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DESIGN METHOD BASED ON THE CONCEPT OF EMERGENCE AND ITS APPLICATION

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ABSTRACT:

In the early process of design, diverse ideas of design must be obtained from global solution search under the constraint of unclear design conditions. It is difficult to derive an adequate design solution to a design object with complicated conception because the current method of deriving diverse solutions depends solely on designer's experience and knowledge. Therefore, it is thought that, with a method of deriving diverse solutions globally, it leads to the further improvement of design environment. In this research, we propose the system based on emergent design that derives diverse solutions that can be applied to the early process of design, by using the concept of emergence that explains the origin and evolution of the organism. Moreover, we aim to indicate the possibility of deriving diverse solutions using the emergent design system, by applying this system to artifact design and comparing this system with the conventional optimization method.

Keywords: Emergence, diverse design solutions, early process of design

1. INTRODUCTION

The design process can be divided roughly into two processes: the early processes of design corresponding to conceptual design and basic design, and the late processes of design corresponding to detailed design. In the early process of design, diverse ideas of design must be obtained from global solution search under the constraint of unclear design conditions. On the other hand, in the late process of design, a unique solution is obtained from local solution search under the constraint of clear design conditions. In conventional engineering design, a unique solution is obtained from local solution search because it uses the optimization methods. This method is not applicable to the early process of design obtaining diverse solutions while it can apply to the late process of design. In the early process of design, it is difficult to derive an adequate design solution to a design object with complicated conception because the current method of deriving current diverse solutions depends solely on designer's experience and knowledge. Therefore, it is thought that, with a method of deriving diverse solutions globally, it leads to the further improvement of design environment. In this research, we propose the emergent design system that derives diverse solutions that can be applied to the early process of design, by using the concept of emergence that explains the origin and evolution of the organism. Moreover, we aim to indicate the possibility of deriving diverse solutions using the emergent design system, by applying this system to artifact design and comparing this system with the conventional optimization method.

2. EMERGENCE AND EMERGENT DESIGN METHOD

2. 1. ANALOGY BETWEEN EMERGENCE PROCESS AND DESIGN PROCESS

In the natural world, various organism species exist in the same environment. In the fields of biology and ecology, scientists began to regard that various organism species were created in the process of emergence. In the field of system engineering, emergence is defined as obtaining new functions, structures, or actions by-two-way dynamic processes (Kitamura S). The first process (bottom-up process) involves the generation of global order using local interactions among elements that behave independently. The second process (top-down process) involves the binding behaviors of elements using the global order (Fig.1).

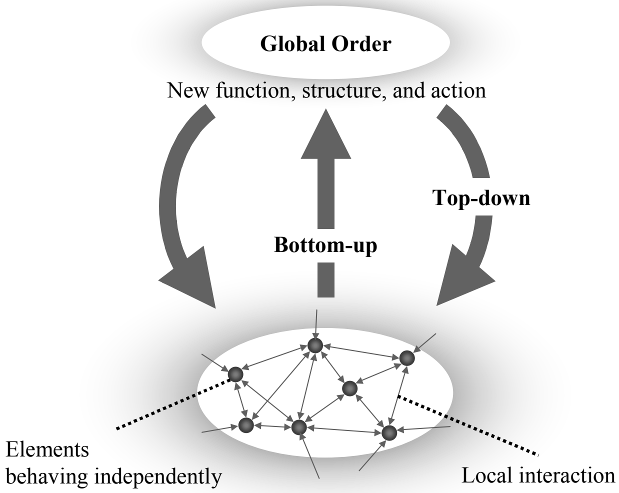


Figure 1: Concept of emergence.

The process of design can be expressed as follows. First, in the early process of design, an evaluation is given to the design proposal, which is obtained from designers' intuition. The design proposal is dismissed when the evaluation does not meet the standard, and the design proposal is adopted when the evaluation fulfils the standard. Then the design proposal obtained in the early process is optimized in the late process of design, and the design solution is derived.

