

Load Distributed Whole-body Motion Generation Method for Humanoids by Minimizing Average Joint Torque Ratio

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Abstract. In this paper, we propose a load distributed whole-body motion generation method for a humanoid robot whose limbs are constrained to environments. To minimize a load over the posture sequence, first, we optimize each key frame posture by searching neighboring postures by using a load evaluation functions. Then, we determine parameters of the whole-body internal force for changing force distribution between arms and legs and whole-body joint torque ratio. We show a method to decrease search space for internal force parameters under symmetric posture assumptions. To evaluate developed methods, numerical experiments for least-loaded and most-loaded standing up from a chair motions and real-world experiments using a HRP-2 humanoid robot are presented.

Keywords. Humanoid robot, Load distribution, Whole-body motion generation method, Joint Torque, Environment Contacting Behavior

1. Introduction

Recently, as a highly stable walking and running control technology progress, much attention on whole body motion generation method for a humanoid robot whose limbs are contacting with an environment [1–6] is paid. In order to develop the environment contacting behavior generation method under whole-body coordination, it is very important to consider a load distribution that reduce internal force or joint torque ratio. Since an inadequate posture and reactive forces causes a high-loaded torque to a joint, which causes joints damaged.

In this paper, we propose a load distributed motion generation method or a humanoid robot by minimizing joint torque ratio.

Previous researches for generating whole body motions of a humanoid robot whose limbs are contacting to an environment is categorized as 1) ZMP based stability motion generation [2–4, 7], 2) Internal force based whole body manipulation control [5, 8]. The former does not consider a load distribution, however the latter does. For example, Yokokoji et al. [5] proposed the static posture evaluation for

a humanoid robot constrained to an surrounding environment. We adopt this approach and extend to the load distributed whole body motion generation method of a humanoid robot. We developed 1) a motion generation method to optimize initial key frame postures by searching neighboring postures by using a load evaluation functions. 2) a method to determine parameters of the whole-body internal force for changing force and joint torque distribution by decreasing search space for internal force parameters under symmetric posture assumptions.

2. Load Distributed Whole-body Motion Generation Method

2.1. Load Distributed Motion Generation Under Coordination of Arms and Legs

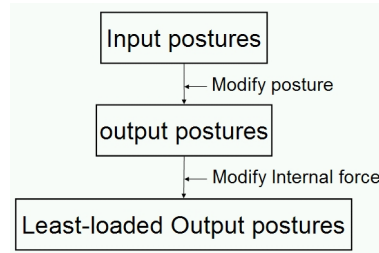


Figure 1. Overview

Figure 1 shows an overview of this research. We optimize each key frame posture by searching neighboring postures by using a load evaluation functions. Then, we determine parameters of the whole-body internal force for changing force distribution between arms and legs and whole-body joint torque ratio.

For example, in standing-up motion from a chair, We give waist's height as key frames, then search neighboring waist's position and rotation. Finally we calculate internal force for each posture, evaluating load of joint torque ratio.

2.2. Design of Load Evaluation Function

To evaluate postures, we are able to consider various functions as joint torque, reaction force at each limb, stability etc. In this paper, we selected the average of all joint torque ratios.

$$\frac{1}{N} \sum_{i=0}^N \frac{\tau_i}{\tau_{maxi}} \quad (N = \text{number of joints}, \tau = \text{joint torque}) \quad (1)$$

2.3. Determining Internal Force Parameters

Forces and joint torques of each arm and leg change even in the same posture because of the whole-body internal force. We selected the whole-body internal force parameters which minimize the average of all joint torque to prevent robot's self destruction.

3. A Method to Determine Whole-body Internal Force

3.1. Definition and Formulation of Whole-body Internal Force [5, 8]

When the robot is constrained to an environment through its limbs, the force \mathbf{f} and the joint torque $\boldsymbol{\tau}$ is calculated as followings:

$$\mathbf{f} = -\mathbf{G}^\# \mathbf{m}g + \mathbf{N}\mathbf{k} \quad (2)$$

$$\boldsymbol{\tau} = \mathbf{J}^T \mathbf{f} + \mathbf{h}g \quad (3)$$

\mathbf{G} indicates the position and rotation of the each limb, and $\mathbf{N}\mathbf{k}$ indicates internal forces. \mathbf{J} is the jacobian, $\mathbf{m}g = \frac{\partial P}{\partial \mathbf{x}_B}$, $\mathbf{h}g = \frac{\partial P}{\partial \boldsymbol{\theta}}$, and P is the potential energy [8].

Although Harada et al. applied it to the circumstance contacts environments with 3 points, we expand the whole-body internal force to the circumstance where a robot contact environments with 4 points.

