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Dance-like Humanoid Motion Generation Through Foot Touch States Classification

Kunio Kojima, Shunichi Nozawa, Kei Okada and Masayuki Inaba

***Abstract*— This paper proposes a humanoid dance motion generation system that deals with a huge variety of leg motions. While previous research only tackled on a few kinds of leg motions, original human dance leg motions contain various foot touch states such as slide, turn, and heel contact, as well as complex motions such as kick and twist. According to the dance literature, we found that there are seven major foot touch states that make dance motion more "dance-like". Thus we present a method to classify the seven kinds of foot touch state from human dance motion data, and describe the various dance leg motions by using combinations of the foot touch states and key-frames. Based on these methods, we designed the humanoid dance motion generation system that enables humanoid robots not only to satisfy the geometric condition but also to imitate various human dance leg motions. Finally we show an experiment using a life-sized humanoid, HRP-2.**

I. INTRODUCTION

While humanoid's leg motions consist of support phases and swing phases, human foot touch states are more various and it is academically important to investigate the foot touch states and methods for imitating by humanoid robots. We focus on human dance motions composed of various foot touch states and try to imitate human dances by humanoid robots.

Recently, the imitation of human dances by humanoid robots has been actively studied[1][2]. Nakaoka et al.[2] enabled a humanoid robot to imitate four kinds of leg motions by classifying human leg motions based on "Leg Task Models".

However, there is a great variety of human dance leg motions including slide, turn, kick (Fig.1), and twist. As a result, it is difficult to classify all the different complex leg motions due to the large number of variety. Therefore, we classify not the leg motions themselves but foot touch states,and describe leg motions using combinations of "foot touch states" and "key-frames".

Foot touch states

In a dance notation (*Labanotation*[3]), as shown in Fig.2, various foot touch states such as slide, heel touch, and toe touch are defined. These touch states are essential from the standpoint of dance. In addition, foot touch states are necessary to generate dynamically balanced humanoid motion trajectories.

Key-frames

Key-frames are poses in which a whole body is almost stationary. Shiratori et al. showed the importance of key-frames and a method for extracting them [4]. We can describe not only simple steps but also complex leg motions by using the key-frames, which are important postures in dance motions.

In this study, we propose a method for generating humanoid motions by focusing on foot touch states and key-frames. We propose a method for measuring human motions through TOF (Time of Flight) sensors and classifying foot touch states according to a set of rules based on *Labanotation*, and evaluate the results. Furthermore, we describe a method for generating humanoid leg motions while preserving the features of the foot touch states, and show experimental results using a life-sized humanoid robot, HRP-2.

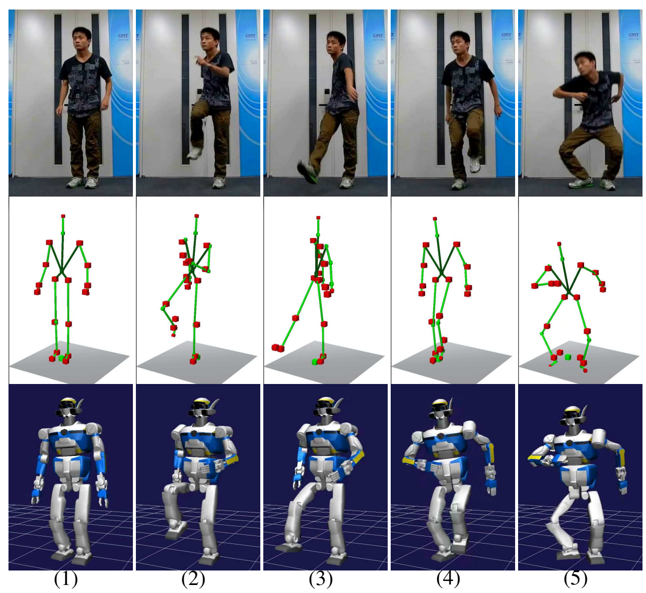

Fig. 1. Kick Walk Motion

II. Method For Humanoid Motion Generation Based on Human Motion

Our proposed system for generating various humanoid leg dance motions is shown in Fig.3. In Sec.III of this paper, we described the component for classifying foot touch states (labeled "A" in Fig.3), and in Sec.IV we describe the component for generating leg choreography (labeled "B" in Fig.3).