In comparison with this design process and the emergent process, the following similarities can be found. First, the process of generating the design proposal with the evaluation meeting a certain standard is similar to the bottom-up process that generating the entire feature by autonomous components' interaction in the emergence. Second, the process of optimizing detailed part of design proposal is similar to the top-down process that binds components by the entire feature in the emergence. These similarities indicate the possibility of applying the concept of emergence to the design.

2. 2. CONCEPT OF EMERGENT DESIGN METHOD

The design method based on emergence is called the emergent design method. This method has two processes; the bottom-up process and the top-down process of emergence. In the bottom-up process, a design proposal is obtained when diverse ideas of design derived under unclear design conditions satisfy the standards set by the designer. In the top-down process, the design ideas derived by the bottom-up process are optimized. As a result, it is possible to derive diverse design solutions maintaining the diversity of the design idea obtained in the bottom-up process.

3. EMERGENT DESIGN SYSTEM

3. 1. BASIC STRUCTURE OF EMERGENT DESIGN SYSTEM

Figure 2 shows the emergent design system based on the emergent design method. The emergent design system consists of bottom-up process and top-down process. In the bottom-up process, diverse solution candidates that meet the low standard set by the designer are derived, and in the top-down process, to satisfy the constraint condition, those solution candidates are optimized. This system derives diverse solutions by going through these two processes.

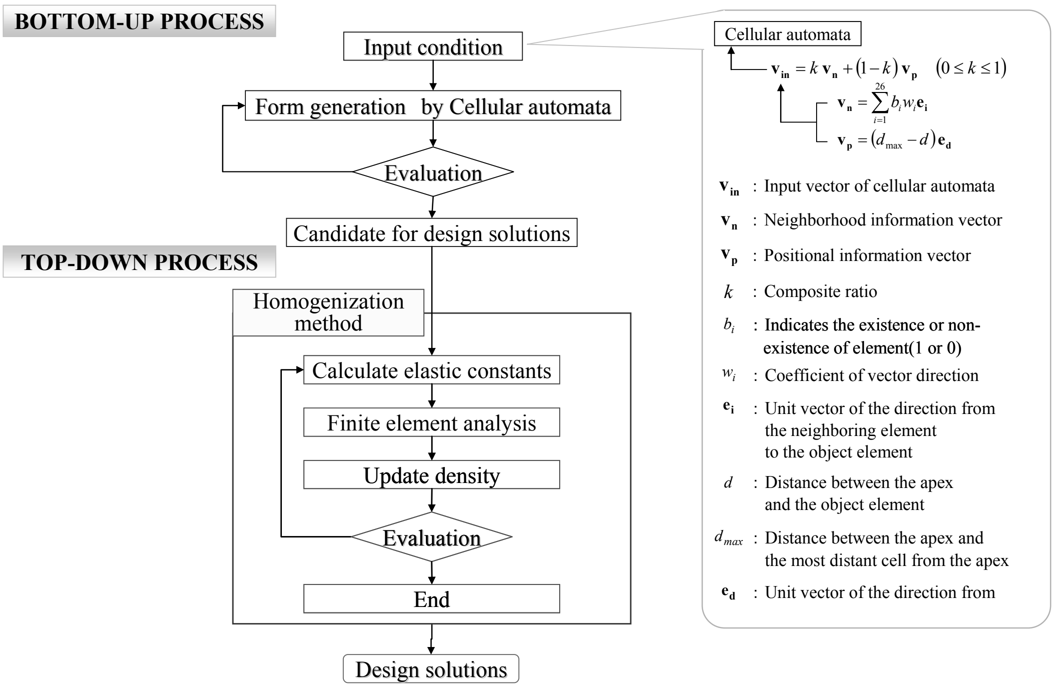


Figure 2: Emergent design system.

3. 2. BOTTOM-UP PROCESS

In bottom-up process, the forms are generated self-organizationally by using the cellular automata (CA). The diversity of an organism is noted, and rules referring to two properties for diverse organism morphogenesis, 'induction' and 'apical dominance,' are input vector to the CA(Fig.3).

