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# Motion Retargeting for Humanoid Robots Based on Identification to Preserve and Reproduce Human Motion Features

Ko Ayusawa[1], Mitsuharu Morisawa[2] and Eiichi Yoshida[1]

*Abstract*— **This paper presents the method to retarget human motion. The method can evaluate the ability of the preservation of the original characteristics of human motion data. It enables to compute the joint trajectories of the human corresponding with the retargeted ones of the robot at the same time, by utilizing the geometric identification technique. The obtained trajectories of a human are the solution to minimize the cost function about motion reproduction. The proposed method is efficient for such applications that the robot needs to mimic human motion without modifying the detailed features of the original movement of each body segment. The results of the retargeted motions to a humanoid robot are shown.**

## I. INTRODUCTION

Thanks to the similarity of their structure to humans, humanoid robots are expected as the mechanical simulator of humans to study the control system and somatosensory sensation. One recent application is a humanoid robot as an evaluator of human assistive devices [1]: the estimation of device effects on a human by utilizing the internal forces when the robot emulates a human. Human motion capture enables the quantitative evaluation of geometric information like joint trajectories; on the other hand, since the force information generated inside human body is difficult to be measured directly, the only way is the estimation from motion data and force plate measurement. One difficulty faced on those estimation problems is the redundancy problem. For example, the multiple contact situation leads the redundant problem if the distributed forces cannot be measured [2]. Humanoid robots with internal sensors are expected to provide the additional force information useful for human motion analysis. However, those applications require that the robot need to mimic human motion without modifying its original features. There exists the difference about the body structure and mechanical properties between a humanoid robot and a human. Though some of recent humanoids have human-like morphology [3], it cannot compensate the detailed difference about their body structure. The important issue in those applications, therefore, is how to generate natural motions of a humanoid robot: the technique of motion retargeting.

Motion retargeting techniques are widely studied in order to design character animations in the field of computer graphics, or to generate robot motions [4], [5], [6], [7], [8], [9], [10], [11], [12]. One typical way is that human motion is recorded by motion capturing and is retargeted to robot or CG characters. When retargeting human motions, the followings have to be considered [4]: the compensation of the difference of the body structure between the human and the retargeted subject (morphing process), and the motion reproduction considering the geometrical and mechanical consistency of the retargeted subject. There are several approaches of morphing process; the virtual markers are attached on the robot so that the motion of robot is converted by directly solving the inverse kinematics or static equilibrium problem [7], [8], or motion capture data can be scaled or fitted on the body of a robot in advance by optimization techniques [11], [12]. After the morphing process, the final motion has to satisfy the physical consistency and can be generated, for example, by motion optimization techniques [10], [12]. Several balance controllers were also designed and proposed in order to realize dynamic stability especially of locomotion [8], [9]. Some efficient retargeting techniques enable the retargeting of walking and dancing motions to humanoid robots [6], [8]. Our goal is the application of a humanoid robot as a human mechanical simulator, and the original human motions before retargeting has also to be evaluated. Since many methods focus on the generation of human-like motion, the new framework needs to evaluate how the features of human motion, such as geometric trajectories of each joint or body segment and the dynamics of the center of total mass or ZMP, is preserved or modified when retargeting.

This paper presents the retargeting method which enables the explicit evaluation of the reproduced motion and the original human motion. The method has the simultaneous optimization problems of following three: human motion reproduction, body structure morphing between a human and a robot, and motion planning of a robot. The method solves not only joint trajectories of the robot but also those of the human and his/her geometric parameters. By designing explicitly the morphing function of the body structures by the geometric identification technique [13], the joint trajectories between the human and the robot can be bridged, and directly optimize the evaluation function related to the human motion reproduction under the physical consistency of the robot. Several captured motions are retargeted to a humanoid robot by the proposed method, and the results are to be shown.

