

Ex vivo protocol to reproduce a forward fall leading to fractured and non-fractured radii

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Abstract Assessments of the bone fracture risk by the standard clinical methods is not sufficiently discriminant. Finite element models (FEM) are accurate when measuring bone strength, but they have not improved bone fracture risk prediction. The risk of fracture is defined as the ratio between external load and the bone strength. Thus, because the FEM estimate the bone strength correctly, a better consideration of the external load should improve the prediction of the risk of fracture. Thus, the aim of this study is to develop an experimental protocol to evaluate bone fragility under realistic loading conditions. The case of a forward fall was considered. Six distal radii were loaded at 75° (between the anterior face of the radius and the ground) with a speed of 2 m/s to simulate a forward fall. Maximum load varied from 852N to 3915N, with an average ($\pm$ Standard Deviation) of 2134 ($\pm$ 1137). Among the six radii, four fractured and two did not. The current protocol allows the classification of radii in two groups – fractured and non-fractured – in response to a unique loading case. Having these two groups with known loading conditions (orientation and speed) will be of great interest to assess the predictive capability of FEM.

Keywords forward fall, risk of fracture, distal radius.

I. INTRODUCTION

The fall represents a public health problem for the elderly. This problem increases in elderly people suffering diseases associated to bone fragility, such as osteoporosis. Osteoporosis affects 75 million people in the United States, Europe and Japan and is the cause for at least 8.9 million fractures annually worldwide [1]. The distal radius fracture is the most common fracture affecting elderly patients. Only in the United States, there were 640.000 cases of distal radius fracture in 2001. Distal radius fractures contribute significantly in the 1.1 billion dollars of expenses associated with osteoporotic fractures [2].

The golden standard method for the clinical diagnosis of osteoporosis and the evaluation of the risk of fracture is the Dual X-ray Absorptiometry (DXA). This method is based on the measure of bone density at different anatomical sites. It has been shown that this measure, which is an x-ray 2D projection, presents an insufficient sensibility because 50% of fractures occur in patients considered non-osteoporotic [3]. This means that bone density alone cannot explain the bone strength or bone fracture risk.

Other methods have been proposed to measure the bone strength and the risk of fracture. One of these methods is the FRAX, which quantifies the probability of fracture over 10 years. The method comprises an algorithm evaluation based on a survey, which integrates clinical risk factors and bone mineral density at the femoral neck to calculate the 10-year probability of fracture. Nevertheless, this method was criticised because the falls and the disturbances of the walking were excluded from the algorithm of prediction [4]. In other words, this survey cannot take into account the external loading conditions that increase the risk of fracture.

The finite element analysis has also been proposed as an alternative measurement of bone fragility. These models can be very accurate when measuring bone strength. The prediction can reach values close to 98% [5]. However, comparisons of several finite element models (FEM) of radius in cohorts [6] have shown that, despite the good prediction of bone strength, the bone fracture risk prediction has not been improved with the use of these models. As a matter of fact, prediction levels of these FEM are not superior of those coming from a clinical standard examination by DXA.

The risk of fracture can be defined by the ratio between external load and the bone strength [7]. Thus, because the FEM estimate the bone strength correctly, a better consideration of the external load should lead to an improved prediction of the risk of fracture.

For most of the radius models [8][5][7-8] the loading condition was a quasi-static axial load. In the case of a fall, however, only 15% of cases are associated with an axial load on the radius [9] and they occur with an average velocity of 2 m/s [10].

Thus, we have made the hypothesis that a dynamic non-axial loading of the radius could be more discriminant of the risk of fracture. This hypothesis is based on a previous study, which evaluated the bone strength of the distal radius [11-13].

In this context, the aim of this study was to load 6 radii under a configuration that simulates the most common kind of forward fall: 75° between the anterior face of the radius and the ground [11], and with a speed of 2m/s [10]. The current *ex vivo* protocol was designed to load the radii with the same loading case, expecting that some of them will fracture and others will not.

