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Extraction of Motion Characteristics in Dances by Statistical Analysis of Joint Motions

Takeshi Miura,†1 Kazutaka Mitobe,†1
Takashi Yukawa,†2 Takaaki Kaiga,†3,†4
Toshiyuki Taniguchi†1 and Hideo Tamamoto†1

In this paper, the authors attempt to develop a technique for the analysis of the motions of dances having no stylized motion structure, focusing on joint motions. The variance-covariance matrix given by the statistical analysis of the time-series data of joint motions is selected for the evaluation index characterizing dance motions. The application of the derived evaluation index to the representation of dissimilarity between dances is shown to be effective when the whole commonness appearing in both the dances compared should be considered. It is also confirmed that the application of multidimensional scaling (MDS) with the orthogonal rotation of coordinate axes is effective to extract the distribution feature of a database of dances. The evaluation items characterizing all the dances belonging to the database are automatically extracted by the analysis of correlation between the coordinate axes given by MDS and the elements of the variance-covariance matrix.

1. Introduction

Recently there has been considerable interest in dance motion analysis. It may be attributed to the fact that the utilization of motion capture systems realizing the quantitative record of human-body motions allows us to analyze dance motions more precisely than previous trials. In particular, the analysis of dance motions in intangible cultural properties including many Japanese traditional and folk performing arts is a subject of growing interest [1),2)]. It has been stimulated by the eager entreaty for the preservation and transmission of them.

It is well known that dances belonging to the group of traditional performing arts, such as the Japanese traditional dance *Nihon Buyō*, have strictly-stylized structures in their motions. There have been many studies on the motions of traditional dances. In several works, the information of the stylization was utilized to define the evaluation indexes of motions and, as a consequence, the successful extraction of motion characteristics was accomplished [1)].

As for dances belonging to the group of folk performing arts, stylization of motions is seen in few cases: e.g., the Japanese folk dance *Bon Odori*. In order to make it possible to extract motion characteristics from such dances, it is necessary to develop an analysis technique in which some evaluation index of motions is prepared to allow us to comprehend how dance motions characterize themselves. For the analysis of the motions of folk dances, efforts have been devoted to extracting the motion primitives included in a folk dance by segmenting the motion data on the time axis [2),3)], to utilizing the keyposes of a folk dance to realize the low-dimensional representation of dance motions [4)], etc. Nevertheless, few studies have been reported on the development of analysis techniques based on the conception of the clarification of the evaluation index characterizing each of the dances.

Turning now to a discussion from the viewpoint of biomechanics, it is well recognized that dance motions are produced by synthesizing, in other words by coordinating, the motions of individual joints, the same as other human-body motions. Each individual joint motion is represented by the rotation of a body segment below the joint [5)]. The rotation is composed of three fundamental joint movements: flexion/extension, adduction/abduction and medial/lateral rotation [5)]. One can obtain the characteristics of a joint motion from the amount of each of the fundamental movements included in it. The information of joint coordination is also obtained by grasping the interrelation among the individual joint motions. This fact leads to the possibility that the evaluation index characterizing dance motions is given by analyzing the obtained joint-coordination information. It is also expected that the derived index has a systematic form attributed to the resolution of a joint motion into the fundamental movements. No information about the stylization of motions is needed in the above analysis.

To our knowledge, there have been several preliminary studies on the analysis

†1 Faculty of Engineering and Resource Science, Akita University
†2 Faculty of Law, North Asia University
†3 Graduate School of Engineering and Resource Science, Akita University
†4 Digital Art Factory, Warabi-za Co., Ltd.

of joint motions in dances [6),7)]. However, the possibility of giving the evaluation index which characterizes dance motions has not been sufficiently elaborated.

In order to gain insight into the above possibility, the authors attempt, in this paper, to develop a technique for the analysis of the motions of dances having no stylized motion structure, using the information of joint motions. The techniques of multivariate statistical analysis [8)] are used for the analysis of joint motions since the time-series data of them are given in the form of multivariate data.

The procedure to extract the characteristics of individual dances is first investigated. The variance-covariance matrix [9)] derived from the statistical analysis of the time-series data representing joint motions is selected for the evaluation index of motion characteristics in a dance. The application of the derived evaluation index to the representation of dissimilarity between two dances is then shown as an example of the effective utilization. The derived dissimilarity is compared with that given by the technique of dynamic time warping (DTW)[10)], which is frequently used to obtain distance between motion data [3)], to confirm the effectiveness of the present method. An attempt to extract the evaluation items which characterize all the dances belonging to a database is finally made. The technique of multidimensional scaling (MDS)[11)] is applied to all the dissimilarities between the dances belonging to the database.

2. Model of a Human Body

In this paper, a human-body model with skeletal structure is used in order to represent dance motions by the information of joint motions, in other words by the temporal variation of joint angles. The influence of difference in body constitution among dancers is eliminated by the use of this type of human-body model.

As mentioned in Section 1, a joint motion consists of the three fundamental movements. The aspect of them is shown in **Fig. 1**. In order to describe all these movements, a joint angle should be represented by the three-degree-of-freedom (3DOF) rotation of a body segment below the joint [6)]. In this paper, the exponential map [12)] $\boldsymbol{v} \in \Re^3$ is used to describe the joint angles; $\boldsymbol{v}/|\boldsymbol{v}|$ is the unit vector along the rotation axis and $|\boldsymbol{v}|$ is the rotation angle. The exponential map parameterizes 3DOF rotations in the Euclidean space, except for the singular point [12)]. In order to eliminate the influence of singularity, the human-body model shown in **Fig. 2** is used in this paper. It has 15 rigid body segments connected at 14 joints, and each segment has a corresponding reference orientation with a local coordinate system arranged so that the singular point is removed to the outside of the movable range of each of the joints [6)]. The local coordinate systems are assigned to the respective body parts indicated by the dotted lines in Fig. 2.

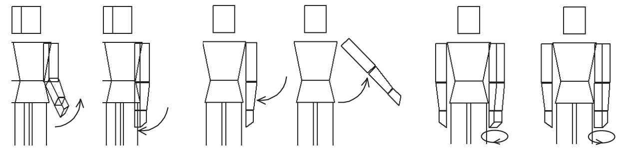


Fig. 1 Fundamental joint movements; (a) flexion/extension, (b) adduction/abduction, (c) medial/lateral rotation.

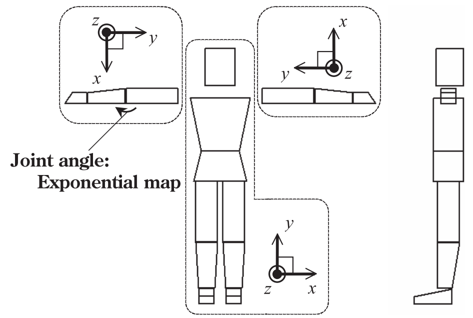


Fig. 2 Model of a human body.

It should also be pointed out that the coordinate axes in this model correspond to the axes of body movement respectively as follows: x−frontal axis, y−vertical axis and z−sagittal axis [5)]. As a result, the individual components of the exponential map correspond to the respective fundamental joint movements as follows: v_x−flexion/extension, v_y−medial/lateral rotation and v_z−adduction/abduction.

