Construction of Simulation Environment for Gait Development in a Biped Robot

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摘要:在发展机器人中，由于机器人本身造价昂贵，因此在实验前应先透过软件仿真评估硬件实验的可行性。仿真环境的建立主要是透过三种计算机辅助工程软件的结合，分别是SolidWorks、ADAMS、Matlab。双足机器人3维物理模型是在SolidWorks下完成，而ADAMS用来评估整体系统的动态反应，最后利用Matlab进行控制器设计与步态设计。双足机器人的步态是基于零力矩点(ZMP)的观念确保能稳定行走，并透过线性倒单摆模型产生双足机器人质心轨迹，将此轨迹与3维模型输入ADAMS进行动态仿真，而仿真结果可作为设计步态轨迹的依据。

关键词:计算机辅助工程软件、线性倒单摆模型、零力矩点、双足机器人

Abstract: In the development of robots, it is important to evaluate the task in simulation environment before the experimental testing due to the high cost of the physical platform. In this paper, the construction of simulation environment for a biped robot based on three different commercial CAE software packages is reported, including SolidWorks, ADAMS, and Matlab. SolidWorks is utilized for constructing the robot’s 3D physical model, ADAMS is used for evaluating the dynamic response of the system, and Matlab provides controller design environment. The gait is developed in Matlab based on the concept of ZMP and a linear inverted pendulum model, where the former one secures the robot stability and the latter one determines the basic trajectory of the robot’s center of mass. Then, the designed gait and the physical model are both imported into ADAMS for dynamic simulation. The simulation results provide realistic information of robot walking and are used to refine the controller design and gait generation.

Key words: CAE software, linear inverted pendulum model, ZMP, biped robot

1. Introduction

Since the humanoid robot WABOT-1 was developed at the Waseda University by the team KATO in 1973 [1, 2], the robotic industry and technology have risen in Japan. It is no doubt that Honda is a pioneer in this area because of the development of the humanoid robot ASIMO, whose innovations continuously inspires the society [3, 4]. Besides that, the HRP series from AIST are also well-known for their achievement [5, 6]. The humanoid robotics has become one of the international brand-academic research fields. One of the most important tasks in developing a humanoid robot is to generate stable walking gaits, so lots of related research has been reported. For example, the method of producing a gait, which is based on the human gait, for biped robot has been proposed [7]. There are some control methods for biped robot with stable walking gaits [8].

Before applying new designed gaits or control methods to a biped robot, however, there are some simulations to ensure the designed gait to let the robot walks stably. In addition, because a biped robot includes a lot of expensive sensors, actuators, and mechanisms, we must prevent it from damaging when taking the experiment. Buschmann et. al. demonstrates that dynamics simulation is a valuable tool for biped robot hardware and controller design [9], and Hirukawa et. al. shows the correspondence between dynamic simulations and the experiments of biped walking of humanoid robots [10].

This work is supported by National Science Council (NSC), Taiwan, under contract 97-2221-E-002-208-MY3

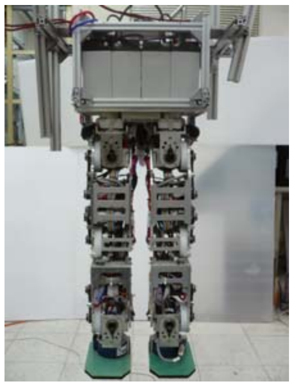

Fig. 1 Picture of the biped robot.

Previously, we developed a biped robot shown in Fig. 1 [11]. It is interesting for us to construct a simulation environment to make an efficient simulation process during gait analysis and design, so we combined some CAE (Computer Aided Engineering) software packages to construct the desired setup. We tested the developed gait in this simulation environment, where the gait was designed based on the concept of Zero-moment Point (ZMP) [12] with a simplified linear inverted pendulum model [13].

This paper is organized as follows. Section 2 introduces the utilized CAE software packages and shows how those cooperate with each other. Section 3 describes how to generate trajectories for a biped robot using simplified linear inverted pendulum model. Section 4 describes the simulation results. Section 5 concludes the work.

