Development of musculoskeletal walking simulator for analysis of human walking and rehabilitation

Nobuo Sakai*, Ryu Yukiho, Tsubasa Ikeda
Mechanical and Control Engineering, Kyushu Institute of Technology
1-1 Sensucho, Tobata-ku, Kitakyushu city, 804-8550, Japan
E-mail: sakai.nobuo@ise.kyutech.ac.jp

Masako Fuchi
Ocupational therapy, Kyushu Nutrition Welfare University
1-5-1 Katsuhara-Takamatsu, Minami-ku, Kitakyushu city, 800-0298, Japan

Katsuki Hayashi
Rehabilitation division, Seiai Rehabilitation Hospital
2-7-1 Minamioori, Onojyo city, 816-1199, Japan

Mochimitsu Komori
Electrical and Electric Engineering, Kyushu Institute of Technology
1-1 Sensucho, Tobata-ku, Kitakyushu city, 804-8550, Japan

Abstract

In the field of rehabilitation, the explanation of walking motion, called 'Rocker function', is one of the practical benchmarks for the facilitation of human walking in clinical settings. If this explanation is true, we can reconstruct it by artificial materials. In this study, we tried to develop the musculoskeletal walking simulator, which can actually reproduce bipedal walking according to the rocker function. Muscles and tendons including biarticular arrangements were represented by springs and cables. In this report, 3 muscles were actuated by servomotors. The simulator reproduced the human musculoskeletal walking motion generated from its intellectual structure in nature. The results would support the insight of the explanation of the rocker function in the rehabilitative treatments.

Keywords: Human walking, Bipedal robot, Musculoskeletal system, Biomechanism, Biomimetics

1. Introduction

Musculoskeletal simulators have been one of the useful tools for considering the motions and their functions of the human body. The spread of computer calculation systems enabled the dynamic mechanical simulation [1]. Around the same time, researches on bipedal robots were carried out by the interests in biomechanics [2] and the powered prostheses [3], as well as mechanical system and control theory. Well-known walking principals would be LIP (Linear Inverted Pendulum) [4] and SLIP (Spring–Loaded Inverted Pendulum) [5] model. Along with these robots, a passive dynamic walking robot [6], which can walk on a slight slope, was advocated.

As the musculoskeletal system of the human leg has peculiar structures, a musculoskeletal legged robot was developed by the rubber artificial muscles [7]. The biarticular arrangement of the muscles can produce high-power output and precise motion simultaneously by its mechanical structure, which was applied in a vertical jumping robot [8]. The robotics on the study of musculoskeletal system is an interesting tool to recognize living bodies and human.

Various biomechanics studies on the analysis of human walking have been reported for the knowledge of clinical application. Perry described the human normal and pathological walking by integrating the elements of human walking, which called 'Rocker function' [9]. Today, the rocker function has become an essential model in clinical gait analysis in Japan.

In concerning the walking facilitation in post stroke therapy, it is important to recognize the normal human walking. If the musculoskeletal structure and its mechanical function are understood, it should be possible to reproduce it in a physical simulator [10]. The aim of this study is to construct the physical simulator of the lower limb to understand the human musculoskeletal structure, and to generate the walking motion according to the rocker function. In this paper, the gait of the robotic walking simulator is described in detail according to the rocker function, than the parametric study for the gait construction [11].

2. Materials and Methods

2.1 Design of the musculoskeletal simulator

A simple description of the rocker function is given in Figure 1. First, the knee joint is flexed from the beginning of the load-response phase, which appears inefficient from an engineering view because the quadriceps muscles needs energy to maintain the knee joint in flexion under load. In addition, direct braking by the soleus muscle during ankle rocker to prevent knee breakage also leads to energy consumption.

In the human musculoskeletal structure, muscles are efficient in isometric to centrifugal contraction. Recent muscle research has found that the Titin is a passive spring mechanism that can change its anchor position in muscle force generation [12]. Although its properties are not fully understood, it was reported to be necessary for fast centrifugal contraction [13]. The elastic recoil of the muscle-tendon complex is thought to contribute to the high energy efficiency of walking in terms of elastic energy recovery. Therefore, the basic idea of this study is to represent each muscle as a spring. The springs were attached via a cable and do not exert force in the compression direction. In the case of active driving, a motor pulls a cable attached to the spring in a spring-motor series configuration [8].

2.2 Development of the simulator

A schematic of the model is shown in Fig. 2. The configuration is a common 9-muscles model including

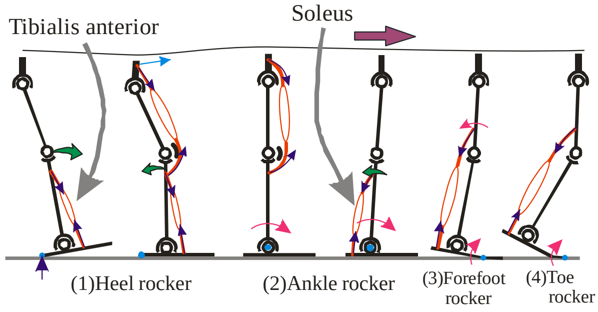


Fig.1 Schematic drawing of the Rocker function.