The number of the variables used for the representation of all the joint angles is 42 (14 joints × 3 components). Hence, the motion data is described as the time-series data of the 42-dimensional vector $\boldsymbol{u}(n) = [\ u_1(n) \quad u_2(n) \quad \cdots \quad u_{42}(n)\ ]^T$ where n is the frame number, and thereby given as multivariate data.

3. Extraction of Motion Characteristics by Statistical Analysis

3.1 Motion Data

The motion data of dances used in this paper are shown in **Table 1**. These were acquired by motion capture systems with magnetic sensors. All the dance numbers in Table 1 are selected from the folk dances of Akita Prefecture, Japan. They belong to the category *Furyū* which is one of the categories of Japanese folk performing arts and includes the subcategories *Bon Odori*, *Nenbutsu Odori*, etc [13]. Many dance numbers belonging to this category have no stylized structure in their motions. The motion data of a walk are added for comparison.

3.2 Representation of the Evaluation Index of Motion Characteristics by the Variance-covariance Matrix

Consider a database to which the motion data of M dances are provided. The motion data of the mth dance in the database ($m = 1, 2, \cdots, M$) consist of the time-series data of the vector ${}^m\boldsymbol{u}(n) = [\ {}^m u_1(n) \quad {}^m u_2(n) \quad \cdots \quad {}^m u_{42}(n)\ ]^T$ ($n = 1, 2, \cdots, {}^m N$). The variance-covariance matrix derived from the statistical analysis of time-series motion data is thought to give the motion characteristics in a dance [6]. The matrix for the mth motion data is given as follows:

$$ {}^m\boldsymbol{S} = \begin{bmatrix} {}^m s_{11} & \cdots & {}^m s_{1\,42} \\ \vdots & \ddots & \vdots \\ {}^m s_{1\,42} & \cdots & {}^m s_{42\,42} \end{bmatrix} \tag{1} $$

$$ {}^m\bar{u}_j = \frac{1}{{}^m N} \sum_{n=1}^{{}^m N} {}^m u_j(n) \tag{2} $$

$$ {}^m s_{jk} = \frac{1}{{}^m N} \sum_{n=1}^{{}^m N} \{{}^m u_j(n) - {}^m\bar{u}_j\}\{{}^m u_k(n) - {}^m\bar{u}_k\} \tag{3} $$

The variances obtained as the diagonal elements give the information of the appearance frequencies of the fundamental movements in the corresponding joints, while the covariances obtained as the non-diagonal elements give the structure of joint coordination in multiple joint motions.

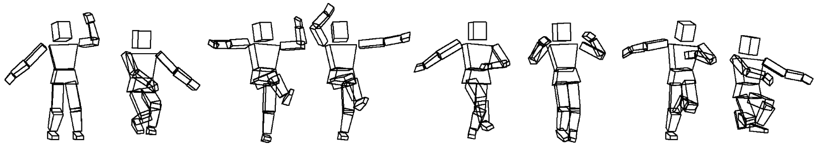
It is noted that the above variance-covariance matrix has the form invariant to the variation of the number of frames. The characteristics of the dance motions, especially those in a spatial aspect, are "summarized" by the statistical calculation in Eqs. (2) and (3). This fact leads to the advantage that the special procedure for the segmentation of motions on the time axis, which is frequently needed in dance motion analysis, is not required.

Figures 3 and **4** show the examples of 3D animations and variance-covariance matrices derived from the motion data of two dances selected from Table 1. Figure 3 is for *Akita Ondo* and Fig. 4 for *Jinku Odori* of *Kemanai Bon Odori*. It is obvious from the 3D animation of *Akita Ondo* shown in Fig. 3 (a) that the individual joints of the limbs actively move. This tendency is reflected on the values of the elements of the variance-covariance matrix shown in Fig. 3 (b). In Fig. 4 (a), on the other hand, the tendency that the motion of the legs in *Jinku Odori* is smaller than that of *Akita Ondo* is confirmed. It is also reflected on

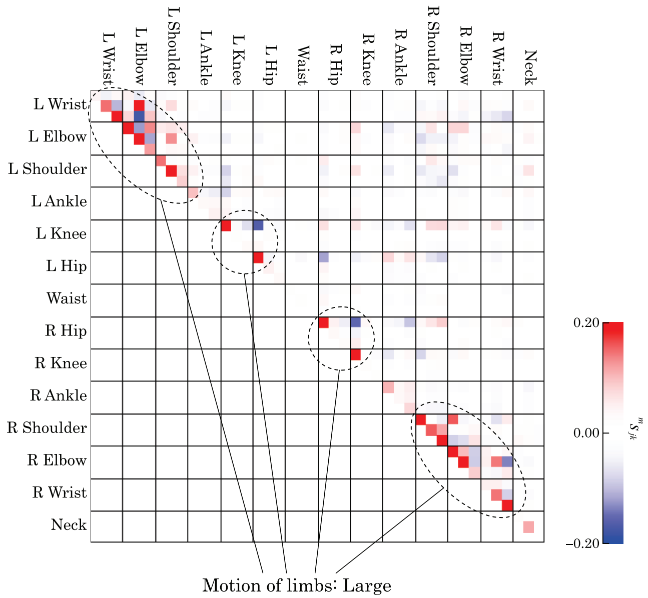
Table 1 Motion data (Folk dances of Akita Prefecture, Japan, frame interval: 33.3 ms).

Dance		Dancer	Frame	System
Akita Obako		female	4,086	A
Akita Ondo		female	2,041	A
Nishimonai Bon Odori	*Ondo*	female	1,351	A
	Ganke	female	1,251	A
Masuda Bon Odori		female	2,096	B
Iwasaki Bon Odori	*Otoko Odori*	male	2,191	B
	Onna Odori	female	2,221	B
Kakumagawa Bon Odori		female	1,766	B
Hitoichi Bon Odori	*Sankatsu Odori*	female	356	B
	Dendenzuku Odori	female	195	B
	Kitasaka Odori	female	169	B
Donpan Odori	*Nishizaki Emazō*	female	1,377	B
	Nishizaki Donpan	female	1,406	B
Gannin Odori		male	851	B
Kemanai Bon Odori	*Jinku Odori*	female	301	C
	Dainosaka Odori	female	316	C
Walk ("02_02" in http://mocap.cs.cmu.edu)		-	75	-

A: STAR*TRAK™ (Polhemus)
B: MotionStar Wireless™ (Ascension Technology Corporation)
C: MotionStar Wireless™ with LIBERTY™ (Polhemus) ×2

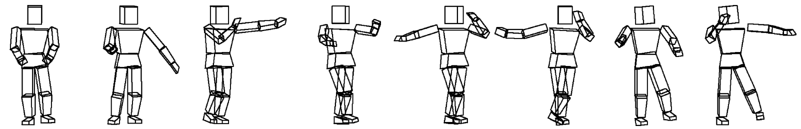


(a)