## II. MOTION RETARGETING TO PRESERVE AND REPRODUCE HUMAN MOTION

Let us formulate the retargeting problem as the simulations optimization problem with respect to the joint trajectories of both the human and the humanoid robot and the body

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[1]K. Ayusawa and E. Yoshida are with CNRS-AIST JRL (Joint Robotics Laboratory), UMI3218/RL, and [2]Mitsuharu Morisawa is with Humanoid Research Group, both Intelligent Systems Research Institute, National Institute of Advanced Industrial Science and Technology (IS-AIST), Japan {k.ayusawa, m.morisawa, e.yoshida}@aist.go.jp

segment parameters like segment lengths. In this paper, the robot and the human are modeled as multi-body systems. We also define $\boldsymbol{q}_h$ as the generalized coordinates of the human multi-body system, and $\boldsymbol{q}_r$ as the coordinates of the robot. Let us assume that the following relationship of the coordinates between the human and the robot holds:

$$\boldsymbol{g}(\boldsymbol{q}_r, \boldsymbol{q}_h, \boldsymbol{\phi}) = \mathbf{0} \tag{1}$$

where, $\boldsymbol{\phi}$ represents the unknown human body segment parameters; on the other hand, all the model parameters of the robot are assumed to be known. Eq.(1) implies how to map the coordinate of each body segments between the robot and the human.

At each time instances $t_1, t_2, \cdots, t_{N_T}$, let $\boldsymbol{q}_{h,t}$ and $\boldsymbol{q}_{r,t}$ $(1 \leq t \leq N_T)$ be the coordinates of the human and the robot respectively. The trajectories for all time instances are then defined as $\boldsymbol{Q}_h \triangleq [\boldsymbol{q}_{h,1}{}^T \cdots \boldsymbol{q}_{h,N_T}{}^T]^T$ and $\boldsymbol{Q}_r \triangleq [\boldsymbol{q}_{r,1}{}^T \cdots \boldsymbol{q}_{r,N_T}{}^T]^T$. We also consider the following inequality constraints about the trajectories $\boldsymbol{Q}_r$:

$$\boldsymbol{h}(\boldsymbol{Q}_r) \leq \mathbf{0} \tag{2}$$

Eq.(2) contains, for example, the joint limitation and the dynamics constraints about the center of total mass or ZMP for the stability. Though Eq.(2) is formulated as inequality constraints, it can also represents the equality constraints. The detail of the implementation is to be shown in the next section.

We now consider the following optimization problem of human motion reproduction from human motion capture data set $\boldsymbol{P}_h$:

$$\min_{\boldsymbol{Q}_h, \boldsymbol{\phi}} f(\boldsymbol{P}_h, \boldsymbol{Q}_h, \boldsymbol{\phi}) \tag{3}$$

where, Eq.(3) is the estimation problem of human joint trajectories $\boldsymbol{Q}_h$ and the identification of segment lengths $\boldsymbol{\phi}$ [14], [13]. Function $f$ can be implemented as, for instance, the squared error norm between the measured markers position and those attached on the model.

We now formulate the retargeting problem as the following optimization problems:

$$\begin{aligned} \min_{\boldsymbol{Q}_h, \boldsymbol{Q}_r, \boldsymbol{\phi}} \quad & f(\boldsymbol{P}_h, \boldsymbol{Q}_h, \boldsymbol{\phi}) \\ \text{subject to} \quad & \widehat{\boldsymbol{g}}(\boldsymbol{Q}_h, \boldsymbol{Q}_r, \boldsymbol{\phi}) = \mathbf{0} \\ & \boldsymbol{h}(\boldsymbol{Q}_r) \leq 0 \end{aligned} \tag{4}$$

where, $\widehat{\boldsymbol{g}}$ is the form which concatenates Eq.(1) for all time instances.

Problem (4) is the large-scale optimization problem which combine human motion reproduction, body structure morphing between a human and a robot, and motion planning of a humanoid robot. Several retargeting methods separate the morphing process and the motion planning process [5], [8], [11], [12]. From the viewpoint of problem (4), it is equivalent that, at first, human capture data $\boldsymbol{P}_h$ is morphed according to Eq.(1) to virtual robot capture data $\boldsymbol{P}_r$, and then, $\boldsymbol{P}_h$ in problem (3) is replaced with $\boldsymbol{P}_r$, and finally, the replaced problem is solved under Eq.(1). Since the conversion from $\boldsymbol{P}_h$ to $\boldsymbol{P}_r$ does not take account robot's physical consistency Eq.(2), the solution of the replaced problem is not guaranteed to be optimal under original cost function Eq.(3). As problem (4) integrates the morphing process and the motion planning process to optimize human motion trajectories at the same time, it can provide the framework to directly evaluate the original human motions and the retargeted robot motions. It should be noted that the proposed framework itself does not conflict with the some other approaches; in Eq.(2), we can integrate the constraints and the strong optimization techniques for motion planning like [10], [12], and can use the Laplacian deformation energy of interaction mesh [11] in Eq.(3). The proposed methods can extend them to problem (4) by introducing the explicit formulation of morphing function Eq.(1) in the similar manner as the geometric parameters identification [13].

