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A Study on the effect of age on the injury criteria and modeling of lower extremity long bone

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Abstract: The incidence and severity of lower extremity fracture increase with age in a vehicle to pedestrian accident, but very little is known about how age-related changes affect the injury mechanisms and injury tolerance, this paper was to study the influence of age on the injury tolerance level of the lower extremity long bone as well as its modeling. The GHBMC lower extremity FE model was used as the basic model, and the age-related bone material parameters were analyzed and adjusted based on the biomechanical tests data, then three different age groups were selected to do the three-point bending virtual tests under the quasi-static and dynamic conditions, and finally the regularity of age-related injury tolerance of lower extremity long bone was found out, which can be used to guide the parameters setting in pedestrian lower extremity FE model and improve its bio-fidelity to predict and study the pedetrian lower extremity injuries.

Keywords:long bone of lower extremity,finite element,age-related,injury tolerance

1 Introduction

Pedestrian is in extremely high risk of injury in road traffic system, especially the elderly people, According to the Ministry of Public Security statistics, in 2012 the proportion of elderly traffic accident was up to 40%. Elderly people have weaker eyesight and hearing, slower response, which made them more likely to be hurt in road accidents [1]. Kong et al. [2] analyzed the accident dates in Changsha district, she found that the age group of 0-10 years and above 46 years were suffered more serious injuries and death threat than other age groups, and the proportion of death of the people over 46 years old was on the rise. Zhang et al. [3] got conclusion that the injury tolerance of elderly people's bones dropped a lot compared to young people, and would be more vulnerable to get ASI2+ injuries. Some researchers used the cadaveric experiments data to study the injury tolerance of human lower extremity long bones, Yamada et al.[4]did the quasi-static three-point bending tests with long bones of several adult age groups, the results indicated that injury tolerance of adults reduced gradually with aging.

In another hand, with the development of computer technology, many researchers have established finite element models [3,5,6] to study the injury mechanisms and injury tolerance of human lower extremity, but they hardly consider the effect of age on the skeletal characters when setting model parameters, with those models, the virtual tests results would not reflect the real responds of human at his age in accidents. What's more, current lower extremity injury criteria, which used to evaluate the occupant and pedestrian protection performance, were not considering the effect of age.

In conclusion, the injury tolerance of elderly people is much different from young people in road accidents, the required treatment and recovery period also extend significantly and when the finite element models were used to predict and study the traffic injuries, the effect of age on the skeletal characters need to be taken into consideration, so it is necessary to finger out how age-related changes affect the injury mechanisms and injury tolerance.

In this study, the FE model of lower extremity long bone derived from the validated France GHBMC model was used as the basic model. The long bone was remodeled with refined mesh, and the skeletal material parameters were adjusted based on the biomechanical tests data. Then the new lower extremity long bone model was validated by relevant experiment data and is used to study the effect of age on long bone injury tolerance. Three different age groups were selected to do three-point bending virtual tests under the quasi-static and dynamic conditions, and the effect of age on material parameters and geometry was studied, based on the virtual tests results and the published past mortal human subject (PMHS) tests data, the regularity of age-related injury tolerance of lower extremity long bone was found out. That would provide an effective support to improve the existing injury evaluation index as well as the bio-fidelity of FE model.

2 IMPROVED AGE-RELATED FE MODEL OF LONG BONE

The FE model of long bone includes femur, tibia and fibula, as shown in Figure 1.The model geometry comes from the CT image data of a 50-percentile male volunteer, who was 26 years old and 174cm high. In this model the cortical bone of long bone shaft and cancellous bone of both ends were modeled with hexahedral solid elements, while the cortical bone of the long bone ends was modeled with quadrilateral shell elements, and connected with the cancellous bone by way of sharing common nodes. Several layers of solid element with intermediate mechanical properties were defined between cortical and cancellous bone in order to avoid stress concentration caused by abrupt changes of mechanical properties. Isotropic elastic-plastic material and visco-elastic plastic material were used to define the properties of cortical bone and cancellous bone respectively. When the element strain reached the maximum value, it would be disabled to simulate bone fracture.