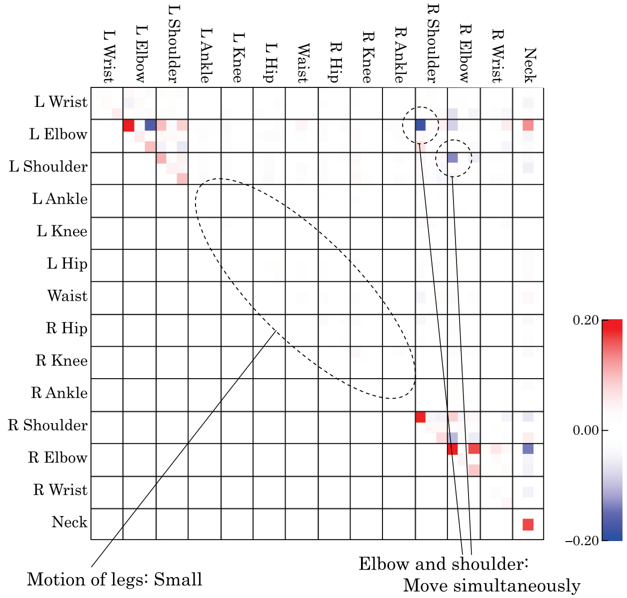


(b)

Fig. 3 Evaluation of motion in *Akita Ondo*; (a) part of the motion, (b) variance-covariance matrix.



(a)



(b)

Fig. 4 Evaluation of motion in *Jinku Odori* of *Kemanai Bon Odori*; (a) part of the motion, (b) variance-covariance matrix.

the variance-covariance matrix as shown in Fig. 4 (b). In addition, the frequent appearance of the motion having the joint coordination consisting of the shoulder-flexion/extension movement and the elbow-flexion/extension movement in *Jinku Odori* is also indicated in Fig. 4 (b), while no similar joint coordination is shown in *Akita Ondo*.

As is evident from the above results, the variance-covariance matrix gives the motion characteristics peculiar to each dance in fact. An additional remark which should be made here is that the joint or joints giving considerably large motions are easily confirmed by obtaining the values of the respective elements of the matrix.

Since there is no use for the information of the stylization of motion in the calculation of the variance-covariance matrix, the application to the analysis of other motion than that in a dance becomes possible. The result obtained from the analysis of the motion data of a walk prepared in Table 1 is shown in **Fig. 5** as an example. The joint-coordination structure shown in Fig. 5 (b) is previously

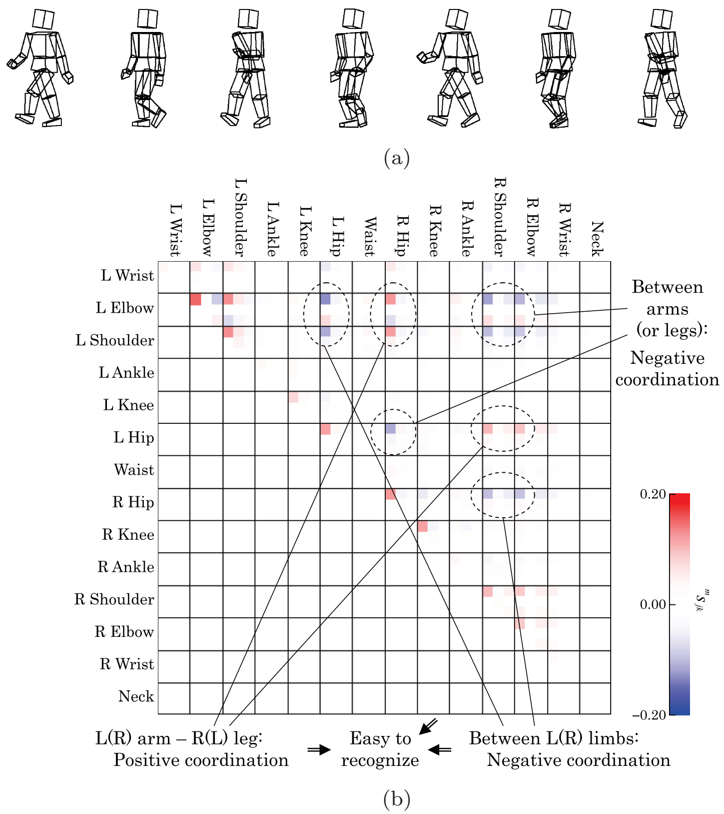


Fig. 5 Evaluation of motion in a walk; (a) part of the motion, (b) variance-covariance matrix.

and easily recognized in the motion data shown in Fig. 5 (a).

In dance motion analysis, on the other hand, the recognition of joint-coordination structure from raw motion data may be difficult since each dance includes a great variety of motions in its relatively long performing period. The utilization of the variance-covariance matrix is expected to assist the recognition of joint coordination under such circumstances. The case of *Otoko Odori* of *Iwasaki Bon Odori* is shown in **Fig. 6** as an example selected from Table 1. No prominent joint coordination is recognized in the motion shown in Fig. 6 (a), while

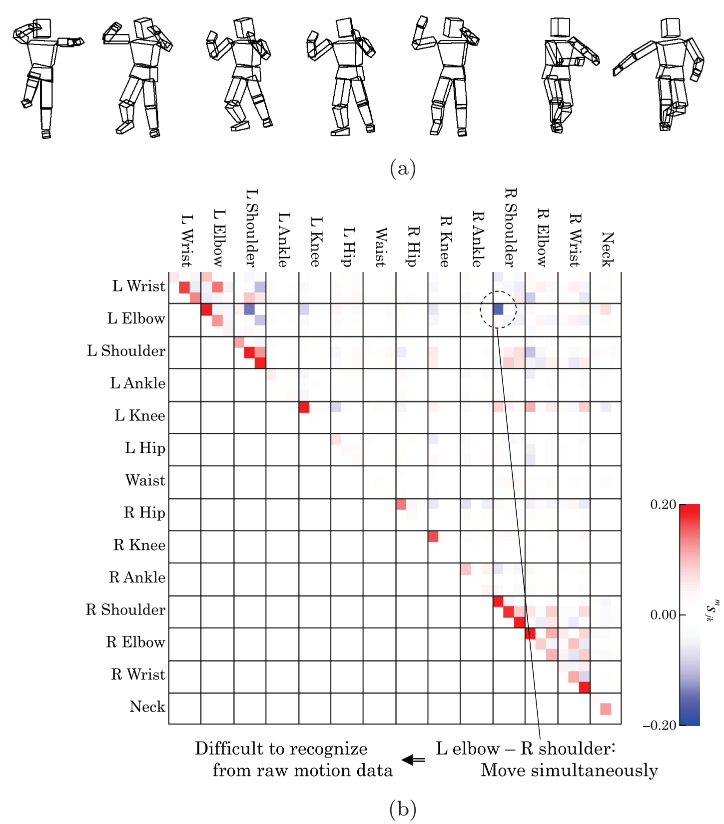


Fig. 6 Evaluation of motion in *Otoko Odori* of *Iwasaki Bon Odori*; (a) part of the motion, (b) variance-covariance matrix.

the existence of the coordination between the left elbow and the right shoulder is clearly confirmed in Fig. 6 (b). This result indicates that the variance-covariance matrix really has the suitability for dance motion analysis.

