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Development of the Lower Limbs for a Humanoid Robot

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Abstract— **This paper gives an overview of the development of a novel biped walking machine for a humanoid robot, Roboray. This lower-limb robot is designed as an experimental system for studying biped locomotion based on force and torque controlled joints. The robot has 13 actuated DOF and torque sensors are integrated at all the joints except the waist joint. We designed a new tendon type joint modules as a pitch joint drive module, which is highly back-drivable and elastic. We also built a decentralized control system using the small controller boards named Smart Driver. The forward walking experiment with this lower limbs was conducted to test the mechanical structure and control system.**

I. INTRODUCTION

It is beyond question that the best helper of human being is human being itself. If a machine should replace the helper's role, a human-like form of biped humanoid expected to fit in the living environment without modification. In this point of view, many companies, research institutes and universities have been developing various humanoid platforms. Among the technologies of humanoid, the lower-limb mechanism and biped locomotion are the most important for successful implementation of a biped humanoid.

The most famous and impressive humanoid robot is ASIMO [1] made by HONDA. After the prototype robot P2 [2] was revealed in 1996, HONDA has steadily released the progress of ASIMO. In the latest release in November 2011, "All-new ASIMO" [3] was unveiled demonstrating its new capability of walking over an uneven surface, running at 9km/h and hopping on one leg or both legs. Waseda University is also one of the consistent institutes developing humanoid robots. It is well known that the first biped robot WABOT-1 was developed by Kato in 1973. This research has been continued by Takanishi Laboratory and recently lead to the development of WABIAN-2R [4], a humanoid robot which has 2 DOF waist joint and several kinds of feet. The HRP series [5], [6], [7], developed at Japanese National Institute of Advanced Industrial Science and Technology (AIST), had not been focused only on the appearance similar to human, but also research for stable walking methods in various environments. Korea Advanced Institute of Science and Technology (KAIST) also developed humanoid robots. The recent humanoid robot, named HUBO2 [8], is capable of balancing during hopping against push and running at 3.24 km/h. H6 [9] and H7 [10] from the University of Tokyo, Jonnie [11] and Lola [12] from the Technical University of Munich, Toyota's Partner Robots [13], Sony's Qrio [14] are also successfully developed and contribute to the advancement of humanoid robot technology.

Fig. 1. Roboray and its lower limbs wihtout cover

Though the robots introduced above are different from each other depending on their purpose, they have the common methodology to realize bipedal walking. A general strategy is to use a dynamics based walking pattern generation which provides the desired trajectories for each joint position controller. The introduction of Zero Moment Point (ZMP) by Vukobratovic [15] deeply influenced the literature of this strategy. Most walking algorithms of above robots decide the center of mass (COM) trajectories, which make ZMP in the support polygon, and generate the joint trajectories from the COM trajectories. These position control based algorithms need stiff joint mechanisms in order to track the exact desired joint angle.

There are other approaches and hardwares to realize bipedal walking. Robot walking based on limit cycle, represented by passive dynamic walking, is a different type of biped walking. Mcgeer [16] established the theory of passive dynamic walking. The first machine was a purely passive system based on the ideas of how a ramp walker descends on a slope. Some researchers [17], [18], [19] advanced this system with control, by simulation or by simplified 2D models, to make the walking motion converge to a limit cycle when walking on level ground or climbing up slopes. And some 3D limit cycle walkers [20], [21] were realized to walk,

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showing high energy efficiency and natural walking motion.

Raibert and Pratt, who designed several creative biped robots in the MIT Leg Laboratory, developed PETMAN [22] and M2V2 [23], respectively. Although Boston Dynamics released the movie of PETMAN without providing detailed information, we can see that it uses the hydraulic actuators and walks in much the same way as humans do. M2V2 was built in Florida Institute for Human & Machine Cognition (IHMC), using the force-controllable Series Elastic Actuators [24] at its joints.

Computational Brain (CB) [25] is another type humanoid robot built by Sarcos. This robot has hydraulic actuators with a torque sensing mechanism. Different balancing algorithms in [26] and [27] were applied to their own CB platforms showing that torque controlled joints are very effective to implement a compliant controller for legs and for robust balancing performance.

