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On-line Human Motion Transition and Control for Humanoid Upper Body Manipulation

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***Abstract*— This paper represents the method to manipulate the objects with the upper body of a humanoid robot by capturing human motions in real-time. To control the upper body of a humanoid robot and make it behave as a human does, we define several virtual spring-damper elements between the humanoid robot and the human. The resultant motions given by the virtual forces of the elements lead the humanoid robot to move as the human acts. We employ the forward dynamics formulation to represent the dynamics model of humanoid upper body as an articulated body system with those virtual spring-damper elements for obtaining the resultant motions. Due to considering the whole dynamics of upper body, it is easy to resolve the ill-posedness or singularity of inverse kinematics problem and to involve external forces. The present method may be of use in teaching a humanoid robot working skills or detailed motions of a human. For validating the proposed method, we transited human motions to a humanoid robot using a motion capture system and controlled the robot to grasp an object passed by a person simultaneously.**

I. INTRODUCTION

The industrial robots are performing heroic feats of manipulation on a daily bases in the factories around the world, while humanoid robots in human environments have only performed sophisticated manipulation tasks in the laboratory level. It is said by some researchers that the promising humanoid robot applications in our daily lives will be only possible with advances in robot manipulation [1], [2]. One of the challenging issue in the humanoid robot manipulation is to transfer human movement skills to humanoid robots and enhance their performances in human environments.

Many researchers suggested the various solving methods to adapt captured human motions to humanoid robots as an inverse kinematics problem. Riley et al. [3] reduced the inverse kinematics problem of converting human actor's full-body postures to a humanoid robot in real-time into simpler inverse kinematics sub-problems. They first determined the torso postures using optimization and then solved several sub-inverse problems based on the torso postures. Kim [4] developed an optimization-based method for a humanoid robot to imitate human upper body motions by minimizing the posture differences between the robot and an actor. Because of the characteristics of inverse kinematics, these methods are complicated for avoiding singularity problem or have the heavy computational burden of numerical optimization-based approach [3]-[6]. The technique or post-processing of reducing the noise of measured marker position in some cases [4] is needed. Ott et al. [7] applied virtual spring forces to control a humanoid robot, which is similar to our method. Their approach was focused on recognizing human motions and imitation by a humanoid robot which was based on marker measurement from a motion capture system, however, they have not mentioned about the manipulation of the objects.

In this work, we discuss an approach to control a humanoid robot directly using human motions in real-time. From the expansion of the well known direct teaching method [8] we propose a method named *touchless direct teaching* that consists in teaching the tasks without touching the robot. This method may help scientists to remotely control the humanoid robot for executing a given task or may enable a user to teach human's complicated work skills to the humanoid robot with ease. For this purpose, we present the method of not only imitations but extended to manipulating the objects with the upper body of a humanoid robot by capturing human motions in real-time. To control the upper body of humanoid robot and make it behave as a human does, we define several virtual spring-damper elements between the humanoid robot and the human. The resultant motions given by the virtual forces of the elements lead the humanoid robot to move as the human acts. For obtaining the resultant motions, we employ the humanoid upper body's forward dynamics formulation representing the dynamics model of an articulated body system with those virtual spring-damper elements.

In Sec. 2, we briefly describe the representation of the system and then discuss the application of virtual spring-damper concept to our humanoid robot in Sec. 3. An experimental case study and the conclusion will be followed in Sec. 4 and 5.