In our foot touch state classification scheme, we recognize seven kinds of foot touch states according to ankle trajectory, toe trajectory, and human ZMP trajectory.

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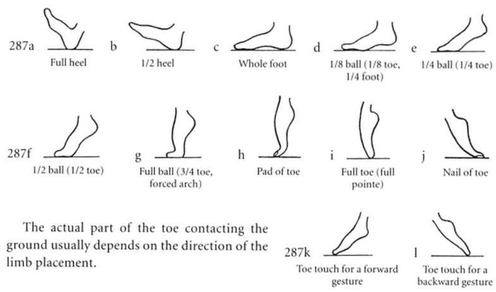


Fig. 2. Description of Foot Touch State in *Labanotation*[3]

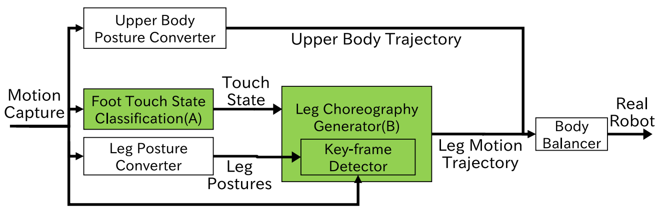


Fig. 3. System Configuration Diagram to Generate Vaious Humanoid Leg Dance Motions

Our leg choreography generator generates humanoid robot motion trajectories both executable in a real machine and preserves dance features by modifying input trajectories to satisfy dance constraints and geometric constraints. Dance constraints require the preservation of important elements of dances such as features of each foot touch state and several key-frames of each foot touch state's time region. Geometric constraints require the avoidance of collisions between the robot's feet or between the robot's foot and the floor.

In upper body posture converter, we converted human upper body postures to humanoid's upper body postures by using joint angle mapping.

III. Classification of Foot Touch States

A. Seven Kinds of Foot Touch States

For imitation of human dances by humanoid robots, Nakaoka et al.[2] distinguished between grounded phases and ungrounded phases using foot velocity, while Yonekura et al.[5] used the depth data from a Kinect camera. Moreover, Miura et al.[6] distinguished three foot touch states of grounded phase, ungrounded phase, and turn phase, using ankle velocities and foot yaw angular velocities.

As described in Sec.I, there is a huge variety of foot touch states in dance motions. Therefore in this paper, we classify the following seven kinds of foot touch state selected from the states defined in *Labanotation*.

Flat	The state in which the whole sole of the support leg is in contact with the floor (Fig.4(1))
Touch	The state in which the sole of the non-support leg is in contact with the floor (Fig.4(2))
Point	The state in which the toe or heel is contact with the floor (Fig.4(3))
Draw	The motion during which the non-support leg slides on the floor (Fig.5)
Slides	The motion during which the support leg slides on the floor (Fig.6)
Fan	The motion during which the foot rotates around the toe or heel (Fig.7)
Ungrounded	The state in which the sole is not in contact with the floor (Fig.4(4))

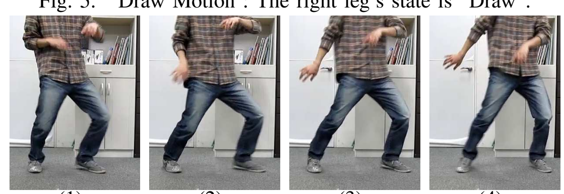
One may think that *Labanotation* is not suitable for describing dance motions because human motions are encoded by a coarse coordination. However, *Labanotation* was invented to be used for learning Western dances such as ballet, which has various foot touch states, and in fact, many kinds of foot touch states are defined in *Labanotation*. Therefore, we consider the Labanotaion definition of foot touch states to be detail enough for describing humanoid dance leg motions.

(1) Flat (2) Touch (3) Point (4) Ungrounded

Fig. 4. Foot Touch States: Flat, Touch, Point, and Ungrounded

(1) (2) (3) (4)

Fig. 5. Draw Motion : The right leg's state is "Draw".