The latest released biped robot which has force-controllable joints is DLR-biped [28] from Institute of Robotics and Mechatronics in German Aerospace Center (DLR). DLR-biped uses the joint module which consists of a motor with an encoder, a reduction mechanism, a torque sensor, and an embedded control system. A compliant balancing control approach for regulating the COM and trunk orientation was implemented in [29].

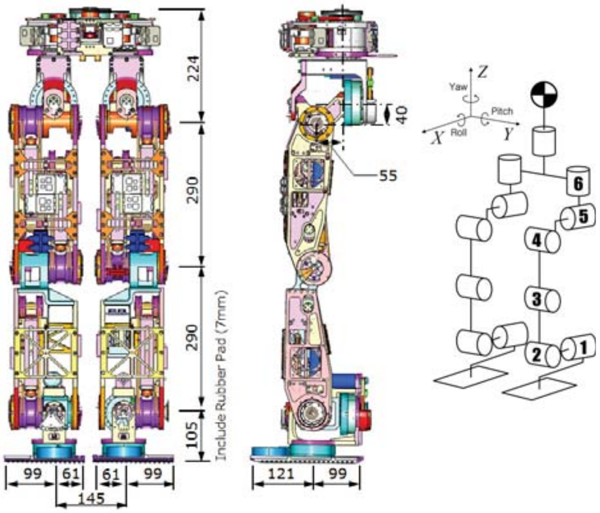
Samsung Electronics CO., Ltd. developed biped humanoid robots, Mahru II, Ahra II and Mahru III [30]. In 2005, Mahru II and Ahra II demonstrated walking motion and dancing performance based on position control through cooperation with Korea Institute of Science and Technology (KIST). And Mahru III is another humanoid platform for walking and whole-body motion based on position control.

In this paper, we present the development of of a lower limbs for a new humanoid robot - Roboray - shown in Fig. 1. The proposed lower-limb machine has two 6 DOF legs and a 1 DOF waist for biped locomotion. This robot has integrated joint torque sensors at every leg joints in order to study the use of joint torque sensing and compliant control in biped walking. The mechanical design of the robot is described first and the control system for motion controller is presented. We discuss the design considerations and show the experimental results of bipedal locomotion for testing hardware.

II. MECHANICAL DESIGN

A. Specification

The target specification of Roboray is determined considering various aspects. The design concept of Roboray is ”a Friend of Children”. For this concept, its cover is intended to be cute and clean and its size to be similar to the size of a child. To be at the level of a 12 year old child, the height of Roboray is determined 155cm, close to the average height of Korean children of that age [31]. We chose the length of a leg according to the height. The detailed dimension of links in lower limbs is shown in Fig. 2(a), including the size of its foot. The weight of Roboray including upper body and its covers is 63 kg. The integration of driving mechanisms and various sensors makes it difficult to reduce the weight while maintaining the required stiffness of links. Though the robot is heavier than the average of 12 year old children, it has been confirmed by simulation that the drive systems are quite capable of biped locomotion like walking and climbing stairs. For the experiment of the lower limbs in this paper, a cylindrical dummy mass has been used in place of the upper body (see Fig. 6).



(a) Front and left view (b) Joints

Fig. 2. Specification and joint configuration of lower limbs

There are two design considerations in developing the lower limbs: One is to make an experimental platform that can be used to develop torque and force based control algorithm and to test conventional position based control algorithm in walking. The other is to make a compliant and elastic leg mechanism to reduce high frequency disturbances which occur at the time of ground contact. To achieve these, the robot has a joint torque sensor at each leg joint and each pitch joint of the robot has a novel tendon drive mechanism which we developed as shown in Fig. 3.

B. Joint Configuration

Figure 2(b) shows the joint configuration of the robot. The robot has two 6 DOF legs and one 1 DOF waist. Like most biped robots, each leg consists of a 3 DOF hip, an 1 DOF knee and a 2 DOF ankle. The ankle joint is a joint of two crossing axes as shown in Fig. 2(a) and Fig. 4(a). The hip joint is not a typical joint with intersecting 3 axes but has offsets between the axes as shown in the left figure of Fig. 2(a). This is because the sizes for the pitch joint module and the joint torque sensor in each joint make it difficult to have enough space for various motions. In order to increase the range of hip joint movement, there is an offset between the axes of hip joint mechanism. This does not make our walking control algorithm difficult to implement because the proposed walking method does not need to solve the inverse kinematics as in conventional methods. We calculate the inverse kinematics indirectly when experimenting with conventional position control method for comparison. The