II. SYSTEM MODELING

The imitation of the human's motion should be well tracked prior to manipulating the object with upper body of humanoid robot. Therefore, in this section, a brief presentation of the control approach for mimicking the human motions to the upper body of humanoid robot based on motion capture system will be introduced. The entire system diagram can be shown as in Fig. 1. Referred to Fig. 1, the trajectories of target position which are extracted from motion capturing system absorb into the virtual spring-

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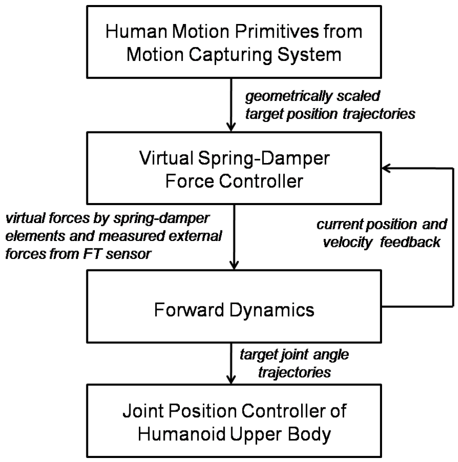


Fig. 1. Overview of the system model

damper controller. Then the controller generates the virtual force to the direction of the target position. Since the computed joint trajectories from the algorithm have to be commanded to the robot's joint position controllers the force obtained from the controller has to be transformed into the joint trajectories exploiting the robotics forward dynamics. We adopted the O(n) recursive forward dynamics algorithm for an articulated body system method based on Lie group formulation for computation efficiency [9]-[13].

III. Virtual Spring-Damper Control

The virtual spring-damper has been used widely as a motion control framework in the field of robotics [8], [14]-[16]. The virtual components create virtual forces when the virtual components interact with a robot system. This strategy is conceptually compact and requires relatively small amount of computation. We have implemented this method by applying ten virtual spring-damper elements on the upper body of the humanoid robot to mimic the human-like motion with real-time conversion (see Fig. 2).

The movement of the robot is calculated by following dynamic equations of the motion:

$$M(q)\ddot{q} + N(q,\dot{q}) + G(q) = \tau + J^T F_{ex} \tag{1}$$

where q is the joint angle vector, $M(q)$ is the inertia matrix, $N(q,\dot{q})$ and $G(q)$ represent the Coriolis and Centrifugal force and gravity term, respectively. τ is the joint torque vector, J is the Jacobian matrix and F_{ex} is virtual external force. We divided the virtual spring-damper controller by the form of two terms as

$$\begin{cases} F_{ex} = k\Delta p - \zeta\sqrt{k}\dot{p_c} \\ \tau = \hat{G}(q) - C_0\dot{q} + \tau_v \end{cases} \tag{2}$$

where k denotes the spring stiffness coefficient, Δp is a differences between the target and current position vector, $\zeta\sqrt{k}$ is the damping coefficient and $\dot{p_c}$ is the current velocity vector from eq. (2). $\hat{G}(q)$ is the compensated gravitation term which is ideally equal to $G(q)$ in eq. (1). C_0 and τ_v is the

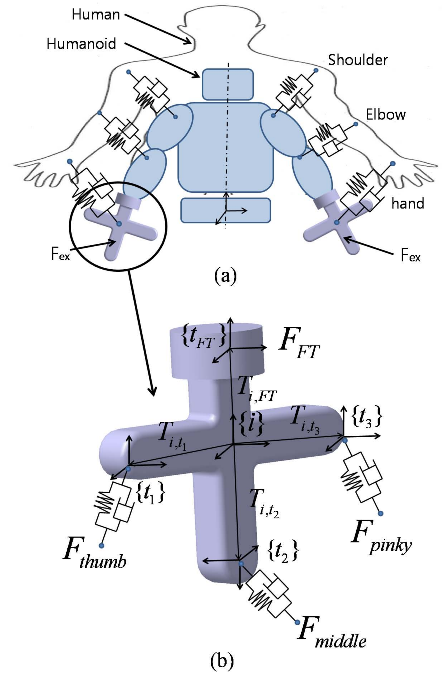


Fig. 2. Controlling humanoid robot with virtual spring-damper elements: (a) the virtual spring-damper elements on the upper body of humanoid and human, (b) the detailed configuration of hand

damping coefficient matrix and limit reaction torque which will be dealt in the next subsection.

