3D registration of micro-CT images for the identification of trabecular fracture region.

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Aims

Microtomographic devices (Micro-CT) are commonly used for in-vitro analysis of trabecular bone structure and its relation to the mechanical behavior of the tissue. The standard examination for the evaluation of the trabecular resistance to load is the assessment of its bone volume fraction (BV/TV) [1, 2]. Even though the BV/TV has been proved to correlate to fracture behavior, it does not allow to determine structural changes within the cancellous bone microarchitecture, which was found to have an important effect on bone strength [3]. Particularly, in [4], a 17% of wrong fracture zone identification was recorded using only BV/TV as a classifier. This quite high classification error was achieved in a situation of controlled involvement of the trabecular structure (i.e. reduced off-axis angle [5]) and with half of the specimen identified as broken (maximum classification error 50%).
The correct identification of the trabecular broken region have a potential impact in the understanding of the structural mechanisms driving the mechanical fracture of bone, by the calculation of morphometric parameters in the actual broken region instead of the whole specimen.
Image processing tools, as 3D image registration, were already presented in literature for the study of mechanical behavior of bone tissue [6]. The combined use of image guide failure analysis of micro-CT datasets and the mechanical tests can lead to a more comprehensive study of the fracture behaviour in the near future.
Aim of the present work is to present a new methodological approach for the automatic identification of trabecular bone fracture zone based on 3D image registration.

Method

Bone Specimens extraction and Micro-CT scanning
Five cylindrical specimens of trabecular bone, with a diameter of 10 mm and a height of 26 mm, were extracted from the epiphysial slices, i.e. femoral condyles, tibial plateau and distal tibia, by means of a holed diamond-coated milling cutter.
Trabecular specimens were acquired using a micro-CT device (model Skyscan 1072, Skyscan, Kontich, Belgium) and applying a previously published protocol [7]. The same acquisition procedure was performed before and after the mechanical test (see below). Global fixed threshold was used for the segmentation of trabecular specimens and the measurement of morphometric parameters (see below) as previously reported in literature [7].

Mechanical testing

All specimens underwent compressive testing [5]. Each specimen was cemented directly onto the testing machine (Mod. 8502, Instron Corp., Canton, MA, USA) to ensure the alignment between the testing direction and the specimen axis. The specimen free length was set to 20 mm. Before testing, the specimen was immersed in Ringer's solution for an additional hour. Each specimen was compressively loaded until failure, with a strain rate of 0.01 s-1 [1, 8, 9].

Visual inspection for the identification of the broken region

A comparison was performed by three operators in the datasets acquired before and after the mechanical compression for the identification of the broken regions. These regions were identified visually, by comparing the stack of pre- and post-failure micro-CT cross-sections (slices) over the whole free height of the specimens, using the pre-failure cross sections as reference. Depending on the presence or absence of trabecular fracture in the post-failure micro-CT slices, each of the corresponding pre-failure slice was labeled as a 'broken cross-section' or 'unbroken cross-section'. Consistency threshold was identified based on the measures of the operators.

The automatic registration method

Automatic identification of the fracture zone was performed by the application of 3D automatic registration method applied on the acquired data sets. For each specimen, two data sets were acquired: the pre-failure data set and the post-failure data set, after mechanical compression. The purpose of the 3D registration is to automatically identify the zone on the pre-failure set that corresponds to the fracture zone of the post-failure data set.

The method presented is a surface-based registration which involves the determination and matching of the surfaces of the two sets and the minimization of a distance measure of these corresponding surfaces [10, 11].

The transformation model employed was the rigid transformation model [12]. No scaling was used.

Identification of the fracture zone using the automatic registration procedure

For all the acquired data the automatic registration procedure was applied. Two subsets of the post-failure set were defined: the upper and the lower subsets relatively to the fracture zone. The upper subset was formed from slices of the post-failure set from the first upper slice of the set up to a randomly selected slice located above the fracture zone that clearly corresponds to an 'unbroken region', whereas the lower subset was formed from slices of the post-failure set from the lowest slice up to a randomly selected slice located below the fracture zone that also clearly corresponds to an 'unbroken region'. The proposed registration method was applied twice: the first registration involving the upper subset with the pre-failure set and the second registration the lower subset with the pre-failure set (Figure 1).

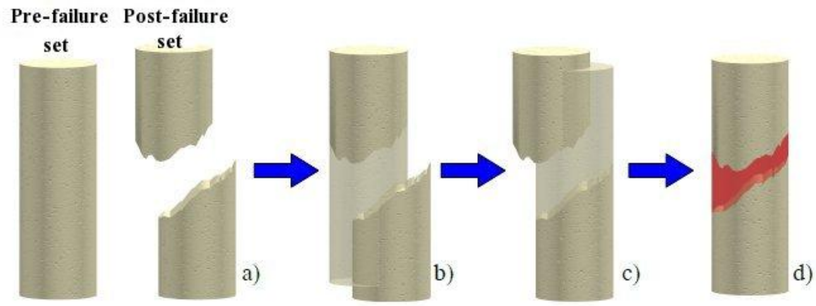

Figure 1 The volume registrations steps are shown. (a) The pre and post-failure sets. The float set is registered on the reference set. The procedure is applied twice: one involving the upper subsets of both sets (b) and the other involving the lower subsets (c). The regions belonging to clearly unbroken regions coincide while the regions belonging to the fracture zone (red fracture zone) present misalignments.

