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True compression of pelvic fractures under lateral impact

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Abstract

Purpose To promote the understanding of pelvic fracture mechanism and make more accurate evaluation of maximal deformity at the moment of fracture, kinematic response of pelvis to lateral impact and the difference between peak and final displacement were investigated.

Methods A total of three human cadaver pelves were seated uprightly on a sled test table, explored to horizontal lateral impact by a 22.1-kg impactor at a speed of 5.2, 4.0, and 4.8 m/s. Kinematic data of pelvic osseous interesting points (POIP) were measured by the motion capture system. Trajectories of POIP, duration of impact, and deflection of pelvis were calculated as well as rotational movement of pelvis was evaluated. After impact, autopsy and CT scan were made to validate the motion capture data.

Results The peak deflection of pelvis under lateral impact was 31.9, 30.1, and 18.5%, while final deflection was 19.6, 13.8, and 13.8%. The final deflection was only 61.5, 45.9, and 74.46% of the peak deflection.

Conclusions In clinical practice, pelvic fracture displacement tends to be underestimated. The peak compression can be 1.3–2.2 times of final compression appearing on images in hospital. Clinicians shall give adequate estimation of displacement and related injuries.

Keywords Pelvic fractures · Impact · Mechanism · Displacement · Motion capture

Introduction

The risk of pelvic fractures is high in motor vehicle crash incidence and falling accidents. However, patient's condition is not always consistent with the images in emergency room. There have been reports about catastrophic circulation and blood pressure breakdown with minor displacement pelvic fractures [1]. Despite it is generally accepted that the displacement of pelvic segment is less than what had happened at the moment of incidence, it is still poorly understood the relationship between peak displacement and final displacement. This study herein investigated the pelvic kinematic response to lateral impact by using the motion capture system and sled test table. We hypothesized that compression at the moment of impact is greater than that after impact, also investigated the correlation between them. Hopefully, this study

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will assist pelvic fracture research in understanding the pathomechanics of injuries.

Materials and methods

A total of three male frozen cadaver pelves without gut, from third lumbar vertebra to middle femur, were applied to investigation with exclusion of bony pathology through CT scan. Small incisions were made to explore pelvic osseous interesting point (POIP), facilitate fixing markers at particular positions precisely. Left posterior superior iliac spine (LPSIS), left iliac crest (LIC), left anterior superior iliac spine (LASIS), left pubic tubercle (LPT), right pubic tubercle (RPT), and right anterior superior iliac spine (RASIS) were selected as POIP. A condom containing 200 ml water was placed in pelvic cavity to simulate gut which provided pressure against pelvic inner wall [2, 3].

A horizontal sled test table was used to conduct lateral impact. The sled tests were run with a 22.1-kg impactor at 5.2, 4.0, and 4.8 m/s respectively. The specimen was seated uprightly and loaded 500 N on the third lumbar vertebra with a load cell. The left great trochanter was set in the path of impactor. A vertical baffle was fixed on the right side 30 cm to the pelvis (Fig. 1). A six-camera optoelectric motion capture system (Qualisys) was used to record the POIP spatial value at 1000 Hz in real time. Motion data were processed to plot positions and trajectories of markers (Fig. 2). Mutual distances between markers were also calculated as well and exported to data analysis and graphing software (OrigionPro 9.0.0). After impact, autopsy was done to examine the inner pelvic surface and simultaneously palpate subfractures and symphysis pubis diastasis. The stability of pelvic girdle was also evaluated at rotational and vertical direction. After autopsy, the subjects were sent to CT scan to figure out deformity and fracture pattern comparing with the pretest CT images.

Results

The whole impact procedure could be divided into four phases based on the impactor and the baffle touching pelvis, since there was a sliding motion that pelvis was pushed by the impactor to slide towards right side baffle (Fig. 2). There was no significant pelvic rotational movement was found.