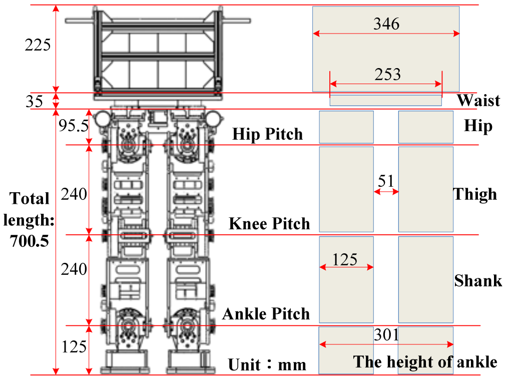

Fig. 2 Dimensions of the biped robot.

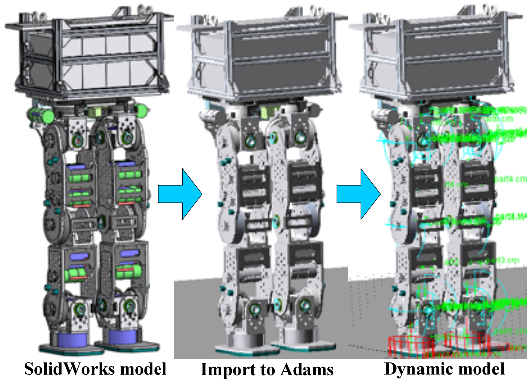

Fig. 4 The steps of building ADAMS model.

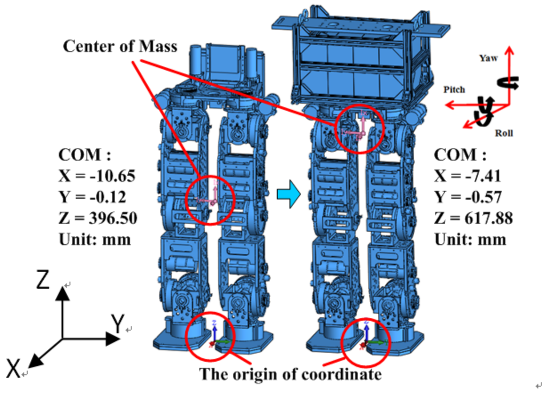

Fig. 3 Locations of the COMs of the robot with and without the batteries.

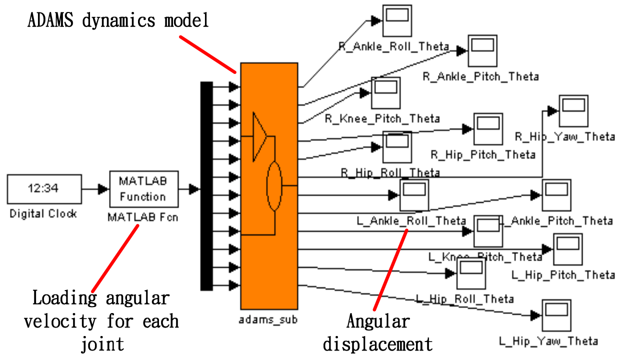

Fig. 5 The Simulink model of controlling ADAMS model with angular velocity input.

2. Construction of simulation environment

When simulating and analyzing locomotion of the biped robot, the physical model of the robot need to be constructed first, and then the robot is controlled and simulated within the dynamic environment. However, among the available commercial CAE software packages, there is no single software package which includes all of those functions. Therefore, several available software packages must be integrated to construct the desired simulation environment. To achieve this goal, there are three types of different software utilized in our work, including SolidWorks, ADAMS, and Matlab. In the full simulation, the first step is to design the mechanism and set the degree of freedoms of biped robot using SolidWorks. In the second step, import the model to ADAMS and set the conditions, such as contact condition, gravity, etc. Finally, export the plant of ADAMS model and use Matlab to control the trajectory for each joint of the biped robot.

The physical model of the biped robot is constructed in SolidWorks shown in Fig. 2. The robot has 12 degree of freedoms (DOFs), 6 on each leg. The model includes the aluminum structure, motors, Harmonic Drives, pulleys, force sensors and batteries. Because the dynamic response is determined the mass and inertia distribution of the whole robot, the main consideration at this stage is not only the dimensions but also the densities of the materials utilized in the robot. Because those mentioned above could determine the actual robot's center of mass (COM), it is important to create a dynamics model in ADAMS and the stability in controlling robot. Fig. 3 shows the shift of the COM after adding the batteries.