A. Virtual Force of Spring-Damper

We suggest the virtual external force of spring-damper in eq. (2) corresponds to the recursive forward dynamics algorithm equations. As shown in fig. 2, we applied translational force on three points denoted as thumb, middle and pinky for the avoidance of representation singularity of rotational matrix. Likewise, for the motion expression of the waist rotation and for the human-like movements, two other translation forces are applied on both shoulder and elbow position; therefore, total ten virtual external forces are applied to control the upper body of the humanoid robot by the following form

$$J^T F_{ex} = \sum_{j=1}^{10} Ad^*_{T_{i,j}} F_j + Ad^*_{T_{FT}} F_{FT} \tag{3}$$

$$F_j = k(p_{d,j} - p_{c,j}) - \zeta\sqrt{k}\dot{p}_{c,j} \tag{4}$$

where j could be the frame of thumb, middle, pinky, elbow and shoulder, $T_{i,j} \in SE(3)$ expresses frame j with respect to i which is the reference frame where the force applied (i could be the frame of hand, elbow and shoulder) and $p_{d,j}$ and $p_{c,j}$ are target and current position vectors of the frame j, respectively. The Jacobian transpose matrix expressed in the first term of eq. (3) has been substituted to dual adjoint mapping Ad^*_T which is the expression of geometrical transformation of the forces from the Lie group formulation [9]-[13]. F_{FT} is the force measured from force and torque

(FT) sensor which is connected to the wrist to consider the force from outside the robotic system. Therefore, F_{FT} is usually zero but only occurs the value when the force from outside is detected.

Following presentation is the joint torque term which is denoted in eq. (2). To solve a problem of ill-posedness of inverse kinematics caused by kinematic redundancy, the adequate choice of damping coefficient is chosen as in [14]. The damping coefficient matrix can be derived as the follows:

$$C_0 = \mathbf{diag}(c_1, c_2, \ldots, c_i, \ldots, c_n) \quad (5)$$

$$c_i = \zeta_0 \sqrt{k} \sqrt{\sum_{j=1}^{n} |M_{ij}|} \qquad (i, j = 1, 2, \ldots, n) \quad (6)$$

where M_{ij} is the i, jth element of the inertia matrix from the dynamic equations of the motion, ζ_0 is the scalar weight factor and n denotes the number of Degree-of-Freedom(DOF). Without the damping component in the joints, the oscillation of the manipulator caused by the exertion of spring-like forces could not be prevented. Some previous paper showed that viscous-like forces were very helpful in this situation [15], [16].

The limit reaction torque τ_v (from eq. (2)) can be obtained where the values are usually zero but occurs negative or positive values near joint limits to avoid the collision between links [17], [18].

B. Self-Collision Avoidance

While transferring human motions to the humanoid robot the outbreak of collision between both hands could frequently occur and damage the robot. Therefore, we propose self-collision avoidance algorithm to prevent this situation. In this subsection, we only deal with the hand-to-hand collision assuming that the limit reaction torque in the previous subsection prevents other self-collisions [17], [18]. The idea is to decrease the applied virtual force as the distance between both hands of the robot gets close to the limit distance defined by the user and finally when the distance gets to the limit distance the virtual force becomes zero as expressed by the following form

$$F_{ex} = \begin{cases} k\Delta p - \zeta\sqrt{k}\dot{p_c} & \text{for } d \geq d_m \\ \sigma(k\Delta p - \zeta\sqrt{k}\dot{p_c}) & \text{for } d_l < d < d_m \\ 0 & \text{for } d \leq d_l \end{cases} \quad (7)$$

