that

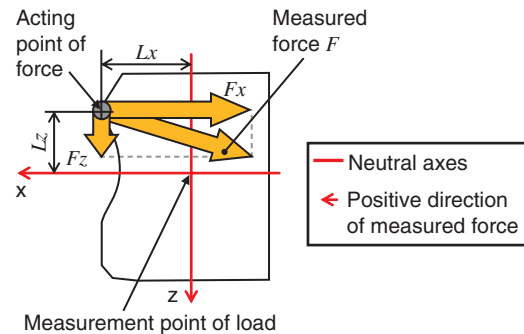


Fig. 6 Vector and acting point of measured force

submarining is more likely to occur as L_z approaches the value of L_2 . This study used this L_z as information for detecting signs of submarining.

2.4. Conditions of Frontal Crash Sled Test for Verification

Sled tests that simulate three cases of frontal crashes, including conditions that intentionally generated submarining, were conducted to verify the method for detecting signs of submarining. Figure 8 shows photos of the sled test condition before conducting the test.

All tests used the same settings that assumed an existing vehicle, and were conducted for the front

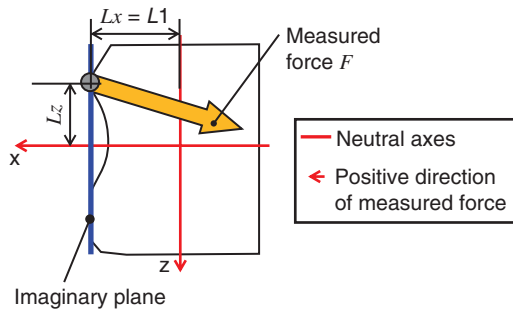


Fig. 7 Imaginary plane of acting point of load

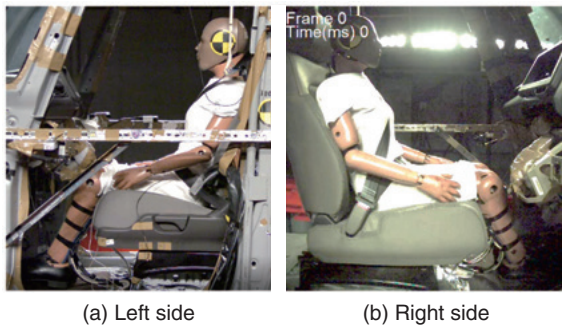


Fig. 8 Photos of sled test

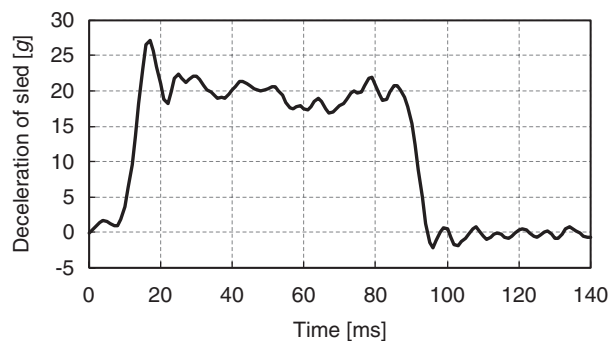


Fig. 9 Deceleration pulse of sled test

passenger seat of a right-hand drive car. An H-III 5F ATD that incorporates the prototype triaxial iliac load cells was used. Figure 9 shows a graph of the vehicle deceleration used in the tests. The initial speed was set to 50 km/h to reduce the damage to the ATD when submarining occurred. The shape of the deceleration pulse was adjusted to enable reproduction by the test apparatus, with deceleration exceeding 20 g by 15 ms, which was the initial stage of the crash, to facilitate the occurrence of submarining. Instrument panel parts that had the potential to contact the ATD's knees were removed to facilitate the occurrence of submarining. A three-point seat belt and a seat belt retractor with a pre-tensioner and a load limiter were used. A SRS (supplemental restraint system) airbag for front passenger, with the same specifications as that of the assumed vehicle, was also used.

In this study, test conditions with different lap belt anchor heights were set for the abovementioned three cases. The reason is that at a higher lap belt anchor height, the center line of the lap belt passes closer to the iliac crest, as shown in Fig. 10, and thus it is thought that submarining in which the lap belt moves to above the iliac crest occurs more easily.