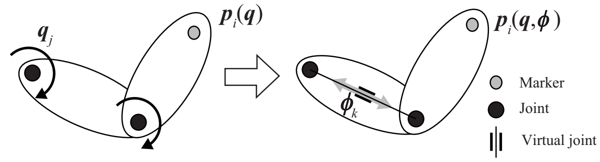


Fig. 1. Virtual joints which represents the geometric parameters of the link structure.

As problem (4) is formulated generally, the actual implementations of the cost function and the constraints are detailed in the next section.

## III. Implementation of Retargeting Optimization Problem

### A. Morphing function between human and humanoid robot

In order to design the relationship between the model of human and that of the robot, we assume the following assumptions:

- $\boldsymbol{\phi}$ represents only the geometric parameters of the human model.
- The geometric parameters of the robot are known, and those of the human model are unknown.
- All the joints of the robot are rotational ones.
- The link connectivity, the joint numbers, and the joint types of the human model are the same as the robot.

The final assumption requires that the joint configuration of the robot is not far from that of the human model used in the human motion reproduction [15].

We now represent the geometric parameters by using some virtual mechanical joint as shown in Fig.1, which shows the example when the distance of the joints is represented by the translational joint between them. $\boldsymbol{\phi}$ can be represented by the coordinates of the virtual mechanical joints. This representation means that the identification problem of $\boldsymbol{\phi}$ can be replaced by the simultaneous inverse kinematics problem of time variant $\boldsymbol{q}_{r,t}$ and time invariant $\boldsymbol{\phi}$ [13].

Let $\boldsymbol{q}_h$ and $\boldsymbol{q}_r$ be represented as follows:

$$\boldsymbol{q}_h = \begin{bmatrix} \boldsymbol{p}_h{}^T & \boldsymbol{\xi}_h{}^T & \boldsymbol{\theta}_h{}^T \end{bmatrix}^T \tag{5}$$

$$\boldsymbol{q}_r = \begin{bmatrix} \boldsymbol{p}_r{}^T & \boldsymbol{\xi}_r{}^T & \boldsymbol{\theta}_r{}^T \end{bmatrix}^T \tag{6}$$

where, $\boldsymbol{p}_h$ and $\boldsymbol{p}_r$ are the vectors of position of the base-link of human and robot respectively, $\boldsymbol{\xi}_h$ and $\boldsymbol{\xi}_r$ represents the orientation of the base-link (quaternion), $\boldsymbol{\theta}_h$ and $\boldsymbol{\theta}_r$ are the vectors of the joint angles.

As all the joints both of the robot and the human are rotational, the coordinates are scale-invariant. We then design the following relationship of the coordinates between the robot and the human.

$$\boldsymbol{\theta}_h = \boldsymbol{\theta}_r \tag{7}$$

In Eq.(7), the joint angles are "shared", which means the same variables are used for both the robot and the human, between them, and the coordinates of the base-link are not shared. The three translational components of the equations of motion of the base-link are equivalent with the dynamics of the center of total mass,which are important for the stability of the biped control [16]. Therefore, in this paper, the coordinates of the base-link remain not to be shared in order to be used for the dynamic constraint of the robot.

### *B. Physical consistency condition of robot*

Let us consider the following conditions about the limits of joint angles and their derivatives:

$$\boldsymbol{\theta}_{r,min} \leq \boldsymbol{\theta}_r \leq \boldsymbol{\theta}_{r,max} \tag{8}$$

$$\dot{\boldsymbol{\theta}}_{r,min} \leq \dot{\boldsymbol{\theta}}_r \leq \dot{\boldsymbol{\theta}}_{r,max} \tag{9}$$

$$\ddot{\boldsymbol{\theta}}_{r,min} \leq \ddot{\boldsymbol{\theta}}_r \leq \ddot{\boldsymbol{\theta}}_{r,max} \tag{10}$$

Eq.(10) originally comes from the condition of the joint torque. The dynamics of the motors is often dominant in the joint with the gear whose reduction ratio is relatively high. In this case, by estimating the maximum load inertia of each joint individually, the upper and lower limits of the acceleration can be computed.

