Bioinspired cane design and production using braiding technology

Jiro SAKAMOTO*, Takanori CHIHARA**, Tomonari AZUMA***, Toshiyasu KINARI*, Satoshi KITAYAMA*, Mitsugu KIMIZU****, Hiroyuki HASEBE**** and Daisuke MORI****

* Advanced Manufacturing Technology Institute, Kanazawa University,
Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan
** Institute for Frontier Science Initiative, Kanazawa University,
Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan
E-mail: chihara@staff.kanazawa-u.ac.jp
*** Graduate School of Natural Science & Technology, Kanazawa University,
Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan
**** Department of Textile and Life, Industrial Research Institute of Ishikawa,
2-1, Kuratsuki, Kanazawa, Ishikawa 920-8203, Japan

Received: 2 September 2020; Revised: 10 October 2020; Accepted: 20 October 2020

Abstract
Elderly people often use a cane to walk; it is an important part of their daily life. The cane must be made of a light weight material of high stiffness. In addition, stress relaxation on impact is required to make the cane easy to grasp. All these factors are affected by the shape design. Therefore, an effective shape design considering the stress relaxation on impact load and the weight of the cane is important. Traditionally, straight-type canes are widely used in the market. In this study, a bioinspired shape design methodology is proposed to produce canes. The basis vector method is used, and a multi-objective design optimization for minimizing the total volume and the maximum stress is performed. A sequential approximate optimization is then adopted to determine the Pareto optimal solutions. The superiority of the proposed method over the straight-type cane is confirmed through numerical results. The optimal cane shapes have more than 90% lower impact stress than the straight-type canes. Finally, a prototype of the optimized cane is produced using the braiding technology. Carbon fiber reinforced plastic is the selected cane material owing to its light weight and high stiffness.

Keywords : Biology, Cane design, Shape optimization, Multi-objective design optimization, Breading technology

1. Introduction
Elderly persons often use a cane to walk; therefore, it plays an important role in their daily life (Kuan et al., 1999; Liu et al, 2011). Conventionally, straight-type canes are widely used. The cane has to be lightweight and made of high stiffness material to ensure usability and safety. Straight-type canes have adjustable lengths and are very portable owing to their light weight. These canes are lightweight because of the uniform hollow section in them. In addition to structure, material selection is important for realizing the lightweight and high stiffness characteristics of the cane. Owing to the ease of production, aluminum and wood are widely used as materials (Mully, 1988). Carbon fibers, which are lighter than aluminum, are also popular.

Straight-type canes can be produced in huge quantities, but their shape design is rarely discussed (Jones et al., 2008; Li and Chou, 2014). Because the cane is subjected to an impact load from the ground, a curved design is preferable for relaxing the impact load. However, no such shape design exists. Shape optimization using the traction method (Azegami and Wu, 1996) is an effective approach to determine the cane shape under impact loads, but a large number of numerical simulations are required. In addition, the method is generally valid for single objective design optimization, but there are
many factors that need to be considered (objectives) in the conceptual design of a cane. Therefore, a multi-objective
design optimization is preferable for the shape design.

In this study, cane shape designs are inspired by biology. We have proposed a new design and manufacturing method
for hollow structures by using a database of biological form, design optimization technique and braiding technology
(Kinari et al., 2018). The braiding technology can manufacture a hollow structure having a complicated shape, so it can
be applied to a structure designed based on a biological form. The proposed method is an effective design and
manufacturing method that can perform optimal design based on biological form and realize it as a lightweight and high
strength structure made of carbon fiber reinforced plastic (CFRP). The outline of the proposed approach is summarized
as follows: First, several candidates for the shape design are selected from an already developed database of biological
forms (Kanazawa University, 2017). Next, candidates for optimal shape are determined using the basis vector method
(Kodiyalam et al., 1991). A preliminary analysis using the finite-element method (FEM) is conducted to select a few
candidates. Note that more than one candidate may be obtained owing to the multi-objective design optimization. In this
study, there are two objective functions: the total volume for reducing the weight, and the maximum stress at the grip to
relax the impact load. Both are minimized, and the Pareto optimal solutions are then determined. A sequential
approximate optimization (SAO) developed by one of the authors (Kitayama et al., 2011; Kitayama et al., 2012;
Kitayama et al. 2013) was adopted to determine the Pareto optimal solutions with limited simulations. Finally, based on
these numerical results, a cane is produced using braiding technology with CFRP as the material owing to its light weight
and high stiffness.