Figure 11 shows the positions of the outside anchors of the lap belt with respect to the hip point (H.P.) of the ATD. An increasing lap belt outside anchor height was

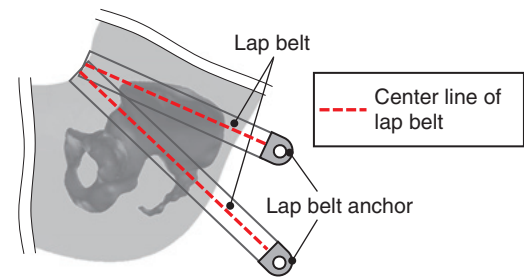


Fig. 10 Difference in lap belt position with respect to height of lap belt anchor

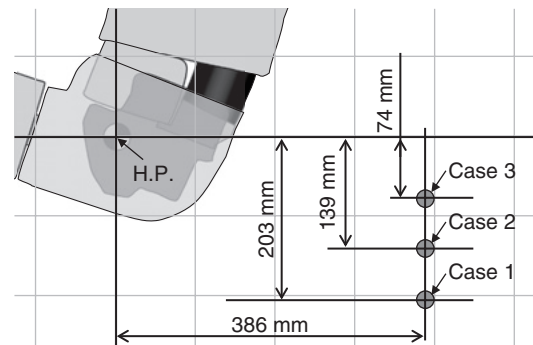


Fig. 11 Positions of lap belt anchor with respect to H.P. of ATD

set in order from Case 1 to Case 3. The intention was for submarining not to occur in Case 1, and to occur in Case 3. Case 2 used an intermediate lap belt outside anchor height with the intention of making submarining more likely to occur compared with Case 1.

2.5. Verification Procedure

In this study, the difference in conditions impacting the occurrence of submarining was the height of the lap belt anchor on the left side of the seated ATD. Therefore, verification focused on the iliac load and moment on the left side.

First, the occurrence of submarining was examined, and the time histories of the measured iliac load and moment in each of the cases were compared.

Next, the height L_z of the acting point of the lap belt restraint load was calculated using Eq. (2), and the relationship with the occurrence of submarining was investigated.

Lastly, in order to simultaneously understand the magnitude, orientation, and position of the acting point of the measured load, the vectors measured by the iliac load cell were drawn on a diagram showing the side outline of the ATD's pelvic bone, and were compared to each other.

3. Verification Results

3.1. Time History of Measured Triaxial Iliac Load and Submarining Occurrence

Figures 12 to 14 show time histories of the left iliac load (F_x , F_z) and moment (M_y) in the three sled test cases. The time history polarity is the same as the polarity drawn in Fig. 5 (b), with F_x pushing backward as negative, the F_z downward load as positive, and M_y rotating the iliac load cell backward as positive. Table 1 lists whether submarining occurred in the three sled tests cases.

Submarining occurred only in Case 3. In addition, the magnitudes of F_x , F_z , and M_y in Case 3 could be seen from Figs. 12 to 14 to decrease sharply after 52 ms.

3.2. Calculation Results of Acting Point of Lap Belt Restraint Load

Figure 15 shows the time history of the height L_z of the acting point of the lap belt restraint load calculated by the left iliac load cell.

In Case 3 with submarining, L_z was 33 mm at 52 ms, which was the timing immediately before submarining occurred. This was roughly the same value as dimension L_2 in Fig. 5(b). The value of L_z fluctuated wildly in the time zone after 52 ms, but Figs. 12 to 14 show that the iliac load in this same time zone decreased to almost zero. Therefore, L_z is considered meaningless in the time period during which the lap belt does not restrain the ilium.

Table 1 Occurrence of submarining in each test

Test No.	Occurrence of submarining
Case 1	No
Case 2	No
Case 3	Yes

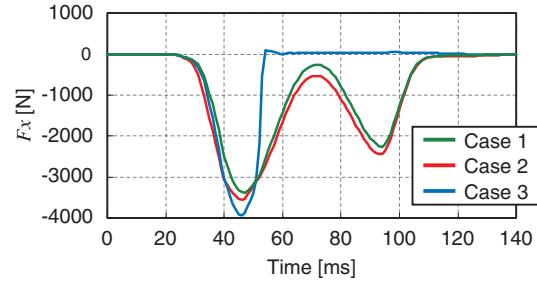


Fig. 12 Time history of longitudinal force F_x of left iliac load cell in each test