From the geometric placement, \mathbf{N} and \mathbf{k} can be described as Equation 4 , Equation 5 .

$$\mathbf{N} = \begin{bmatrix} \mathbf{e}_{01} & \mathbf{e}_{02} & \mathbf{e}_{03} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ -\mathbf{e}_{01} & \mathbf{0} & \mathbf{0} & \mathbf{e}_{12} & \mathbf{e}_{13} & \mathbf{0} \\ \mathbf{0} & -\mathbf{e}_{02} & \mathbf{0} & -\mathbf{e}_{12} & \mathbf{0} & \mathbf{e}_{23} \\ \mathbf{0} & \mathbf{0} & -\mathbf{e}_{03} & \mathbf{0} & -\mathbf{e}_{13} & -\mathbf{e}_{23} \end{bmatrix} \in R^{12 \times 6} \quad (4)$$

$$\mathbf{k} = [k_0 \ k_1 \ k_2 \ k_3 \ k_4 \ k_5]^T \quad (5)$$

where \mathbf{e}_{ij} denotes the unit vector directing from one contact point to another one.

3.2. Searching Minimal Torqued Internal Forces

Figure 3 shows the internal force ratio and joint torque ratio by changing the internal force parameter \mathbf{k} . We searched from -20000 to 20000 at every 50 steps. The number of Parameters which control the internal force is 12 in Equation 2 . After we apply the whole-body internal force, the number of that becomes 6 (Equation 5 , Figure 2 (a)). Then we assume that the robot's posture and the force exerted by the robot are symmetric, the number of that becomes 4 (Equation 6 , Figure 2 (b)). Finally, the number of that becomes 2 (Equation 7 ,Equation 8 ,Figure 2 (c)), when we calculate the 2 parameters (k_0, k_5) so as to cancel the lateral component of forces exerted between both hands and between both feet.

It is quite useful that right and left hands and feet exert the same force in symmetric postures like standing-up posture from a chair. In this situation, Equation 5 is described as Equation 6 .

$$\mathbf{k} = [k_0 \ k_1 \ k_2 \ k_2 \ k_1 \ k_5]^T \quad (6)$$

It's desirable that internal forces compensate only the robot's own weight, because too much internal force leads to the destruction of robot itself and environments. Then we can cancel the lateral component of forces by using internal forces exerted between both hands and both feet (Equation 7 ,Equation 8).

$$k_0 = -e_{02y}k_1 - e_{03y}k_2 \quad (7)$$

$$k_5 = e_{02y}k_1 + e_{12y}k_2 \quad (8)$$

where e_{ijy} denotes the lateral component of e_{ij} .

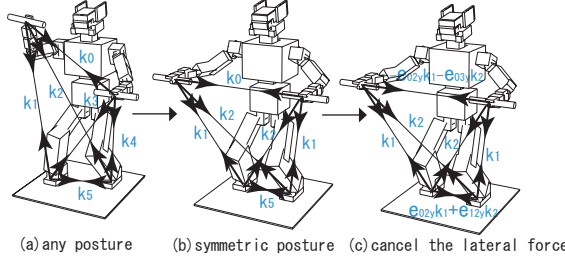


Figure 2. Changes the Number of Internal Force Parameters

Using this method decreases the dimension of search space from 12 to 2. Then we can get the appropriate whole-body internal force in less calculating time.

3.3. Torque Ratio Control Experiment based on Internal Force

Changing parameters of internal force enables us to vary the ratio of forces exerted by hands and feet. So we can distribute joint load considering the joint torque in each posture. Figure 3 shows the variation of the average torque ratio, and the ratio of vertical components of arm and leg force, when we change ' k_1 ', one of the internal force parameters. The value of $arm\ force\ norm / (arm\ force\ norm + leg\ force\ norm)$ changes from 0.08, at the minimum, to 0.67, at the maximum. The minimal point ($k_1 = -15548$) shows the vertical components of arm forces come to 0, and the maximum point ($k_1 = -15235$) shows the vertical components of leg forces come to 0. According to this, we can distribute joint loads by using this method, considering the robot stands up under its own weight only at both hands and feet.

Experiments using a real hardware are shown in Figure 5. We apply impedance control to each limb and the desired force are calculated using Equation 6, Equation 7, and Equation 8. Figure 4 (simulation), Figure 5 (experiment by real robot) shows the joint torque ratio and reaction force when $k_1 = 10918$ and $k_2 = -11968$, which gives minimum torque ratio over the search space, and that when k_1 is 0 and k_2 is 0. This results show that it is possible to control torque ratio by changing internal force parameter.

4. Least-loaded Motion Sequence Generation Method

This section describes a method to calculate optimized postures.

We made input postures(key frame postures) by moving robot's waist straight upward in ten times from 250[mm] (sitting posture) to 650[mm] (standing-up posture), while fixing the position and rotation of its hands and feet to environments. Search space is where the solution of inverse kinematics exists. Then we selected the solution of minimal average torque ratio from each waist height.