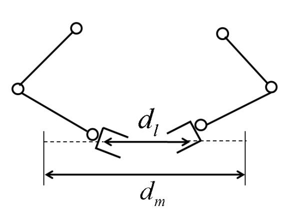


Fig. 3. Simplified picture of humanoid's dual arm (d_l and d_m are the limit distance and marginally distance respectively defined by the user)

where F_{ex} is the same virtual external force as dealt in eq. (2), d is the current distance of both hands, d_l and d_m are limit distance and marginally distance which are necessary to cease the motion of the arms at the limit position. The marginally distance is indispensable to decelerate the motion between both hands otherwise the remaining acceleration can enforce the position of the hands inside the limit distance. σ denotes the margin coefficient which can be defined as the following form:

$$\sigma = \frac{d - d_l}{d_m - d_l} \quad (8)$$

C. Object Manipulation

Tasks such as lifting objects can be taken place while teaching the humanoid robot. Unlikely to the direct teaching, our method (*touchless direct teaching*) cannot directly enforce the robot to hold such an object by touching. Therefore, we deal with the object manipulation with upper body of the humanoid robot in this subsection. The object manipulation with dual arm has been investigated by many researchers but highlighting the implementation problem in real situation; this is due to the complexity and intricacies of the formulations [10]. We introduce simple and practical method for manipulating object with dual arm by directly using virtual forces generated by the controller. To solve the above mentioned problem, basically the virtual forces are generated from the controller to grab the object with the humanoid's dual arm. Since the contact surface of the hand is sufficient enough to hold the object we assume that the situations such as dropping the object from the moments or slip will be ignored. The conceptual picture of the dual-arm manipulation in 2D space is shown in Fig. 4. Referred to Fig. 4, the virtual forces generated to track the target motion and the reaction forces generated when the contact occur can be expressed as the following form

$$F_d = k\Delta p = -F_r \quad (9)$$

where F_d is the virtual force generated from the controller, F_r is the reaction force that can be measured from FT sensor and Δp can be considered as same as in eq. (2). Then the force which is necessary to hold the object can be derived by multiplying force scaling coefficient ρ ($0 < \rho < 1$) as the form

$$F_{hold} = F_d + \rho F_r = (1 - \rho) F_d \quad (10)$$

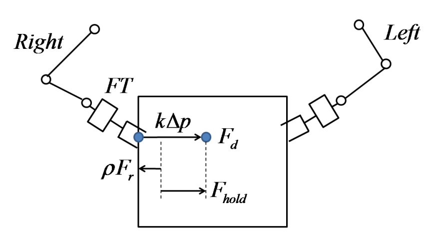


Fig. 4. Conceptual picture of humanoid's dual arm holding the object (Left hand has same property as right hand)

where F_{hold} is the remaining force that is used to hold the object. Without F_{hold}, the robot will not be able to grab the object but just slightly contact the object. Even though the formulation seems simple as in eq. (9)-(10) the values measured from FT sensor are decomposed of forces and torques of x-, y- and z-axis direction. The proposed method guarantees the natural arm posture of the final state and the stability of manipulating object without considering any directivities of the arm posture by directly treating only with force intensities from the controller and feedbacks from the FT sensors. The suitable force scaling coefficient ρ should be tuned by the user since it is dependent to the spring stiffness coefficient k. Once the force scaling coefficient is tuned properly the fluidity of F_{hold} (since it is dependant to Δp) makes it adaptive to other different types of object that have different stiffnesses as shown in the experiments section.

IV. Experimental Case Study

This section treats with few experimental case studies of the method presented in the previous sections: A. Human-like movement comparison, B. self-collision avoidance and C. object manipulation with upper body of a actual humanoid robot.

For the simulation, kinematics and dynamics formulation of the upper body of a humanoid robot was programmed. The upper body of virtual humanoid robot has 13 DOF, which is composed of 6 DOF for each arm and 1 DOF for the waist as seen in Fig. 5. In Fig. 5, three small checker balls denote the current positions of thumb, middle and pinky of robot hand, while three big checker balls indicate the target positions for those finger points. In the simulation, the target positions can be given from the human motion capture data. The distance differences between the current and target positions of the hand generate the virtual forces at the virtual spring-dampers, which affect the dynamics of the upper body.