Full 3D identification of broken region

A full 3D definition of the broken region (ROI), not related to the identification of broken slices, was performed starting from the 3D distribution of misaligned ROIs. The 3D volume (VOI) was identified applying a dilation procedure around the misaligned ROIs. Every ROI was dilated in every direction of 0.5mm obtaining for every ROI an ellipsoidal VOI centered on broken trabecula. When ROIs were close enough, the VOIs were fused creating a single 3D VOI.

Validation of the registration procedure

The procedure has been applied on 5 specimens, which have previously been mechanically tested. The outcome of the 3D registration, the fracture zone, was compared to the broken regions as visually identified by the operators. When differences between the two procedures were greater than the consistency threshold identified during the visual inspection, the operators were asked to verify if the error was due to the 3D registration approach or the visual one.

Results

Five trabecular bone specimens were mechanically tested in compression and acquired by means of a micro-CT device before and after the mechanical test. Figure 2 shows the result of applying the automatic registration procedure on a specimen underwent mechanical testing in order to define the fracture zone. Pre and post-failure sets were compared (Figure 2 a) and the broken region was identified both visually and automatically in order to identify the starting and ending broken slides. A plot for the identification of the fracture zone was obtained by the automatic registration procedure (blue line) while the visual inspection of the observers gave as result the starting and ending broken slides (red straight lines) (Figure 2 b). Finally the full 3D identification of the broken structure was performed for every specimen (Figure 2 c).

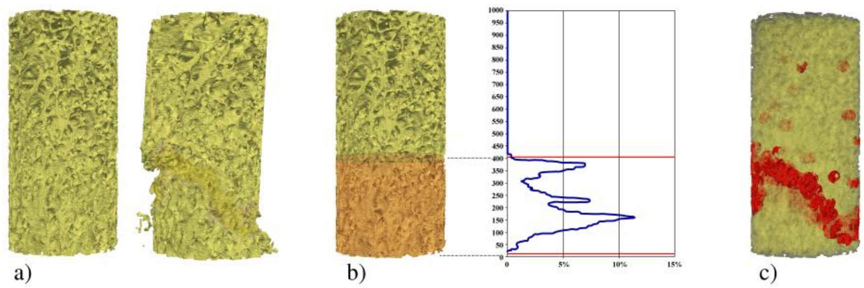

Fig. 2 The whole identification process is shown. (a) Micro-CT volumes of the bone specimen before and after the mechanical test are shown. (b) The visual procedure by the observers is compared to the automatic identification of the fracture zone. The percentage of overlapping of all ROIs for each slice as obtained by the proposed registration procedure is shown in the graph. (c) Finally a full 3D broken region is identified.

The visual approach and automatic registration procedure were in agreement in 7 out of 10 cases. In fact, the difference between the procedures was smaller than the operators variability in the identification (18 slices). In the last three cases, the visual approach and the automatic registration procedure disagreed of 37, 76 and 103 slices. For these cases, the operators had to compare their findings against the ones suggested by the automatic registration procedure. In all three cases, the operators had to correct their findings suggesting that the proposed automatic registration procedure was successfully performed and the identification of the fracture zone was correct.
The full 3D broken region was also identified for every specimen (Figure 2 c). Through this kind of visualization was possible to identify the 3D shape of every principal and secondary broken region. Moreover, was possible to identify some single broken trabeculae. Once again the operators were asked to verify the presence of the broken trabeculae. Operators agreed in the validation of the principal broken region fully 3D identified. Moreover, operators generally agreed with the automatic identification of single broken trabeculae, but in some cases they disagreed among themselves.

Conclusion

Aim of the present work was to present a new methodological approach for the automatic identification of trabecular bone fracture zone, based on 3D image registration. The technique was presented and validated against the visual approach of three expert operators. The presented study has shown comparable results between the visual approach and the automatic registration procedure, in the identification of the principal “broken region”. Moreover, the execution time for the application of the proposed registration procedure was 50 sec in total, for all data sets within this study. This result in a substantial reduction of the time for the identification of the fracture zone compared with the 20 to 30 minutes that required for the visual approach by each observer.
Image guide failure analysis is becoming an important field of study for the comprehension of bone mechanical behavior. New technologies are nowadays able to produce huge amount of data, but researchers need more tools for a more exhaustive mechanical study. The combined use of image guide failure analysis of micro-CT datasets and the mechanical tests can lead to a more comprehensive study of the fracture behaviour in the near future.
In conclusion, a novel procedure for the identification of trabecular bone fracture zone was presented and validated throughout this study. The correct identification of the trabecular broken region have a potential impact in the understanding of the structural mechanisms driving the

mechanical fracture of bone, by the calculation of morphometric parameters in the actual broken region instead of the whole specimen.

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