The above results lead to the consequence that the utilization of the variance-covariance matrix for the representation of the evaluation index of dance motion characteristics is quite reasonable. Furthermore, this index has the unified form, the form of a 42 × 42 matrix, irrespective of the diversification of motion data such as the difference of the number of frames, the variation of choreography, etc. Therefore, comparison of multiple dances becomes quite easy.

It should also be noted here that only the "summarized" information of motions in a dance is provided by the variance-covariance matrix. Several characteristics on the time axis such as the order of the motions included in the dance are not evaluated in the statistically-summarizing calculation in Eqs. (2) and (3).

3.3 Derivation of Dissimilarity between Dance Motions Using the Variance-covariance Matrix

In the field of dance motion analysis, it has been recognized that the establishment of the evaluation technique giving the degree of similarity, or dissimilarity, between motion data is desirable for the development of systems for similarity retrieval [14], the classification of dance motions [6], etc.

In order to obtain some insight into the above request, the authors try to derive the novel representation of dissimilarity between dances in this subsection, taking the advantage given by the evaluation index of motion characteristics represented by the variance-covariance matrix.

First, the time-series correlation matrix originally proposed in Ref. 15) is modified to permit an application to the motion data having the form mentioned in Section 2. The matrix is used in order to comprehend the correspondence between the motions of two dances on the time axis.

Dissimilarity between the posture in the n_lth frame of the lth motion data ${}^l\boldsymbol{u}(n_l)$ and that in the n_mth frame of the mth motion data ${}^m\boldsymbol{u}(n_m)$ is represented by using the Euclidean distance between ${}^l\boldsymbol{u}(n_l)$ and ${}^m\boldsymbol{u}(n_m)$ as follows:

$$d_p({}^l\boldsymbol{u}(n_l), {}^m\boldsymbol{u}(n_m)) = \sqrt{\sum_{k=1}^{42}\{{}^lu_k(n_l) - {}^mu_k(n_m)\}^2} \tag{4}$$

In Ref. 15), values of the elements of a time-series correlation matrix are given by calculating similarities between frames each extracted from each of the dances compared. Instead, in this paper, the dissimilarity obtained from Eq. (4) is used as a value of each element as follows:

$$\boldsymbol{D}(l,m) = \begin{bmatrix} d_p({}^l\boldsymbol{u}(1), {}^m\boldsymbol{u}(1)) & \cdots & d_p({}^l\boldsymbol{u}(1), {}^m\boldsymbol{u}({}^mN)) \\ \vdots & \ddots & \vdots \\ d_p({}^l\boldsymbol{u}({}^lN), {}^m\boldsymbol{u}(1)) & \cdots & d_p({}^l\boldsymbol{u}({}^lN), {}^m\boldsymbol{u}({}^mN)) \end{bmatrix} \tag{5}$$

The posture-normalization procedure [15] in which the direction of the body is normalized is unnecessary in the calculation of the elements of Eq. (5).

Next, the effectiveness of the novel representation of dissimilarity is investigated, being compared with the dissimilarity given by DTW as already mentioned in Section 1.

The DTW distance in which Eq. (4) is used as the distance between feature vectors is given as follows [10]:

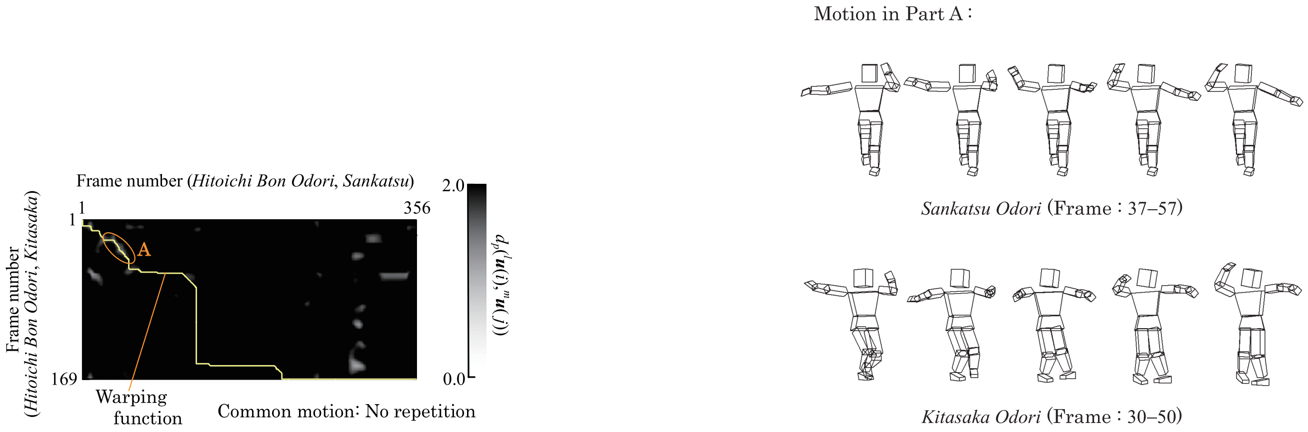
$$d_{\mathrm{DTW}}(l,m) = \frac{\min\left\{\sum_{c=1}^{C} d_p({}^l\boldsymbol{u}(n_{l_c}), {}^m\boldsymbol{u}(n_{m_c}))\cdot w_c\right\}}{{}^lN + {}^mN} \tag{6}$$

where

$$n_{l_c} = n_{l_{c-1}} \quad \text{or} \quad n_{l_c} = n_{l_{c-1}} + 1$$
$$n_{m_c} = n_{m_{c-1}} \quad \text{or} \quad n_{m_c} = n_{m_{c-1}} + 1$$
$$n_{l_C} = {}^lN, \quad n_{m_C} = {}^mN$$
$$w_c = \begin{cases} 1 & \text{for} \quad n_{l_c} = n_{l_{c-1}} + 1, \quad n_{m_c} = n_{m_{c-1}} \quad \text{or} \\ & \phantom{\text{for}} \quad n_{l_c} = n_{l_{c-1}}, \quad n_{m_c} = n_{m_{c-1}} + 1 \\ 2 & \text{for} \quad n_{l_c} = n_{l_{c-1}} + 1, \quad n_{m_c} = n_{m_{c-1}} + 1 \end{cases}$$

Figures 7 and **8** show the examples of comparisons between the dances selected from Table 1. Figure 7 is for the comparison between *Sankatsu Odori* and *Kitasaka Odori* of *Hitoichi Bon Odori* and Fig. 8 for *Ondo* and *Ganke* of *Nishimonai Bon Odori*. The modified time-series correlation matrix and DTW are used in these comparisons.