II. METHODS

Six left radii from older donors (50–96 y.o.) were considered. The samples were scanned using a Cone Beam CT scan (NewTom 5G, QR, Verona, Italy) in order to retrieve their geometry for a further finite element analysis. For the experimentation, the 2/3 of distal radius was cut and cleaned of soft tissues. The radii were then frozen at -20° C. The samples were thawed before testing. They were placed for 16 hours at 4°C and for 6 hours at room temperature, while preparation took place.

Proximal half of the previously cut radius were potted in a polyurethane resin in a steel cylinder (61 mm in diameter). Using a positioning laser, radii were potted with an alignment of 75° between the anterior face of the radius and the ground (anterior face looking up), without any tilt in any other plane (Fig. 1). This position reproduces alignment of the radius in the most common forward fall [11]. After potted, the third part of the distal radius is exposed for loading.

A rigid polyurethane mold was made for each articular surface of the radii. This mold is a simplified reproduction of the joint, which consists of scaphoid and lunate. Both bones are involved in the mechanism of fracture of the distal radius [12]. This mold attempts to distribute the loading uniformly on the articular surface of the radius during the impact. The mold was attached to the distal end of the radius using a silicon rubber. This silicon rubber positions the mold on the radius, but also allows few displacements in perpendicular directions to the impact, as expected in real life.

After a total polymerisation of both pot and mold, the radii were painted using a white make-up. Then, a black painting pattern was made using a spray. Four high-speed cameras (FASTCAM SA3, Photron, Japan) recorded the impact. Two cameras were placed in the front, facing the ulnar face of the radius, and recorded the test using 105mm F2.8 DG Macro sigma lens. The other two cameras were placed upper the system, facing the anterior face of the radius, and recorded the test using 50 mm Z1.4/50 mm ZF planar Zeiss lens. The cameras were set to record with a resolution of 1024x1024 pixels at 2,000 images per second, with a shutter speed of 50µs (Fig.1B-C). The radius was illuminated using 3 projectors (400D, Dedolight, Germany). Points of the pattern are used as a speckle pattern to compute surface strain by stereo-correlation (Vic-3D, Correlated Solutions, Germany).

A six-axis sensor (105515TF, Humanetics, Germany), which measures forces and moments, was tightened to the impactor. Accelerations, velocities and positions were also obtained by instrumentation systems of the testing machine

The pot was placed in a horizontal cylinder bar on a rail system, which is free to slide along the loading axis (Fig. 1A). This bar has a weight of 12.5 kg, which is an arbitrary value representing the mass involved in a fall, i.e a percentage of the body weight. In the present study, this weight is the same for all of the tests. Previous studies used 49-50% of the body weight [13], [14], using as reference the study of Chiu and Robinovitch [10]. Nevertheless, this is a value measured in a static configuration. We hypothesize that in a dynamic case, which is the case of a fall, this value is lower. The loading would be systematically avoided by the flexibility and inertia of the rotator cuff. The radius was then loaded through the mold at 2m/s using a hydraulic high-speed impact machine (LF technologies, France). At the beginning of the test the distance between the impactor and the mold was 50 mm. This distance allows the acceleration of the impactor and stabilisation of its speed to reach 2 m/s.

All the samples were impacted under the same conditions.