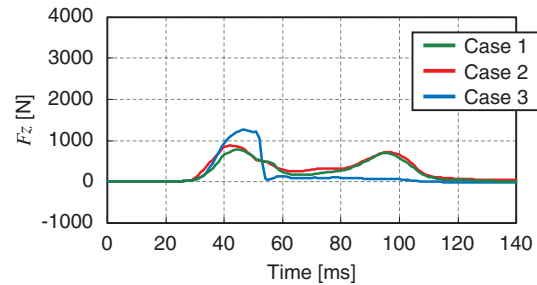


Fig. 13 Time history of vertical force F_z of left iliac load cell in each test

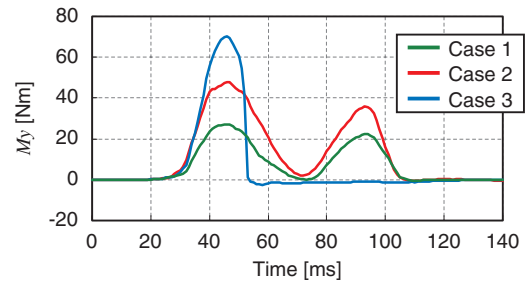


Fig. 14 Time history of moment M_y of left iliac load cell in each test

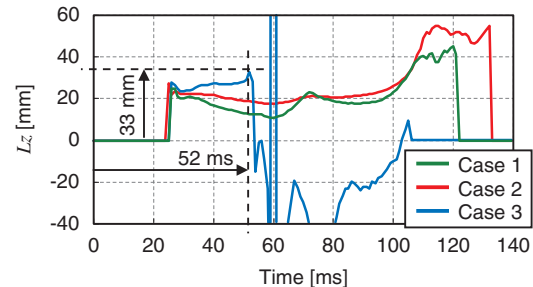


Fig. 15 Time history of height of load acting point L_z of left iliac load cell in each test

The same phenomena are observed when lap belt restraint of the occupant ends after approximately 100 ms in Cases 1 and 2 without submarining.

3.3. Results of Visualization of Lap Belt Restraint Load Vector

Figures 16 to 18 show the lap belt restraint load vectors obtained by the left iliac load cell at 40 ms, 44 ms, 48 ms, 52 ms, and 54 ms in the three sled test cases. The load vectors are drawn overlapping on the left side view of the outline of the ATD's pelvic bone.

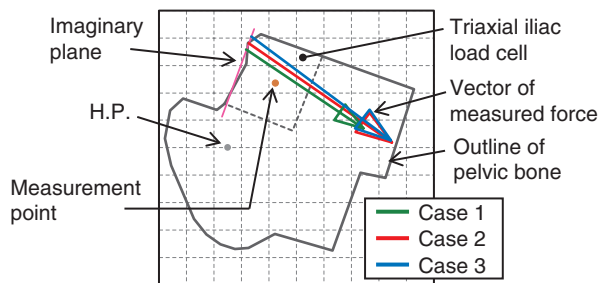


Fig. 16 Vector of restraint force acting on left iliac load cell at 40 ms

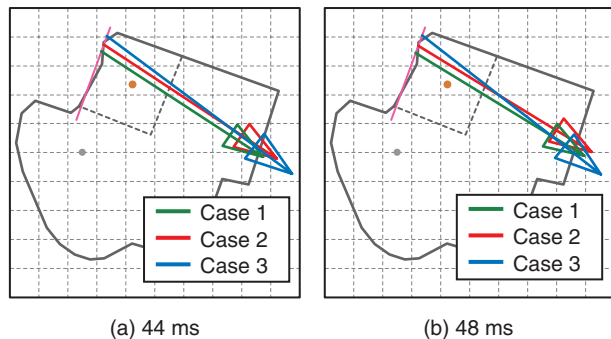


Fig. 17 Vector of restraint force acting on left iliac load cell at 44 and 48 ms

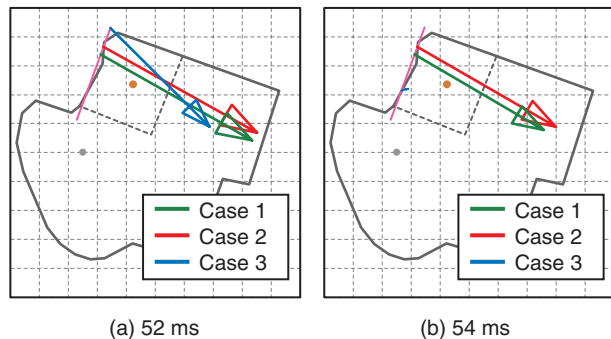


Fig. 18 Vector of restraint force acting on left iliac load cell at 52 and 54 ms

The position of the measurement point of load and the direction of the load vector were adjusted relative to the outline of the pelvic bone to reproduce the actual iliac load cell mounting position and orientation. The drawing scale was 20 mm per grid, the load vectors were drawn at 500 N per grid, and the angle of the pelvic bone outline diagram was fixed to the initial angle prior to crash.