A. Human-like Movement Comparison

To compare the human-like movements of the humanoid robot we introduce the concept of elbow elevation angle (EEA) which can be the criteria of human-like motion [19]. The elbow posture is defined by the angle between a plane vertical to the ground and the plane defined by the position of shoulder, elbow and wrist(see Fig. 6). Human arm motions can be characterized since the angle is represented in terms

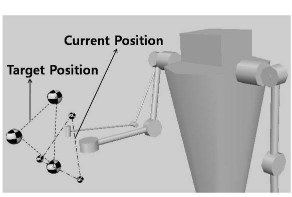


Fig. 5. Target and current finger positions in simulator

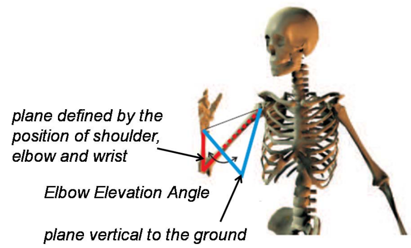


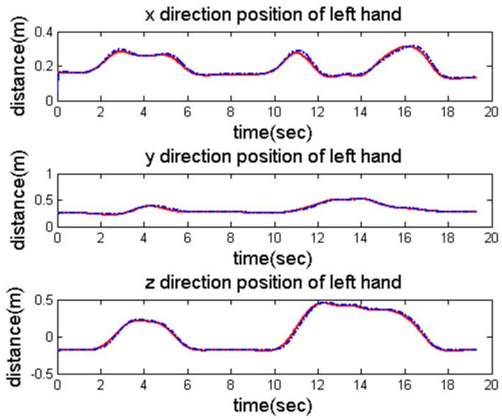
Fig. 6. The definition of elbow elevation angle for a human arm

of wrist position and elbow position that are the key factors for natural postures of human arms.

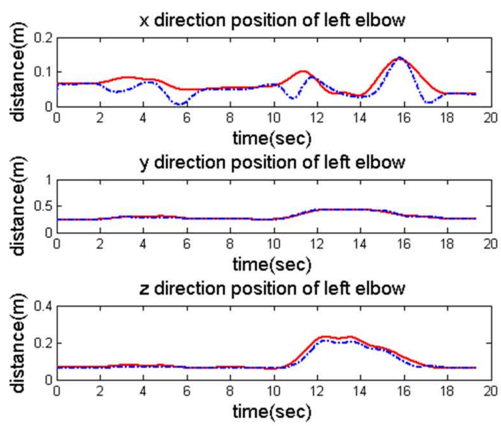
Based on this reason, both human and humanoid robot's position trajectories of left hand, elbow and EEA of each arm are calculated and then compared (see Fig. 7). The human motion data are obtained from motion capturing system geometrically scaled to resolve the length difference between human and robot's arm [17], [18], while the robot's motion data are extracted directly from the controller. Therefore in the resultant graphs, there is no kinematic difference between human and robot motion data. As shown in Fig. 7 (a) the humanoid's left hand position trajectories of the x-, y-, and z-axis values are well tracking the human motion trajectories as we predicted, however, as shown in Fig. 7 (b) and (c), considerable error can be observed in both elbow position trajectories and EEA comparison of human and robot motion data. We have found that the fundamental initial error exists from the calibration of the motion capture system and the humanoid robot has only 6 DOF for each arm underlining the impossibility to express the exact motions from the human since human has almost more than 7DOF for each arm. For these reasons, the error exists in the results, however, it can be seen that the trends of the robot's trajectory are well replicating human's trajectories, which means the actual motion of the robot is almost similar to the human motion seen by the naked eye. Even though the error is observed in the results, we estimate that by using 7DOF humanoid robot the error could be much more reduced.

