Extraction of Behavior Primitives for Understanding Human Standing-up Motion

Qi An  
Department of Precision Engineering  
The University of Tokyo  
anqi@race.u-tokyo.ac.jp

Hiroki Matsuoka  
IHI Corporation

Yusuke Ikemoto  
Department of Research into Artifacts, Center for Engineering  
The University of Tokyo

Hajime Asama  
Department of Research into Artifacts, Center for Engineering  
The University of Tokyo

Abstract—Recently the aging society is very rapid, and it has brought many problems to our society. In order to avoid these difficult situations, we focus on human standing up motion in our research because this motion is so important to our daily life that it is considered meaningful to support the motion.

However, the way of human standing up is still unknown because the analysis of human motion is very difficult. Therefore, we develop integrated simulation methods to understanding the motion from human body data, such as muscle activations (EMG) and human joint torques. We carefully analyze human standing up motion based on muscle movements since muscles do move human body. Through our experiments and analysis, two important muscle coordinations (behavior primitives) are found out; one primitive has a function of generating dynamics of the motion by controlling hip, knee, and ankle and the other primitive controls posture of the body with their ankles. These behavior primitives are elucidated to be such an essential factor toward the motion that the way of standing up becomes unstable without them.

Index Terms—Synergy, EMG, Torque Estimation, Motion Trajectory Estimation

I. INTRODUCTION

A. Background

The aging society becomes very big issue especially in developed countries. While the population of younger people will decline, changes in the population of elderly has been very rapid until now, and this trend seems to continue into the future[1]. The aging society has brought many problems to both elder people and care givers. For example, QOL (Quality of Life) is supposed to be decreased for those who are bedridden, and many care givers are suffered from physical problem such as backache since getting up people is a weary task. Today, an idea of preventing nursing care is becoming more and more important to avoid these problems. The idea suggests that people should train by themselves for keeping themselves healthy and in order not to rely on others.

In our research, human standing-up motion is considered to be very important. Since many daily actions such as walking, shopping, or cleaning up their rooms, all start from standing-up motion, the motion should be regarded as an essential motion for their daily life. Thus sufficient machines or methods to train elderly people are really needed. However, the way how a person stands up is still unclear.

Human muscle coordinated movements are considered to be important in our study because it is the fact that when a person moves, they have to use their several muscles. Also, since many elder people have some difficulties in their motions due to weakened muscles, analysis based on their muscle strength is supposed to be very meaningful. Therefore, it is important to know how every muscle is activated and what effect they have on the motion.

B. Objective

Through this study, our objective is to understand the mechanism of human standing-up motion by extracting behavior primitives which are muscle coordinated activations and also consist human motion. In order to analyze the standing-up motion, the integrated simulation method is developed to elucidate the contribution of muscle coordinations toward the actual motion. In this paper, we demonstrate that the motion can be divided into two main primitives: one primitive makes dynamics of the movement, and the other controls posture of the body.

II. METHODS FOR EXTRACTION BEHAVIOR PRIMITIVES

A. Behavior Primitives

In our research, behavior primitives are defined as an element which consists of human motion, and they are coordination of several human muscles activation and each primitive has specific contribution toward the motion.

To illustrate the idea of muscle coordination, synergy hypothesis, which was suggested by Bernstein[3], is very sufficient. The hypothesis indicates that every human motion can be divided into several muscles coordinations called a synergy and when a person actually moves, they coordinate each synergy sufficiently.

To demonstrate an example of contribution of human primitive actions, proceeding study about a human bending
their trunk forward motion can be cited[7]. The research revealed that human bending forward motion consists of two parts; one is pulling their hip backward in order to make dynamics of the motion, and the other is controlling their ankles in order to keep their posture stable. In the research, muscles coordinations are not considered, however the functions of human actions are elucidated.

B. Model of Human Motion Generating

In order to extract human behavior primitives, it is necessary to understand the way a person moves. Fig. 1 shows a simple model of it.