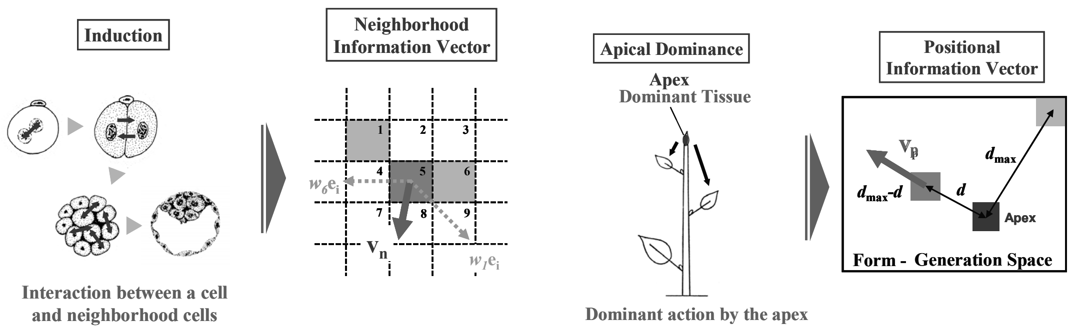
Firstly, we describe 'induction'. An organism is formed by interaction between neighborhood cells. Neighborhood cells affect a cell and change it into a cell exhibiting different features. This property is called induction. The first input is defined as neighborhood information vector $\mathbf{v_n}$, which is expressed by Eq. (1).

$$\mathbf{v_n} = \sum_{i=1}^{26} b_i w_i \mathbf{e_i} \quad (1)$$

Where i is the surrounding element number, b_i indicates the existence or non-existence of element (1 or 0), w_i is the coefficient of vector direction, and $\mathbf{e_i}$ is the unit vector of the direction to the object element.

Secondly, we describe 'apical dominance'. In the developmental process, a certain tissue dominates; for example, the buds of plants and heads of animals. Such tissue is called an apex, and dominant action by the apex is called apical dominance. The second input is defined as positional information vector $\mathbf{v_p}$, which is expressed by Eq. (2)

$$\mathbf{v_p} = (d_{\max} - d)\,\mathbf{e_d} \quad (2)$$



(a) Induction (b) Apical dominance

Figure 3: Modelling of input vector.

Where d_{max} is the distance between the apex and the most distant cell from the apex, d is the distance between the apex and the object element, and $\mathbf{e_d}$ is the unit vector of the direction to the object element. Moreover, the composite ratio k is set, and input vector $\mathbf{v_{in}}$ is defined as expressed by Eq. (3).

$$\mathbf{v_{in}} = k\,\mathbf{v_n} + (1-k)\,\mathbf{v_p} \tag{3}$$

Diverse forms can be generated by changing the composite ratio k. Thus, diverse design ideas are generated self-organizationally in the bottom-up process.

3. 3. TOP-DOWN PROCESS

In the top-down process, diverse solutions are derived by optimizing diverse ideas of design generated with the bottom-up process respectively. In this research, we execute topology optimization based on the homogenization method.

The homogenization method is explained as follows. The design domain is assumed to be composed of microstructures with periodicity, and the homogenized material constant is calculated from this relation between microstructures and macrostructures. In the topology optimization based on the homogenization method, the entire design domain is assumed to be composed of porous microstructures with regular periodicity, and the macro elastic constant homogenized from porous microstructures is calculated by the homogenization method. In addition, the state equation of the domain is solved by the finite element method using the elasticity tensor of each homogenized part, and repeatedly calculated until satisfying the objective function and the constraint condition (Kikuchi N). As a result of such topology optimization, the density of the design domain increases as the hole of porous microstructures narrows in the load part of the stress, and the density of the design domain decreases as the hole of porous microstructures extends in the no-load part of the stress. Hence, the optimal material distribution in the design domain can be derived.

4. APPLICATION OF EMERGENT DESIGN SYSTEM TO ARTIFACT DESIGN

In this research, when applying the emergent design system to a concrete artifact design, we selected an artificial hip, an artifact that is difficult to conceive for designers.