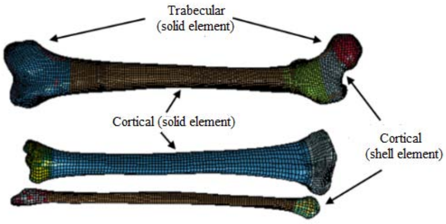
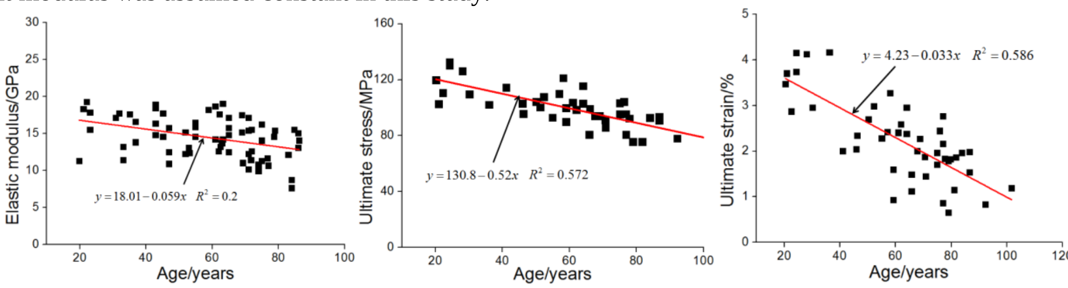


Figure 1. FE model of the lower extremity long bones

2.1 Age-related material properties of long bones

A large number of experimental studies [8-12] have shown that the organic matter in bone would loss gradually with aging, and resulted in the changes of its mechanical property. Reilly [8] and Mather [9] studied the elastic modulus of different ages' femoral cortical bone, the results were shown in Figure 2 (a), it can be seen that the elastic modulus decreased with age. Mccalden et al [10] carried the tensile tests with human femoral cortical bone; the ultimate stress and failure strain was shown in Figure 2 (b) and(c), the ultimate stress and failure strain also decreased with age. In order to find out the change rules, large deviation points were removed and then the linear fitting algorithm was used to construct the relation curves of skeletal material parameters and age, as well as its mathematical function. Due to the shorter plasticity zone, the stress - strain curves of cortical bone were usually simplified to linear. Currey et al. [11] got the conclusion that the slope of plastic zone would just change slightly with age by doing tensile tests with several age groups, so the tangent modulus was assumed constant in this study.



(a) (b) (c)

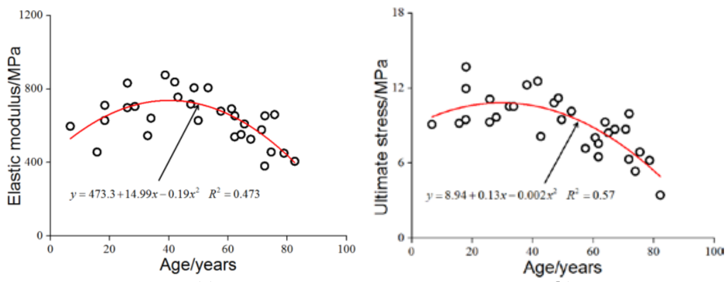
Figure 2.Effect of age on femoral cortical bone material properties (a)elastic modulus,(b)ultimate stress and (c)ultimate strain

Due to the lack of sufficient experiment data, it was hard to get the change rule of age-related material properties of tibia and fibula cortical bone. In this study, the material parameters of tibia and fibula were set using the scaling method, from Untaroiu et al[10],the scaling ratio of tibia and fibula to femur cortical bone were as follows:

$\eta_E = 1.13$, $\eta_{\sigma^u} = 1.20$, $\eta_{\varepsilon^u} = 1.06$

Where, η_E, η_{σ^u} and η_{σ^u} was the scaling factor for elastic modulus, ultimate stress and failure strain respectively.

Ding et al [12] conducted the compress experiment with several age groups' human tibia proximal cancellous bone; the results were as Fig.3shown, there was a increase for the elastic modulus and ultimate stress between 20 to 40 years old, but a sharp decline after 40 years old. The polynomial-fitting algorithm was used to construct the relation curve as well as its mathematical function.



(a) (b)

Figure 3 Effect of age on tibia cancellous bone material properties for (a)elastic modulus and (b) ultimate stress.

The yield stress of cancellous bone was usually set equal to the ultimate stress in virtual tests, given ultimate strain a constant value of 13.4%[3.5.6], but due to the lack of sufficient experiment data, it was hard to get the change rule of age-related material properties of femur cancellous bone, the same scaling method was used,from Untaroiu et al [10],the scaling ratio of femur to tibia cancellous bone were as follows:

$\lambda_E = 1.38$, $\lambda_{\sigma^u} = 1.24$

Where, λ_E and λ_{σ^u} is scaling factor for elastic modulus and ultimate stress respectively.