Before considering the conditions of the dynamics of the robot, we assume the following assumption about the motion data of human and the feet of the robot:

- All the contact situation in human motion data are known for all time instances.
- Center of Pressure (CoP) of the human can be measured or estimated from the data, and all the motions are balanced in contact with ground; CoP coincides with ZMP.
- The sole of the foot of the robot is flat, and the XY plane of the coordinate system of the foot link plane is parallel to the sole.

During when the foot of the human contact on the ground, we add the following condition of the corresponding foot:

$$\begin{bmatrix}0 & 0 & 1\end{bmatrix} \boldsymbol{R}_{r,foot} \begin{bmatrix}0 & 0 & 1\end{bmatrix}^T = 1 \tag{11}$$

$$\dot{\boldsymbol{p}}_{r,foot} = \boldsymbol{0} \tag{12}$$

where, $\boldsymbol{p}_{r,foot} \in \mathbb{R}^3$ $(foot = rfoot, lfoot)$ is the position of the coordinate attached on the left or right foot, and $\boldsymbol{R}_{r,foot} \in \mathbb{R}^{3\times3}$ is the orientation matrix. When the both feet contacts on the ground, the following condition is also considered at the corresponding time instances.

$$\begin{bmatrix}0 & 0 & 1\end{bmatrix} (\boldsymbol{p}_{r,lfoot} - \boldsymbol{p}_{r,rfoot}) = 0 \tag{13}$$

Let be $\boldsymbol{p}_{h,zmp}$ ZMP of the human at each time instance. It is directly used as the desire value of ZMP of the robot. Though the morphing of ZMP will be actually required when the motion space of feet are different between the robot and the human, we assume that the difference is small and can be neglected. However, when $\boldsymbol{p}_{h,zmp}$ is outside of the supporting polygon of the feet of the robot, $\boldsymbol{p}_{h,zmp}$ is modified to the nearest point inside the polygon. In this paper, we approximate ZMP equation of the whole system by the liner inverted pendulum model whose mass is concentrated on the center of total mass and manipulated by ZMP [16], [17]. Let us assume the following condition:

$$\ddot{\boldsymbol{p}}_c = \frac{g}{p_{c,z}}(\boldsymbol{p}_c - \boldsymbol{p}_{zmp}) \tag{14}$$

where, $\boldsymbol{p}_c \in \mathbb{R}^3$ is the position of the center of total mass, $p_{c,z}$ is its z-axis component, and $g$ is the gravity acceleration constant.

We also assume the following limitation of the center of total mass, in order to satisfy static equilibrium preferentially for complicated postures when the reference ZMP from human motion data is unreliable.

$$\boldsymbol{p}_c \subset \mathbb{P} \tag{15}$$

where, $\mathbb{P}$ represents the motion range of the center of total mass, and the area projected on the XY plane is designed to be equal to the supporting area.

### *C. Evaluation function for human motion reproduction*

Let $\boldsymbol{p}_{i,t}{}^{ref}$ $(1 \leq t \leq N_M)$ be the measured position of captured markers at time instances $t_1, t_2, \cdots, t_{N_T}$. We now define the following evaluation function with respect to $\boldsymbol{q}_{h,t}$ $(1 \leq t \leq N_T)$.

$$f(\boldsymbol{Q}_h, \boldsymbol{\phi}) \triangleq \frac{1}{2} \sum_{t=1}^{N_T} \sum_{i=1}^{N_M} ||\boldsymbol{p}_i(\boldsymbol{q}_{h,t}) - \boldsymbol{p}_{i,t}{}^{ref}||^2 \tag{16}$$

where, $\boldsymbol{p}_i$ is the position of the marker attached on the human model, and it is the function of $\boldsymbol{q}_h$ and is obtained by the forward kinematics computation. Eq.(16) represents the problem to reproduce the human joint trajectories and the human segment lengths from human motion capture data [13].

### *D. Implementation of computation*

If we directly optimize $\boldsymbol{Q}_h$, $\boldsymbol{Q}_r$, and $\boldsymbol{\phi}$ of problem (4), it requires huge computation cost because of the large number of variables. The complexity of the problem becomes larger than the case of the geometric identification [13]. Since the velocities and the accelerations need not be considered, we usually select the minimal identifiable set of the discontinues samples of $\boldsymbol{Q}_h$. In this paper, problem (4) is solved as follows:

(A). the velocities and the accelerations are computed by the Euler method,

(B). all the equality and inequality constraints are solved by the penalty function method [18], (C). the geometric parameters are assumed to be slightly time-variant.