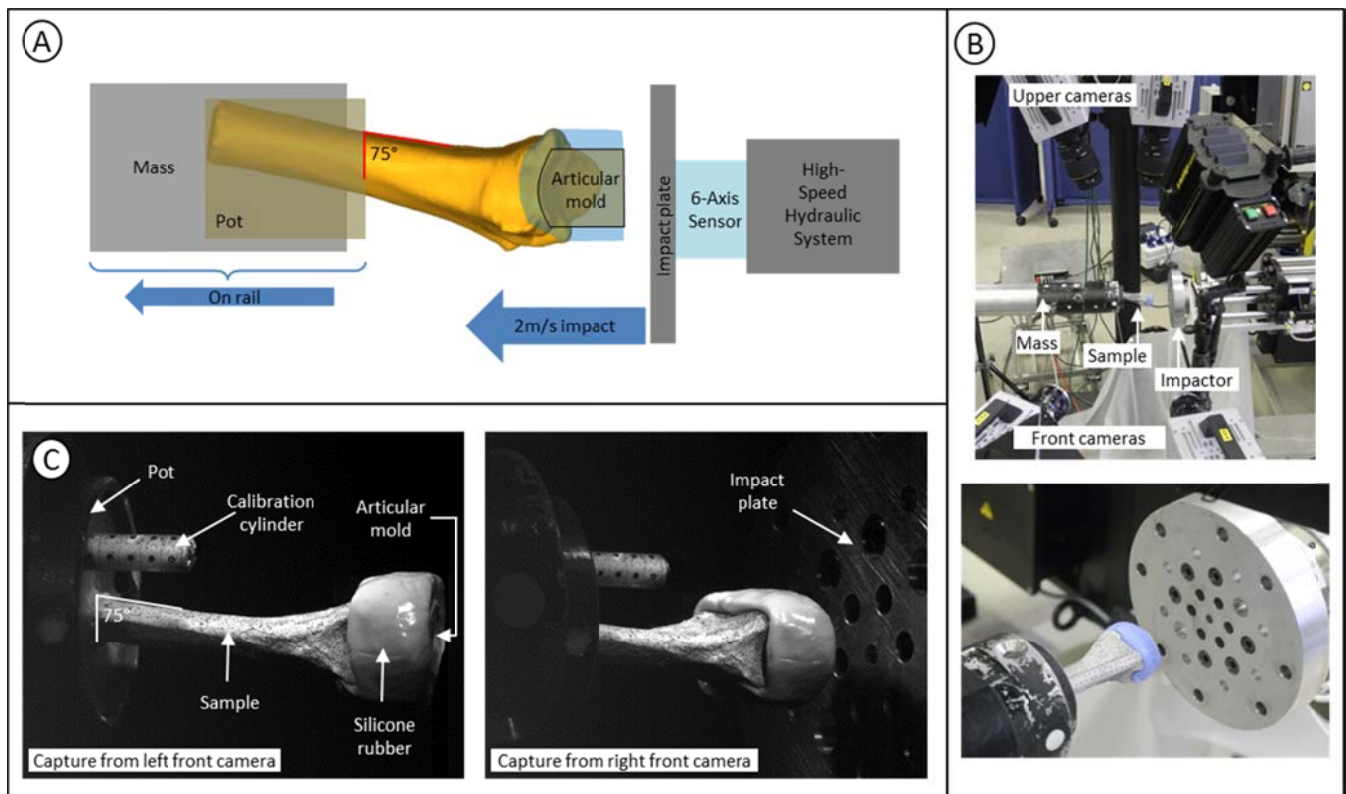


Fig. 1. A. Schema of the impact test. B. Experimental set-up showing the main components of the experimentation. C. Images from front cameras showing sample set-up.

III. RESULTS

Among the six radii, four fractured and two did not. Maximum loads are shown in Table 1. Force vs Time curves for each sample are shown in Fig. 2. The total cycle (loading and unloading) lasts 4 ms on average.

For the weakest bone (Radius 1), the maximum measured von Mises strain value before fracture was 1.5% on the anterior region, and 3.1% on the ulnar side. For the strongest bone (Radius 6), von Mises strain reached a maximum value of 0.9% on the anterior region and 2% on the ulnar side (Fig. 3).