2.2 Effect of age on long bone geometry

It is known that with the increase of age, the outside diameter of the cortical bone is increased slightly, and in another hand, due to the osteoporosis, the cortical bone was gradually changed into cancellous bone, it means that the cancellous bone would increase with age, as Fig.4 shown.

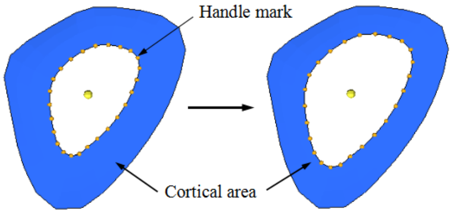


Figure 4. Changes of cortical bone with age

Ruff et al [13] measured the size of femur and tibia shaft for adults from 20 to100 years old, and did statistical analysis to explore the change rule of shaft cross-sectional thickness by 10-year age groups.Figure.5 shown the ratio of cross-sectional area of cortical bone and cancellous bone in different parts of long bone shaft by every 10 years.

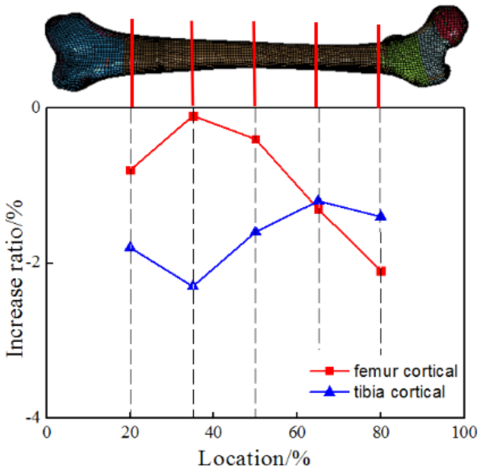


Figure 5. Changes with age in cross-sectional geometric properties(every 10 years in males)

3 VALIDATION OF AGE-RELATED LONG BONES FE MODEL

In vehicle to pedestrian accident, adult pedestrian’s lower extremity impact with the vehicle, the long bone fracture in middle shaft is the most common injury, so the FE model of lower extremity used for vehicle crash safety research need to be validated by quasi-static and dynamic three-point bending test.

3.1 Validation of quasi-static three-point bending test

In quasi-static test, the long bone was horizontally placed on a rigid platform by their posterior sides, as shown in Figure 6, and the loading condition and boundary conditions were set according to the work of Untaroiu et al. [6], the axial degrees of freedom of 10% proximal end and the translational degrees of freedom of 10% distal end were constrained, these part of proximal and distal ends were assumed to be rigid, since they were encased in plaster blocks. The load was applied at the mid-shaft with a 25 mm diameter rigid impactor with 0.01 m/s constant velocity along vertical direction.

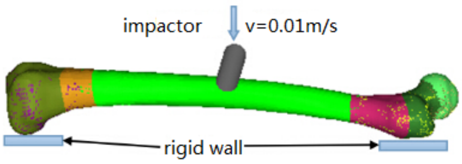


Figure 6.The FE model of quasi-static three bending test of femur

3.2 Validation of dynamic three-point bending

In real road accident, the lower extremity injury is caused by dynamic load, so it is necessary to further validate the model under dynamic load. In dynamic three-point bending test, as reported by Kerrigan [15], the basic information of specimens' donators was listed in Table 1.

Table 1. The specimens of dynamic three-point bending test[15]

Bone	Gender	Age (year)	Bone Length (mm)
	male	55	485
Femur	female	59	455
	female	54	435
	male	63	385
Tibia	male	44	418
	male	60	405

The two ends of the specimens were potted and fixed using rigid polyurethane foam in roller supports, as Figure 7 shown. The dynamic load was applied at the mid-shaft using a 12.7 mm diameter impactor moving vertically to the long bones, and the load speed to femur is 1.2 m/s, while tibia and fibula is 1.45m/s. To minimize local deformations, 25 mm thick ConforTM foam was used to wrap the impactor for the tibia and fibula tests, the foam material parameter come from Li et al[16].The supports were meshed with shell elements and the impactor was meshed with solid elements, both of them were assumed to be rigid. Shared node interface was created between the bone and the potting material.

