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Mechanical loading at the organ level: which consequences for bones?

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Abstract Previous studies have shown that failure loads are sensitive to loadings (e.g. direction, speed). The fracture risk could be defined by the ratio between the external loading and the failure load. The prediction of the failure load using finite element models is encouraging but the external loading considered are still simplistic.

Keywords Bone loading, Fracture risk, Failure load, Finite element model, Bone strength

Introduction

The mechanical loading at the organ level can have at least two consequences. Firstly, it affects the structural bone organization on the basis of Wolf's law [1]. Indeed the physiological loadings can be linked to the cortical thickness (e.g. in the proximal femur) and to the trabecular network (e.g. in the femoral head and neck). Secondly, the mechanical loading on a specific bone can induce failure. A better prediction of the fracture risk would be of interest for diagnostic purposes and to limit the consequences of an accident. Finite element models have been proposed to contribute to this goal.

Advanced finite element approaches reach a certain level of confidence during the past 10 years. The geometry can be derived from quantitative computed tomography [2] or high-resolution computed tomography to catch microarchitectural features in vivo for distal segments such as the distal radius or

that the failure strength can be affected by the speed of loading [10, 11].

On vertebra, previous studies showed that the location of the external load has a major effect on the failure load. For instance, Travert et al. showed that an anterior displacement of the load by as little as 1 cm decrease the vertebral strength by 50 % on average [12]. This result suggests considering anterior bending when estimating vertebral fracture risk with finite element models. The load location has a crucial effect.

The failure load of the radius is also dependent on the loading. Edwards et al. reported that if the radius is loaded until failure as an isolated bone (e.g. [13]), the failure load is 1.5 to 3 times greater in comparison to intact wrist loading configuration [14].

Whatever the bone considered (femur, vertebra or radius), these studies suggested that failure load depends on the loading: orientation, speed, location and distribution.

2. What are the loadings considered in finite element model to predict failure load?

When using finite element models, the geometry (macrostructure and microstructure) is taken into account with an improved accuracy. The mechanical properties are derived from indirect assessment and are still a key point. Accurate estimation of the mechanical properties is needed including elasticity and failure criterion. But on top of that, the loading conditions have to be considered. The loading conditions considered in most of the finite elements approaches are based on simple quasi-static loadings (stance configuration on the

tibia [3]. The mechanical properties of the bone tissues can be derived from bone mineral density using quantitative computed tomography [4, 5]. However, further accurate assessment is still needed and researches are currently oriented towards this aim [6]. These two input data (geometry and mechanical properties) are requested to build realistic bone models. Such specimen-specific models can predict the bone strength [2].

To assess the fracture risk from a mechanical point of view, the external load applied on the bone should also be considered [7]. Our assumption is that the mechanical loading can be a key factor to predict the fracture risk. Thus, the goal of this paper is to discuss the clues coming from previous studies on human femur, vertebrae and radius to assess the importance of the external loading and to suggest future works.

1. Sensitivity to loadings (directions, speed, ...)

It has been shown on the femur from *ex vivo* studies that the failure load in the stance phase configuration compared to the lateral load configuration (on the greater trochanter) leads to extremely different results. For example, Duchemin et al. obtained on 40 pairs of femurs 9,000 and 2,500 N for the average failure respectively in the stance and lateral loading configurations [8]. The load direction sensitivity was also assessed by modeling [9]. In addition, it was recently showed

(distal forearm fracture) and 105 controls using high-resolution peripheral quantitative computed tomography. The odd ratio obtained from the finite element model (OR 1.99) is similar to the one based on the bone mineral density measurement using the same imaging modality (OR 1.86) [17]. Most of these simulations are based on a linear constitutive law for the bone. It was shown that plastic parameters could improve the separation of cases and controls by one third (OR 2.66) [17]. Another limitation is the simplistic loading cases as mentioned in Vilayphiou et al. [18].

5. What are the loading scenarios leading to fracture?

Melton et al., in Osteoporosis Int, studied 100 cases of distal forearm fractures [16]. Eighty-nine percent of the fractures resulted from a fall from the standing height and only 15 % from an axial compression. However, in a clinical setup, the loading of the finite elements model is exclusively an axial compression. In addition to the previous observations, it seems important to pay attention to the external loading that can be considered for the various bones. In a large number of cases, multiaxial loading seems to be more realistic.

6. Can multiaxial loading affect damage?

The influence of the external loading at the organ level can be related to the fracture events, but before the fracture, the bone can be damaged. Very recently, bone microdamage was assessed in cancellous bone specimens from the upper extremity of the femur according to the type of the external loadings [19]. The authors showed that multiaxial loading (representing a fall or an accident) combining compression and shear caused much more damage than either simple compression or shear and caused greatest stiffness loss than either simple compression or shear.

Conclusion

This paper focused only on the effect of the mechanical loading of bone at the organ level. The physiological effect of the

femur, axial loading on the spine, axial loading on the radius) and not on multiaxial loadings nor on high speed loadings reproducing a fall. When the same boundary conditions as the experiments are applied in the finite element models, the bone strength is predicted from 75 % up to 90 % [13, 14].

3. How fracture risk is estimated from a mechanical point of view?

The bone strength (failure load) is a part of the fracture risk assessment from a mechanical point of view. Indeed the fracture risk (called fracture risk index or Φ factor [7]) is defined by the ratio between the external loading and the bone strength. The external loading can be computed using some assumptions. The real loading applied on the bone is not precisely known. Musculoskeletal models have been developed to assess the joint loadings (e.g. [15]) but their predictions are still hard to validate due to the lack of experimental measurements. Most of the time, simplified computation of the loading considers the subject height in case of a fall from a standing height (e.g. [16]). The estimation of the external loading might be a limitation of these methods.

4. What is the prediction capacity of the finite element model approaches?

The fracture risk index was used in clinical studies to assess fractured and non-fractured groups. In a recent study, finite element models were built for 100 postmenopausal women

mechanical loadings has been well known for a long time (Wolf's law), and is responsible of the shape of the bones (e.g. femoral cortical thickness and femoral trabecular network). The mechanical loading can affect the ultimate behavior of bones. Based on previous studies, the following highlights can be listed:

1. Bone strength is sensitive to loading (orientation, position, speed, distribution)
2. In most of the studies quasi-static loadings (axial compression, stance configuration...) are considered to predict bone strength (in finite element models)
3. Fracture risk from a mechanical point of view is computed from simplistic loadings
4. Up to now fracture risk is moderately predicted from a mechanical approach
5. The loading scenarios are not well known but seem to involve more complex external loading than currently considered
6. Multiaxial loading can affect the damage initiation

Knowing that the bone structure will be adapted to sustain the main loadings, the bone "optimization" will maintain the bone strength along the main loading pattern. But the bone strength could be reduced under more complex and unusual loadings. The bone strength with regards to these "exceptional" loading cases could be a key factor for the fracture risk prediction. These "exceptional" loading cases have to be estimated (e.g. during a fall) and simulated, using subject-specific bone models, to assess whether they are key aspects of the fracture risk prediction. In addition, bone strength is sensitive to the loading speed and this effect should be considered in the future finite element models.

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