TABLE I

JOINT DRIVE SPECIFICATION

Joint	Motor Power [W]	Gear Ratio	Operating Range [°]	Max. Velocity [$°/s$]	Torque Limit [Nm]
Waist Yaw	50	240	-45∼45	200	NA
Hip Yaw	50	300	-45∼45	160	34.3
Hip Roll	200	592	-40∼20	152	98
Hip Pitch	200	360.3	-100∼30	250	150
Knee Pitch	200	360.3	0∼130	250	150
Ankle Pitch	200	360.3	-60∼30	250	150
Ankle Roll	200	376.8	-20∼17	318	98

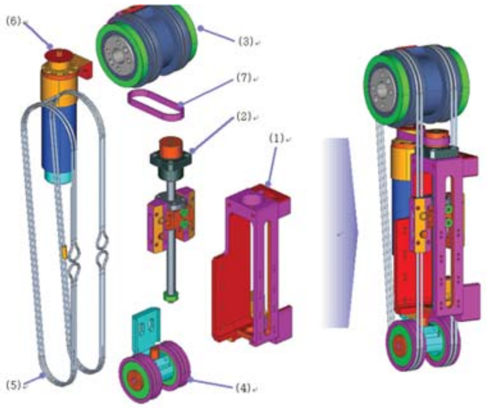


Fig. 3. Pitch Joint Module: (1) guide for ball-screw (2) ball-screw (3) joint including torque sensor (4) guid for wire maintaining wire tension (5) a loop of wire (6) motor with gearhead (7) belt of pulley

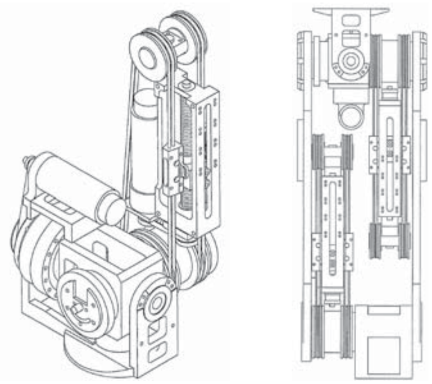
operational range of each joint is shown in Table I.

C. Drive System

Each joints of the lower limbs is a rotary joint. In order to meet the requirements of bipedal locomotion, the torque and speed requirements for each joint has been determined by simulation. Motions like forward walking, climbing stairs and one leg squat have been simulated with an approximate model of Roboray and the joint specification in Table I has determined based on the simulation results. In Table I, the torque limit does not mean the maximum torques that can be generated by a joint mechanism but the maximum range of a torque sensor.

Through simulation and experience in making humanoid robots, the necessary characteristics of lower limb joints are specified. A yaw joint of hip is essential for changing directions, but it does not need to move fast nor require high torque. Roll joints must be stiff enough not to droop when one leg is in the air. Pitch joints, which play the most important role in bipedal gait motion, have to be fast and compliant.

The drive system for a joint is basically composed of a brushless DC motor and a reduction mechanism. For yaw and roll joints, a pulley and a harmonic drive mechanism is used for reduction. This harmonic drive mechanism is widely used in other humanoids because of its high rigidity and high precision. In Figs. 4(a) and 4(b), the ankle roll joint and the hip roll joint are shown, respectively. Figure 3 presents a new pitch joint module developed for Roboray. As shown in Fig.4, the same module are used at the pitch joints of hip, knee located in the thigh link and ankle in the calf link. This module drives the joint as follows.



(a) Ankle (b) Hip and knee

Fig. 4. Assembly drawings of joints. (a) is top-left view of left ankle and (b) is frontal view of left thigh.

1) The motor with gear head (6) drives the belt-pulley (7).
2) The belt-pulley makes the linear motion through the ball screw (2).
3) The linear motion of ball screw turns the joint axis (3) by pulling the wire (5).

This mechanism is elastic and highly backdrivable with low friction. The tendon, which looks like four strands of wire in the assembled figure of Fig. 3, is a loop of one long pre-tensioned wire as shown in Fig. 3(5). This tendon functions as a stiff spring which reduces harmful high frequency movements.