Figure 4 illustrates the steps of building ADAMS model. After finishing the construction of the physical model, the biped robot is divided into 13 parts, including 6 parts for each leg and 1 part for lumbar, based on the locations of the active degree of freedoms (DOFs). Those parts are imported to make a dynamic model in ADMS. In addition, it is necessary to build motion type between connecting joints, the contact force type between foot and ground and set the direction and magnitude of gravity. Before exporting this dynamic model to Matlab file, there are some variables which are needed to be set. Those variables depend on the input and output of the dynamic plant, and this paper will discuss the difference between angular velocity input and torque input. On the other hand, the output of the plant is determined by what we want to record, like COM trajectory, angular displacement for each joint, etc.

While the robot walks on the ground, the trajectory control is vital because a biped robot is not a stable system. Thus, after exporting plant from the ADAMS file, the function of Matlab is to provide a platform which the gait control simulation can be carried out. As mentioned in the previous paragraph, there are two types of plant inputs, angular velocity and torque, used in this paper. Figure 5 shows the Simulink model in Matlab with angular velocity input, so the main concern focus on whether the planned gait can be applied when robot walks or not. In other words, it is assumed the controller and actuator are very powerful for control

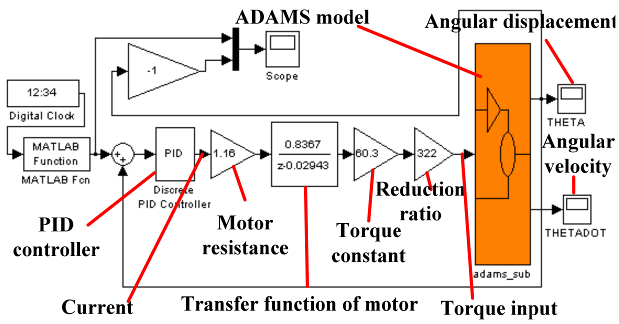

Fig. 6 The Simulink model of controlling ADAMS model with torque input.

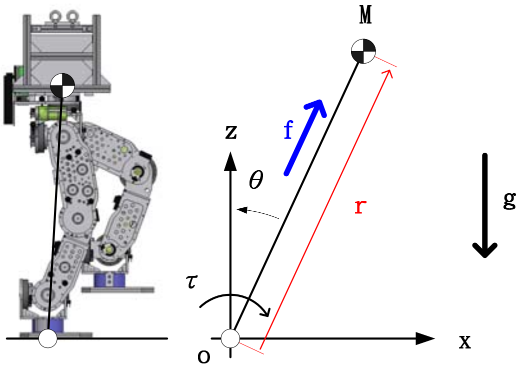

Fig. 7 Inverted pendulum model in sagittal x-z plane.

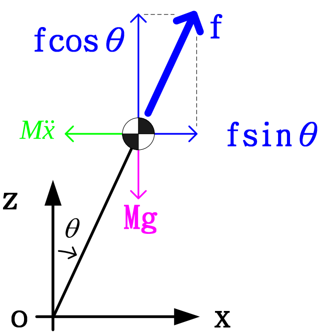

Fig. 8 Free body diagram of the inverted pendulum model constrained with constant height.

without any delay or uncertainty happened in this simulation. On the other hand, Fig. 7 demonstrates the plant which is controlled with torque input for each joint, and it is considered all the parameters of controllers, motors, and reduction ratio. Therefore, the result of simulation is close to the real situation.

3. Simplified dynamic model for gait planning

While biped robot walks stably, not only reaction force between sole and ground and inertia force but also all the moment created by those force must balance, so the ZMP (Zero-Moment Point) of the robot on the sole must lie in the support plane on the ground[12]. In order to simplify dynamic model, there are some assumptions needed to be considered. Furthermore, it is

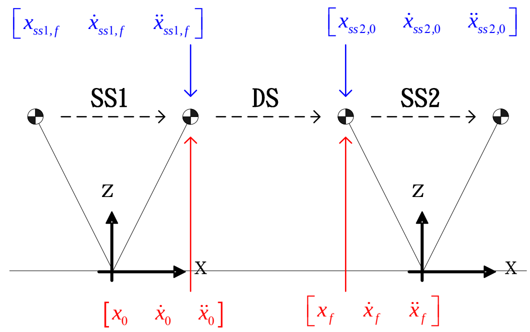

Fig. 9 Generation of the trajectory in the DS phase by polynomial function with given boundary conditions.

necessary to consider two general phases when robot walks, one is SS (Single Support) phase, and the other is DS (double support) phase. Because the underlying physical principals are different, the trajectory of COM is derived from different dynamic models. This section describes how to generate COM trajectories while the robot operates in the SS and DS phases.