The distance between LASIS and RASIS parallel to the impactor track is shown in Fig. 2. Before impact, the initial distance “a” was 217.9 mm; after impact, the distance was decreased to “c” 191.8 mm, that illustrated pelvic fracture happened and displacement was not completely reduced, the compression was 26.1 mm. Meanwhile, the peak compression was 64.6 mm. However, the diminution of mutual distance between LASIS and RASIS did not coincide with previous statement. The decrease of mutual distance was finally 30.8 mm, but its peak value was 67.0 mm (Fig. 3). Postimpact mutual distances calculated from the motion capture data were validated by CT scan through the titanium screws which were inserted into POIP to flag the positions of markers. The details of mutual distance change are shown in Table 1.

After sled test, autopsy was made. Interestingly, an oblique fracture was noted at right superior ramus of pubis in these three pelves, no visible sign of fracture was observed at pubic symphysis or left hemipelvis. Palpation revealed minor rotational pelvic girdle instability but no vertical instability. In CT scan, similar fracture pattern was observed.

Discussion

It is universally accepted that the displacement of pelvic fracture presented on images in hospital may always minor than that at injury moment. However, few reports studied the relationship between final deformity and peak deformity. In current test, the peak compression was 30.1%, 1.3–2.2 times of deformity after impact. To the best of our knowledge, this is the first report about relationship between the peak and final compression of pelvic lateral impact.

Wang et al. reported, in cadaver experiment, pelvis was horizontally crashed by a 22.1-kg impactor from lateral side at a speed of five m/s, the maximal compression of pelvis was 31.88% [4]. Jun et al. reported that exploring children cadaveric pelves under lateral impact load with a 24-kg impactor at

Fig. 1 Sled test table. The impactor weighed 22.1 kg and ran at speed of 5.2, 4.0, and 4.8 m/s

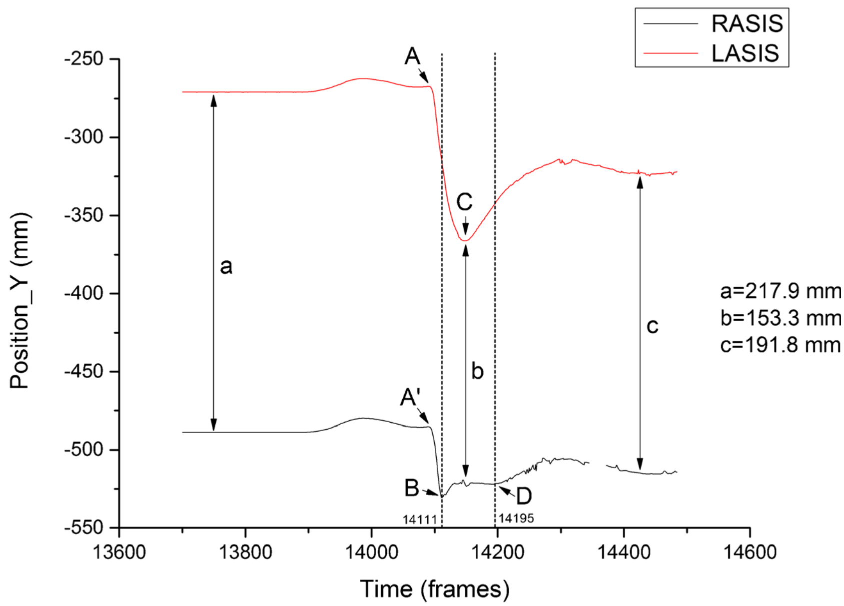

Fig. 2 RASIS and LASIS position-Y-time curve. Note: *Y* axis of global coordinate was set along the rear track of the sled test table deviating from the pelvis. A, A′: frame 14,095, impactor touched pelvis and pelvis began to slide. B: frame 14,111, pelvis touched baffle on the right side and right hemipelvis stopped moving. C: frame 14,145, pelvis was maximally compressed and began to reduce. D: frame 14,195 pelvis left baffle. The whole process consisted of four stages. The first stage was from A/A′ to B, referred to impactor push pelvis slide towards right side. This stage did not create significant deflection. The second stage was from B to C, meant pelvis was compressed between impactor and baffle. The third stage was from C to D, demonstrated the main reduction procedure of pelvis. The fourth stage was after D, which represented pelvis left baffle until stop movement