B. Experiment of Self-Collision Avoidance

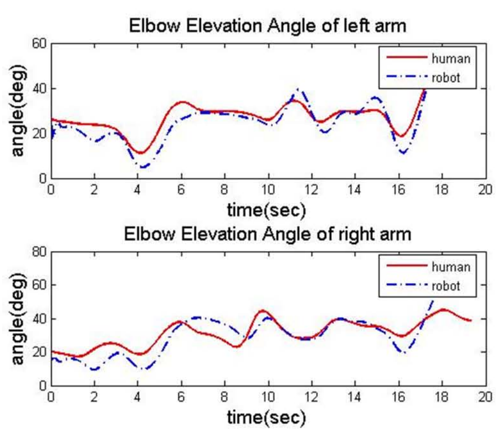
While manipulating the humanoid robot with the motion capture system self-collision of the humanoid robot could occur between the both hands since the geometrical length of the arms between the robot and human are different therefore, the self-collision avoidance is necessary to prevent the damage of robot. By using the proposed method referred in the previous section, we tested the collision avoidance between both hands of the humanoid robot as shown in Fig. 8. The red solid line is the distance between both hands of human from the motion capture system and the blue dashed line implies the distance between both hands of humanoid robot. In this experiment the limit distance is defined as 0.2m (20cm). As shown in Fig. 8, the distance between both hands of robot is standing still even though the distance between both hands of human gets over the limit distance. Therefore we conclude that the self-collision of the robot is prevented.



(a)



(b)



(c)

Fig. 7. (a) Left hand position trajectory, (b) Left elbow position trajectory (c) Left and right hand EEA of human and robot's motion data (red solid line: target position trajectory of human data, blue dashed line: current position trajectory of humanoid robot). In the experiment, $k = 9.0$ and $\zeta = 1.0$ was used.

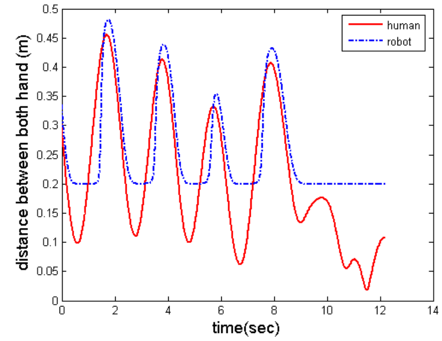


Fig. 8. Resultant graph of self-collision avoidance with the limit distance $d_l = 0.2$ (red solid line: distance between both hands of human, blue dashed line: distance between both hands of humanoid robot).

C. Experiment of Object Manipulation

The goal of the experiment in this subsection is to manipulate objects with upper body of the humanoid robot with the proposed direct force control. As shown in Fig. 10, lifting different objects (rubber ball, paper box and plastic box) that have different stiffnesses has been executed for the experiment without changing any of gains in the algorithm for each object (The force scaling coefficient $\rho = 0.1$ was used for the experiments). Fig. 9 shows the force intensity measurements of each object from the FT sensor which can be the approximated estimation of the force to maintain the object in holding pose. In Fig. 9, the oscillations are observed in the resultant graphs since the robot is continually pushing both hands to maintain the objects in holding pose. Although the oscillations make it difficult to obtain the accurate force to hold the objects, we can roughly estimate the necessary force to maintain the holding pose that can be used for teaching the robot. Finally as shown in Fig. 11, a human is teaching the humanoid robot to grasp a paper box by using the proposed direct force control method.