The results for Case 3 with submarining show that the acting point of the lap belt restraint load rises as the time approaches 52 ms, which is immediately before submarining occurs, and the load vector almost disappears when 52 ms is passed. Furthermore, the restraint load vector was observed to become oriented downward during the time period from 48 to 52 ms, near the occurrence of submarining.

The results for Cases 1 and 2 without submarining show that the acting point of the lap belt restraint load did not exceed the upper end of the slope between the ASIS and the iliac crest, and remained around the recess below the ASIS.

These findings demonstrate that signs of submarining can be detected by observing the rise of the acting point of the lap belt restraint load.

4. Discussion

In Case 3 with submarining, the lap belt restraint load vector became oriented downward as described above. This looks contrary to the general thought that the direction of the restraint load of Case 3, because of its highest lap belt anchor location among the three cases as shown in Fig. 11, was expected to become closest to the horizontal line. The reason for this is considered below.

Figures 16 to 18 show that in Case 3 with submarining, the position of the acting point of the lap belt restraint load rose to near the upper end of the iliac load cell in the time period immediately before submarining occurred. Comparison of the height L_z of the acting point at this time with the shape of the load cell shown in Fig. 5 shows that the acting point was positioned on the slope between the ASIS and the iliac crest. Here, focusing on the changes in F_x and F_z from 48 to 52 ms shows there was little change in F_z , whereas F_x decreased. This infers that the restraint load in the F_x direction decreased as the lap belt slipped along the slope between the ASIS and the iliac crest in this time period resulting in the lap belt restraint load vector becoming oriented downward.

In addition to the height L_z of the acting point of the lap belt restraint load, the iliac moment M_y was also given as a candidate for a physical quantity that could be a sign of submarining. The usefulness of each when considered as a sign is examined below.

The time history shown in Fig. 14 shows that the peak value of the iliac moment M_y near 46 ms increased in order from Case 1 to Case 3, and exhibited a large

value especially for Case 3 with submarining. Therefore, it appears at first glance that M_y can be used to measure signs of submarining. In Case 3, however, the peak value of M_y was generated earlier than 52 ms, the timing at which submarining occurred, and the value of M_y at the timing when submarining occurred was close to that of Case 2 without submarining. This means that it is not easy to establish a boundary for the occurrence of submarining with respect to the time history of iliac moment M_y .

In contrast, the height L_z of the acting point of the lap belt restraint load rose to the slope between the ASIS and the iliac crest in Case 3 with submarining, as described above. From this it can be inferred that the lap belt slipped upward along this slope and then off the ilium.

Next, Figs. 16 to 18 show that L_z was positioned in the recess below the ASIS in Cases 1 and 2 without submarining. This infers that submarining did not occur because the lap belt restrained the ilium by getting caught in this recess. In Case 2, L_z is positioned near the ASIS at the upper end of this recess, and if the acting point rises further for some reason such as variance, it is expected that the lap belt will slip upward along the slope between the ASIS and the iliac crest and then off the ilium in the same manner as Case 3. Therefore, the upper limit of L_z at which submarining does not occur is expected to be around the same position as the height of the ASIS.

The above findings demonstrate that the signs of submarining before it occurs could be detected in a more quantitative manner by continuous observation of the height L_z of the acting point of the lap belt restraint load relative to the geometric shape of the ASIS to which the lap belt restraint load is applied over time. Furthermore, it is expected that the boundary for submarining occurrence in L_z can be established by way of contrasting with the ilium shape around the ASIS.

However, as only a limited number of tests were conducted in this study, setting a specific upper limit L_z at which submarining does not occur remains a future issue. Going forward, it is hoped that a number of the tests will be performed under other conditions in order to increase the reliability and repeatability of the method used in this study.

5. Conclusion

This study performed the following with the goal of developing a method for detecting the signs preceding the occurrence of submarining in an ATD.

- (1) A pair of triaxial iliac load cells was prototyped and a method was devised for calculating the height L_z of the acting point of the lap belt restraint load applied to the ASIS for use as information to detect signs of submarining.
- (2) Three cases of frontal crash sled tests were

conducted, including conditions that intentionally generated submarining, the change in L_z was compared with the ASIS shape, and various examinations were performed.

As a result, the following knowledge was obtained.

- (1) In the case with submarining, L_z rose to the slope between the ASIS and the iliac crest in the time period immediately before submarining occurred. In addition, the lap belt was inferred to have slipped off along this slope.
- (2) In the cases without submarining, L_z remained in the recess below the ASIS. In addition, it was inferred that submarining did not occur because the lap belt restrained the ilium by getting caught in this recess.

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