(1) (2) (3) (4)

Fig. 6. Slide Motion : The left leg's state is "Slide".

(1) (2) (3) (4)

Fig. 7. Fan Motion : The right legs' state is "Fan"

Table.I shows a comparison with previous studies. It can be seen from the table that our method can deal with more kinds of foot touch states.

We need to describe the features of each foot touch state by some parameters for the definite classification. Therefore, we described the features using five parameters: ankle height, toe height, ankle velocity, foot yaw angular velocity,and supporting-foot (Table.II).

TABLE I

COMPARISON OF FOOT TOUCH STATE CLASSIFICATION WITH PREVIOUS STUDIES

	Flat	Touch	Point	Slide	Draw	Fan	Ungrounded
A	○	-	-	-	-	-	○
B	○	-	-	-	-	-	○
C	○	-	-	-	-	○	○
D	○	○	◇	△	○	△	○

A is Nakaoka et. al[2], B is Yonekura et.al[5], C is Miura et.al[7], D is this research. ○ means the state is possible by real robots. △ means the state is possible only by robot models since the motion satisfies geometric constraints but does not satisfy dynamic constraints. ◇ means the state is possible by real robots if the other foot touch state is Flat.

TABLE II

FEATURES OF FOOT TOUCH STATES

<table>
<tr><th>Touch States</th><th>Ankle Height</th><th>Toe Height</th><th>Yaw Angular Velocity</th><th>Ankle Velocity</th><th>Supporting foot</th></tr>
<tr><td>Flat</td><td rowspan="2">L</td><td rowspan="3">L</td><td rowspan="6">L</td><td rowspan="4">L</td><td>Yes</td></tr>
<tr><td>Touch</td><td>No</td></tr>
<tr><td rowspan="2">Point</td><td>H</td><td rowspan="2">-</td></tr>
<tr><td rowspan="4">L</td><td>H</td></tr>
<tr><td>Slide</td><td rowspan="3">L</td><td rowspan="2">H</td><td>Yes</td></tr>
<tr><td>Draw</td><td>No</td></tr>
<tr><td>Fan</td><td>H</td><td>-</td><td>-</td></tr>
<tr><td>Ungrounded</td><td>H</td><td>H</td><td>-</td><td>-</td><td>No</td></tr>
</table>

H means that the value is higher than a threshold. L means that the value is lower than a threshold.

B. Discussion on the Classification Method

There are two methods for classifying foot touch states: a rule-based method and a non-rule-based method. We adopt the rule-based method since the features of each foot touch state are described in *Labanotation*.

C. Discussion on the Measuring Method

There are mainly two methods for measuring human dance motions: using dynamic measurements or using kinetic measurements. Using dynamic measurements is suitable for distinguishing between Float and Touch or between Slide and Draw. However, the other foot touch states are different from each other in foot positions and postures. In addition, while we need to place markers on the floor or our soles for making dynamic measurements, we need not place sensors or markers on our bodies for making kinematic measurements with the use of TOF sensors. Therefore, we choose to measure human dance motions kinematically using a Kinect.

D. Proposed Classification Method

Considering the features of foot touch states shown in Table.II , we classified foot touch states according to the flow shown in Fig.8, using ankle height, toe height, ankle velocity, foot yaw angular velocity, and human ZMP trajectory. "Supporting-Foot" (labeled "A" in Fig.8) is the foot which is in contact with the floor and supporting one's weight. In dance terminology, defined as such in distinction from the foot which is in contact with the floor but does not support one's weight. We used ZMP trajectories calculated from approximating the human body as multi-mass-points to identify the supporting-foot. For example, we determine if the right foot is the supporting-foot by using the ratio of the distance between the left foot and the ZMP to the distance between the two feet.

The purpose of identifying the supporting-foot is for the humanoid to imitate human waist movements. When we compensate for humanoid body balance by using its waist horizontal position, the humanoid waist movements have a correlation with its ZMP trajectories. Therefore, we intended to make humanoids imitate human waist movements by not shifting the reference ZMP trajectories to the non-supporting-foot.