4. 1. INPUT CONDITIONS IN BOTTOM-UP PROCESS

The input conditions for the proposed system execution are: the form generation space that shows generation range of element, the initial seed element position that is position of element generation beginning, a size of element, the position of apex, the element-generation number that is the number of updating forms, and the composite ratio *k*. The form generation space and an initial seed element position were decided as shown in Figure 4. The form generation space was decided as follows. First, the femoral model like Figure 4(b) was made referring to an average size of thighbone of Japanese men shown in Figure 4(a) (Baba H). The position of the ball when the artificial hip was inserted from the center of femoral head as shown from this model in Figure 4(c) was decided, and the form generation space like Figure 4(d) was decided by basing the lesser trochanter on the position and the femoral diameter, etc. So as not to decrease the flexibility of the generation form, the initial seed elements were set as contact side with the ball shown in Figure 4(d) as the elements that existed in all the design solutions. The element size

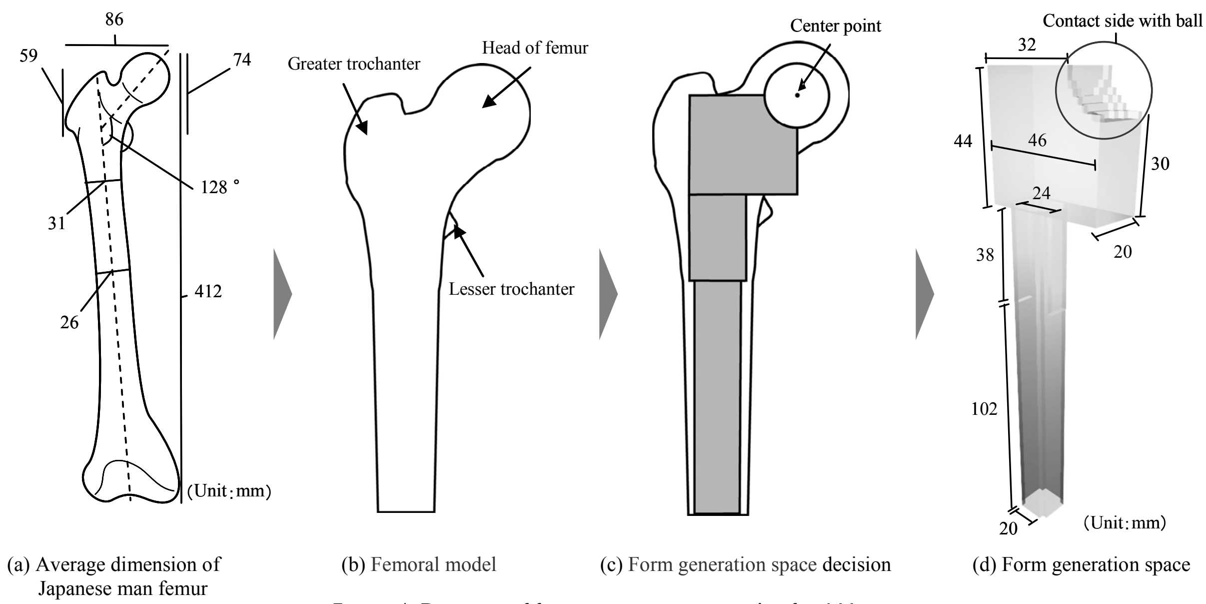


Figure 4: Decision of form generation space Artificial Hip.

was set to the length of 2mm on a side in consideration of the number of elements, and the position of apex was set to the center point of the ball supporting the load. The element-generation number was set to 150, and the forms were generated respectively as the composite ratio *k* was changed from 0.1 to 1.0 at 0.1 intervals, and 50 solution candidates were generated.