The derivative of the generalized coordinates at time $t$ can be computed from (A) as follows:

$$\dot{\boldsymbol{x}}_t = \frac{1}{\Delta t}(\boldsymbol{x}_t - \boldsymbol{x}_{t-1}) \tag{17}$$

$$\omega_t = \boldsymbol{K}(\boldsymbol{\xi}_t)\frac{1}{\Delta t}(\dot{\boldsymbol{\xi}}_t - \dot{\boldsymbol{\xi}}_{t-1}) \tag{18}$$

where, $\boldsymbol{x}$ represents the variables expect for rotation variables, and $\boldsymbol{K}(\boldsymbol{\xi}_t)$ is the matrix to convert the derivative of quaternion to the angular velocity. The initial velocity and accelerations are considered as to be zeros.

Let us identify the geometric parameters before retargeting, and let the identified values be defined as $\widehat{\boldsymbol{\phi}}$. $\widehat{\boldsymbol{\phi}}$ can be identified by solving Eq.(3) [13]. According to (C), we add the penalty against time variant geometric parameters $\boldsymbol{\phi}_t$. Finally, problem (4) can be computed by solving the following problem along time series:

$$\min_{\boldsymbol{q}_{h,t},\boldsymbol{q}_{r,t},\boldsymbol{\phi}_t} \frac{1}{2}\sum_{i=1}^{N_M} ||\boldsymbol{p}_i(\boldsymbol{q}_{h,t},\boldsymbol{\phi}_t) - \boldsymbol{p}_{i,t}{}^{ref}||^2 + \omega_\phi||\boldsymbol{\phi}_t - \widehat{\boldsymbol{\phi}}||^2 + \omega_{g_k}\sum_k ||\min(0, g_k)||^2 \tag{19}$$

where, $g_k$ represents the individual inequality constraints from Eq.(7) to Eq.(15), $\omega_\phi$ and $\omega_{g_k}$ are the weighing factor of each penalty term. Each penalty weight is usually designed according to the allowable amount of the penetration of the inequality constraint.

Since problem (19) can be regarded as the inverse kinematics problem of two multibody systems, it can be solved by the usual inverse kinematics techniques. As the number of variables in (19) is two times higher than the normal inverse kinematics, we solve the problem by the method for large-scale multi-body systems [19]. The method [19] solves the inverse kinematics problem without computing the Jacobian matrix of each link and its inverse; it computes the gradient vector of the cost function by solving the static equilibrium problem, and updates the solution by a superliner method like a conjugate gradient method [18]. The method realized that its computational complexity of each iterative computation is $O(N)$, where N is the number of the variables of the problem.

One note is that the all the equality and inequality constraints can be solved by the other method like sequential quadratic programing (SQP) [18]. Though the penalty function method allows the penetration of the constraints, SQP can obtain the precise solution. In this paper, we originally aimed at the fast implementation for the future application like on-line retargeting. The retargeting framework contains not only the variables of the robot but also those of the human and the geometric parameters; the total DOF exceeds over one hundred. Since the computational complexity of even quasi-Newton type SQP is much higher, we adopted the above method [19]. The penetration can also be decrease by increasing the weight of the penalty until they are enough small and can be neglected with respect to the tracking error of the controllers when the robot actually play back the motion. However, if the accuracy rather than the speed is important, for example, when there are so severe conditions that the range of the solution is narrow, the proposed framework should be implemented by SQP.

Fig. 2. Overview of humanoid robot HRP-4 (Left). The robot can wear the human assistive device (Right).

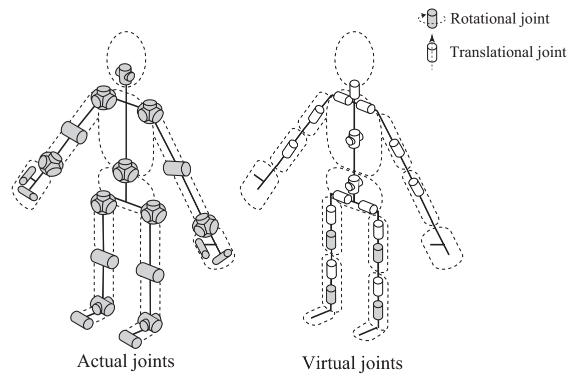


Fig. 3. Joint configuration of HRP-4 (Left) and configuration of virtual mechanical joints representing geometric parameters (Right).