III. CONTROL SYSTEM

Figure 5 is a conceptual diagram describing the control system of Roboray. It includes a computer system, local joint and sensor control boards (Smart Driver) and the network system. The details of parts will be shown in the following subsections.

A. Computer System

The lower limbs is controlled by a single board computer. This computer is consisted of Mini-ITX mother board, Intel Core 2 Quad Q6600 CPU clocked at 2.4 GHz, 128GB SSD and 2GB RAM. A network interface card is used for EtherCAT (Ethernet for Control Automation Technology) communication with Smart Drivers. As for the operating system (OS), we chose MontaVista Linux, patched with a real-time package and customized, for reliable real-time performance and using existing libraries. The main role of the computer is to develop various algorithms for motion and decision, and communicates with Smart Drivers every 1ms. Moreover, it communicates wirelessly with outside network

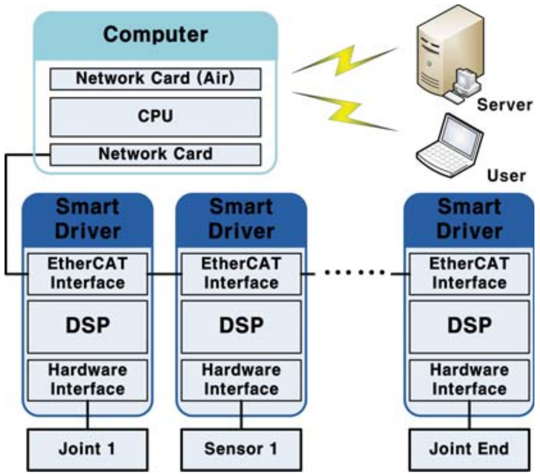


Fig. 5. Control System

to exchange data with servers or receive orders from a user's console.

B. Smart Driver Control System

Many robots adopt a distributed control method to facilitate joint control, to guarantee safe operation and to reduce the load of a main computer. We have developed a distributed control board, named Smart Driver, which consists of upper and lower parts. The upper part includes EtherCAT interface, DSP for communication, sensor data processing and joint control. The lower includes the hardware interfaces such as a motor driver, an AD converter and a power regulator. While the upper part of each Smart Drivers is the same, the lower part varies according to hardware interface.

A Smart Driver for a joint in Fig. 7(a) receives the reference input signal and sends the collected sensor data, communicating with the main computer. It is connected to a motor and joint sensors such as incremental encoders, torque sensors and so on. It receives input signals from the motion controller and controls a joint. The control period of this joint servo for tracking the desired torque is 0.2 ms and the controller is implemented in the programmable area in DSP. Another type of Smart Driver for the six-axis force torque (F/T) sensor shown in Fig. 7(b), has a different hardware interface, which processes the data from the amplifier of F/T sensor. In the programmable area of the Smart Driver, filters process raw data from F/T sensor.

C. Sensors

Each joint of a leg has different combination of sensors. Each hip yaw joint and roll joint has an incremental encoder attached to the motor and a joint torque sensor. In each pitch joint, there is an absolute encoder in addition to an incremental encoder and a torque sensor. The waist yaw joint only has an incremental encoder attached to the motor. Two different types of torque sensors are used in roll and pitch joints. A cylindrical torque sensor, commercialized by Futek Advanced Sensors Technology, Inc., is integrated in the pitch module in Fig. 3 (3). For the roll and yaw joints, we developed disc type torque sensor which can be inserted in the housing of harmonic drive mechanism. The operational limits of torque sensors for each joints are shown in Table I.

(a) Smart Driver for a joint (b) Smart Driver for F/T sensor

Fig. 7. Smart Driver. Dimensions of (a) and (b) are 38×60 mm and 38×50 mm, respectively.

Additionally, an inertia measurement unit (IMU) from Xsens Technologies B.V. is integrated in the pelvis link. The sampling time of IMU data is 10 ms and the data baud rate is 115200 bps using RS232 communication. In order to measure the contact forces and moments, F/T sensors are located between foot and ankle links. The measurement range of F/T sensors is up to 2000 N in vertical (Z) direction and 1000 N in horizontal (X-Y) plane directions. The measurement range of the torque sensors is 50 Nm for all three axes. The data of the F/T sensors is read with 1kHz sampling frequency.