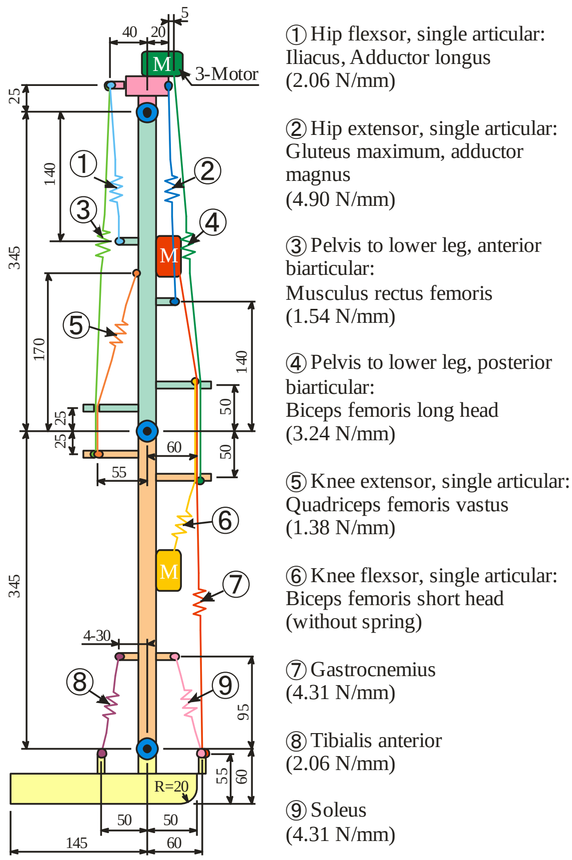


Fig. 2 Configuration of the robotic walking simulator.

biarticular muscles [1]. The robotic simulator does not have any foot structures such as foot arches or toes. The total height of the robot is 800 mm, the hip joint width is 200 mm, and the weight is 5.66 kg including 6 motors for both legs and 500 g weight for the waist to improve the gait. At this stage, the robot is designed by two-dimensional walking with ball rollers between two acrylic plates placed 452 mm apart.

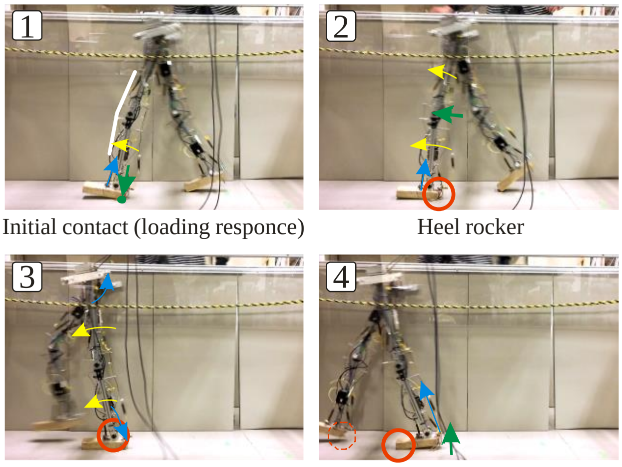
The springs, which simulate muscles, are placed in the order of Origin-Cable-Spring-Cable-Insertion, through a cable passage hole in order to adjust the moment arm. The corresponding muscles are shown in Fig. 2 as a reference. The position of some springs seems to be different from the common 9-muscles model, but the function is physically the same no matter where the springs are placed on the spring-cable series. The motor module (Dynamixel MX-106, Robotis Inc.) is placed at the origin or insertion of the cable in series to the spring.

2.3 Actuation of the simulator and evaluation

In this paper, we report the results of active driving of the three posterior muscles (④⑥⑦ in Fig. 2). With regard to the spring constant, each muscle does not generate a force proportional to its muscle cross-sectional area during walking. The motor arrangement and its drive timing, and especially the spring constant, were adjusted by trial and error. The heuristic search for drive timing and algorithms with reference to the living body is commonly shown in robotics researches [7,8,14,15]. The evaluation was based on the similarity of the obtained gait to that of a human, based on joint angles and functionalities on rocker function. The start of walking is a very interesting topic, but in this paper it was initiated with the assistance of the experimenter.

3. Results

A part of the results of the rocker function is shown in Fig. 3. The explanation of the rocker function by Perry starts from the initial contact (Fig. 3 (1)). The loading response immediately after the initial contact causes increase of the knee joint flexion by the rapid contraction of the anterior Tibialis anterior muscle. Ongoing Tibialis anterior contraction limits the plantar flexion of the ankle joint and produces a rolling action around the heel as shown in Fig. 3 (2). After the heel rocker, the simulator body rolls forward by the ankle joint with keeping the knee joint flexed at same level over the mid stance as shown in Fig. 3 (3). In the latter half of the ankle rocker into the terminal stance, the knee joint is starting extension while the ankle joint continues rolling forward. This knee joint extension is supported by the ⑨Soleus muscle contraction. Before the falling of the forward foot as shown by the red doted circle in Fig. 3 (9), the contraction of the Gastrocnemius muscle (⑦) raises the heel of the left leg, which called as "forefoot rocker", to keep the position of the center of mass. Then, the heel of the forward foot falls to the ground which leads the loading response.



