Modeling and Constructive Understanding of Human Standing-up Motion Using Muscle Synergy

その他のタイトル	筋シナジーを用いたヒトの起立動作のモデル化と構成論的理解
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論 文 の 内 容 の 要 旨

論文題目　Modeling and Constructive Understanding of Human Standing-up Motion Using Muscle Synergy
（筋シナジーを用いたヒトの起立動作のモデル化と構成論的理解）

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Recently, many elderly people have suffered from declined motor functions. It has caused healthcare issues to our society. In order to solve the problems of the aging society and to improve their mobility, human standing-up motion is focused as a basic daily activity.

Important aspect to improve body function of the elderly is training. In order to develop the effective training methodology, it is necessary to understand how humans coordinate their redundant body system to achieve the standing-up motion. To deal with the problem of body redundancy (an ill-posed problem), the concept of muscle synergy was employed. Muscle synergy was previously proposed by Bernstein to suggest that humans did not control their individual degrees of freedom, but they controlled small number of modules. In particular, this module was defined as coordinative muscle activation, and it was called muscle synergy. Using muscle synergy analysis, muscle activation of human standing-up motion was decomposed into the spatial structure (synchronized muscle activation) and the temporal structure (time-varying weighting coefficients). Using this muscle synergy model, two approaches were employed. The first approach was analytic methodology to observe the human standing-up motion and to extract necessary condition to achieve the motion. Especially, the human ability of adaptation was focused to clarify the variant and invariant structures underlying in the motions. The other approach was the constructive methodology to ensure the sufficient conditions to achieve the motion. Simulation study with human musculoskeletal model was conducted to clarify the sufficient coordinative structure of muscle synergy.

In this doctor thesis, analytic methodology was conducted first. In the standing-up motion, it is known that humans can perform the adaptive motion according to the external environment or depending on their own purpose. If there are variant and invariant structures in the human standing-up motion, they would be useful information for training. This study particularly examined spatiotemporal patterns (muscle synergy) of muscle activation to elucidate necessary components to achieve the standing-up motion in different environments.

The present thesis particularly studied two conditions; different chair heights and motion speeds were focused as external environments and internal objectives respectively. In the measurement experiment, seven young healthy people participated. During the experiment, body kinematics, floor reaction force, and 12 muscle activations of lower limb and upper body were measured from different conditions.

The results showed that four muscle synergies could explain most of the muscle activations during the standing-up motion. Comparing extracted muscle synergies, it showed that spatial patterns were highly similar each other regardless of different chair heights and motion speeds. In addition, four muscle synergies were corresponded to characteristic kinematic event of the standing-up motion (forward trunk bending, rising hip, whole body extension, and posture stabilization). Although spatial patterns of the four synergies were similar (invariant structure), their temporal patterns were properly controlled according to the different conditions (variant structure). It was indicated that in order to stand up from different chair heights, humans likely controlled the amplitude of temporal patterns of muscle synergies. On the other hand, the duration of temporal patterns were adjusted to different motion speeds.

Next, human neuro-musculoskeletal model was developed for constructive methodology to ensure that muscle synergy could achieve the human standing-up motion. Moreover, it was studied how muscle synergy contribute to the standing-up motion. The developed neuro-musculoskeletal model consisted of the body dynamics, the muscle model, and the nervous system. In the body dynamics, the human body was represented with the four rigid body segments (shank, thigh, pelvis, and HAT). The body dynamics used the equation of motion to calculate body posture from joint torque, joint resistance force, and floor reaction force. Joint torque is generated from muscle model, joint resistance force was exerted on the joint according to their angles and angular velocities, and floor reaction force was applied to the hip joint using viscous and kinetic elements. Muscle dynamics was developed based on the Hill type muscle model to calculate joint torques from muscle activation and muscle dynamics. Thirteen muscles of upper and lower body muscles were considered in the muscle model. At last, nervous system generated muscle activations from muscle synergy model and postural control. Using the developed neuro-musculoskeletal models, forward dynamic simulation was conducted to verify the contribution of muscle synergies.