The remainder of this paper is organized as follows. In Section 2, shape optimization based on a database of ulna
forms and the numerical simulation model are described. The SAO using a radial basis function network for the multi-
objective design is also briefly explained in Section 2. In Section 3, the numerical results and discussion, and the cane
based on the numerical results, made of CFRP using the braiding technology, are presented. Finally, this study is
concluded in Section 4.

2. Methods

In this section, the shape optimization of a cane using the basis vector method is described. The numerical simulation
model is also described.

2.1 Multi-objective design optimization

In general, a multi-objective design optimization is formulated as follows (Miettinen, 1998):

$$\begin{equation}
\min_{x \in X} f_1(x), f_2(x), \ldots, f_k(x) \rightarrow \min
\end{equation}$$

where $f_i(x)$ is the $i$-th objective function to be minimized and $k$ represents the number of objective functions.

$x = (x_1, x_2, \ldots, x_n)^T$ denotes the design variables with $n$ dimensions, and $X$ is the feasible region.

2.2 Basis vector method

The basis vector method proposed by Kodiyalam et al. (1991) is a shape optimization technique in which several
candidates, called the basis vectors, are selected and the final shape $B$ is determined by Eq. (2).

$$B = B_0 + \sum_{i=1}^{n} x_i^B (B_i - B_0)$$

where $B_0$ is the reference vector that denotes the basic shape, $B_i$ denotes the $i$-th basis vector, $x_i^B$ is the $i$-th design variable,
and $n$ is the number of basis vectors, which is equal to the number of design variables. From Eq. (2), various shapes can
be expressed according to the design variables. The basis vector method can directly handle three-dimensional (3D)
shapes with few design variables; representative works are published (Thiyagarajan and Grandhi, 2005; Weickum et al.,
2009; Yonekura and Watanabe, 2014).
2.3 Selection of basis vectors from a database of ulna forms

2.3.1 FEM analysis of impact load

Animals live in different environments, and their bone shapes are optimized for specific mechanical conditions (Sakamoto et al., 2010; Simons et al., 2011). We have developed a database of biological forms (Kanazawa University, 2017), from which several candidates for the basis vector method are selected. Only the outer shape of the cortical bone was of interest owing to the hollow structure required for cane design. Therefore, cancellous bone was not considered. A preliminary mechanical analysis, the FEM, was conducted to select a few candidates from the nine possible models. Figure 1 shows nine ulna models used in the preliminary analysis. These models were selected to cover various shapes. In addition, we focused on the ulna assuming that the ulna plays an important role in relaxing the impact load while walking.

Figure 2 shows the boundary conditions of the FEM analysis. The top and bottom edges of the models were in contact with the rigid wall and floor, respectively. The top edge was assumed to be the grip. We assume that the ground is a rigid body, with friction coefficient $\mu$ set to 0.5, and that the cane was contiguous with the ground. Then, an initial velocity of 0.1 m/s in the xy-plane was set for the cane to mimic walking. The stress at the grip was evaluated. Marc Mentat 2015.0.0 (MSC Software Inc.), which is a dynamic explicit finite-element analysis code, was used in the numerical simulation. The grip edge had 16 nodes. We assumed that the appropriate cane length for elderly persons would be 700 mm based on the styliion height of Japanese elderly people (National Institute of Advanced Industrial Science and Technology, 2020). The mesh matching method (Couteau et al., 2000) was then used to develop the computer-aided design (CAD) models for numerical simulations. A 4-node shell-type element with isotropic elasticity was used. Because the cane is to be manufactured as a CFRP hollow structure of constant thickness using braid technology, the shell thickness was set to 2.0 mm, and the average material properties of CFRP was used. The CFRP woven with carbon fiber by braiding technology has a relatively small in-plane anisotropy, unlike CFRPs laminated with unidirectionally-strengthened prepregs. Therefore, the Young's modulus is isotropic. The material properties are listed in Table 1.