First, motor commands are sent to human muscle from a human brain, and after their muscles receive signals to move, each muscle generate a tension by extending or shrinking. Next, joint torques are generated by tensions of muscles attached to joints. Then, human body actually moves according to its kinematics.

![Flow Chart of How a Human Moves](image)

Although the model of human body movement can be indicated very simply, it is very difficult to express those processes accurately because there are many parameters to be putted for a human body and each parameter is very different between individuals. In this paper, muscle EMG patterns are used for motor command from a brain, neural networks are suitable for representing the relationship between muscles and torques, and a recurrent neural network is making a mapping between torques and human body movement.

C. Synergy Analysis

1) Synergy Hypothesis: The synergy hypothesis was suggested by Bernstein in 1967[3]. Synergy is a group of several muscles performing a coordinated movement. We can observe various patterns of muscle activity by surface electromyography (EMG). The synergy hypothesis suggests that those observed muscle activities can be divided into fundamental elements called synergy. Actually, d’Avella’s modeling of the synergy is efficient because their model suggests that muscle patterns can be generated as linear combinations of time-varying synergy, which are time-varying profiles of muscle activity. Each synergy has intensity and onset delay. Synergies represent the time course of the activation level for each muscle. To generate the original muscle profiles, every i-th synergy must be scaled in amplitude by a non-negative coefficient (ci); every synergy is shifted in time by an onset delay (ti). Then the elements of different synergies are summed together corresponding to the same muscle and same time. Therefore, even though each synergy has its own muscle profile, it can regenerate muscle patterns of various kinds by changing the amplitude and time delay[2]. Although d’Avella’s model is simple, it is an efficient way to describe the synergy hypothesis in a quantitative manner. In this study, we define synergies as human behavior primitives and extract them.

2) Decomposition Algorithm: This algorithm which was developed by d’Avella[4].

In this model, let m(t) be a matrix representing activation of d muscles at a certain time t (0 < t ≤ t_{synergy}), and these muscles patterns are approximated by the linear-summation of time-varying synergy \{w_i(t)\}_{i=1...n} (let n be the number of synergies to be extracted) with non-negative coefficient c_i, and onset delay t_i as in eq. (1).

\[ m(t) \approx m'(t) = \sum_{i=1}^{N} c_i w_i(t - t_i) \quad (1) \]

By the algorithm, every synergy pattern w_i(t), non-negative coefficient c_i, and onset delay t_i are obtained in order to minimize the total squared reconstruction error E^2 calculated from eq. (2).

\[ E^2 = \text{trace}\left( (M_s - WH)' (M_s - WH) \right) \quad (2) \]

3) Cross-Validation Method: In this synergy model, the number of synergies to extract is an important issue. The accuracy of the model must be tested in order to determine the number[5]. If the number is smaller than the best fitted number, the model cannot explain the observed data sufficiently; if it is beyond the best number, it is also not good because the model extracts the specific data noise. Therefore, it is important to try the model using different numbers. The cross-validation procedure is as follows.

First, twelve observed data are divided into four groups; each group has three datasets. Then three datasets are chosen for training data and the other one dataset is for testing data. Next, particular set of synergies is calculated from the chosen three datasets from the decomposition algorithm, and computed the mean validation R^2 from eq. (3) with the testing dataset. E^2 is the squared error calculated from eq. (2); S_M^2 is the variance of all observed EMG patterns. Repeat this process four times changing the test dataset to obtain the accuracy of the model for the particular number of synergy. Doing this calculation for certain numbers, the specific number is obtained.

\[ R^2 = 1 - \frac{E^2}{S_M^2} \quad (3) \]

D. Link Model

1) Human Body Model: Four links with three joints model is used to represent the human body in this study because three joints, such as foot, knee, and hip, are only concerned. Each link indicates a particular human body part. Some assumptions are applied to this model.