In the modified time-series correlation matrix shown in Fig. 7 (a), the existence of a motion appearing in both *Sankatsu Odori* and *Kitasaka Odori* is confirmed as a white line in Part A. The 3D animations of the motion are shown in Fig. 7 (b). It is seen that both the animations extracted from the respective dances are similar to each other. The path of the warping function [10] given by DTW passes



(a) (b)

Fig. 7 Time-series correlation matrix and warping function between *Sankatsu Odori* and *Kitasaka Odori* of *Hitoichi Bon Odori*; (a) correlation matrix and warping function, (b) 3D animations of common motion.

through the part of the motion as shown in Fig. 7 (a).

In the modified time-series correlation matrix shown in Fig. 8 (a), on the other hand, a motion appearing multiple times in both *Ondo* and *Ganke* is confirmed. An example of the appearance is shown as a white line in Part A. The 3D animations of the motion are shown in Fig. 8 (b). It is confirmed that the commonness between the dances is high in this motion. Although the motion appears three times in *Ondo* and twice in *Ganke*, the path of the warping function given by DTW passes through the part of the motion only once as shown in Fig. 8 (a). It is understood from these results that common motions included in both the dances compared are not sufficiently considered in DTW when their appearance instants are different in the respective dances.

Here, the authors suggest the application of the novel representation of dissimilarity between dance motions. It is derived from distance between variance-covariance matrices as follows:

$$d_{\mathrm{VC}}(l,m) = \sqrt{\sum_{j=1}^{42}\sum_{k=j}^{42}({}^{l}s_{jk} - {}^{m}s_{jk})^2} \tag{7}$$

The most striking feature of the above dissimilarity is that the variation of the appearance instants of common motions included in both the dances compared gives no influence. In addition, the calculation of Eq. (7) is easily performed for all the combinations of motion data without any special procedure since the matrix has the unified form irrespective of the variation of motion data as mentioned in Section 3.2.

Table 2 shows the dissimilarities of the dance combinations identical to Fig. 7 and Fig. 8. The DTW distance between *Sankatsu Odori* and *Kitasaka Odori* is nearly the same as that between *Ondo* and *Ganke*, while the variance-covariance-matrix distance of the former combination is larger than that of the latter. The insufficient consideration for the appearance instants of common motions may be responsible for the increase in the DTW distance of the latter combination.

The disadvantage of DTW shown in the above results may be solved by utilizing the motion primitives extracted by segmenting the motion data of dances on the time axis [3]. However, the segmenting method whose performance is clearly and sufficiently confirmed is not established in the present stage. On the other hand, no special procedure is demanded to calculate the variance-covariance-matrix

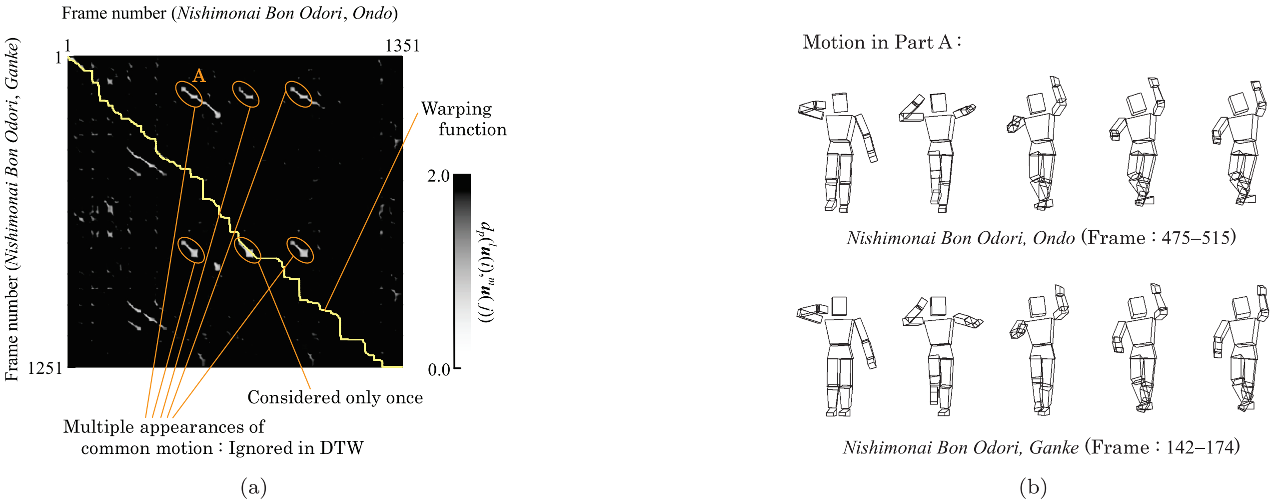


Fig. 8 Time-series correlation matrix and warping function between *Ondo* and *Ganke* of *Nishimonai Bon Odori*; (a) correlation matrix and warping function, (b) 3D animations of common motion.

Table 2 Dissimilarities between dances.

Dance combination	d_{DTW}	d_{VC}
Sankatsu Odori-Kitasaka Odori (*Hitoichi Bon Odori*)	2.329	0.920
Ondo-Ganke (*Nishimonai Bon Odori*)	2.323	0.656

distance as already mentioned.

These facts mean that the variance-covariance-matrix distance is more suitable for the representation of dissimilarity between dances than the DTW distance when all the appearances of the common motions included in both the dances compared should be considered. It should also be pointed out that the utilization of the variance-covariance-matrix distance is particularly effective for the comparison of multiple dance numbers, because the difference in the length of performing period and the variety of the appearance instants of motions, both are known as the major cause of the difficulty of dance motion analysis, are absorbed in the procedure of statistical calculation for time-series data.

The variance-covariance-matrix distance has the added advantage that the joint or joints indicating considerable difference between dances are easily recognized, since the differences appearing at the individual elements are separately represented as $({}^l s_{jk} - {}^m s_{jk})^2$ in Eq. (7). Examples for the dance combinations used in Fig. 7 and Fig. 8 are shown in **Fig. 9** and **Fig. 10**, respectively. It is confirmed by these results that the number of the joints giving considerable differences between *Sankatsu Odori* and *Kitasaka Odori* is greater than that between *Ondo* and *Ganke*, being consistent with the distances shown in Table 2.

Attention should also be given to the fact that the variance-covariance matrix provides only the summarized motion characteristics of each of the dances compared as mentioned in Section 3.2. This implies that the application of the DTW distance rather than that of the variance-covariance-matrix distance may be preferred when subtle differences of motions on the time axis should be considered: e.g., comparison between two dancers who perform the same dance number, etc.