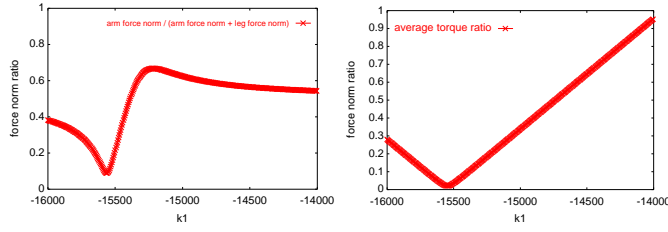


Figure 3. Changes of $\text{arm force norm}/(\text{arm force norm} + \text{leg force norm})$ and the average torque ratio when k_1 changes

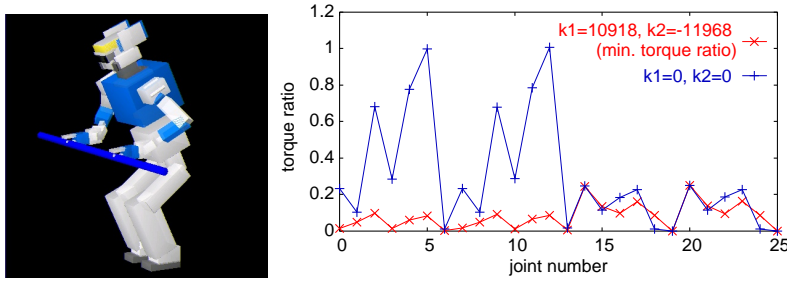


Figure 4. Joint Torque Ratio of Each Joint in Simulation

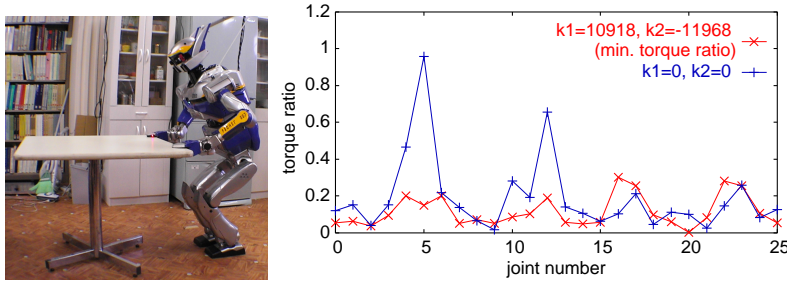


Figure 5. Joint Torque Ratio of Each Joint in Real Robot

5. Experiments of Standing-Up Motion from a chair

5.1. Simulation

This section shows numerical examples of standing-up motion using the method showed in Section 4. Then we evaluate the changes of average torque ratio about the least/most-loaded motion sequence. Figure 6 and Figure 7 show the least/most-loaded motion sequence. Figure 8 and Figure 9 show the joint load of arms(left) and legs(right) of least/most-loaded motion sequence. Comparing most-loaded sequence and least-loaded one, although changes of leg joints torque is small, changes of arm joints torque is large as the robot stands up. Especially joint torque around shoulder pitch axis and knee pitch axis is decreasing about 15%(20% to 5%). This is because space of solutions of inverse kinematics is broader in standing-up posture than in sitting posture.

5.2. Experiments of Standing-Up Motion from a chair with real robot

We did experiments by using the same motion sequence as the numerical examples. We used HRP-2 [9] for this experiment, which has 7 DOFs for each arm and 6 DOFs for each leg. To do experiments using a real robot, we applied impedance control to each limb. Figure 10 and Figure 11 show the least/most-loaded motion sequence. Figure 12 and Figure 13 show the joint load of arms(left) and legs(right) of least/most-loaded motion sequence. We calculated each joint torque from 6-axis force sensor in wrists and ankles of HRP-2 using jacobian.

Although joint loads are not exactly the same with numerical examples, the least-loaded motion sequence is less loaded than the most-loaded motion sequence, especially in joint loads of arms, which is similar to the numerical examples.

6. Conclusions

In this paper, we proposed a load distributed whole-body motion generation method for a humanoid robot whose limbs are constrained to environments. Our proposed method consists of 1)a method to determine parameters of the whole-body internal force to minimize average torque ratio, 2)a motion generation method to initial key frame postures. We made least-loaded and most-loaded standing-up motions from a chair as a numerical example. We also did experiments with HRP-2 and confirmed that the numerical examples and the experiments showed similar results.

As the future works, we should consider time axis, not only dynamics but also to reflect that motors usually able to output over the limit for short time or a continuous output of a certain level of current raises motor temperature and causes a breakout. Another direction is motion planner that generates when and where a robot contacts whose limbs for a load distribution for a environment contacting behaviors such as a climbing ladder or a standing up and down form a chair. And we should also extend these methods to generate online trajectory with varying loads and to absorb modeling errors.

