Biomechanical Analysis of Femoral Damage Mechanisms Related to Total Hip Arthroplasty

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論　文　内　容　の　要　旨
Thesis Summary

Total hip arthroplasty (THA) has become a common solution for addressing end-stage hip diseases in middle-aged and older patients. Risk factors that contribute to the complications following THA may related to bone variables (quality, strength, geometry), implant design and implant position. Numerous studies have focused on improving THA outcomes by utilizing computational techniques such as finite element analysis to enhance implant design. However, these studies have been limited to homogeneous bone models, which do not accurately reflect the reality of bone structure. Due to the unrealistic computational bone model, biomechanical analyses investigating the relationship between bone variables and outcomes after THA are rarely conducted.

In Chapter 1, I discussed the different fixation methods employed in THA procedures, namely cemented and cementless methods, as well as the current implant designs that assist in choosing between these methods. I also identified the association between fixation methods and implant design, to the potential biomechanical complications such as implant loosening and periprosthetic femoral fractures. Additionally, this chapter reviewed existing biomechanical studies concerning implant design and computational bone models.

In Chapter 2, I investigated the mechanisms of micro-damage formation in femoral bones using the CT-image-based finite element method under two different boundary conditions: lateral bending and torsional conditions. Two inhomogeneous finite element bone models were developed based on CT images of 61-year-old and 87-year-old patients, and three types of stems were introduced to represent corresponding cementless THA models. The results revealed that implant geometries, such as shoulder size, stem length, and cross-section shape, influenced the damage behaviour of the models. Furthermore, it was observed that the elderly patient had a higher risk of implant loosening, even at lower loading magnitudes, compared to the younger patient. Additionally, several fracture locations were predicted on both femoral models upon complete failure. Notably, the fracture types were clearly classified according to the Vancouver

classification and the AO Foundation/Orthopaedic Trauma Association.

In Chapter 3, I conducted further investigation to determine the mechanism of bone micro-damage formation under different falling configurations, specifically from the lateral to posterolateral side of the femur. The study revealed a correlation between stem geometry and damage behaviour in the internal region of bone X under varying falling configurations. However, no correlation was observed in bone Y. Additionally, the internal damage distribution of the THA models in bone X exhibited a pattern of concentrated damage at zone 1 and zone 7 of the Gruen zone system, which remained consistent across all stem designs and falling configurations. In THA models of bone Y, the damaged distributions were scattered throughout the bone-stem interfaces, with damaged elements found in all zones of the Gruen zone system. Furthermore, it was found that the observed fractures aligned with type AG of the Vancouver fracture classification, which occurred in all THA models.

In Chapter 4, I examined the impact of bone variables, including density, geometry, angle of femoral torsion, and thickness of the femoral cortices, on the formation of bone micro-damage following THA, using 28 intact femoral bone models with different ages. Among these models, 10 femoral bones were selected for implantation with the Zweymuller stem, divided into two groups based on the highest and lowest bone mineral density. The study revealed a strong correlation between bone density and fracture load. However, a moderate correlation was observed between bone density and the number of solid element failures, which also remained consistent across all boundary conditions. Furthermore, femoral models with a bent shape of the femoral shaft and thin cortices experienced greater bone damage compared to models with normal geometry. Additionally, THA models with retroversion stem placement resulted in higher bone damage compared to models with normal anteversion placement.

In Chapter 5, a collarless and collared version of a similar cementless THA stem was implanted into a finite element bone model developed from a CT image of a 61-year-old patient with avascular necrosis. The results revealed higher strain values in the bone model implanted with the collarless stem compared to the collared stem under both boundary conditions. However, the percentage difference in strain values between the two models was more significant under axial compression. Furthermore, greater internal bone damage was observed in the collarless model than in the collared model under both boundary conditions, as indicated by the distribution of solid element failures. Additionally, the presence of a collar was found to affect the strength of the bone, and the location of the bone fracture was similar in both models, as illustrated by the shell element failures. The collared stem version may improve implant stability following cementless total hip arthroplasty and promote better outcomes.

Finally, in Chapter 6, all results are summarized as a general conclusion.