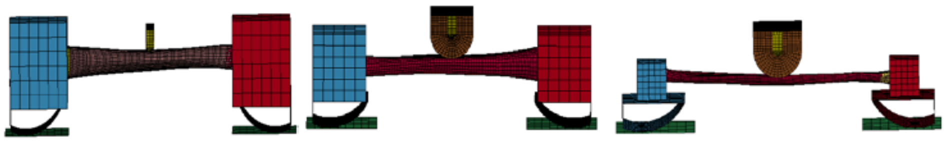


Figure 7.The FE model of dynamic three-point bending test of long bones

4 RESULTS AND DISSCUSION

In all quasi-static three-point bending virtual tests, the fracture sites were near impactor. Figure 8 demonstrated the von Mises stress contour of two age groups of 30 and 80 years old when fracture happened. The fracture equivalent stress of young people was 126MPa, while just 89.7MPa for elderly people, which was lower than the range of 100-125MPa from Hang et al[17].

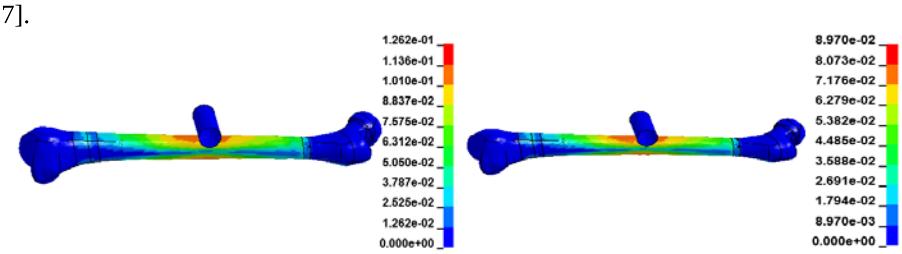


Figure 8.The von Mises stress cloud graphics of 30 and 80 years old when fracture happened.

A comparison of force-displacement curve between quasi-static virtual tests and published experiments of two age groups was given in Figure 9. In virtual tests, the femur ultimate bending moment of 30-year-old people was 237Nm, while 178Nm for 80-year-old people, which was consistent with the experimental results of Yamada et al [4]. The comparison result indicated that the simulation predictions were close to reported studies data, and the age-related parameters selected to describe the static properties of long bone were reliable.

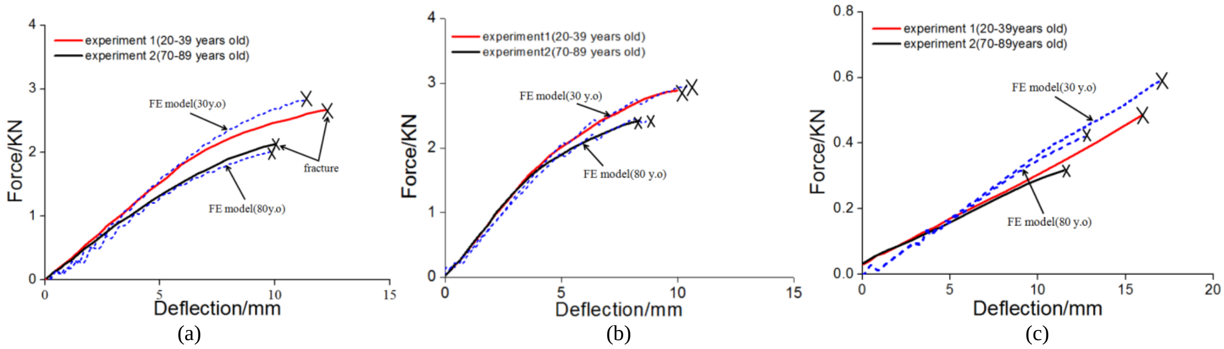


Figure 9. Quasi-static validation results for (a)femur,(b)tibia and (c)fibula.

The average age of specimen donators was about 55 years old in dynamic three-point bending tests, so the material parameters of long bone model were set based on previous research results. And the results of dynamic three-point bending tests were shown in Figure 10; the bones were fractured at the opposite side of the impactor.