As shown in the above discussion, the effectiveness and limitation of the variance-covariance-matrix distance in the representation of dissimilarity between

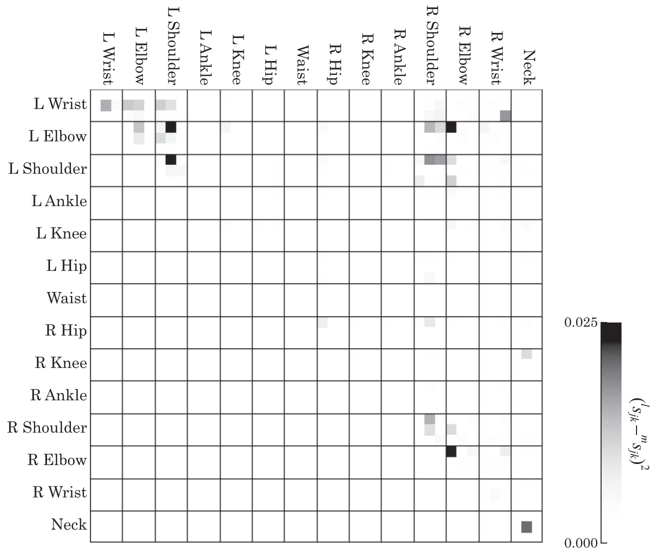


Fig. 9 Difference between *Sankatsu Odori* and *Kitasaka Odori* of *Hitoich Bon Odori* obtained from $({}^l s_{jk} - {}^m s_{jk})^2$.

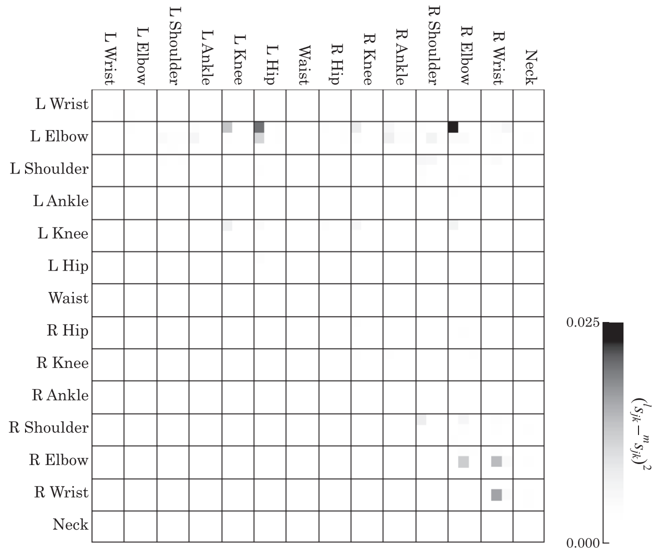


Fig. 10 Difference between *Ondo* and *Ganke* of *Nishimonai Bon Odori* obtained from $({}^l s_{jk} - {}^m s_{jk})^2$.

dances is finally confirmed.

3.4 Extraction of Evaluation Items for Characterization of a Database of Dances

Upon analyzing both the motion characteristics in the individual dances included in a database and all the dissimilarities between the dances, the comprehension of the interrelation among all the dances may become possible. Considering this possibility, an attempt is made, in this subsection, to develop the analysis technique giving the distribution feature of the characteristics of all the dances in the database.

The technique of MDS is adopted for the above analysis as already mentioned in Section 1. This technique is frequently used to represent the interrelation among objects belonging to a group, by distances in a low-dimensional space. Since the variance-covariance-matrix distance is defined on the concept of Euclidean distance as shown in Eq. (7), in other words defined in the metric space, the technique of metric MDS [8),11)] is applied.

In order to make the interpretability for the comprehension of interrelation among dances high, the evaluation items characterizing all the dances are extracted by analyzing the correlation between the coordinate axes of the space given by MDS and the elements of the variance-covariance matrix. The orthogonal rotation [16)] of the coordinate axes is performed in the above correlation analysis in order to make the solution given by MDS more interpretable. The detail is shown below.

A degree of correlation between a coordinate axis given by MDS and an element of the variance-covariance matrix is evaluated by the covariance between them. It is given by the statistical analysis of all the dances included in the database as follows:

$$c_{i,jk} = \frac{1}{M} \sum_{m=1}^{M} ({}^m a_i - \bar{a}_i)({}^m s_{jk} - \bar{s}_{jk}) \tag{8}$$

$$\bar{a}_i = \frac{1}{M} \sum_{m=1}^{M} {}^m a_i \tag{9}$$

$$\bar{s}_{jk} = \frac{1}{M} \sum_{m=1}^{M} {}^m s_{jk} \tag{10}$$

where $c_{i,jk}$ is the covariance between the ith axis and the j-k element, and ${}^m a_i$ is the coordinate of the ith axis given to the mth dance.

Let $\hat{c}_{i,jk}$ be the covariance between the rotated ith axis and the j-k element. When the squares of the $\hat{c}_{i,jk}$'s tend toward zero and some high value, the joint or joints considerably affected by the variation of the coordinate of the ith axis are clarified. As a result, the interpretability of this axis as that which gives an evaluation item characterizing dances becomes greater. The above condition is realized for all the axes by maximizing the varimax criterion given as the following formula [8),16)]:

$$V = \frac{1}{K} \sum_{i=1}^{p} \left\{ \sum_{j=1}^{42} \sum_{k=j}^{42} \hat{c}_{i,jk}^4 - \frac{1}{K} \left(\sum_{j=1}^{42} \sum_{k=j}^{42} \hat{c}_{i,jk}^2 \right)^2 \right\} \tag{11}$$

where p is the number of rotated axes and K is the substantial number of elements of the variance-covariance matrix; $K = 903$ since the matrix is a symmetric one as shown in Eq. (1). In this paper, the rotation angles maximizing the above criterion for all combinations of the axes are numerically searched.

Figure 11 shows the scatter plot of all the dances in Table 1. This is given by applying the metric MDS with the orthogonal rotation of the coordinate axes to the set of all the dissimilarities between the dances. The number of the rotated axes is ten. It is determined so that the stress [8)] becomes smaller than 0.1. The first two axes with high variances of coordinates are used for plotting.

Figure 12 shows the degrees of correlation between the axes of Fig. 11 and the elements of the variance-covariance matrix. Figure 12 (a) is for the correlation between Axis 1 and the elements and Fig. 12 (b) for Axis 2.

It is confirmed from Fig. 12 (a) that the coordinate of Axis 1 shows the prominent correlation with each of the diagonal elements which are the variances of the individual joint motions. In particular, the variances corresponding to the joints of the limbs indicate the strong correlation, while most of the other elements show little correlation. This result leads to the fact that the value of the coordinate of Axis 1 for each dance principally depends on the amount of the individual joint motions of the limbs. Therefore, the coordinate of Axis 1 can be regarded as the index corresponding to the item in which the amount of the joint motions of the limbs in each dance is evaluated.

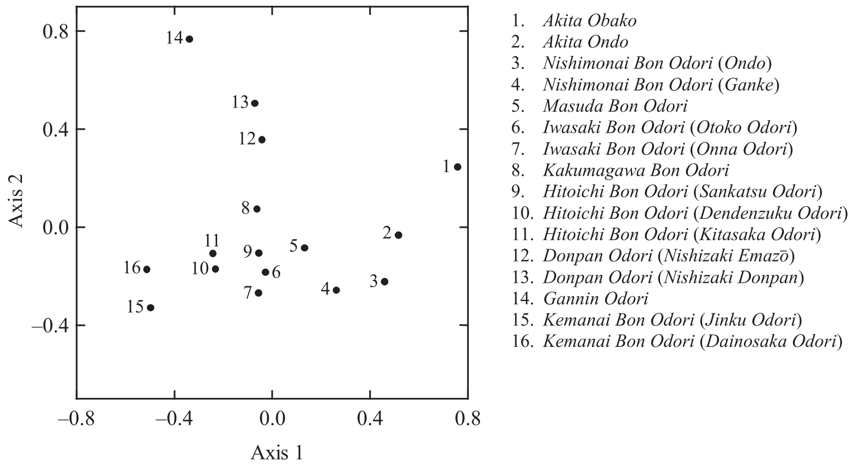


Fig. 11 Scatter plot of folk dances of Akita Prefecture.