1) Every link is rigid.
2) Every joint is uniaxial; body movement is expressible in the x-z plane.
EMG articulatio genus great trochanter

$\theta_{\text{hip}}$, $\tau_{\text{hip}}$

Link4

$\theta_{\text{ankle}}$, $\tau_{\text{ankle}}$

Fig. 2. Link Model

(a) This figure portrays the positions measured by the motion capture machine: the ankle, knee, hip, and shoulder.
(b) This shows parameters being defined to every link.

3) The foot does not move.

2) Calculation of Torque: Floor reaction forces are monitored by using a force plate for computing joint torques. Forces and torques to the body are defined as shown in Fig.2-(b), where $m$ is the mass of the body represented by a link, $g$ is gravity acceleration, $(x_n,y_n)$ is the position of center of gravity of each link, $f_{x_i}$ and $f_{y_i}$ is the horizontal force of particular position, $\tau_{ji}$ is the vertical force, $\tau_{i}(i=\text{ankle,knee,hip})$ is the torque of each joint, $I$ is the inertial moment, and $M$ is the moment from the center of gravity. The equations of motion can be written as follows.

$$m\ddot{x}_n = f_{x_j} - f_{x_i} \tag{4}$$

$$m\ddot{y}_n = f_{y_j} - f_{y_i} - mg \tag{5}$$

$$I\dot{\theta} = M - \tau_i - \tau_j \tag{6}$$

Those equations are approved to every link $n_{(n=1,2,3,4)}$. Therefore, these equations are solved for each torque by inverse calculation under the conditions of a link model.

E. Joint Torque Estimation

In this study, each human joint torque is estimated by every neural network which was proposed by Koike[6]. Since joint torques are generated from each tension of muscles which are attached to the joints, muscle EMG patterns are putted as inputs of the network and torques are obtained as an output signals. There are ten hidden nodes for the network, and back-propagating rule is adopted for a learning rule. In order to test the accuracy of the estimation, $R^2$ from eq. (3) is used. When checking this, observed twelve data are divided into six training data which are only used for teaching the network and six testing data which are used for calculating accuracy of the model.

F. Joint Angle Estimation

Human joint angles are also estimated by a neural network. For input signals, three joint torques $\tau_i(t)$, joint angles $\theta_i(t)$, and joint angular velocity $\dot{\theta}_i(t)$ at $t = t$ are putted ($i=\text{ankle, knee, and hip}$). Throughout fifteen nodes of a hidden layer, $\Delta\theta_i(t+1)$ and $\Delta\dot{\theta}_i(t+1)$ are obtained. For next inputs at $t = t+1$, angle $\theta_i(t+1)$ and angular velocity $\dot{\theta}_i(t+1)$ are added by outputs $\Delta\theta_i(t+1)$ and $\Delta\dot{\theta}_i(t+1)$.

In order to test the accuracy of the model, same method for torque estimation is used here.

G. Extraction of Behavior Primitives

1) Method of Checking The Contribution of Behavior Primitives: In this research, behavior primitives are defined as muscle coordinated movements, and in order to see contributions of them, weakened EMG patterns, which are reconstructed by weakened synergies, are putted into the neural network model which estimates joint torque from EMG patterns. The outputs of torque from neural networks should be different from normal one because unusual patterns are used on purpose. Then, the recurrent neural network, which estimates human joint angles, receives changed inputs of joint torques. Therefore, this network outputs different change of angles and angular velocity according to already learned nodes of the network.

To make methods clear, following procedures are used.

1) Put weakened EMG patterns based on synergy patterns

2) The first neural networks, which estimate joint torques of human, give out changed torques simulated from real data.

3) The next recurrent neural network, which estimate joint angles of human, receives usual torques, and it outputs changed angle of human.

Three procedures are repeatedly used to simulate human motion from changed EMG patterns lacking particular synergy.