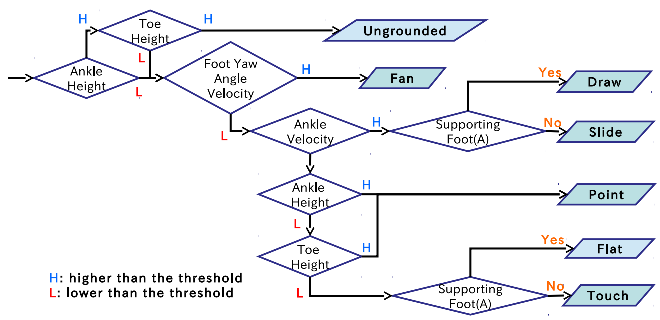


Fig. 8. Foot Touch State Classification Method

E. Results of Classification and Consideration

Fig.9 shows part of the results of foot touch state classification. We classified human leg motions containing each foot touch state more than 20 times using the proposed method and manually.

The lag between foot touch states' transition time identified using the proposed method and the transition time identified manually is less than 0.09 seconds. We interpreted this as an appropriate result considering that the frame rate of the input motion capture data is 30 fps and that there is noise in the data.

The foot touch states between transitions identified by our method and the ones identified manually for Ungrounded, Fan, and Point were in agreement. On the other hand, we were able to distinguish Touch from Flat or Draw from Slide (or identify the supporting-foot) correctly only approximately 90 percent of the times. Originally, the purpose for identifying the supporting-foot is for the humanoid to imitate human waist movements. Therefore, it is considered as another way to reflect the continuous value of the each leg's weight degree to the generation of reference ZMP trajectories. It is also considered valid to reflect the waist's relative position from the feet. Therefore, we had better generate the reference ZMP trajectories using the waist's horizontal positions instead of identifying the supporting-foot.

IV. LEG CHOREOGRAPHY GENERATOR

In this section, we explain the method for modifying the humanoid's motion trajectories to satisfy the geometric constraints and the dance constraints. The humanoid's motion has to satisfy geometric constraints for a real machine to execute them. In addition, if the motion is a kind of dance, the humanoid's motion also needs to preserve the important elements of dance such as key-frames. Therefore,

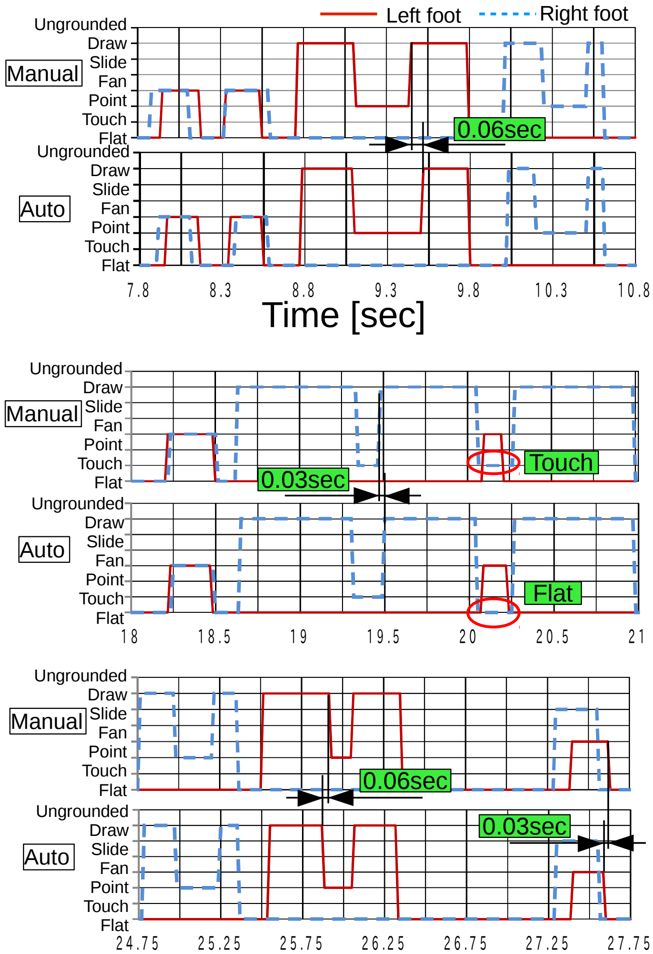


Fig. 9. The Result of Foot Touch State Classification: The upper is the manual classification, the lower is the result by the proposed method.

we generate the humanoid leg motion trajectories not only to satisfy geometric constraints but also dance constraints shown below.