TABLE 1		
Radius	Maximum Load (N)	Fracture
1	852	YES
2	1171	YES
3	1780	YES
4	2181	NO
5	2906	YES
6	3915	NO
Average ($\pm$ SD)	2134 ($\pm$ 1137)	

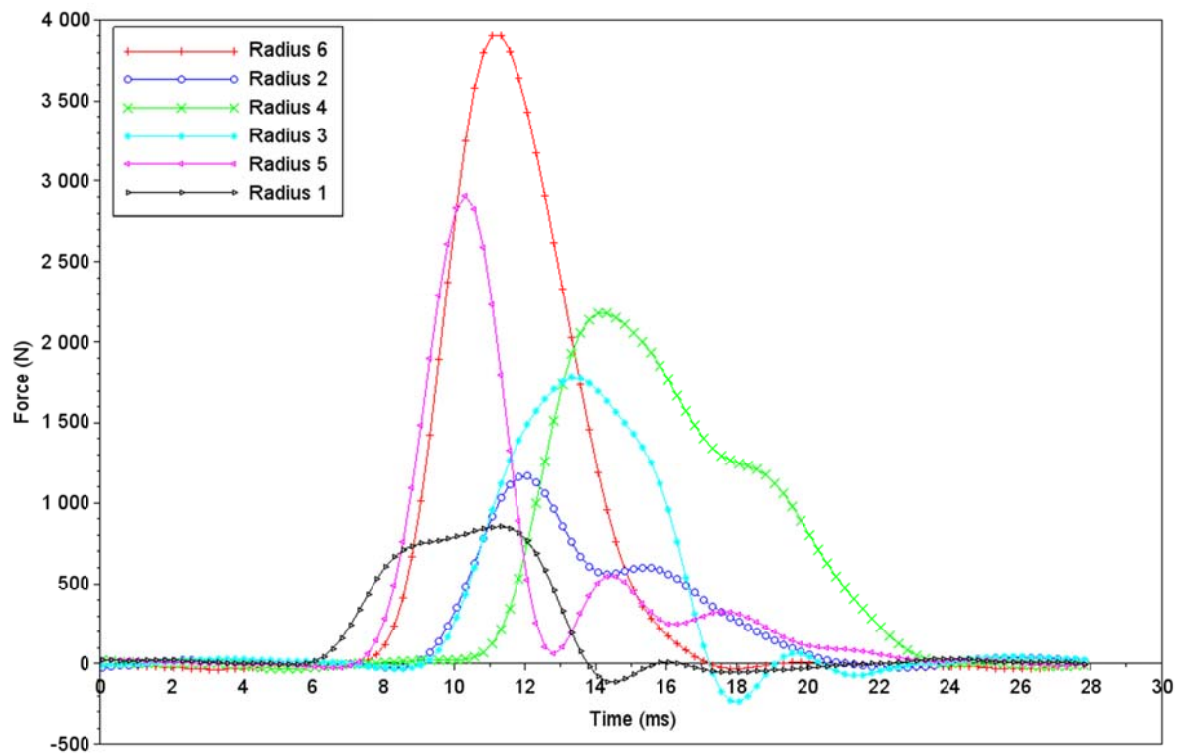


Fig. 2. Experimental forces for each radius. Fractured Radius: 1, 2, 3 and 5. Non-Fractured: 4 and 6.