7.5 m/s caused pelvic maximal compression of 21–54% and there was a trend that the compression value decreased with the growing age of cadaver [5]. Laing investigated pelvic deflection during sideways fall from 5-cm height. The results indicated that average peak deflection of pelvis was 26.3 mm at the instant of impact, considering initial pelvic width was 342 mm, and the compression was 7.6% [6]. Current results correspond closely to Wang's, and Jun's study and show discordance with Laing's study. The weight of impactor in current study, Wang's and Jun's study was 22.1, 22.1, and 24 kg. Meanwhile, the speed of impactor touching cadaver was 4–7.5 m/s, and thus probably is the reason these

Fig. 3 Mutual distance between RASIS and LASIS. Note: The LASIS-RASIS mutual distance of pre-impact and post-impact was 222.4 and 191.6 mm respectively, a discrepancy of 30.8 mm was observed. The peak reduction of mutual distance was 67.0 mm

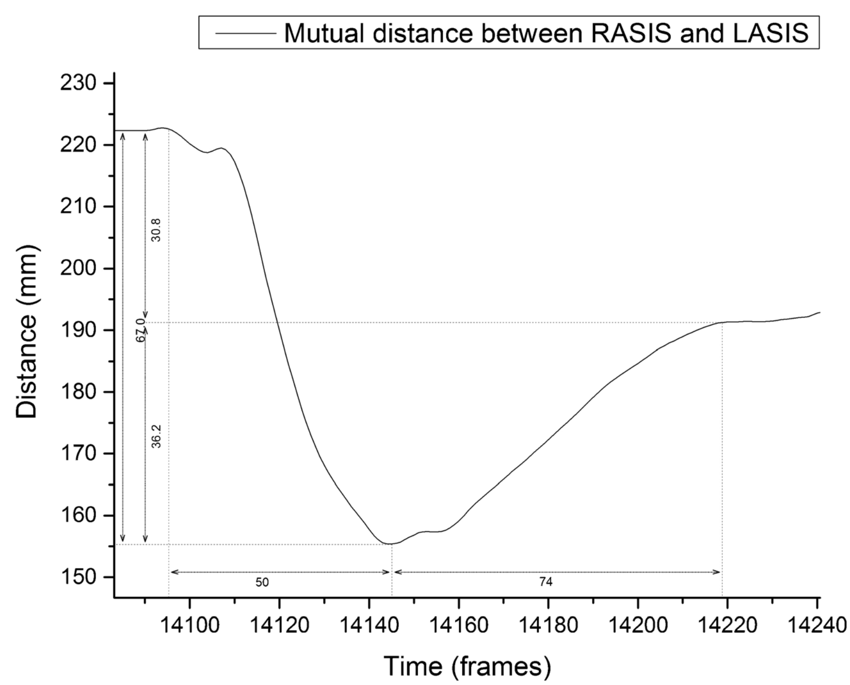

Table 1 The diminution of mutual distance between LASIS and RASIS

	Specimen 1	Specimen 2	Specimen 3
ID	160,309	160,310	160,315
Impact speed of impactor (m/s)	5.2	4.0	4.8
Peak deflection of mutual distance between RASIS and LASIS (mm/%)	82.4/31.9%	67.0/30.1%	59.1/18.5%
Final deflection of mutual distance between RASIS and LASIS (mm/%)	50.7/19.62%	30.8/13.8%	44.0/13.8%
Ratio of peak/final deflection	1.6	2.2	1.3
Percentage of final/peak deflection (%)	61.5	45.9	74.46

The impactor weighs 22.1 kg

three studies got the similar peak pelvic compression. Nevertheless, Laing's test involved 14 women participants in sideways fall configuration. Besides different impact mechanics, the deviation from soft tissue shall also be considered when calculating the deflection of skeletal pelvis. However, it is a pity Wang's, Jun's, and Laing's study did not compare the peak and final compression.

To investigate the kinematic response of pelvis to lateral impact, different devices were applied. Sled test was widely used in vehicle safety test. But not like the present study, those investigations fixed subject on a sliding table moving towards a wall to perform impact [7–9]. This sort of mechanism is typically deceleration injury. Pendulum was used to conduct pelvic lateral impact previously [10, 11]. The impact structure is easy to set up, but rotational motion shall be taken into account. Sideways falling is carried to investigate participant kinematic response to lateral falls on hip [8, 12]. For safety reason, the height of falling was limited, thus causing the shortage of simulating high energy impact. Dropping mass was also applied to pelvic lateral crash [13]. The repetitive impact caused by bounce of dropping mass shall be considered. Horizontal sliding impactor has some superiorities to simulate lateral crash in the real world comparing former strategies. Thus, the current study applied this method to practice.