Geometric constraints

1) The right and left feet do not collide with each other.
2) The support legs do not collide with or lift off the floor.
3) The swing legs do not collide with the floor.

Dance constraints

1) The features of foot touch states identified in Sec.III are preserved.
2) The key-frames defined by each foot touch state are preserved.

First, we explain the outline of the leg choreography generator. A humanoid's leg motion is sometimes generated by the spline interpolation of the starting, middle, and end point of each phase. However, there are a lot of kinds of foot touch states such as a heel contact and slide, and each foot touch state's phase often contains several key-frames. Thus in this paper, we described humanoid leg motions using a combination of foot touch states and key-frames to address their variation as below.

1) Detect key-frames(A in Fig.10)
2) Convert each human leg key-frame posture to humanoid leg posture(B in Fig.10)
3) Apply dance constraint 1) and geometric constraints to each key-frame(C in Fig.10)
4) Interpolate between key-frames in each foot touch state phase(D in Fig.10)

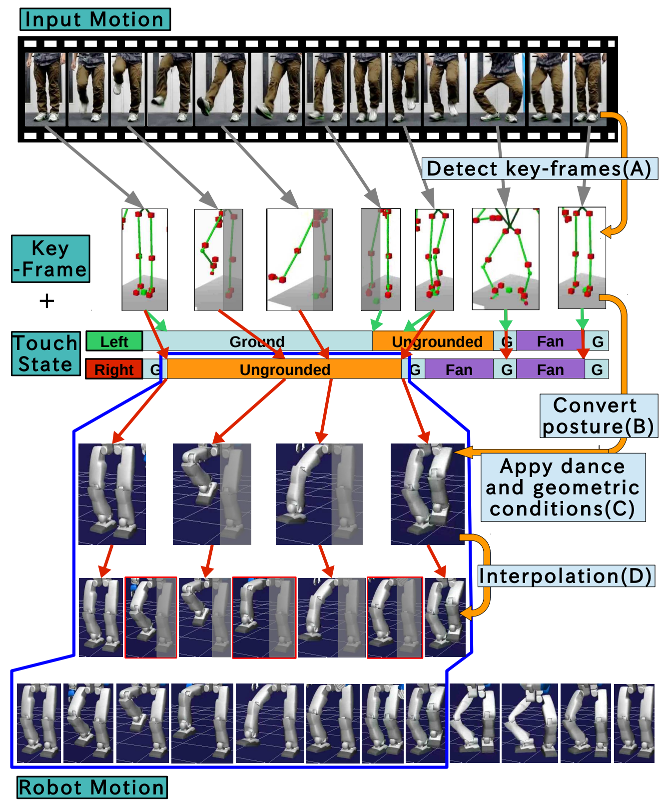


Fig. 10. Leg Choreography Generator

We used Shiratori's method[4] as reference and selected a start and end point of each foot touch state phase (classified by our proposed method in Sec.III) and velocity local minimums of hands, feet, and waist as key-frames(A in Fig.10).

Next, we explain how to apply dance constraints 1) and geometric constraints to each key-frame (C in Fig.10). We take the collision avoidance between the foot and the floor for example. In the case of Point, whose feature is the foot pitch angle according to Table.II , we avoid the collision by raising the foot (Fig.11(1)). By contrast, in the case of Draw, whose feature is the low height of the foot, we avoid the collision by leveling the foot (Fig.11(2)). The way to deal with the geometric constraints according to the foot touch state is summed up in Table.III .

In this way, we deal with the same geometric constraints in the different way according to the foot touch state to preserve the features of each foot touch state and to satisfy geometric constraints.