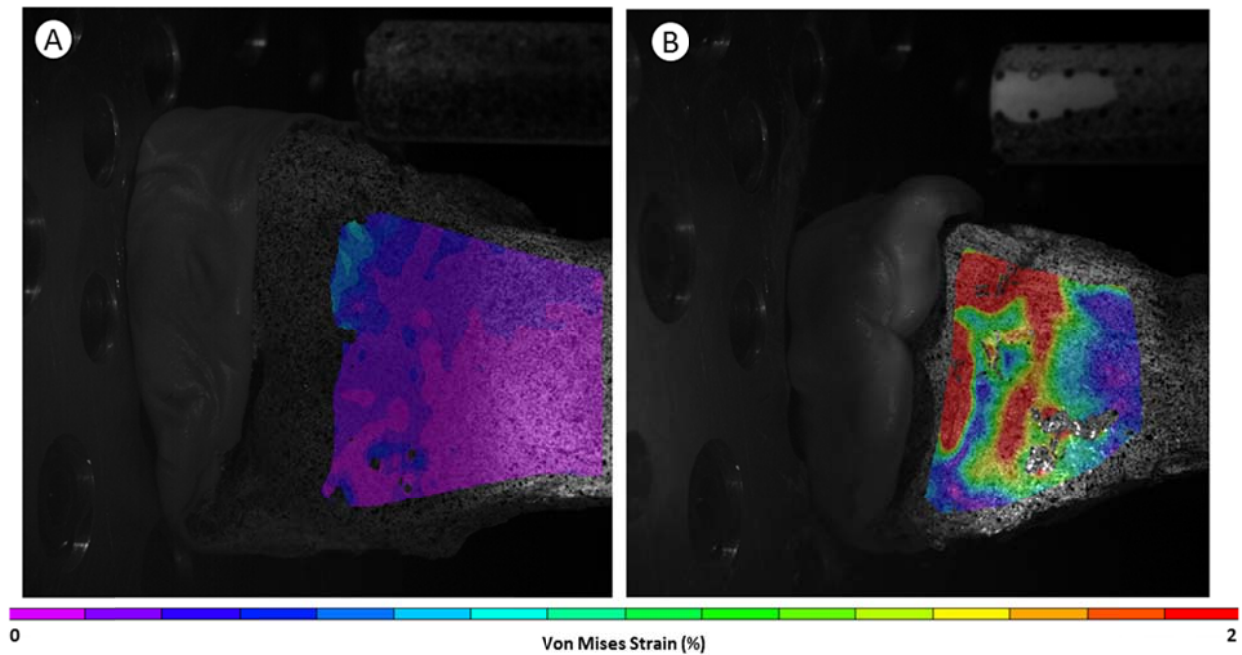


Fig. 3. von Mises Strain distribution in the anterior region. A. Non-Fractured radius at the maximum load. B. Fractured radius (Colles' type fracture). First frame after fracture (the red part of the strain pattern is equal to or above 2%).

IV. DISCUSSION

This study provides a protocol to reproduce a forward fall on the radius. Most previous studies evaluate bone strength under static conditions. Moreover, previous studies loaded radii until failure in all cases [8][5][7-8]. In the current protocol a unique loading case was considered for all radii to get fractured and non-fractured groups. This goal was achieved. Among the six radii, four fractured and two did not. Having these two groups with known loading conditions (orientation and speed) will be of great interest to assess the predictive capability of finite element models.

For some radii having an articular surface tilted with respect to the surface of the impact plate, the articular mold slid. This effect has been observed in the high-speed video. This is not a drawback of the protocol. In fact, it reveals an expected behaviour of the joint in real life. During a forward fall over the forearm, the scaphoid and lunate move partially in the plane perpendicular to the longitudinal axis of the radius [15]. Thus, the loading can change compared to the initial loading conditions. As a consequence, bone with a tilted articular surface may not fracture, not because its strength is high but because the loading was lowered due to the joint shape.

Highest strain deformation was found at the ulnar side, as presented in literature previously [16]. Further analysis will provide a more detailed description of the localisation and the value of these strains over time.

V. CONCLUSIONS

Six radii were tested under a dynamic non-axial loading, which simulates the most common forward fall configuration. Most previous studies evaluated bone strength under static conditions. Moreover, previous studies loaded radii until failure in all cases. In the current protocol a unique loading case was considered to get fractured and non-fractured groups. This protocol will be applied in 24 additional radii to get a larger database. Having these two groups with known loading conditions (orientation and speed) will be of great interest to assess the predictive capability of finite element models.

This ex-vivo protocol and the further analysis by finite element models will be helpful to assess fracture risk prediction. The results will be applicable not only for the study of pathological fragility fractures, but also to determinate safeguard parameters in trauma studies (e.g. snowboarding and inline skating).

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VII. REFERENCES

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