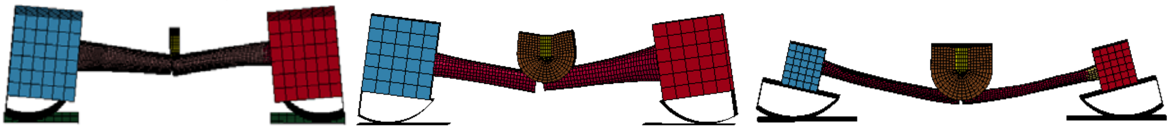


Figure 10.The simulation results of dynamic tests

A comparison of force-displacement curve between quasi-static virtual tests and published experiments of three age groups was given in Figure 11. It can be seen that the femur fracture force was 4.4KN, moment was 361Nm, this result was coincident with the research result of Kerrigan etal[15](412±114Nm) and Martens et al[18](373±84Nm). The tibia fracture force was 3.7KN, moment was 296Nm, which was coincident with the research result of Kerrigan et al[15](3.57±0.8KN and 310±50Nm). And the ratio of femur moment to tibia was 1.22, it coincident with the research result of Nyquist et al[19](1.21) and Kerrigan et al[15](1.33).

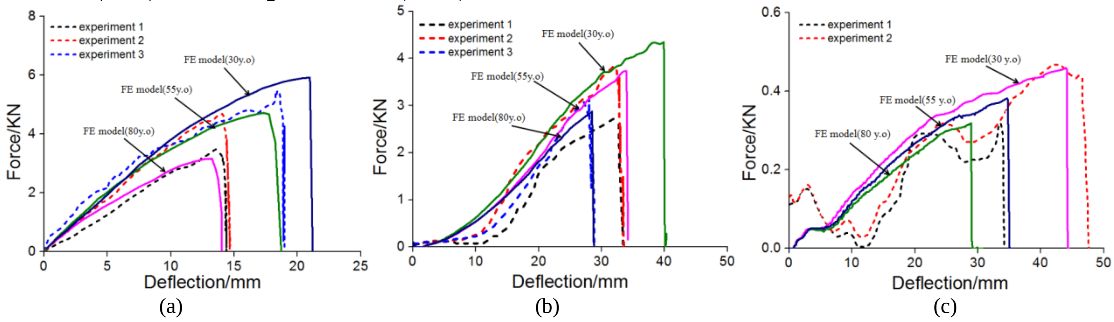


Figure 11. Dynamic validation results for (a) femur,(b)tibia and (c)fibula.

All the virtual tests results indicated that the updated long bones FE model had high bio-fidelity, and could accurately reproduce the dynamic stiffness and failure condition for different age groups.

And then the relationship of long bones injury tolerance with age under dynamic loads was studied based on this model. As shown in Figure 12, the injury tolerance of femur, tibia and fibula were decreased with age, and the tolerance would decline 27.6Nm, 18Nm and 1.4Nm respectively for the femur, tibia and fibula every 10 years. It means when people at his 80-year-old, his tolerance of femur was only 68.8%, tibia was 74.1%, while fibula was 77.3% of the tolerance at his 30-year-old.

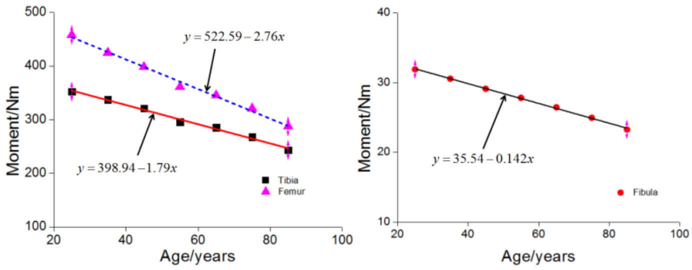


Figure 12.Effect of age on long bone tolerance

5 CONCLUSION

This paper studied the effect of age on lower extremity skeletal material properties and injury tolerance based on published biomechanical experiment data and finite element virtual tests. An updated FE model of lower extremity long bone was built and validated with three-point bending virtual tests under the quasi-static and dynamic conditions, and the effect of age on skeletal material parameters and geometry was studied, based on the virtual tests results and the published past mortal human subject (PMHS) tests data, the regularity of age-related injury tolerance of lower extremity long bone was found out. That would provide an effective support to improve the existing injury evaluation index as well as the bio-fidelity of FE model. The lower extremity FE model with age-related property, which built in this study, could be used in the research of injury mechanism in vehicle to elderly people accident. The research results of this study would also be available and useful for further study of age-related biomaterial properties, such as ligaments, muscles and other soft tissues.

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