Initial contact (loading responce) | Heel rocker

Ancle rocker (terminal stance) | Forefoot rocker

Fig. 3 Sequential photographs of the musculoskeletal walking simulator.

4. Discussion

There are approaches to improve the performance of bipedal robots by applying musculoskeletal configurations and locomotion patterns related to human walking [16]. In this study, a musculoskeletal physical simulator of the lower limb was constructed by replacing muscles with springs. Some parts of the posterior muscles were driven and walked by pulling cables placed in series with the spring. As a result, the robot was able to walk while performing the various actions described in the rocker function description. Because the human knee joint is a roll-on-plate structure and the contact conditions are severe, one possible reason for knee bending in initial contact might be to reduce the impact load on articular cartilage as a biphasic gel layer [17].

We would like to discuss the problem that this walking simulator did not have a foot structure such as a toe structure along with an arch structure. The toe structure is necessary for the forefoot rocker to flex at the metatarsophalangeal joint. In other words, it is thought to have an effect of switching the foot length. At the same time, elastic recoil of the gastrocnemius and flexor digitorum longus is expected. The elastic recoil energy at the end of the stance phase is used for generation of the next swing leg, rather than contributing to the acceleration of the hip. This swing leg generation is called "push-off" [18].

One interesting theme should be how we constructed the gait by trial-and-error method in the physics simulator. At first, we constructed the gait in order from the loading response as Perry's description. While we noticed the movement on the opposite side, we had to consider the walking motion as a cyclic movement, so we needed to consider the gait as the whole, not in order. It is also interesting to know which muscle should be driven by the motor. Before the three-motor model shown in this report, the authors had confirmed a certain walking in a two-motor model. In these two physical simulators, it was very difficult to generate walking motion without the drive of the single articular muscle for knee flexor (Fig. 2 ⑥). The role is to maintain knee flexion during the swing phase. From a physical point of view, it is thought that the generation of the swing leg should be one of the energy-consuming factors. The importance of the 'push-off' action could also be found here.

In the development of the musculoskeletal walking simulator, the authors felt that the tumbling motion and failure of the simulator was interesting to bring a new idea for walking generation. Currently, there are many issues to be solved, such as actual measurement of COP and long walking time, in addition to the fact that it is a two-dimensional gait and the moment arm is not physiological, but the reproduction of foot structure and push-off will be the next issue to be addressed.

5. Conclusion

In this study, we developed a musculoskeletal robotic walking simulator for the study of biomechanics in rehabilitation. By driving some muscles of the simulator with servomotors, the simulator was able to generate actual walking motion based on the rocker function. Then, the generated walking motion was compared with the motion description of the rocker function. It was confirmed that the simulator was able to generate most of the actions of the rocker function. In addition, the joint angles were compared with the standard human walking motion. In the future, we plan to introduce the forefoot and the arch structure to the musculoskeletal simulator.

Acknowledgements

This work is partly supported by JSPS KAKENHI 18K10747.

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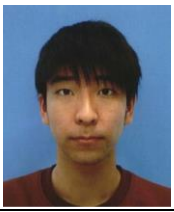
Authors Introduction

Prof. Nobuo Sakai

Associate professor of Mechanical and Control Systems, Kyushu Institute of Technology in Japan. He graduated Intelligent Machinery and Systems, Kyushu University in 2002. His research interests are Robotics, Bioengineering, Tribology.

Mr. Yukiho Ryu



He is currently a Master course student of Mechanical and Control Systems, Kyushu Institute of Technology. He graduated Integrated System Engineering, Kyushu Institute of Technology, 2020.

Mr. Tsubasa Ikeda

He is currently a Master course student of Mechanical and Control Systems, Kyushu Institute of Technology. He graduated Integrated System Engineering, Kyushu Institute of Technology, 2021.

Prof. Masako Fuchi

Professor, Occupational therapist, Department dean of Occupational Therapy, Kyushu Nutrition Welfare University. She graduated National Kyushu Rehabilitation College, 1981. After the working career of Kyushu Rosai Hospital, she graduated English Course of Foreign Studies, University of Kitakyushu. After 1990, she worked in Seiai Rehabilitation Hospital, then Vice-president of the hospital. Also, she received Master degree in Social and Information Science, Nihon Fukushi University in 2000. She moved to the present post in 2016.

Mr. Katsuki Hayashi

Occupational therapist. He graduated National Kyushu Rehabilitation College, 1975. After the working careers of Yamaguchi Rosai Hospital and Kyushu Rosai Hospital, he moved in Seiai Rehabilitation Hospital, then Vice-president of the hospital. He is now Specially Appointed Vice-president of the hospital.

Prof. Mochimitsu Komori

Professor of Electrical Engineering and Electronics, Kyushu Institute of Technology in Japan. He graduated Osaka University in 1984. After the career of National Railway Technical Research Institute, he moved in Kyushu Institute of Technology as an associate professor. Then, he is a professor from 2003.