## IV. Experiments of Retargeting Motion

The proposed method was tested on retargeting to humanoid robot HRP-4 [3] with a soft suit instead of hard plastic cover as shown in the left side of Fig.2. Since the geometric structure of HRP-4 is designed to be close to the measured average of humans, it can wear clothes or devices designed for humans. The high similarity to humans enables that the robot actually wears the assistive device [20] as shown in the right side of Fig.2. The robot is expected to be used as an evaluator of assistive devices [1].

Though the total degree of freedom (DOF) of the robot is originally 34 [3], the toe joints and the roll joint of the hip were added in our case; DOF of the robot is 37. The joint replacement of the robot is shown in the left side of Fig.3. In our method, the geometric parameters are represented by several virtual mechanical joints. They consist of rotational and translational joints. The replacement of the virtual joints is also shown in the right side of Fig.3. Since HRP-4 has the high similarity to humans, the 37-DOF model with the virtual joints was used as a human model when retargeting.

The following motions of a care worker were recorded by the motion capture system (Motion Analysis):

1. assisting someone to roll over and change the posture in a bed (Fig.4).
2. assisting someone to transfer from a bed to a char (Fig.5).

The motions were retargeted to HRP-4. When retargeting by Eq.(19), $\omega_{\phi} = 2$, $\omega_{g_k} = 200$ for joint limits, $\omega_{g_k} = 40$ for ZMP constraints, $\omega_{g_k} = 400$ for COM constraints, and $\omega_{g_k} = 4000$ for foot contacts. The snapshots of retargeted motions are shown in Fig.4 and Fig.5 with the original captured motions on the upper row. The retargeted motions are shown on the bottom of them. Though the sampling period of the captured motions was originally 5 [ms], we also made them three times slower; the data was resampled after changing the sampling period to 15 [ms]. It is because the operation speed of the measured human was originally far from the maximum speeds of the joints of the robot. Since this paper mainly focuses on the geometric features of the motion of each body segments as shown in cost function Eq.(19), we allowed this operation. However, it will actually lose the detailed dynamics features of quick motions, the automatic method of time scaling with the constraints of speed limits will be investigated in future works.

All the motions were successfully retargeted to the humanoid robot. The robot could mimic the characteristics of the original motion without falling down. In Fig.4, the original motion is such that the human supports the upper body of the person on the bed by the right hand, and then help the person roll over by pushing by both hands. The sequence and its features could be recognized in the retargeted motion to the robot. In Fig.5, the human bends the waist, and supports under the shoulders of the person sitting on the bed, and lifts up and transfers from the bed and the chair with his total center of mass on the right foot; the robot could mimic whole features of the motion without falling down.

Some retargeting methods [8], [12] separate the morphing process and the motion planning process. Therefore, the morphing process cannot consider the constraints about the joint configurations in advance. In addition to the singularity problem of the inverse kinematics computation, the features of the motion with extended joints are often not preserved. The proposed method integrates the morphing process and the motion planning process by utilizing the geometric parameters identification, and can overcome such a problem. During the captured motions, the joints in arms or legs of the human are sometimes fully extended. The retargeted motions by the proposed method could preserve the extended joints under its joint limits.

This paper showed that the detailed geometric feature of the motion of each body segment was preserved according to the designed evaluation function. On the other hand, the robot sometimes need to archive some tasks during the motion. For example, in reaching motion, the hand of the robot need to reach the target. The way to design the cost function according to the motion is to be focused on in future works.

## V. Conclusion

This paper presents the retargeting method for humanoid robots, which can evaluate the ability of the preservation of the original feature of human motion data. In the method, the human motion reproduction, the body structure morphing between a human and a humanoid, and the planning problem of a robot are solved simultaneously. It enables to compute the pre-retargeting joint trajectories of the human at the same time. The obtained trajectories of the human are the solution to minimize the cost function about the motion reproduction under the constraints of retargeting constraints. Therefore, the method provides the frameworks to evaluate how the features of human motion is preserved or modified when retargeting. In recent days, the humanoid robots are expected as the mechanical simulator of human body, for example, to evaluate human devices [1]. Those applications require that the robot should mimic human motion as close as possible to original features; the method can handle such a demand.