In Fig. 12 (b), on the other hand, it is shown that the coordinate of Axis 2 indicates the strong correlation with the elements corresponding to the motion of the shoulders. In particular, the correlation with the elements corresponding to the joint coordination between both the shoulders should be noted. This implies that the amount of simultaneous motion of both the shoulders governs the variation of the coordinate of Axis 2. As a result, the coordinate of Axis 2 can be regarded as the index corresponding to the item in which the amount of the simultaneous motion of both the shoulders in each dance is evaluated.

Figure 13 shows the 3D animations of the dances giving the maximum and minimum coordinates for the respective axes used in Fig. 11. In Fig. 13 (a), it is confirmed that the joint motions of the limbs in *Akita Obako* giving the maximum

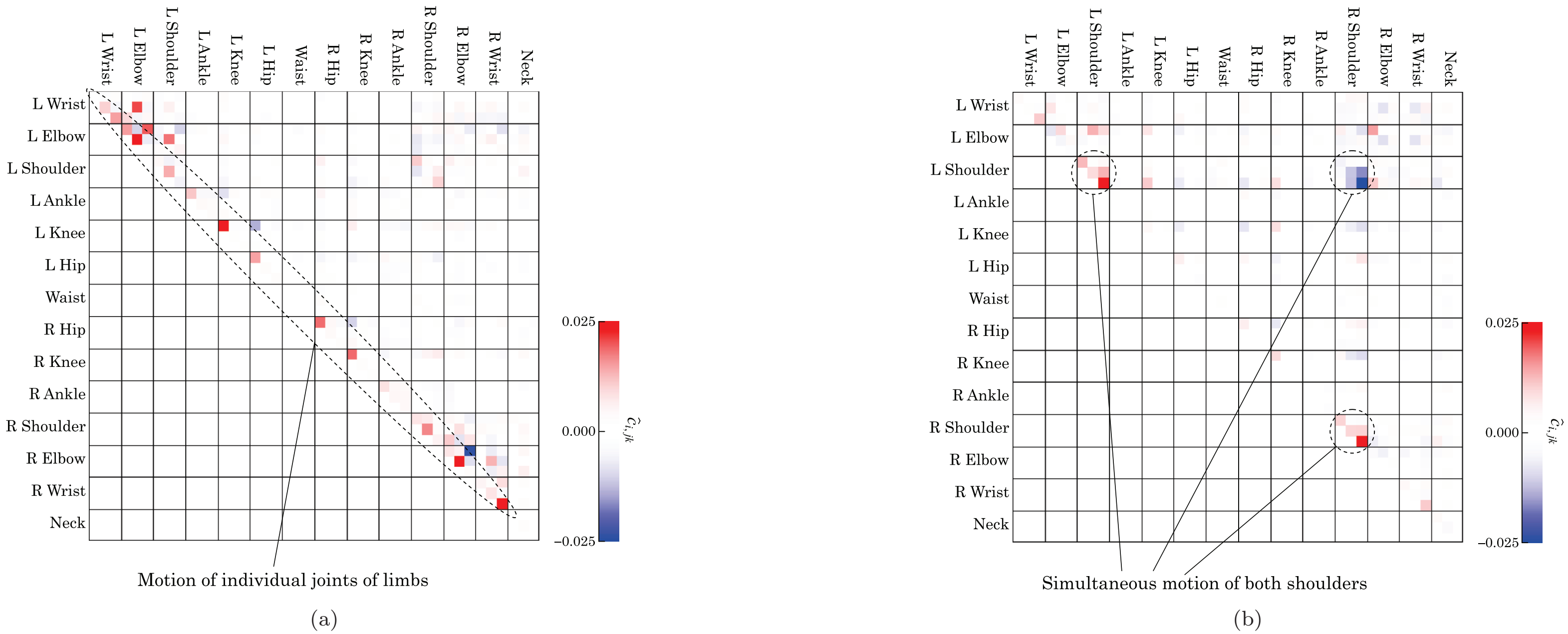


Fig. 12 Correlation of the axes given by MDS with the elements of the variance-covariance matrix; (a) Axis 1, (b) Axis 2.

coordinate for Axis 1 show a greater activity than those in *Dainosaka Odori* of *Kemanai Bon Odori* giving the minimum coordinate. The motions of the legs in the latter are particularly smaller than those in the former. In Fig. 13 (b), on the other hand, the simultaneous motions of both the shoulders are clearly confirmed in *Gannin Odori* giving the maximum coordinate for Axis 2, while the motions of the individual shoulders are separated from each other in *Jinku Odori* of *Kemanai Bon Odori* giving the minimum coordinate. These tendencies agree with the results of Fig. 12.

As mentioned in Section 3.2, the utilization of the variance-covariance matrix as the index of motion characteristics in a dance leads to the advantage that the segmentation of motions on the time axis is not required. This does not mean the prohibition of the segmentation. Therefore, the motion segment clipped from the entire time-series data of each dance can be used in the present method as the need arises.

Figure 14 shows the example of the analysis in which the motion segments clipped from the motion data of all the dances in Table 1 are used; only the beginning part of each dance (length: 150 frames) is clipped. The aspect of the distribution feature of the dances shown in Fig. 14 is quite different from that in Fig. 11. The difference arises from the concentration of the analyzed region upon the very short beginning part of each of the dances. This implies that the extraction of the motion characteristics peculiar to the specific parts receiving attention are also possible by the present method.

The development of a technique to segment dance motion on the time axis, such as that for the extraction of motion primitives in a dance, is insufficient in the present stage as mentioned in Section 3.3. However, trials to solve the problems in the segmentation are still proceeding and some successful technique