We used "Choreonoid"[8],the integrated GUI application development framework for robots, to interpolate between key-frames in each foot touch state phase(Fig.10D). Nakaoka et al.[8] described the detail.

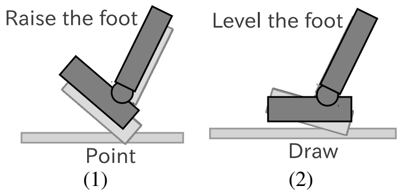


Fig. 11. Avoidance of Collision with Floor in "Point" and "Draw"

V. Experiment of Dance Motion by HRP-2

In this paper, we used an HRP-2 for imitating human dances. In addition, we used the balancer plugin of Choreonoid[8] to generate the humanoid's dynamically balanced motion. The balancer plugin of Choreonoid uses the ZMP control of Nishiwaki et al.[9][10], which works well under the assumption that the humanoid's sole contacts with the floor without slipping. This is why we made a real machine perform dance motions composed of five kinds of state - Flat, Touch, Point, Draw and Ungrounded, omitting Slide and Fan, which are sliding motions of a supporting-foot.

The dance motion executed in this paper is shown in Fig.13. Starting from the left, each one frame shows the input human dance motion, the result of the classification of foot touch states, the humanoid's executable motion satisfying both dance constraints and geometric constraints, and the performance of the dance motion by the real machine. It can be seen from them that several foot touch states of the dance motion are classified and that the features of each state are preserved.

The result of the experiment with HRP-2 is shown in Fig.12. Starting from the top, each graph shows the result of the foot touch state classification of the input human motion, the result of the foot touch state classification of the HRP-2 motion, and the output of the 6-axis force-torque sensors of the each foot. We classified the foot touch states of the HRP-2 motion by calculating each joint's position from joint angles and by the method described in Sec.III.

We can understand that HRP-2 can imitate the human foot touch states from the upper two graphs. We were able to classify the HRP-2 motions into the same foot touch states as the states of the input human motions (52 seconds), which contain Touch 26 times, Point 6 times, and Draw 4 times. The lags between foot touch states' transition times were shorter than 0.09 seconds.

We can also confirm that HRP-2 can imitate some of the human foot touch states from the output of the 6-axis force-torque sensors. While the left foot (Touch) bears little weight around 22.5 second, the left foot (Point) bears about 200N weight around 22.8 second.

We can verify that the robot's imitation of foot touch states from the real robot's output data as described above. It is expected that we will be able to modify humanoid motions to imitate foot touch states better through the use of the real robot's outputs.

TABLE III

The Way to Preserve the Features of Each Foot Touch State

Geometric constraint	Touch states	The way to satisfy the geometric constraint
The collision between the right and left foot	Flat	$\boldsymbol{p}'_{\boldsymbol{L}} = \tilde{\boldsymbol{p}}_{\boldsymbol{L}}(k_{min}, H, \boldsymbol{p_L} - \boldsymbol{p_R}), k_{min} = min(k)$ $s.t. k > 0, f_{LR}(\tilde{\boldsymbol{p}}_{\boldsymbol{L}}(k, H, \boldsymbol{p_L} - \boldsymbol{p_R}), \boldsymbol{p_R}) = false$ k_{min} is constant during a single phase.
	Touch	
	Point	
	Fan	
	Slide	$\boldsymbol{p}'_{\boldsymbol{L}} = \tilde{\boldsymbol{p}}_{\boldsymbol{L}}(k_{min}, H, \boldsymbol{p_L} - \boldsymbol{p_R}), k_{min} = min(k)$ $s.t. k > 0, f_{LR}(\tilde{\boldsymbol{p}}_{\boldsymbol{L}}(k, H, \boldsymbol{p_L} - \boldsymbol{p_R}), \boldsymbol{p_R}) = false$
	Draw	
	Ungrounded	Replace H with I and the same modification as Flat.
The collision between the foot and the floor	Flat	$\boldsymbol{p}'_{\boldsymbol{L}} = H\boldsymbol{p_L}$ $R'_L = \begin{bmatrix} cos(\phi_L) & -sin(\phi_L) & 0 \\ sin(\phi_L) & cos(\phi_L) & 0 \\ 0 & 0 & 1 \end{bmatrix}$
	Touch	
	Fan	
	Slide	
	Draw	
	Point	$\boldsymbol{p}'_{\boldsymbol{L}} = \tilde{\boldsymbol{p}}_{\boldsymbol{L}} + k_{min}\boldsymbol{e_z}, k_{min} = min(k)$ $s.t. k > 0, f_{floor}(\tilde{\boldsymbol{p}}_{\boldsymbol{L}}(i, I, \boldsymbol{e_z})) = false$
	Ungrounded	
The foot's floating above the floor	Flat	$\boldsymbol{p}'_{\boldsymbol{L}} = H\boldsymbol{p_L}$ $R'_L = \begin{bmatrix} cos(\phi_L) & -sin(\phi_L) & 0 \\ sin(\phi_L) & cos(\phi_L) & 0 \\ 0 & 0 & 1 \end{bmatrix}$
	Touch	
	Fan	
	Slide	
	Draw	
	Point	$\boldsymbol{p}'_{\boldsymbol{L}} = \tilde{\boldsymbol{p}}_{\boldsymbol{L}} - k_{max}\boldsymbol{e_z}, k_{max} = max(k)$ $s.t. k < 0, f_{floor}(\tilde{\boldsymbol{p}}_{\boldsymbol{L}}(k, I, \boldsymbol{e_z})) = false$
	Ungrounded	With no change