![Ulna bone models of nine animals for the preliminary FEM analysis to select models for shape optimization.](image-url)
2.3.2 Results of preliminary analysis

The results of the preliminary analysis are shown in Fig. 3. Note that the impact value will be defined in Section 2.4. An ulna with lower volume and impact values implies a better shape to effectively absorb the impact from the ground. The ulnas of the flying squirrel and serow have relatively lower volume and impact values. In addition, an ox ulna has a lower impact value with intermediate volume. Therefore, the three ulna models (i.e., the flying squirrel, serow, and ox) were selected as candidates for shape optimization.

The ulna of the flying squirrel was selected as the reference vector $B_0$. The ulnas of the serow and ox were selected as the basis vectors $B_1$ and $B_2$, respectively. $x_1^B$ and $x_2^B$ denote the weight coefficients of these two models, respectively. Therefore, $x = (x_1^B, x_2^B)^T$ is the design variable vector.

The model generated using the basis vector method is called the BV model. For clarity, two illustrative examples using the basis vector method are shown in Fig. 4, where various shapes are expressed using only two design variables.

2.4 Objective function

As described earlier, a cane must be light for portability. Therefore, the total volume of the cane is taken as the first objective function, $f_1(x)$. Next, let us consider the second objective function $f_2(x)$. A cane is subjected to an impact load from the ground, which is transmitted to the grip. Minimizing this impact load makes the cane easy to grasp. Therefore, the following is taken as the second objective function (hereafter referred to as the impact value) and minimized.

$$f_2(x) = \int_{\Delta t} \sigma_{bv}(x, t) dt$$  \hspace{1cm} (3)

where $\sigma_{bv}(x, t)$ denotes the magnitude of the stress on the top plane on the grip for the BV model, and is calculated by averaging the absolute stress in the vertical direction ($z$-direction in Fig. 2) of 16 nodes on the top edge in time $t$. $\Delta t$ represents the time duration of the impact. In this study, $\Delta t = 3.0 \times 10^{-4}$ s.
Fig. 3 Volume and impact values of the nine ulna models. Lower volume and impact values imply better performance as a cane. The ulnas of flying squirrel, serow, and ox show relatively better performance compared with the other ulnas.

Fig. 4 Illustrative example of shape using basis vector method. An arbitrary shape is generated from the three ulna shapes by changing the design variables $x_1^B$ and $x_2^B$.

2.5 Flow to identify Pareto frontier by SAO

SAO, which repeatedly constructs and optimizes the response surface, is recognized as a powerful design optimization tool. In this study, SAO using a radial basis function (RBF) is adopted to identify the Pareto frontier between the total volume and the impact value. The detailed procedure is available in the literature (Kitayama and Yamazaki, 2011). Here, we briefly describe the flow to identify the Pareto frontier. The detailed procedure for constructing a response surface using the RBF network is provided in Appendixes.

The flow to identify the Pareto frontier between the total volume and the maximum stress is summarized as follows:

(STEP1) Initial sampling points are determined using the Latin hypercube design (LHD).

(STEP2) Numerical simulations are carried out at sampling points, and objective functions (the total volume and the impact value) are numerically evaluated.

(STEP3) The objective functions are approximated using the RBF network. Here, the approximated objective functions are denoted as $\tilde{f}_i(x)$ ($i = 1, 2, \cdots, k$).

(STEP4) The Pareto optimal solutions of the response surface are determined using the weighted $l_p$ norm method formulated as follows:
\[
\left\{ \begin{array}{l}
\sum_{i=1}^{k} \left( \alpha_i f_i(x) \right)^{1/p} \rightarrow \min \\
\sum_{i=1}^{k} \alpha_i = 1 \\
\alpha_i \geq 0
\end{array} \right. 
\]  

where \( \alpha_i \) (i = 1, 2, \ldots, k) represents the weight of the \( i \)-th objective function and \( p \) is the parameter, which is set to 4. To obtain a set of Pareto optimal solutions, various weights are assigned. The optimal solution of Eq. (4) is taken as the new sampling point for updating the response surface. Thereby, the local accuracy is improved.