In the single support phase, the inverted pendulum model is used to generate the trajectory of COM. Figure 7 explains the simplified model in the sagittal x-z plane, which assumes point mass, weightless leg , and no-slip on the ground. M is the mass of robot, g represents gravity, r is the vector from the contact point to the center of mass, and τ is zero while the inverted pendulum is point-contact to the ground. In order to reduce the computation requirement of trajectory generation, a constraint of constant height is added to the inverted model, and this model is called a linear inverted pendulum. Figure 8 shows the free body diagram of the inverted pendulum model with constant height. Mg represents the gravity force, f is the reacting force by the ground, and $M\ddot{x}$ is the inertia force created by the acceleration. In addition, this model is not only generating the trajectory for the single support phase but also providing the initial and final condition for the double support phase.

While the robot walks, there is one double support phase between two single support phases, but the linear inverted pendulum is not suitable for the double support phase. Therefore, to keep continuous motion when the phase changing, the polynomial is used to connect the trajectory for the double support phase with initial and final conditions provided by the boundary conditions of the single support phase shown in Fig. 9. In the whole process of trajectory planning, the first step is to analyze the walking pattern and separate a full walking into several stages, such as single support phase, double support phase, and some steps of adjusting posture at the beginning and at the end of the whole walking period. The second step is to generate the trajectory of COM (Center Of Mass).The third step is to use the method called Inverse Kinematics to produce the whole trajectory for each motor. However, the third step is not the last one because the final step is to confirm stability of generated trajectory. As the beginning of this section is mentioned, the ZMP of generated trajectory for each motor must be in the support areas, otherwise the designed trajectory will let the robot fall down when robot move on the ground. All of the process of trajectory planning is shown in Fig. 10.

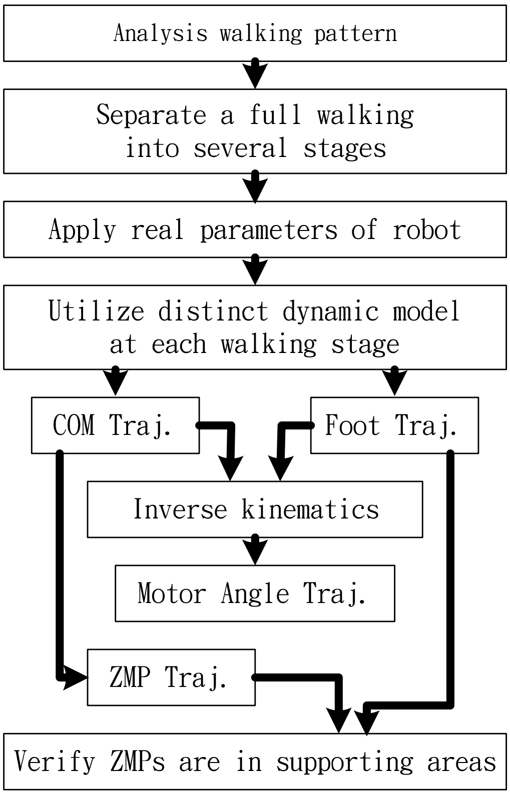

Fig. 10 The flowchart of trajectory planning.

4. Simulation results

The simulations results can be read from Simulink in Matlab, and these results can also be exported to ADAMS for simulating 3D motion. As mentioned in Section 2, there are two different inputs in the ADAMS models. Therefore, the results can be discussed separately, with angular velocity input or torque input. The following section will show the results with angular velocity input firstly and then the results with torque input. These results include COM trajectory, 3D motion snapshots, and the angular displacements for all joints.

4.1 The results with angular velocity input

Because the angular velocities for all joints are directly loaded from Matlab, it is assumed that the trajectories of all joints follow the designed trajectories correctly. The main purpose of this simulation is to test whether the robot can walk stably under the designed trajectory with the contact between soles and ground. Figure 11 illustrates the designed COM trajectory (the blue line), and the output COM trajectory (the green line), with the c. The error between those lines is very small in the x, y, and z direction, and the robot can walk without falling down.

Figure 12 demonstrates the snapshots of 3D motion using ADAMS. The whole walking stages include squatting, shifting the COM, walking, and standing. The squatting stage is to lower the COM position because the constraint, the height is the same in walking period, exits. Shifting the COM is to make sure that the ZMP also shift to the supporting leg at the beginning, and the standing stage is to shift the COM back to the initial position.