One of the advantages in the present study is to use a human cadaver with soft tissue envelope covering the pelvis. Not like a dummy [10], postmortem human subject (PMHS) [14], hybrid [15], human cadaver pelvis with soft tissue had the real geometric, mineral, and dynamic properties, which minimize the deviation from the experimental subject [12, 16].

A discrepancy of pelvic compression between mutual distance and deflection along impactor track (26.1 and 30.8, 64.6 and 67) demonstrated the real compression trajectory was not parallel with the impactor track, considering no significant rotational motion was found. The sacroiliac joint articular surfaces are from proximal lateral to distal medial and from posteromedial to anterolateral. Hefzv proved pubis on injured side displaced inferiorly and posteriorly. It could be speculated, in the current study, LASIS relative to right hemipelvis displaced medially, superiorly, and anteriorly. But, this hypothesis needs validation in further investigation [17].

Potential weakness of this study must be mentioned. Small sample size restricts the generalization of the finding in the present study; more subjects shall be applied in further investigation. The other weakness is that all these three cadavers were crashed at a similar speed. It is hard to evaluate the pelvic response to different impact energy.

In the real world, pelvic fractures are usually caused by vehicle crash or high falling. To study potential body damage responding to these kinds of injury, a lot of sled tests were presented. Naturally, varied crash speed were applied. In Shaw's sled test, impacting speed was 30 km/h, which equaled 8.3 m/s [7]. Nicholas carried sled test at 6.7 and 8.9 m/s [8]. In a far-side crash tests, impacting speed were from 15 km/h through 35 km/h, which equals 4.16 through 9.72 m/s [18]. The general impact speed employed in these kinds of tests goes from 4.0 m/s through 10 m/s [7–13]. Meanwhile, there is also impact energy to consider. Reviewing previous literature, based on different speed, impactor weight, and occupant's fixing condition, dramatic variation of impact energy was observed. In preliminary test, we found that a 22.1-kg impactor moving at a speed above 4.0 m/s could successfully cause pelvic fractures. To avert excessive movement of cadaver and cut down the loss of motion capture data, we selected relative slow impact speed and light impactor.

Generally speaking, repeating sled test at different speed, impact position, and crash direction will give more information to help understand the mechanics of pelvic fracture. However, the main purpose of the present analysis is to reveal the true pelvic displacement is significantly serious than imaging manifestations in hospital under lateral impact. Although only three cadavers can hardly bring out the exact ratio of true displacement to imaging displacement, we can see the displacement happened at fracture moment is substantially larger than imaging findings still. That can be over two times albeit at low injury energy.

Besides lateral compression, anterior-posterior compression and vertical shearing are another two important mechanisms of pelvic fracture. Based on the experience of the current study, it is reasonable to steeply investigate pelvic fracture mechanics under different damage conditions in the future.

Conclusion

Despite this is a limited analysis, the kinematics of pelvic fracture in this study is meaningful to understand the mechanism of pelvic fracture in lateral impact. Given the finding of this study, we advocate paying more attention to pelvic lateral impact injuries, since displacement showed on the images in emergency room may be significantly minor than peak displacement during accident. Dissemination of this information could help clinicians make more consistent evaluation of lateral impact pelvic fractures.

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Authors' contributions Zhijian Ma designed the study, analyzed the data, and drafted the manuscript. Zizheng Wu, Liping Bai, Chun Bi, Xiangsen Zeng, and Aili Qu participated in the experiment and measurement. Liping Bai helped draft the manuscript. Qiugeng Wang prepared the supporting grant, provided advice for experiment design and analysis, and revised the manuscript. All authors have reviewed and approved the final manuscript.

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Compliance with ethical standards

Conflict of the interest The authors declare that they have no conflict of interest.

Ethical approval Each author certifies that Shanghai Jiao Tong University approved the human protocol for this investigation that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

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