$$\tilde{\boldsymbol{p}}_{*}(k, A, \boldsymbol{x}) = \boldsymbol{p}_{*} + kA\boldsymbol{x}$$

I : Identity matrix of size 3, ϕ_* : Yaw angle of robot foot
$\boldsymbol{p}_*$: Input position of the robot foot, $\boldsymbol{p}'_*$: Modified position of the robot foot
R_* : Input orientation of the robot foot, R'_* : Modified orientation of the robot foot
(* is L(left foot) or R(right foot))

$$H = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \ \boldsymbol{e_z} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

function $f_{LR}(\boldsymbol{p_0}, \boldsymbol{p_1})$ ▷ Check collision between the left and right foot
  Place left foot at $\boldsymbol{p_0}$
  Place right foot at $\boldsymbol{p_1}$
  if Left and Right foot collide with each other **then**
    return TRUE
  else
    return FALSE
  end if
end function

function $f_{floor}(\boldsymbol{p})$ ▷ Check collision between the foot and the floor
  Place left foot at $\boldsymbol{p}$
  if The foot collides with the floor **then**
    return TRUE
  else
    return FALSE
  end if
end function

VI. Conclusion

This paper proposed a method for generating humanoid motion from human dances. The method consists of a classification scheme of foot touch states and a leg choreography generator.

In a classification scheme, we presented a method for classifying human leg motions into different foot touch states, proposed and evaluated a rule-based method, and showed its validity.

In a leg choreography generator, we described the dance leg movements using a combination of foot touch states and key-frames. This method enabled us to generate humanoid dance motions containing various complex leg movements.

In addition, we confirmed that the generated motions were feasible on a HRP-2 and that HRP-2 could imitate some of the human foot touch states by the experiment.

By improving the balance controller to be applicable to a

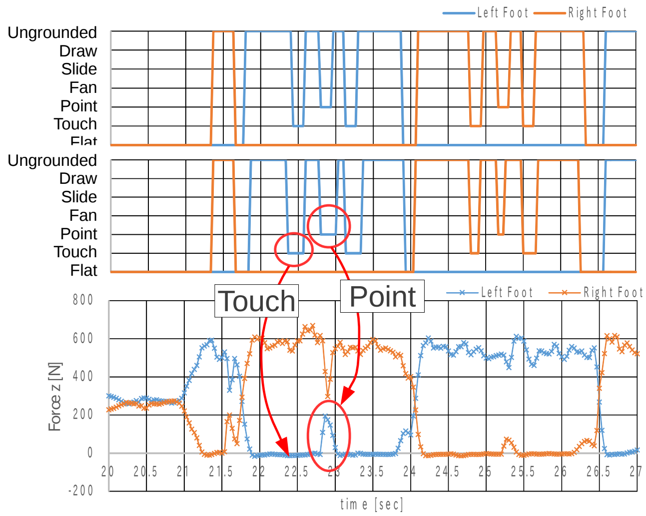


Fig. 12. Results of the Real Robot Experiments:
Time-chart of foot touch states for the input human motion (top graph), the Real Robot's motion (middle graph),
and Measured force profiles for both foot (bottom graph)

slide motion such as "Slide" and "Fan", it is expected that a real robot will be able to imitate the human-like dances containing all seven kinds of foot touch states. The proposed method is the foundation for it.