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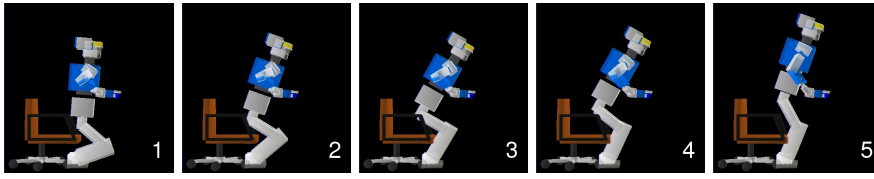


Figure 6. Least-loaded Standing-Up Motion(frame=0,2,4,6,8)

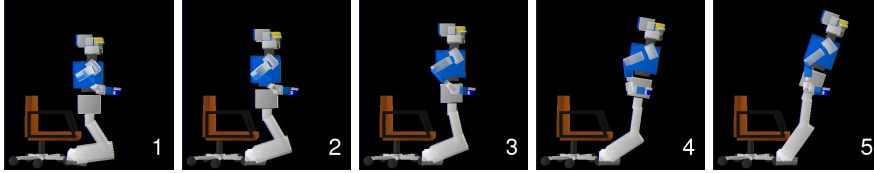


Figure 7. Most-loaded Standing-Up Motion (frame=0,2,4,6,8)

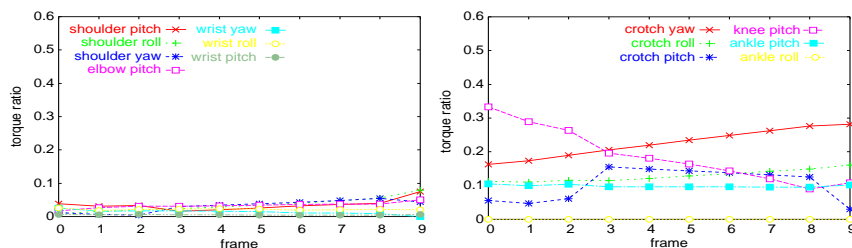


Figure 8. Joint Torque of Least-loaded Standing-Up Motion(LEFT:Arm RIGHT:Leg)

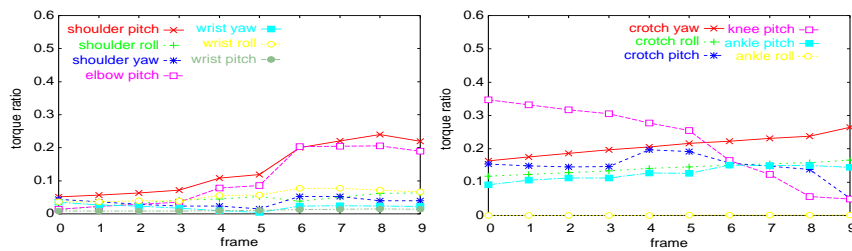


Figure 9. Joint Torque of Most-loaded Standing-Up Motion(LEFT:Arm RIGHT:Leg)

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Figure 10. Least-loaded Standing-Up Motion (frame=0,2,4,6,8)



Figure 11. Most-loaded Standing-Up Motion (frame=0,2,4,6,8)

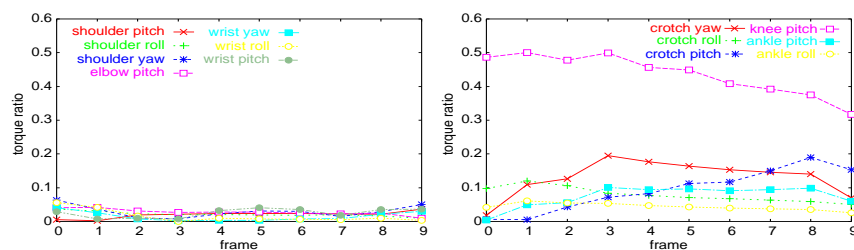


Figure 12. Joint Torque of Least-loaded Standing-Up Motion(LEFT:Arm RIGHT:Leg)

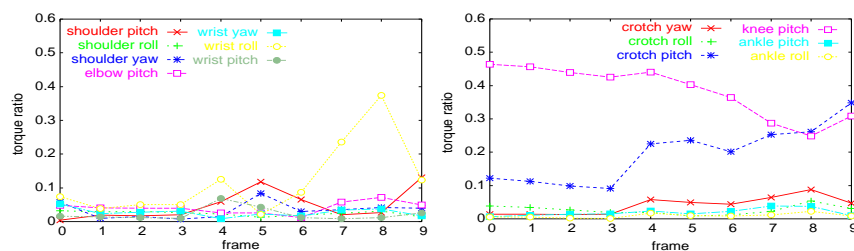


Figure 13. Joint Torque of Most-loaded Standing-Up Motion(LEFT:Arm RIGHT:Leg)

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