4. 2. INPUT CONDITIONS IN TOP-DOWN PROCESS

In top-down process, the femoral model without femoral head was set on the assumption that the stem is inserted inside of human body. The greater trochanter was kept in this femoral model, and the cancellous bone and the cortical bone were set as shown in Figure 5. The solution candidates obtained in a bottom-up process were inserted in this model, and optimized. Figure 5 shows the mechanics condition. In this research, the load to the femoral head and the abductor muscle were assumed at the one foot geostationary upright positioning, and the compressive load of 1500N was set from the perpendicular line to the inside of 13° at the stem head top part, the tension load of 1000N was set from the perpendicular line to the inside of 20° at the greater trochanter. Moreover, the constraint condition is a complete restraint on the thighbone bottom side (Sakamoto J. and Oda J). In addition, the material property value used in the top down process is indicated in Table 1. In this research, the titanium alloy (Ti-6Al-4V) with a remarkable affinity for human body was used as the material of the stem (Sakamaki T). The objective function was

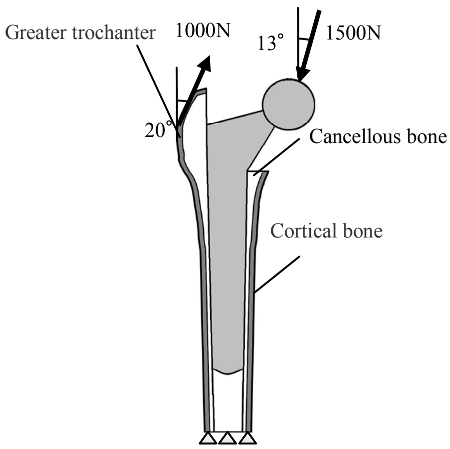


Figure 5: Loding and fixing conditions.

Table 1: Young's modulus and poisson's ratio.

	Young's modulus	Poisson's ratio
Cortical bone	15GPa	0.3
Cancellous bone	1GPa	0.3
Titanium alloy	126GPa	0.27

assumed to be average compliance (Eq. (4)), and the restriction condition was assumed to be a volume (Eq. (5)).

$$\text{minimize} \quad \Phi = \frac{1}{2}\int_{\Omega} \varepsilon^{T} \boldsymbol{D}^{H} \varepsilon d\Omega \tag{4}$$

$$\text{subject to} \quad \int_{\Omega} \rho d\Omega \le \boldsymbol{V} \tag{5}$$

Here, Ω is the design domain, *ε* is the strain, $\boldsymbol{D}^H$ is stress-strain matrix, *ρ* is dimensionless amount of the value from 0 to 1 that shows whether the element exists, and ***V*** is volume. As for expression (4), the strain energy conserved in the whole when the external force acts is shown, and forms with high stiffness are derived by minimizing the objective function (Kikuchi N).

4. 3. RESULT AND CONSIDERATION

Figure 6 and 7 shows the form generation process and examples of design candidates in bottom-up process. It was confirmed that diverse forms, forms with different length of stem, forms with different topology, skeleton forms, to have various features were generated from these results. Figure 8 shows design candidates in the bottom-up process, the solution in the top-down process, and idea sketches. From Figure 8, it was confirmed that the structure to satisfy the mechanics condition to have diverse topology had been generated. From these results, diverse forms were derived under the same initial condition in the bottom-up process. It was confirmed that diverse

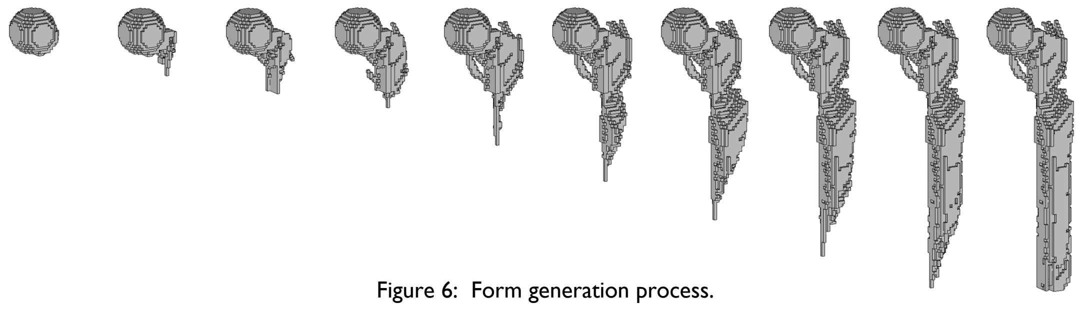


Figure 6: Form generation process.