The proposed method was tested on humanoid robot HRP-4, and retargeted the several captured human motions to HRP4. Several care operations were recorded by motion capturing, and they were successfully retargeted to the humanoid robot. The robot could mimic the characteristics of the original motion without falling down, and the results showed the detailed geometric feature of the motion of each body segments was preserved according to the designed evaluation function. The way to design the cost function according to the task of the motion remains as a future work.

This paper mainly focused on retargeting the geometric features of the human motions. In order to preserve the feature of the dynamics of the motion, the morphing technique of dynamics features like forces and ZMP are required. The proposed optimization frame is expected to be generalized by combining the identification techniques of inertial parameters [21], and will be addressed in our future work.

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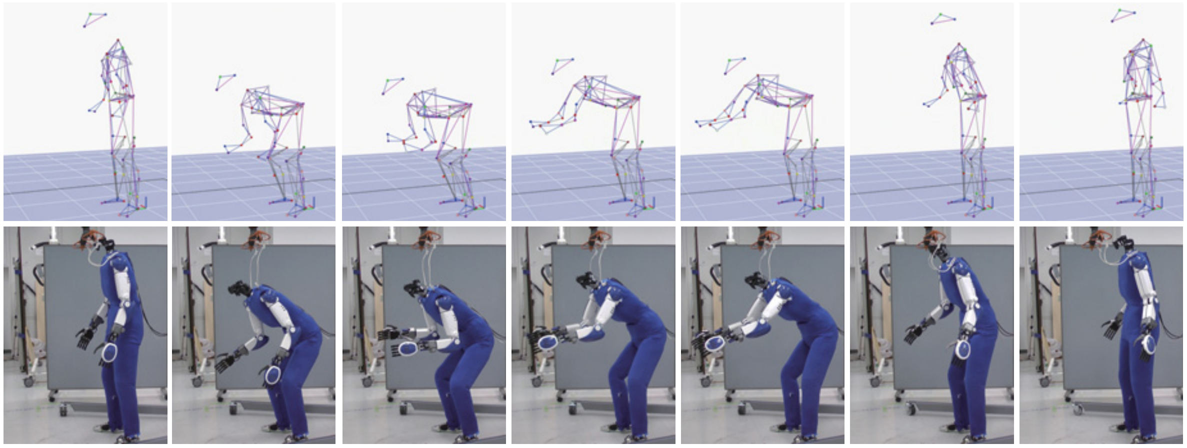

Fig. 4. Snapshots of assisting motion for rolling over. The top figures show the captured motion and the bottom figures show the retargeted motion.

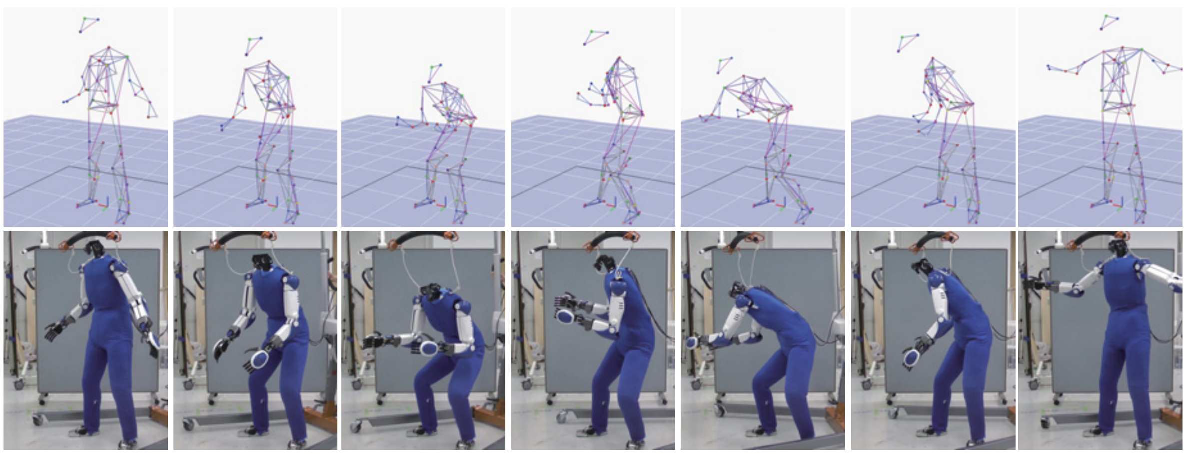

Fig. 5. Snapshots of assisting motion for transferring.


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