(STEP5) The density function described in Section A.2 is used to find the unexplored region. The optimal solution of the density function is added as a new sampling point. This step is repeated until the terminal criterion is satisfied. This step is introduced for the uniform distribution of sampling points. Thereby, global approximation is achieved.

(STEP6) If a terminal criterion is satisfied, the SAO algorithm terminates. Otherwise, it returns to STEP 2. The average error between the response surface and the numerical simulation at the Pareto optimal solutions in STEP 4 is taken as the terminal criterion, which is set to be within 5%.

3. Results and discussion

3.1 Numerical results

Figure 5 shows the Pareto frontier. The objective functions at the Pareto frontier are listed in Table 2. The stresses at Pareto optimal solutions of OP2 and OP3 are less than those of the three candidate models (i.e., the flying squirrel, serow, and ox). This indicates that the optimization based on our method improved the stress acting on the grip. The weight vectors (\( x_1^B \) and \( x_2^B \)) of the serow and ox models at the Pareto optimal solution are approximately 0.43–0.64 and 0.21–0.32, respectively. This indicates that the optimum cane shape is not significantly affected by the specific model. However, the cane shape that minimizes the volume and stress on the grip is obtained by fusing the three different ulnas and the effectiveness of the proposed optimal design method was clarified.

![Fig. 5 Pareto frontier of the volume versus the impact value. The black diamonds and grey circles show the objective function values of the three candidate ulna models and Pareto optimal solutions, respectively.](image)

| Pareto optimal solution | Weight coefficient of serow model \( x_1^B \) | Weight coefficient of ox model \( x_2^B \) | Volume \( f_1 \) [\( \times 10^4 \) mm\(^3\)] | Impact value \( f_2 \) [\( \times 10^{-5} \) MPa·s] |
|------------------------|---------------------------------|---------------------------------|-----------------|-----------------|
| OP1                    | 0.433                           | 0.210                           | 13.3            | 3.10            |
| OP2                    | 0.581                           | 0.267                           | 16.3            | 2.43            |
| OP3                    | 0.644                           | 0.318                           | 18.4            | 1.32            |
In Fig. 5, it is interesting that the value of the serow model is on the Pareto front and is comparable to the optimal solution. As typified by Roux's maximum-minimum law, bone has a morphology adapted to its mechanical load environment (Roux, 1883). Since flying squirrels fly, their bones are extremely light, and oxen bear a large weight, so they have thick bones. Although serows are not as big as oxen, their bones need to be both light and strong because they move a long distance while supporting the same weight as a human. It is probable that the ulnar shape of the serow was suitable for the loading conditions set for the design of the cane. This suggests the effectiveness of selecting the ulna shape as the basis vector in the mechanical shape optimization.

### 3.2 Comparison with straight cane

The validity of the curved shape cane shown in Section 3.1 is examined. A typical straight-type cane of length 700 mm was used for comparison. The cylindrical diameters of the straight-type cane models for OP1, OP2, and OP3 were 30.5 mm, 37.4 mm, and 42.2 mm, respectively. A thickness of 2.0 mm is used for the same volume.

Figure 6 shows the comparison of the stress between Pareto optimal solutions and the straight-type canes. Compared to straight-type canes, the stress in the Pareto optimal solutions are drastically improved. The curved part of the optimal shape absorbs the impact load and consequently reduces the stress at the grip. It is clear from Fig. 6 that the cane, designed by the proposed method, achieves lower impact value than the typical straight-type cane.