D. Software

We have our own software framework for robotic systems. The framework supports hardware abstraction layer for joints, sensors, and actuators and effectively minimizes dependency of robot control algorithms on robot hardware. Low-overhead framework is leveraging modern CPU's features, while still maintaining effective hardware abstraction by SIMD architecture and considering the structure of CPU Cache. The combination of this framework and real-time OS makes the reliable circumstances for motion control algorithms.

IV. EXPERIMENTS

In this section, the experimental results for testing hardware are presented. We have been developing force-torque control based walking algorithms in various approaches [32], [33], [34]. Figure 6, 8 and 9 are presenting the results of sam experiment applying one of stable walking algorithms. The experiment was 30 step forward walking on normal office floor with a step time 0.7 s and a step length of 0.2 m. Figure 6 shows the series motion of two steps, captured at an interval of 0.2 s. The torques of right leg and the Z-directional forces from F/T sensors are shown in Fig. 8. In the last graph of Fig. 8, the experimental values go zero turn by turn and that means the change of steps. The phase portraits of all the joints in right leg are shown in Fig. 9. We can observe stable limit cycles in the phase portraits of hip and knee (a few orbital trajectories which are off from the limit cycles are transition motions from the initial and the

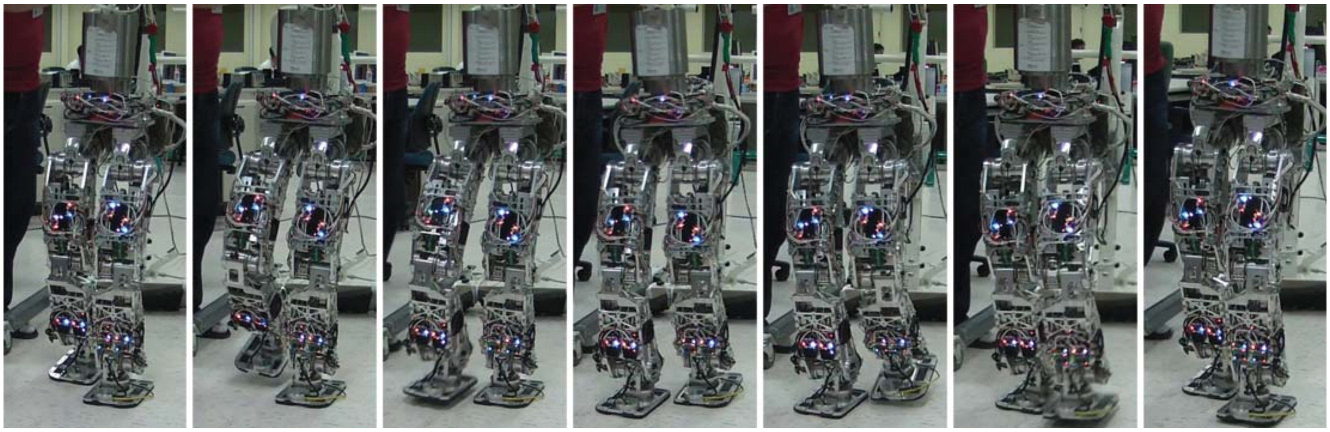


Fig. 6. Snapshots of forward walking

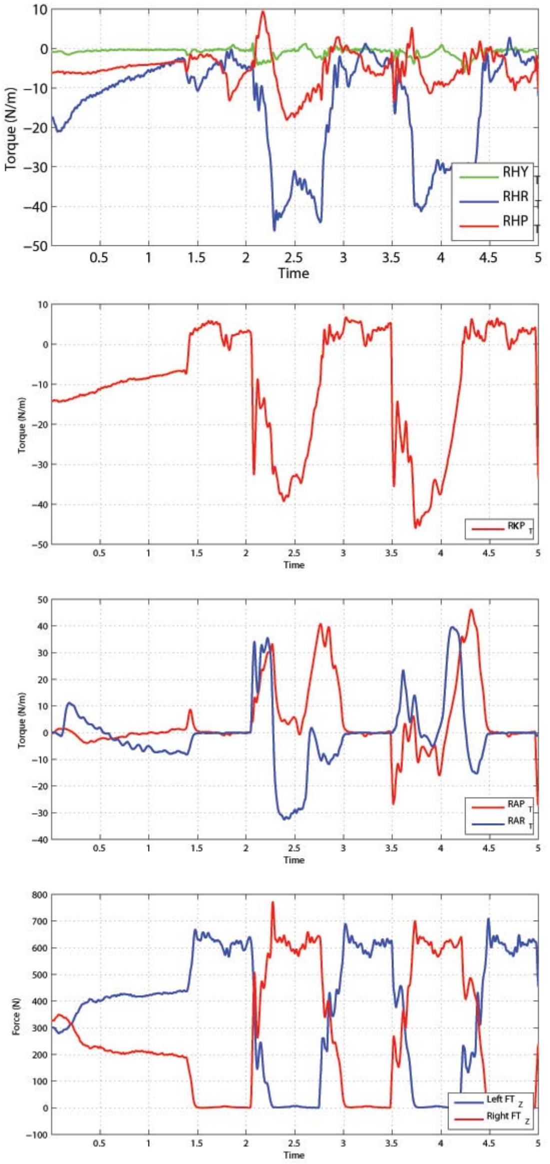


Fig. 8. Data of the right leg during five steps of forward walking experiment: (1) torques of hip, (2) torque of knee, (3) torques of ankle and (4) vertical force from F/T sensor.

final posture to the steady state walk). Since the floor is not perfectly flat, the phase portraits of ankle did not converge limit cycles in order to adapt compliantly on the ground.

V. CONCLUSIONS

This paper presented the development of a lower-limb machine for our new humanoid robot: Roboray. The development goal was achieved by integrating torque sensors at every joints in the legs, developing a new pitch joint drive module with tendon and employing the distributed control system with Smart Drivers we built.

Future work with this system will focus on realization of various walking algorithm based on force torque control and comparison the results of these algorithms with the result of conventional position control based algorithms. And to make the most of this hardware's characteristics, many kinds of foot mechanisms and shoes will be considered to apply.

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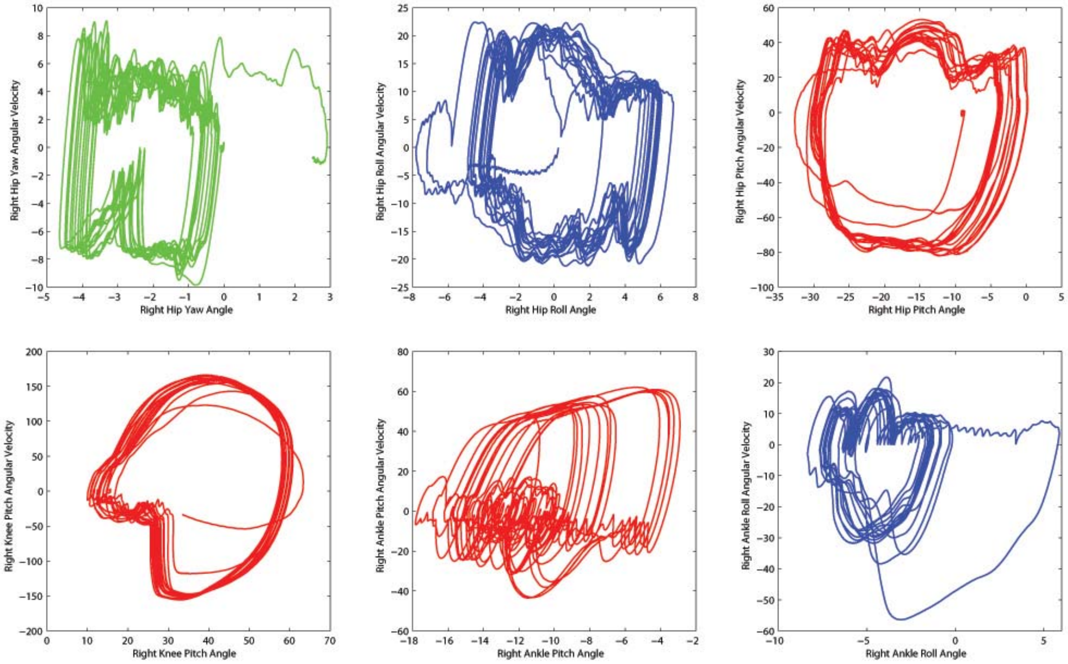

Fig. 9. Phase portraits of right leg

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