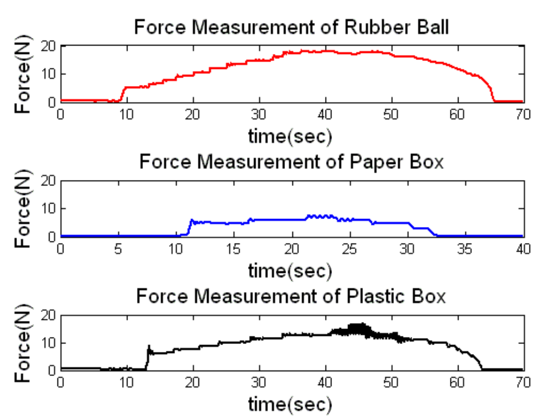


Fig. 9. Force intensity measurements of rubber ball, paper box and plastic box (from left hand FT sensor). Solid objects (plastic box or paper box) has more oscillations than the soft objects (rubber ball) since the object stiffness is larger.

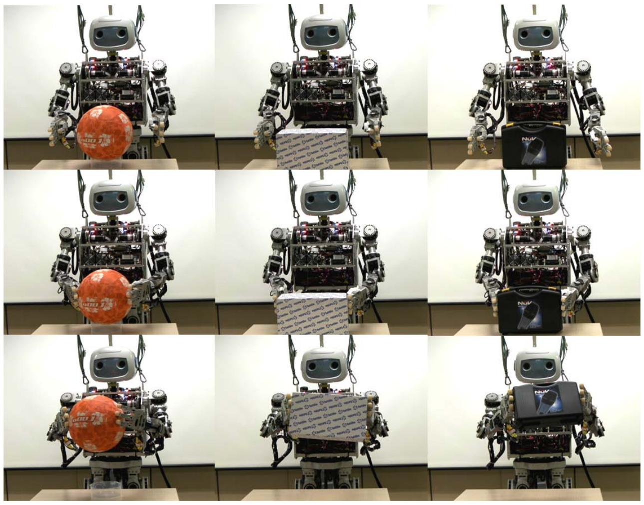


Fig. 10. The humanoid robot Mahru1 from KIST (Korea Institute of Science and Technology) is lifting the different types of object (first column: rubber ball(diameter: 25cm, weight: 280g), second column: paper box(size: 28×16×9.5cm, weight: 280g), third column: plastic box(size: 26×18×7cm, weight: 300g)) with the cooperation of both hands.

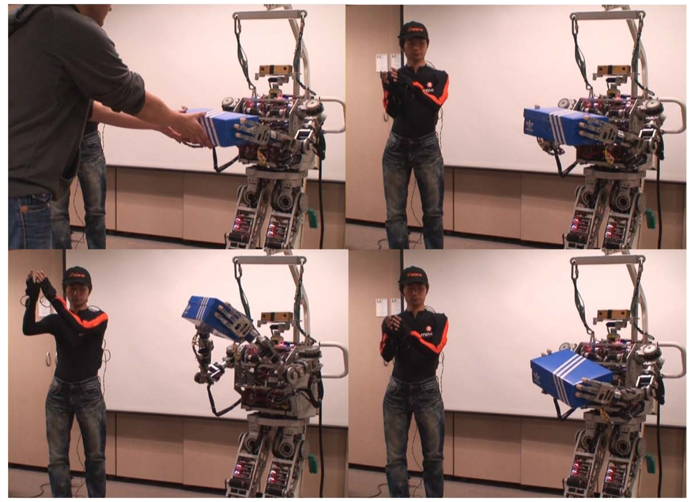


Fig. 11. Real-time human motion transition and control. The human is teaching the robot to grasp a box with both hands.

V. Conclusions

We have presented the methodology to manipulate the upper body of a humanoid robot using human motion capture data in real-time. Through the simulations and experiment results, it is observed that the present algorithm may help one to control the humanoid robot remotely preserving the human-like motion characteristics. Moreover, it is shown that the robot can flexibly manipulate the objects with the cooperation of both hands using the external forces measured from FT sensor. Consequently we have proposed the method of human motion transition and control that can be applied to remotely control the humanoid robot to perform a given task or may enable a user to teach human's complicated work skills. For the future work, by considering teaching and learning skills, we will extend this method to *touchless direct teaching* that would enable a user to teach human's complicated work skills directly using human motions.

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