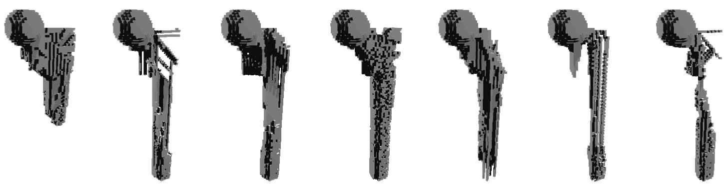


Figure 7: Examples of design candidates by bottom-up process.

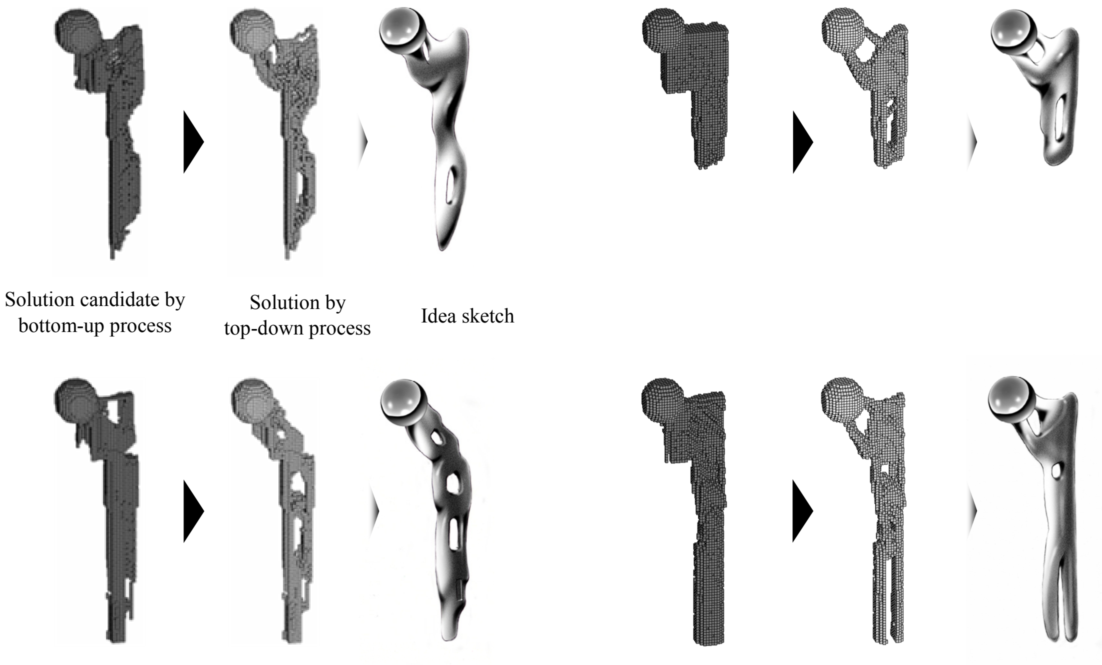


Figure 8: Examples of design solutions.

solutions were derived by optimizing each form in the top-down process, which was not possible with the established optimization methods that only derive a unique solution depending on initial form.

5. EFFECTIVENESS ANALYSIS OF PROPOSED SYSTEM

The form generation space filled with elements is set as initial form, and figure 9 shows a form to optimize the initial form by the topology optimization that uses the homogenization method. The solution shown in Figure 9 derived without going through the bottom-up process by the topology optimization that uses the homogenization method is defined as a conventional solution. Moreover, the solution derived through the bottom-up process and the top down process was

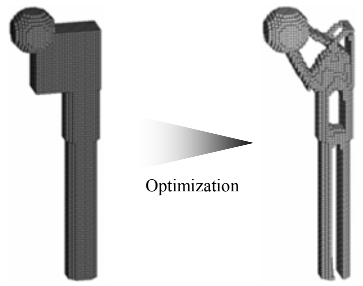


Figure 9: Solution by conventional optimization method.