4.2 The results with angular torque input

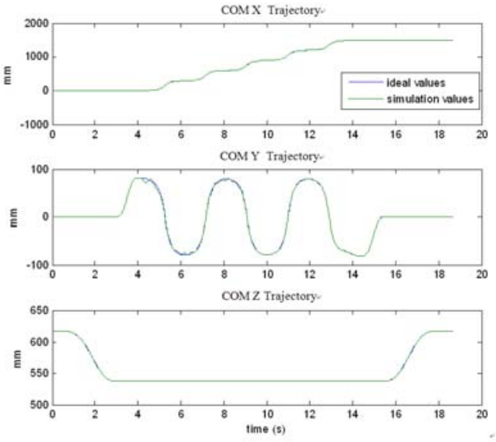

Fig. 11 The plots of the ideal and simulated COM trajectories.

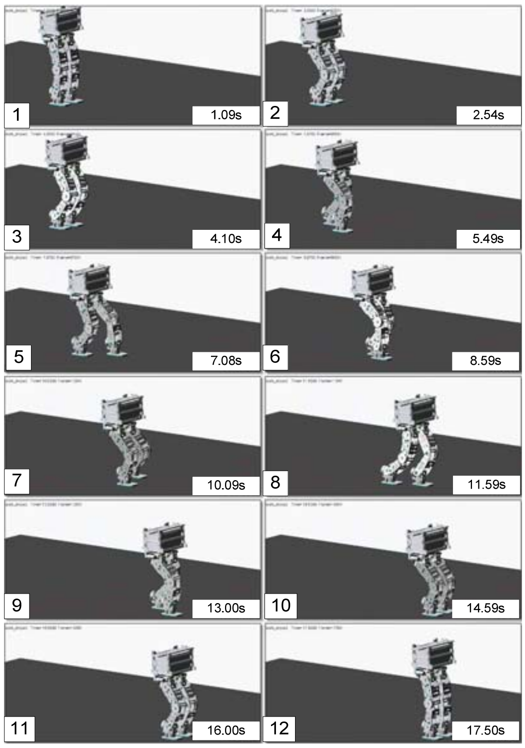

Fig. 12 The snapshots of the robot walking on the flat ground.

In this section, the functions of Matlab are both to load the file of angular displacement for each joint and to construct the environment of position feedback control. Because it is not directly to give the trajectory to the ADAMS model, there are some uncertainties caused by controller and the fictitious motor model in Matlab. Figure 13 shows the walking pattern which the robot's waist is fixed on the supporting mechanism in ADAMS, so the soles will leave the ground while walking. The top of the small snapshot is in the lateral plane, and the bottom of the snapshot is in sagittal plane. The whole walking stages also include squatting, shifting the COM, walking, and standing.

Figure 14 and 15 show the designed trajectory and simulating trajectory for each revolute joint in the right leg and in the left leg respectively. The errors between designed trajectory and controlled trajectory are very small, and the max error is less than

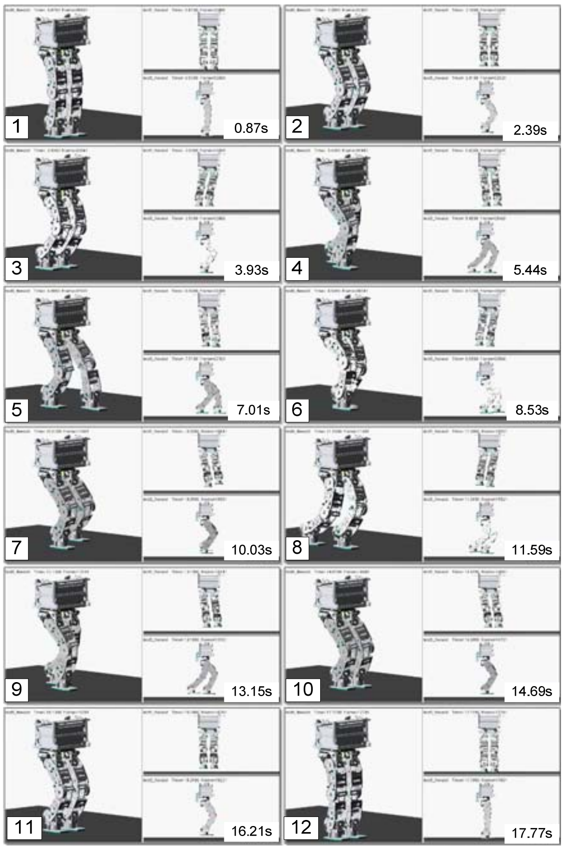

Fig. 13 The simulation results with torque input in ADAMS.