2) Synergy Weakened Muscle Patterns: To complement the method, it is necessary to explain how to generate inputs of EMG patterns by weakening particular synergy. To prepare changed patterns, it is needed to think of rates of contribution of each synergy; for example limiting synergy1 activation to 50%. Although synergy model is very sufficient and useful method, it cannot duplicate observed EMG patterns perfectly.
due to observed data noise. Then, the rate of contributions of each synergy is considered to make changed input data.

Suppose that one muscle activation level of synergy1 is 0.6 and one of synergy2 is 0.2 at one certain time step \( t = T \), and also actual observed muscle activation is 1.0 which is not equal to a linearly-summation of muscle activations from synergy1 and synergy2. Then the contribution rate of synergy1 and synergy2 are decided to 75% and 25% since fraction of muscle activation from two synergies are \( 3 : 1 \left( 0.6 : 0.2 \right) \). In the example, trying to limit synergy1 to 50%, it is needed to divide actual observed value into 0.75 and 0.25 first according to the ratio of each synergy. Then, muscle activation is weakened from 0.75 to 0.375, and just leave 0.25 remaind for synergy2. At last, their activations are summed together again since synergy hypothesis suggests it is linearly-summation of different synergies.

### III. Experimental Setup

In the experiment we did, there are three main parts to measure.

1) Body Trajectory
2) Floor Reaction Force
3) Muscle EMG

These three parts are all important for the analysis of the human standing-up motion.

#### A. Measurement of Human Body Trajectory

Fig. 4-(a) shows the motion capture machine [HMK-200RT; MotionAnalysis], which is used in the experiment to monitor the movement of the human while standing up. The recorded parts are four points: acromion, greater trochanter, articulatio genus, and ankle as in Fig. 4-(b). Positions of those regions are necessary because they are endpoints of each link. Although the sampling rate was 64 Hz in this experiment, data are down-sampled to the 12.8 Hz when using this data for computation. At the beginning of the standing-up motion, the subject keeps the angle of his ankle at 80 deg. His back was straight; the chair height was 425 mm. Also, the subject is asked to have his arms crossed in front of his chest to avoid the model becomes too complex by considering an inertia of arms. Those conditions were the initial state of the subject. From this experiment, angle of each joint is obtained, \( \theta_{i\{\text{ankle,knee,hip}\}} \) shown in Fig. 2-(a).

#### B. Measurement of Floor Reaction Force

Two force plates are used in this experiment. Each plate measures the reaction force by the foot and hip of the subject. The figure of force plate is shown in Fig. 5. Same as motion capture, although sampling rate of observed data is 64 Hz, it is down-sampled to 12.8 Hz when used.

#### C. Measurement of EMG

One healthy 22-years-old man participated in this experiment. To analyze EMG signals while standing up, they are recorded from eight muscles, as presented in Fig.6. Those muscles are considered important for standing-up motion from an anatomic viewpoint because every observed muscle is supposed to be related to inflection of three concerned joints. The EMG data are filtered with an upper cut-off frequency of 500 Hz and lower cut-off frequency of 200 Hz. Twelve trial data are obtained from this experiment. In addition, those data are filtered using a smoothing filter and down-sampled these data sampling rates of 12.8 Hz from 11200 Hz. Additionally, muscle data are normalized as 0–1 using the benchmark in maximum muscle activity for all trials. The EMG patterns obtained from this experiment were eight (four muscles for each half of the body), yet the function of muscles of the whole body is regarded as equivalent. Therefore, the values of the EMG patterns are averaged from the same muscle.

Fig. 6. This figure shows EMG sensor locations; the gastrocnemius muscle, quadriceps femoris muscle, gluteus muscle, latissimus dorsi muscle, and the prevertebral muscle.
IV. ANALYSIS OF HUMAN STANDING-UP MOTION

A. Extraction of Synergies

The number of synergies to be extracted from the observed EMG patterns is clarified by cross-validation. The relationship between mean value of $R^2$ and the synergy number is depicted in Fig.7.