![Fig. 6 Comparison of impact values between Pareto optimal solutions in Fig. 5 and straight-type canes with same volumes of corresponding Pareto optimal solutions.](image)

### 3.3 Production using braiding technology

Based on the three ulnar shapes of the flying squirrel, serow, and ox, the optimum design of the cane takes weight and shock absorption as multi-purpose functions. The shape of the flying squirrel ulna is strongly reflected in the lightweight design among the Pareto optimal solutions. Figure 7 shows the shape of the flying squirrel ulna model that was used as the basic vector, in side view (xz-plane), front view (yz-plane), and horizontal cross-section including the upper and lower surfaces. A gentle S-shaped curve is observed in the side view, and the cross-sectional shape varies depending on the height. The cross-section is large on the hand side and smaller toward the tip. The shape of the cross section is close to an ellipse with its major axis in the front–rear direction on the hand side; toward the tip, the shape is closer to a circle. Because a gentle curve is present in the front and side views, the structure is a complicated 3D curve. It is difficult to manufacture such a shaft-like hollow structure. 3D printers can create such shapes; however, the strength of printable materials are low. Therefore, a hollow structure cannot achieve sufficient strength; a solid structure makes the cane heavier.

However, the braiding technique can create a hollow structure, as shown in Fig. 7, that is light and strong. For demonstrating this, a cane shaped as a flying squirrel ulnar bone is manufactured with CFRP using braiding technology. The manufacturing process is as follows: Using the stereolithographic (STL) data of the outer shape of the cane model, a mandrel for braiding was made from acrylonitrile butadiene styrene (ABS) resin using a 3D printer. A carbon fiber preform was braided on the mandrel with continuous carbon fiber 12K yarn (Torayca T700SC, Toray) using a circular braiding machine (Kokubun Ltd.). The mandrel was controlled by a 7-axis robot arm (MR20L, NACHI-Fujikoshi Co.)
during the braiding to adapt to the complicated curved shape of the cane. An overview of the braiding machine and the production system is given in Fig. 8. Then, the mandrel and preform were placed in a vacuum-assisted resin transfer molding (VaRTM) process to maintain the preform structure with vinyl ester resin. Finally, the mandrel was dissolved, using a solvent specific to ABS resin, to form the hollow structure.

Figure 9 shows a braided CFRP cane. A cane similar to the model shown in Fig. 7 can be manufactured. In this prototype, the mandrel was created according to the outer shape of the model. Therefore, the cane was enlarged by the thickness of the CFRP. If the mandrel size considers the CFRP thickness, the product will be exactly as designed. Furthermore, the aforementioned optimum designs of the cane can be realized using the proposed method.

![Fig. 7 Side and front views, and cross sections of the flying squirrel ulna model.](image1)

![Fig. 8 Braiding machine (48 + 32 carrier braider) and production system.](image2)

![Fig. 9 Cane produced using the proposed method.](image3)
4. Conclusions

In this study, a bioinspired shape design methodology is proposed and applied to the cane design. The basis vector method was used for shape optimization. Two objective functions, the total volume of a cane for reducing weight and the maximum stress for relaxing the impact load are simultaneously minimized. To achieve these objectives, three types of ulnas are selected using the basis vector method. The SAO using the RBF network is used to identify the Pareto frontier. Through numerical results, an optimal cane that drastically reduces the impact load at the grip in comparison with a conventional straight-type cane was designed. Finally, an optimal cane of braided CFRP is produced.

Acknowledgments

Several results of this work are technically and financially supported by the Innovative Design/Manufacturing Technologies, Strategic Innovation Promotion Program (SIP) in Japan. This work was supported by JSPS KAKENHI Grant Number JP16K05972. We would like to express our sincere gratitude to all members of SIP. We would also like to thank Maho Kitayama and Yuka Maki, technical staff at Kanazawa University, for their contributions. We would like to express our gratitude to the Ishikawa Museum of Natural History for providing us animal bone samples.