one degree. Figure 16 shows the maximal torque in the whole motion at the right hip joint because the robot's waist is fixed on the support mechanism. The red line represent the edge of nominal maximal torque, and the torque exceeding the edge can be regard as peak maximal torque. This information can help us design the type of motors and the new trajectory.

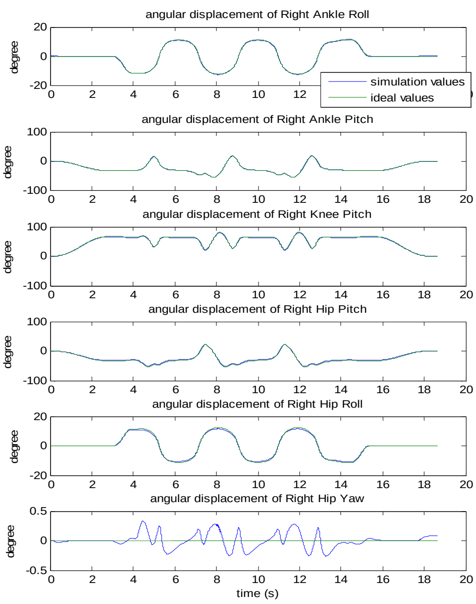

Fig. 14 The designed and simulating trajectories of all joints in the right leg.

5. Conclusion

We successfully integrate three different commercial CAE software packages to construct simulation environment for gait development in a biped robot. Current simulation results provide valuable information about the behavior and performance of the developed walking patterns; thus, significantly reducing the development time. Comparing the results with torque input and angular velocity input, controlling angular velocity is more straightforward, and it indeed reveals the behaviors of the desired trajectories. However, it is not realistic because the physical system may not be able to follow the trajectories. In this sense, controlling torque is a more adequate choice. However, the simulation seems to be hard to converge due to challenge computation setups. Therefore, both setups are used for the development.

We are currently working on adjustments of some parameters in the controller, to refine the stability of the walking gaits. In the meantime, the global feedback algorithm is also under development, to provide better control mechanism of the robot.

6. Acknowledgment

The authors gratefully thank the National Instruments Taiwan Branch for their kindly support of equipments and technical consulting.

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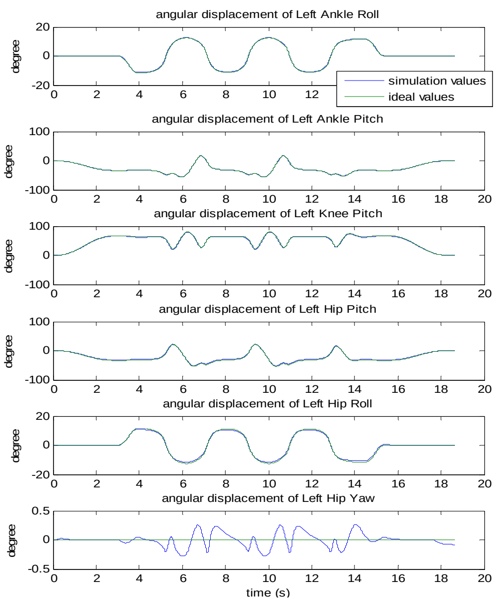

Fig. 15 The designed and simulating trajectories of all joints in the left leg.

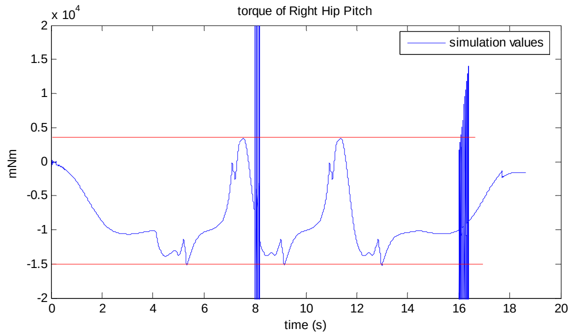

Fig. 16 The maximum torque of the right hip joint during whole motion.

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