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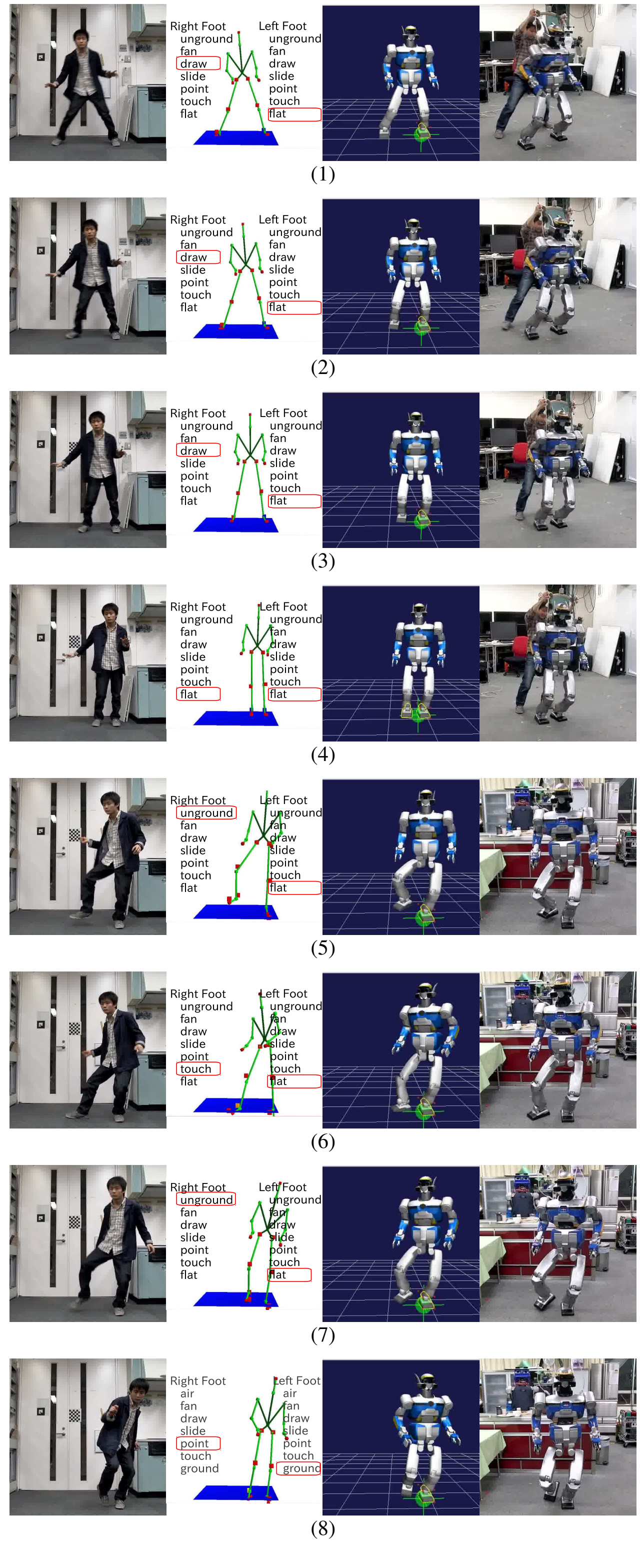

Fig. 13. Dance Motion of Human and HRP-2 : Starting from the left, each one frame shows the input human dance motion, the result of the classification of foot touch states, the humanoid's executable motion satisfying both dance conditions and geometric conditions, and the performance of the dance motion by real machines.