Appendixes

A.1 RBF network

The response surface using the RBF network is given by

$$\hat{y}(x) = \sum_{j=1}^{m} w_j K(x, x_j)$$  \hspace{1cm} (A1)

where $m$ denotes the number of sampling points, which is equal to the number of simulations. $K(x, x_j)$ is the $j$-th basis function and $w_j$ denotes the weight of the $j$-th basis function. The following Gaussian kernel is generally used as the basis function:

$$K(x, x_j) = \exp\left(-\frac{(x - x_j)^T(x - x_j)}{r_j^2}\right)$$  \hspace{1cm} (A2)

In Eq. (A2), $x_j$ represents the $j$-th sampling point, and $r_j$ is the width of the $j$-th basis function. The response $y_j$ is calculated at sampling point $x_j$. The RBF network learning is accomplished by solving the following equation:

$$\sum_{j=1}^{m} \left(y_j - \hat{y}(x_j)\right)^2 + \sum_{j=1}^{m} \lambda_j w_j^2 \rightarrow \text{min}$$  \hspace{1cm} (A3)

where the second term is introduced for regularization. It is recommended that $\lambda_j$ in Eq. (A3) be made sufficiently small (e.g., $\lambda_j = 1.0 \times 10^{-2}$). The conditions for Eq. (A3) results in the following equation:

$$w = (H^T H + A)^{-1} H^T y$$  \hspace{1cm} (A4)

where $H$, $A$, and $y$ are as follows:

$$H = \begin{bmatrix} K(x_1, x_1) & K(x_1, x_2) & \cdots & K(x_1, x_m) \\ K(x_2, x_1) & K(x_2, x_2) & \cdots & K(x_2, x_m) \\ \vdots & \vdots & \ddots & \vdots \\ K(x_m, x_1) & K(x_m, x_2) & \cdots & K(x_m, x_m) \end{bmatrix}$$  \hspace{1cm} (A5)
It is clear from Eq. (A4) that the weight vector $\mathbf{w}$ can be obtained through matrix inversion. The following simple estimate is adopted to determine the width in Eq. (A2) (Kitayama et al., 2011):

$$r_j = \frac{d_{j,\text{max}}}{\sqrt{n} \sqrt{m - 1}}$$  \hspace{1cm} j = 1, 2, \ldots, m \tag{A8}$$

where $n$ denotes the number of design variables, $m$ is the number of sampling points, $d_{j,\text{max}}$ is the maximum distance between the $j$-th sampling point and other sampling points.

### A.2 Density function

In the SAO, it is important to determine the unexplored region for global approximation (Sobester et al., 2005). Therefore, the addition of new sampling points around the unexplored region is needed. For determining the unexplored region with the RBF network, we have developed a function called the density function (Kitayama et al., 2011). The procedure for constructing the density function is summarized as follows:

1. **(D-STEP1)** The following vector $\mathbf{y}^D$ is prepared at the sampling points.

2. **(D-STEP2)** The weight vector $\mathbf{w}^D$ of the density function $D(\mathbf{x})$ is calculated as follows:

$$\mathbf{y}^D = (y_1, y_2, \cdots, y_m)^T \tag{A7}$$

$$\mathbf{w}^D = (\mathbf{H}^T \mathbf{H} + A)^{-1} \mathbf{H}^T \mathbf{y}^D \tag{A10}$$

3. **(D-STEP3)** The density function $D(\mathbf{x})$ is minimized. The point minimizing $D(\mathbf{x})$ is then taken as the new sampling point.

$$D(\mathbf{x}) = \sum_{j=1}^{m} w_j^D K(\mathbf{x}, \mathbf{x}_j) \rightarrow \min \tag{A11}$$

### References

Azegami, H. and Wu, Z.C., Domain optimization analysis in linear elastic problems: (Approach using traction method), JSME International Journal Series-A Mechanics and Material Engineering, Vol.39, No.2, (1996), pp.272–278.

Couteau, B., Payan, Y. and Lavallée, S., The mesh-matching algorithm: an automatic 3D mesh generator for finite element structures, Journal of Biomechanics, Vol.33, No.8, (2000), pp.1005–1009.

Jones, A., Monteiro Alves, A.C., de Oliveira, L.M., Saad, M. and Natour, J., Energy expenditure during cane-assisted gait in patients with knee osteoarthritis, Clinics, Vol.63, No.2, (2008), pp.197–200.

Kanazawa University, Design and production system, Japan patent JP 6614649, (2017) (in Japanese).