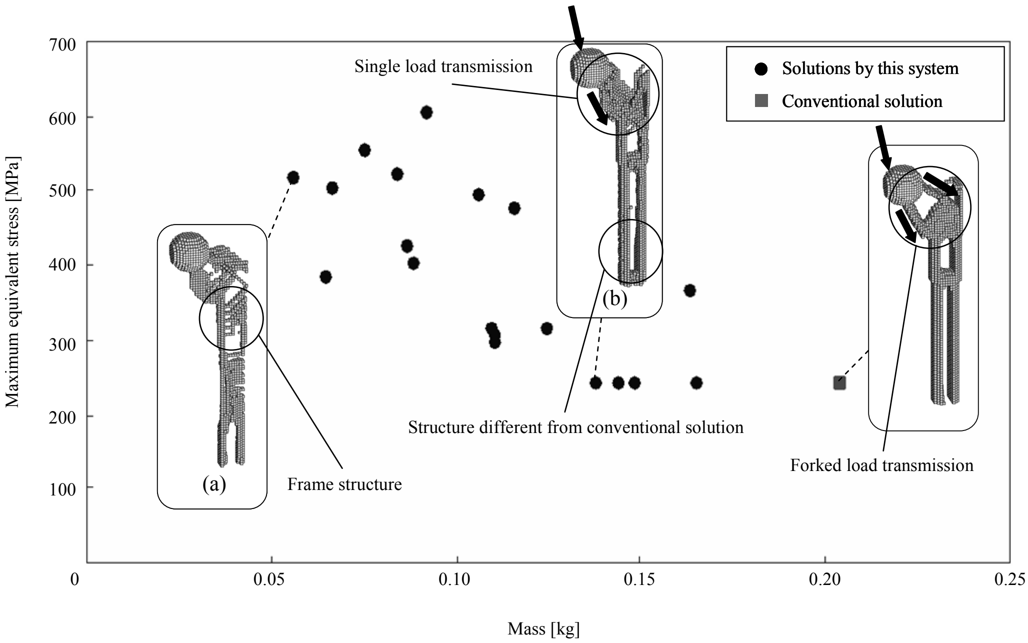


Figure 10: Comparison between mass and maximum equivalent stress.

defined as the solution by this system. Figure 10 shows the result of comparing 20 solutions derived by this system with the conventional solution about the mass and maximum equivalent stress. The stem of Figure 10(a) is lightened to about 25% compared with the conventional solution because the form is like a skeleton that has a number of holes. However, there is a part where high stress is shown in the structure of skeleton form.

Moreover, the form in the upper part of the stem of Figure 10(b) transmits the load from the ball by a different route from the conventional solution, and the form under the stem has improved the stiffness by uniting forked form at the bottom. From these results, it was confirmed that diverse solutions were derived; for example, a solution that is lightened maintaining the strength equal to the conventional solution and a solution that is lightened more than half weight compared to the conventional solution though the maximum equivalent stress indicates high value. Thus, the solutions, different from the conventional solution, were derived with reducing the weight and maintaining the strength, and the possibility of deriving diverse solutions using this system was indicated.

6. CONCLUSION

In this research, we proposed the emergent design system that derived diverse solutions and was applicable to the early process of design by using the concept of emergence, and applied to the artificial hip design. The possibility of deriving various solutions from this system was indicated by comparing the solutions derived from this system with the solution derived from conventional optimization method.

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REFERENCES:

Kitamura S. ,Emergent Systems-Toward a New Paradigm for Artificial Systems. Toward System Theory of Function Emergence. Society of Instrument and Control Engineers, 1996, 35(7), 492-495.

Kikuchi N. Optimum design theory by homogenization method. Bulletin of the Japan Society for Industrial and Appleied Mathematics, 1993,3(1), 2-26

Baba H. Anthropology 13 vols. And 3 additional vols.: Osteometry, 1991 (Yuzankaku Inc, Tokyo).

Sakamoto J. and Oda J. A Study on Development of the Total Hip Prosthesis Design Fitted for Japanese Patients (2nd Report, Shape Accuracy Estimation of the Femur CAD Model and Improvement in the Canal Fill Ratio of Prosthesis). Japan Society Mechanical Engineering, 2004, 70(697), 1186-1192.

Sakamaki T. The Recent Advance of the Artificial Hip Joint. Journal of the Keio Medical Society, 1997, 74(5), 293-302.