Chapter 1
Gait Generation and Transition of a Biped Robot Based on Kinematic Synergy in Human Locomotion

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ABSTRACT

Humans have an extremely redundant system for locomotion. To handle the redundancy problem, humans use coordinative structures using conditions of constraint in their joint movements to reduce the number of degrees of freedom, which is called kinematic synergy. This chapter shows some characteristics in the kinematic synergy in human locomotion and shows a locomotion control system for a biped robot, which is inspired by the physiological concept of Central Pattern Generator (CPG) and phase resetting to produce gaits (quadrupedal and bipedal locomotion) and change them based on the kinematic synergy to tackle the redundancy problem in the motion planning of the robot.

1. INTRODUCTION

Robotics and mechatronics have evolved through interdisciplinary studies (Maki, 2007). An important object in robotics and mechatronics is to produce adaptive locomotor behaviors of legged robots, as observed in humans and animals. For that purpose, robot mechanical and control systems have been developed based on biologically inspired approaches by integrating the knowledge from biomechanics and neurophysiology. This chapter shows the knowledge about locomotion control mechanisms in humans and a design of locomotion control system for a biped robot from the knowledge.

Humans produce adaptive locomotion in diverse environments by skillfully manipulating their complicated musculoskeletal systems. To create such locomotion, motor commands from the nervous system produce muscle activity, and muscle tensions around joints generate joint movements. Locomotion involves moving the center of mass (COM) of the body using the legs. Humans have more degrees

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of freedom (DOFs) in their joints than necessary for producing such a movement and, in addition, have more DOFs in their muscles than in their joints. Furthermore, various parts of the nervous system, such as the cerebral cortex, the basal ganglia, the cerebellum, the brainstem, and the spinal cord, contribute to generating motor commands for locomotion by integrating such sensory information as visual, vestibular, and somatosensory information. That is, humans use many DOFs and much information to achieve locomotion.

As mentioned above, humans have an extremely redundant system for locomotion. It is obvious that such redundancy plays an important role in achieving adaptive locomotion. However, humans have to solve the redundancy problem in some way. To overcome the redundancy problem, it has been suggested that individual DOFs are not manipulated independently, but some DOFs are functionally connected by object tasks. In other words, humans use conditions of constraint to decrease the number of DOFs to solve the redundancy problem. This functional coordinative structure is associated with simultaneous movements in several joints and co-variations of muscle activities.

These relationships among DOFs appear as low-dimensional structures by analyzing measured data during human locomotion (Bianchi *et al*., 1998; Funato *et al*., 2010; Ivanenko *et al*., 2004, 2005, 2006, 2007, 2008; Lacquaniti *et al.*, 1999; Poppele & Bosco, 2003). In particular, low-dimensional structures in joint movements and muscle activities are called kinematic and muscle synergies, respectively. In addition to locomotion, low-dimensional structures are observed in various tasks from simple to complex (e.g., a single arm reaching task and whole body standing quietly and sit-to-stand tasks) and also observed in many animals (Alexandrov *et al*., 1998, 2001; Danna-dos-Santos *et al.*, 2007; d'Avella *et al.*, 2003; d'Avella & Bizzi, 2005; Dominici *et al.*, 2011; Drew *et al.*, 2008; Freitas *et al*., 2006; Latash, 2008; Ting & Macpherson, 2005; Todorov & Jordan, 2002). These kinematic and muscle synergies are viewed as one solution to handle the redundancy problem in biological systems.

This chapter focuses on the kinematic synergy and shows some of its characteristics observed in human locomotion. Furthermore, it shows a locomotion control system for biped robots to produce gaits (quadurupedal and bipedal locomotion) and change them inspired by the kinematic synergy (Aoi *et al*., 2012).

2. KINEMATIC SYNERGY IN HUMAN LOCOMOTION

When elevation angles at the thigh, shank, and foot during human walking are plotted, these angles show regular loops that are almost on a plane (Figure 1) (Bianchi *et al*., 1998; Ivanenko *et al.*, 2007, 2008; Lacquaniti *et al.*, 1999; Poppele & Bosco, 2003). This suggests that these three DOFs have one linear relationship that constrains these motions on a plane. This relationship represents the intersegmental (intralimb) coordination of lower-limb movements during walking.

This planar motion in the lower-limb movements is not limited to human walking. It is observed in various gaits in human locomotion, such as running, hopping, upstairs stepping, and stepping over an obstacle (Ivanenko *et al.*, 2007, 2008). Moreover, the orientation of the constraint plane changes depending on the locomotion condition, such as the locomotion speed. This suggests a change in the intersegmental coordination of lower-limb movements and is associated with the control of the limb axis length and orientation (i.e., the position of the limb endpoint relative to the root and its direction) (Ivanenko *et al.*, 2007). The planar motion of the limb segmental movements is also observed in the locomotion of other animals, such as cats (Poppele & Bosco, 2003) and monkeys (Ivanenko *et al.*, 2008; Ogihara *et al.*, 2012).