A Stability Analysis of a Standing Posture in Paraplegia*

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Abstract — A paraplegic patient can keep a standing posture called ‘C-posture’ with an orthosis. The foot joints are fixed in dorsiflexion, and the knee joints are fixed in maximum extension with the orthosis. A feature of the C-posture is that the body center of mass is located behind the hip joints. In the present study, assuming the C-posture to be an equilibrium attractor in a paraplegic musculo-skeletal system, we discuss the mechanism and stability of the C-posture on the basis of measured and simulated standing postures in paraplegia. Measurement and simulation results suggest that C-posture could be regarded as a stable equilibrium attractor in the musculo-skeletal dynamics of paraplegics.

Keywords: Paraplegia, Orthosis, C-posture, Dynamics model

1 Introduction

Although a wheelchair is used as a locomotor in paraplegia, the life with the wheelchair may result in atrophies of the paralyzed muscles and joints. It is important for improvement of paraplegic musculo-skeletal functions to load paralyzed muscles and joints and to expand the joint range of motion[1]. For this purpose, training with an orthosis is performed for a paraplegic patient.

A paraplegic patient can keep a standing posture called ‘C-posture’ with a Knee-Ankle-Foot Orthosis (KAFO). The foot joints are fixed in dorsiflexion, and the knee joints are fixed in maximum extension with the orthosis. A feature of the C-posture is that the body center of mass is located behind the hip joints. The extension moment of gravity acts on the hip joints, while the hip desitve flexion moment reacts against the hip joint hyperextension.

For reconstruct motor function of paraplegic patients, many investigators have worked functional electrical stimulation (FES). It is considered that a paraplegic patient can keep the C-posture without the control of the hip joint because of the equilibrium of the gravity moment and the resistive moment. However, the stable region to keep standing posture without support is narrow, and the appropriate alignment of the orthosis is required for an individual paraplegic patient. Furthermore, a paraplegic patient has to train in order to keep the C-posture. In the present study, assuming the C-posture to be an equilibrium attractor in a paraplegic musculo-skeletal system, we discuss the mechanism and stability of the C-posture on the basis of measured and simulated standing postures in paraplegia.

2 Measurement of the C-posture

To approach the mechanism of the C-posture, the measurement experiments of standing posture were performed for paraplegic patients. Two paraplegic patients (male) participated in the experiments. The injury levels of the subjects were T6 and T10. The subjects gave informed consent, and they agreed to participate in the experiments in writing. For the standing postures, a pelvis, a trunk, toes, foot joints, knee joints, hip joints, shoulder joints and wrist joints were measured by a 3 dimensional position measurement device OPTOTRACK3020 (Northern Digital Inc.). The standing postures were recorded at 100 Hz for 30 sec. The angles of the foot joints, the hip joints, the lumbar joint and the shoulder joints were estimated from measured positions regarding the skeletal system as a 7 rigid link model.

Since the subjects kept the standing postures without the support of crutches or a walker for 30 sec, their standing postures were mechanically stable. Their standing postures showed the feature of the C-posture in which the body center of mass is behind the hip joint. The hip hyperextension coped with foot joint dorsiflexion in the standing postures.

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3 Analysis for the dynamics of the C-posture

A dynamics model of the paraplegic musculo-skeletal system is formulated to analyze the dynamics of the C-posture[2]. The paraplegic musculo-skeletal system in sagittal plane is regarded as a 7 rigid link model consisting of a foot, a shank, a thigh, a pelvis, a trunk, an upper arm and a forearm, and the equations of motion are formulated. Interactions of the ground and the orthosis are considered with kinematical constraints for the dynamics equations. In addition, the passive resistive moments of the joints are considered.

Equilibrium attractors are calculated by a return map analysis. The dynamics model is represented by a difference equation.

\[ q_{n+1} = f(q_n) \]  

(1)

For an equilibrium state \( q^* \) representing a standing posture, the following equation must be satisfied.

\[ q^* = f(q^*) \]  

(2)

From the condition, we obtain the equilibrium state \( q^* \) by iterative calculation of Newton method.

\[ \Delta q = \left( \frac{\partial f(q_n)}{\partial q_n} - I \right)^{-1} \{ q_n - f(q_n) \} \]  

(3)

The stability of the standing posture is examined on the basis of the maximum eigen value of Jacobi matrix \( \frac{\partial f(q^*)}{\partial q^*} \) and the center of pressure.

The stability analysis found that the standing postures like normal human were unstable, while the standing postures showing the feature of the C-posture were stable. With respect to the relation between the foot joint angle and stability, the maximum eigen value increased as foot joint dorsiflexed, while the center of pressure moved toward the heel as foot joint plantarflexed. These results suggest that there is a trade-off between the maximum eigen value and the center of pressure for the foot joint angle. Considering the basin of an attractor, it was found that a little flexion velocity of hip joint leads to a falling on the ground.

4 Conclusion

Since both the simulated stable posture and measured postures showed the feature of the C-posture, we insist that the mechanically stable C-posture can be regarded as an equilibrium attractor in the dynamics of the paraplegic musculo-skeletal system. It is suggested that a paraplegic patient can keep standing posture because the equilibrium of gravity moment and resistive moment of hip joint is locally stable. The results of the stability analysis reveal the trade-off between the maximum eigen values of Jacobi matrix and the center of pressure for the foot joint angle. The foot joint angle should be adjusted so that the following two conditions of stability are satisfied: (1) the equilibrium between gravity moment and resistive moment in hip joints must be stable, (2) the margin between the center of pressure and boundary points of foot support area must be sufficiently large. The analysis of the basin of an attractor showed that the C-posture has the low robustness for the flexion velocity of the hip joint angle. These problems result from insufficient stability of the equilibrium. It is a future work to stabilize the hip joint using the functional electrical stimulation, mechanical systems, and so on.

References

[1] F.J. Kottke, “Therapeutic exercise to maintain mobility,” Krusen’s Handbook of physical medicine and