Results of the simulation showed that muscle synergies could successfully generate the similar standing-up motion as the measured data in the empirical experiment. Contributions of each muscle synergy were clarified as follows;

1. Muscle Synergy 1
It activates rectus abdominis to flex HAT at the beginning of the motion.
2. Muscle Synergy 2
It activates tibialis anterior to dorsi-flex their feet to move the center of mass (CoM) forward.
3. Muscle Synergy 3
It activates vastus lateralis and elector spine to extend the knee and lumbar to lift up their body.
4. Muscle Synergy 4
It activates soleus to plantar-flex their feet to decelerate the forward movement of the CoM.

Additionally, it was investigated whether the same spatial patterns of muscle synergy could generate the standing-up motion from different chair heights. The same neuro-musculoskeletal model was used to demonstrate that the muscle synergy model could generate the adaptive standing-up motion only by controlling the amplitude of temporal patterns. This simulation verified that my previous finding satisfied a sufficient condition to generate the adaptive motions using the same spatial patterns of muscle synergies.

Afterwards, the effect of different start times of muscle synergies was investigated to clarify the sufficient coordinative structure to achieve the standing-up motions. The simulation results showed that three strategies of human standing-up motion (stabilization, momentum transfer, and hybrid strategies) could be generated from different combinations of muscle synergies. The main difference of three strategies was found in the trajectory of CoM. In the stabilization strategy, humans firstly moved their CoM on the foot and lifted up their body afterwards. However, in the momentum transfer strategy humans started moving upward even before their CoM reached on the feet. The hybrid strategy was defined as the middle of these two strategies. These simulation results also revealed that muscle synergy 3 was a dominant factor to decide the motion strategy. When humans started the muscle synergy 3 earlier, then momentum transfer strategy had to be used. On the other hand, the stabilization strategy was chosen when the muscle synergy 3 started later. In the middle range, it was shown that humans could utilize three strategies by appropriately selecting start times of each muscle synergy. Moreover, it was demonstrated that humans could utilize less muscular force to achieve the standing-up motion in the stabilization strategy than in the momentum transfer strategy. This result could validate the previous study that the elderly persons tended to use the stabilization strategy than others.

In order for the elderly people or patients to utilize the stabilization strategy and to extend their mobility, they need to bend their trunk deeply to move the CoM on the feet. However, they could not always achieve this movement due to their self-imposed limitation. In order to enhance the functional ability of the elderly, they need to have self-efficacy which is the belief that people can achieve the goal. The self-efficacy is provided to people when they could overcome the difficulty. Therefore, new reference trajectories of the training program should subliminally extend the movement range of the elderly to exceed their self-imposed limitation to obtain self-efficacy. In order to realize the suggested trajectories, human perceptual ability was investigated to measure the unnoticeable amount about their body movement. This amount was defined as just noticeable difference (JND) that humans could not notice clearly.

In this thesis, trunk bending movement at the beginning of the standing-up motion has been especially focused because it was important to generate necessary momentum and move their CoM forward. In order to utilize JND for the robotic therapy, JND was measured in three different types of sensation: active, passive slow, and passive fast movements. Totally 14 people participated at the measurement experiment, and they were divided into two groups of the elderly and the young groups to clarify the declined perceptual ability of the elderly. The results suggested that the elderly people had larger JND to sense their trunk bending than the young people when they were moved passively in relatively faster speed. Based on the obtained results of JND, new reference trajectories were calculated to gradually extend the movement range of users to realize the stabilization strategy within the amount that they did not notice.

In conclusion, human standing-up motion was studied in this thesis in terms of muscle synergies. From both analytic and constructive approaches, it was clarified that four muscle synergies could account for the standing-up motion. Each synergy has specific function to bend their trunk, to move the CoM forward, to extend their whole body, and to stabilize the posture. Moreover, it was shown that the same spatial patterns of muscle synergies could generate the adaptive standing-up motion in different environments. However, amplitudes and duration time of temporal patterns were necessarily adjusted to the different chair heights and motion speeds respectively. The simulation study with the human neuro-musculoskeletal model indicated that muscle synergy 3 was the dominant factor to determine the motion strategies. Simulation results also revealed that less muscular force could be utilized to achieve the motion in the stabilization strategy than the momentum transfer strategy. At last, new reference trajectories were suggested for a training methodology based on human perceptual ability. The new reference trajectories were shown to gradually extend the motion range of the participants within the amount that they did not notice.