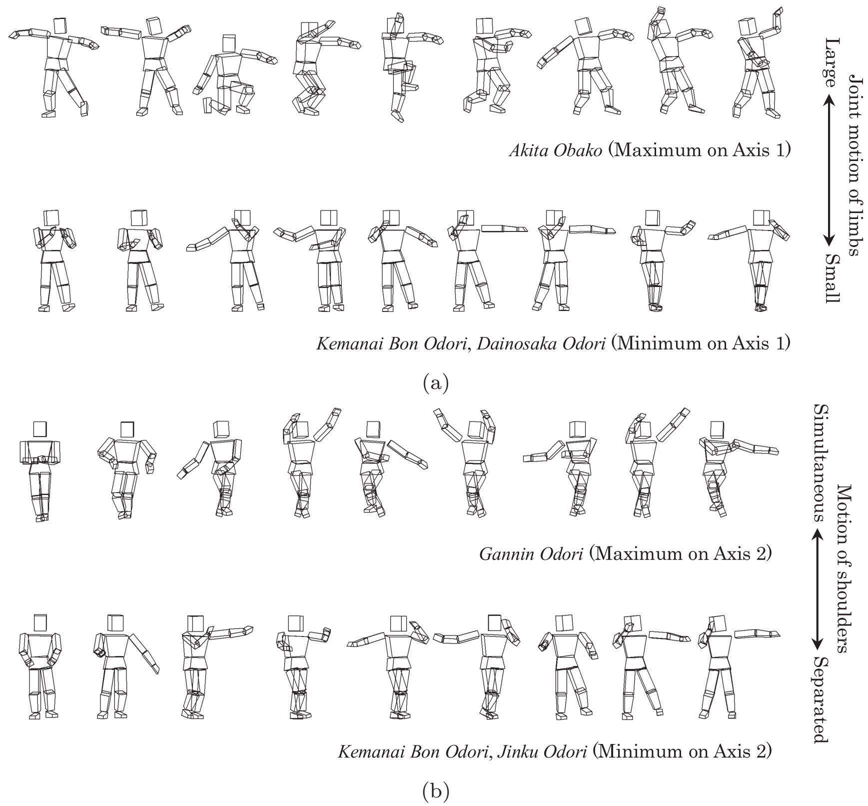


Fig. 13 Motion of dances giving the maximum and minimum coordinates for the axes given by MDS; (a) Axis 1, (b) Axis 2.

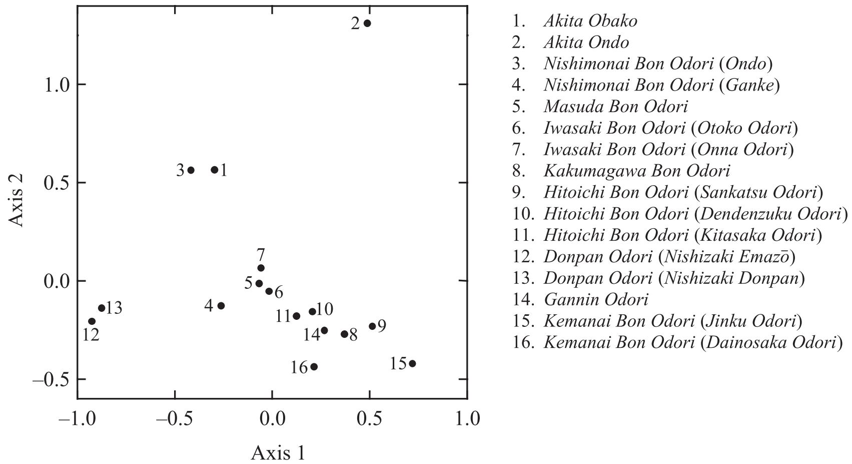


Fig. 14 Scatter plot of folk dances of Akita Prefecture (Evaluated frames: 1–150).

may be obtained. The present method can accept the obtained technique by the procedure used for the analysis shown in Fig. 14.

As shown in the above, the effectiveness of the present method as the technique giving the distribution feature of the characteristics of all the dances in the database is confirmed. This fact leads to the possibility that the present method contributes to the development of a systematic analysis technique to extract not only the characteristics of the motions of a single dance number but also the distribution feature of the motions of multiple dance numbers. It should particularly be noted that the evaluation items characterizing all the dances belonging to the database are automatically extracted by the present method. It is expected from this fact that dance motions can be analyzed from a more objective viewpoint than the previous trials.

However, the number of samples used in this paper is limited. Therefore, more detailed work may be necessary for the practical use of the present method.

4. Conclusion

In this paper, the authors attempt to develop a technique for the analysis of the motions of dances having no stylized motion structure, focusing on joint-motion analysis which allows us to obtain the evaluation index of motion characteristics with a systematic representation form. The techniques of multivariate statistical analysis are used for practical calculation in each analysis procedure. The effectiveness of the present method is verified by analyzing the motion data acquired in the performances of Japanese folk dances which have no strictly-stylized motion structure. The conclusions are summarized as follows:

(1) The variance-covariance matrix derived from the statistical analysis of the time-series data of joint motions is selected for the evaluation index char-

acterizing motions in individual dances. It gives the information of joints giving considerably large motions and the structure of joint coordination. It also provides the advantage that the comparison of multiple dances becomes easy because of the unified representation form unaffected by the variation of motion data.

(2) The derived evaluation index shows the effectiveness in the application to the representation of dissimilarity between two dances. It should particularly be noted that the derived dissimilarity, the variance-covariance-matrix distance, is more effective than the DTW distance when the whole commonness appearing in both the dances compared should be considered.

(3) The application of MDS with the orthogonal rotation of coordinate axes is shown to be effective to extract the distribution feature of a database of dances. It is also shown that the interrelation among all the dances in the database is easily conprehended by using the evaluation items automatically extracted from the correlation relationship between the coordinate axes given by MDS and the elements of the variance-covariance matrix.

For further work, it is necessary to verify the effectiveness of the present method in the application to a database consisting of a greater number of samples than the present study. The use of the samples comprising not only the motion data of a single dance number but also those of multiple dance numbers belonging to multiple dance categories if possible, performed by multiple dancers including both experts and beginners if possible, is desirable to confirm the robustness of the present method against the diversification of dance motions.

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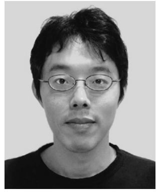
Takeshi Miura received a D.Eng. degree in electrical engineering from Hokkaido University in 1998. He is currently a lecturer in the Department of Electrical and Electronic Engineering, Faculty of Engineering and Resource Science, Akita University.

Kazutaka Mitobe received a D.Eng. degree in biomedical engineering from Hokkaido University in 1996. He is currently an associate professor in the Department of Electrical and Electronic Engineering, Faculty of Engineering and Resource Science, Akita University. His research work is on biomedical engineering such as human motion analysis and psychophysical experiments for older adults.

Takashi Yukawa received a Ph.D. degree in Computer Systems Engineering from Akita University in 2009. He is currently a professor at the Faculty of Law, North Asia University. His research interests include human motion analysis and computer graphics. He is a member of the IPSJ and VRSJ (Virtual Reality Society of Japan).



Takaaki Kaiga received a M.E. degree in mechanical engineering from Ibaraki University in 1995. Since 1996, he has been with the computer division of Digital Art Factory, Warabi-za Co., Ltd.

Toshiyuki Taniguchi received a D.Eng. degree in electrical engineering from Hokkaido University in 1979. He is currently a professor in the Department of Electrical and Electronic Engineering, Faculty of Engineering and Resource Science, Akita University.

Hideo Tamamoto received a D.Eng. degree in electrical engineering from the University of Tokyo in 1976. He is currently a professor in the Department of Computer Science and Engineering, Faculty of Engineering and Resource Science, Akita University. His research interests include design-for-testability of logic circuits, archiving and bequeathing technique for traditional folk dances, e-learning system.