Kinari, T., Sakamoto, J., Kitayama, S., Maki, Y., Kawai, K., Suehiro, T., Kimizu, M., Mori, D. and Hasebe, H., Bio-innovative design technology and manufacturing system for CFRP preform by braiding structure, 2018 International Symposium on Flexible Automation, (2018), Paper No. L088.

Kitayama, S., Arakawa, M. and Yamazaki, K., Sequential approximate optimization using radial basis function network for engineering optimization, Optimization and Engineering., Vol.12, (2011), pp.535–557.

Kitayama, S., Arakawa, M. and Yamazaki, K., Sequential approximate optimization for discrete design variable problems using radial basis function network, Applied Mathematics and Computation, Vol.219, No.8, (2012), pp.4143–4156.

Kitayama, S., Srirat, J., Arakawa, M. and Yamazaki, K., Sequential approximate multi-objective optimization using radial basis function network, Structural and Multidisciplinary Optimization, Vol.48, (2013), pp.501–515.
Kitayama, S. and Yamazaki, K., Simple estimate of the width in gaussian kernel with adaptive scaling technique, Applied Soft Computing, Vol.11, No.8, (2011), pp.4726–4737.

Kodiyalam, S., Vanderplaats, G.N. and Miura, H.S., Structural shape optimization with MSC/NASTRAN, Computers & Structures, Vol.40, No.4, (1991), pp.821–829.

Kuan, T.S., Tsou, J.Y. and Su, F.C., Hemiplegic gait of stroke patients: The effect of using a cane, Archives of Physical Medicine and Rehabilitation, Vol.80, No.7, (1999), pp.777–784.

Li, Z.Y. and Chou, C., The effect of cane length and step height on muscle strength and body balance of elderly people in a stairway environment, Journal of Physiological Anthropology, Vol.33, No.1, (2014), Paper No. PMC4416409.

Liu, H., Eaves, J., Wang, W., Womack, J. and Bullock, P., Assessment of canes used by older adults in senior living communities, Archives of Gerontology and Geriatrics, Vol.52, No.3, (2011), pp.299–303.

Miettinen, K.M., Nonlinear Multiobjective Optimization (1998). Kluwer Academic.

Mully, G.P., Everyday aids and appliances: walking sticks, British Medical Journal, Vol.296, (1988), pp.475–476.

National Institute of Advanced Industrial Science and Technology, AIST Database on Anthropometric Dimensions 1991-92, available from <https://www.airc.aist.go.jp/dhrt/91-92/data/list.html>, (accessed on 24 August, 2020) (in Japanese).

Roux, W., Beiträge zur morphologie der funktionellen anpassung. I. Struktur eines hochdifferenzierten bindegewebigen organs, Arch. Anat. Physiol., (1883), pp.76–162.

Sakamoto, J., Arihara, K., Yamazaki, T. and Tai, H., A Study on mechanical adaptation of cervical vertebrae of giraffe. Proceedings of 6th China-Japan-Korea Joint Symposium on Optimization of Structural and Mechanical Systems, (2010), Paper No.8-85.

Simons, E.L.R., Hieronymus, T.L. and O’Connor, P., Cross sectional geometry of the forelimb skeleton and flight mode in pelicaniform birds, Journal of Morphology, Vol.272, No.8, (2011), pp.958–971.

Sobester, A., Leary, S.J. and Keane, A.J., On the design of optimization strategies based on global response surface approximation models, Journal of Global Optimization, Vol.33, (2005), pp.31–59.

Thiyagarajan, N. and Grandhi, R.V., Multi-level design process for 3-D preform shape optimization in metal forming, Journal of Materials Processing Technology, Vol.170, No.1-2, (2005), pp.421–429.

Weickum, G., Eldred, M.S. and Maute, K., A multi-point reduced-order modeling approach of transient structural dynamics with application to robust design optimization, Structural and Multidisciplinary Optimization, Vol.38, (2009), pp.599–611.

Yonekura, K. and Watanabe, O., A shape parameterization method using principal component analysis in applications to parametric shape optimization, Journal of Mechanical Design, Vol.136, No.12, (2014), Paper No.121401.