Specifically regarding synergy number three, it is a sufficient number; before that number, the slope of the graph increases rapidly; after that point, the slope does not change sharply.

It seems that the number of synergies to be extracted is three from the result, however one of the synergies does not include any activated muscles and its contribution toward the body is rather small. This synergy is supposed only to work as removing specific small noise of patterns.

Fig.8 indicates actual extracted two synergies. In synergy1, every four muscles are activated and there are only two muscles are active in synergy2, such as musculus gastrocnemius and musculus latissimus dorsi.

B. Estimation Results of Joint Torques and Angles

Fig.9 (a) shows one example of torque estimation by neural networks. The model of generating torques by several muscles is very accurately indicates really observed torques. In order to evaluate the accuracy of the model, equation (3) is used. The results are shown in Table.I.

Fig.9 (b) is one of the examples of comparing the estimated angles and actual observed angles. Table.II also indicates high score on $R^2$.

These results suggest the reliability of the model for both torque and angle estimation.

C. Contribution of Behavior Primitive

Fig.10 shows error value calculated by formation (7) where $\theta_{dop}(t)$ is observed angle for each joint angle and $\theta_{est}(t)$ is estimated joint angle. Error values are normalized according to max error of each joint angle in order to understand contribution of the model easily.

$$E_i = \sum_{t=1}^{t} |\theta_{dop}(t) - \theta_{est}(t)|_i$$  (7)

As limitation toward each synergy is increased, error values are also increased. In addition, errors of knee, and hip suddenly increase rapidly at 30% point.

While normal standing motion lets knee go straight upward, the simulated angle line shows knee angle of weakened
synergy1 model does not go straight as much as normal one. The angle of their foot is also changed rapidly compared to normal one.

Thus, this synergy1 is supposed to make large movement of the motion, such as returning their bended back, or lifting their upper body upward by their knee in order to carry their center of gravity forward.

On the other hand, synergy2 works only for controlling human foot because as more limitation putted on the synergy, more errors are occurred only to foot angle. Synergy2 can be thought to control human posture because it starts at middle of the motion. At that moment people easily become unstable because they have to move their center of gravity from hip to their foot. Synergy2 mainly works for compensation of movement of center of gravity. In the contrast, Fig. 10 and 11 imply that synergy 2 has less effect on knee and hip than synergy1.

![Fig. 10. Contribution of Each Synergy to Joint Angle](image)

V. CONCLUSION

Human complex musculoskeletal system is expressed sufficiently in this paper. It constructs a mapping between human muscles and their joint toques, and between joint toques and human body trajectory. Using this integrated analysis method, a contribution of several muscle movements toward a motion is elucidated.

In addition, the synergy analysis is applied to human- standing up motion, and sufficient two important muscle coordinations are extracted. From the model, it is clear that both two coordinated muscle patterns have significant function to their movement. One behavior primitive works for making dynamics of the body by moving their ankle, knee, and hip. The other controls their ankle in order to keep their posture stable. Even when a person lacks either of behavior primitives, the motion is obviously changed and they cannot stand up.

![Fig. 11. Angle Changes with Weakened Particular Synergy](image)

(a) angle changes with weakened synergy1
(b) angle changes with weakened synergy2

VI. DISCUSSION AND FUTURE WORKS

Although we are able to extract two sufficient behavior primitives and check their contributions in this paper, it is still unknown whether these behavior primitives are common to every person. It is very important to see if this developed simulation method is also useful to other people.

Furthermore, in order to achieve our goal, which prevents elder people from needing a nursing care, new training machines or methods should be developed. From the results obtained in this research, two ways of muscle coordinations are observed, and since both of two has important contributions, we are going to think of new methods to enhance these behavior primitives.

ACKNOWLEDGMENT

We thank Mr. Okamoto for help in constructing our experimental machines, and also thank Prof. Kandou Kobayashi for giving us experimental opportunities.

REFERENCES