Lower Limb Joint Control Method based on Muscle-Skeleton Model and Biomechanics in Human Walking

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Abstract

Human walking and posture are determined by joint movement which is controlled by muscle force. Muscle force working as the internal force is the most important factor which determine human movement and posture.

In this paper, based on muscle-skeleton model and biomechanics, we propose useful joint control method which is suitable to apply muscle work to joint control. This method will help us to visualize the simulation of individual muscle function in human walking.

1 Introduction

We should understand muscle mechanism to explore human movement consisting of complicated mechanism. Therefore, to simulate human walking, we should consider constructing the system where human motion is controlled by the muscle force.

In this paper, to describe the system for human walking simulation, we present Joint muscle force function (JMFF) which generates a muscle force and propose the algorithm to control muscle force generated. By applying this method to muscle skeleton model, we can simulate a scientific visualization of human walking based on biomechanics.

2 Related Work

Walking is the basis of human locomotion and plays an important part in human movement. Therefore many scientists have researched the human walking as a part of the research on human.

In the past, the research about human walking have been conducted in traditional sciences such as biomechanics, sport science and is recently a gaining affection in computer graphics especially in game software and virtual reality.

In biomechanics, many scientists [2],[6],[7], [8],[9] researched the muscle mechanism as the main motive factor in human motion. By using experimental data, they analyzed the nonlinear characteristics of muscle and modeled the mechanism of muscle force. Hill [2] proposed the muscle theory which was modeled from contraction velocity. Based on Hill's theory, many researches about muscle mechanism has been conducted and one more parameter, the muscle length have been added to Hill's theory as the factor to change the magnitude of muscle force.

There are some researches which aimed to simulate muscle movement by computer graphics techni- que. These researches can be broadly divided into two camps; researches [1],[16],[18],[19] involving biomechanics, and those that do not involve biomechanics [10],[4],[5],[11].

Chen [1] use Zajac's model[7] based on Hill's theory to simulate the expansion and contraction of muscle shape. But Chen did not consider the joint control based on muscle characteristics.

In scientific visualization area, Delp[16] constructed the visualization system which use the precise data of muscle and the skeleton data. However this system was not constructed to simulate human walking but constructed to simulate a function of individual muscle. Taku[18] simulated the motion of leg by the control of muscle force which is generated by the mechanism based on Hill model [2]. But he did not consider a gravity and centrifugal coriolis which are the most important environment factors to simulate realistic human motion. Min [19] generated human walking by limiting a joint movement range to maximum joint movement which is calculated by Joint Muscle Function based on Hill model. But this system has a problem about the range of joint movement which is very wide. This problem makes the control of joint difficult. Added to this, as the Joint Muscle Function in this system is constructed by basic Hill model [2], this system is not enough to apply the biomechanical characteristic of muscle to joint movement generation.

of muscle when there is a change in muscle shape with joint movement. The other researchers who are Terozopoulo[10] and Yamada[11] modeled a face with a triangle patch which use sub-cutaneous tissue to control face tissue's movement. For example, Terozopoulo[10] made use of spring to imitate muscle activity while Yamada[11] used a motion capture to calculate muscle movement. But these researches just imitated the activity of muscle on certain parts of the body without consideration for biomechanical characteristic.

In this paper, we aim to visualize human walking which is consider the muscle mechanism based on biomechanical characteristic and applied the muscle skeleton data. To realize this aim, we present the system, which is considered a muscle mechanism and can control the activity of muscle to simulate desired motion. This system can be used not only in general computer animation but also in the areas related with human motion research which needs to visualize the simulation of their results.

3 Biomechanical characteristic of joint muscle

As shown in Figure 1, the muscle generates the muscle force \( F^T(t) \) depending on the command \( u(t) \) from the brain. In this process, both the contraction velocity \( V \) and the length \( L_M \) of muscle are changed.

![Generation process of muscle force](image)

Figure 1: Generation process of muscle force

The Figures 2(a)(b) quoted from [9] show us what the maximum muscle force varies with these two factors. In the case that the contraction velocity of muscle is zero, the relation between a muscle length and muscle force is shown in Figure 2(a). This net force-length characteristic depends on three factors which are a contractile element \( CE \), passive parallel element \( K_p \), and series elastic-element \( K_e \).

In Figure 2(a), the thin line shows the characteristic of \( CE \) which generates a maximum muscle force at the resting length \( l_o \). As the muscle lengthens, a muscle force decreases and when the muscle length reaches \( 1.5l_o \), a muscle force drops to zero. As the muscle shortens to less than resting length, muscle force is reduced until the length reaches about \( 0.5l_o \) and then the muscle force drops to zero.

As both \( K_p \) and \( K_e \) which are called passive muscles lengthen more than the resting length \( l_o \), a muscle force increases as the dotted line shown in Figure 2(a). If we sum forces from both elements of muscle, we can observe the overall muscle force-length characteristic as a thick line shown in Figure 2(a). The relation between a muscle force and a contraction velocity is like as shown in Figure 2(b). This characteristic of muscle is made from tendon activity.

We define the sign of velocity as minus in case that a muscle lengthens more than the current one and define the sign of velocity as plus in case of muscle decreasing less than the current one. Therefore, in case of contraction velocity increasing, a muscle force decreases.

As both elements which effect the change of maximum muscle force always vary at the same time, we should calculate the maximum muscle force by the summation of effects from both elements. This maximum muscle force as the above explanation in this section is controlled by the command \( u(t) \) from the brain as shown in Figure 1. Based on this control command, a muscle can control 75,50,25 % force values below 100 % maximum force as shown in Figure 2(b).

4 Calculation of muscle force based on Joint Muscle Force Function

When we simulate the movement of joint muscle, the joint muscle which consist of multiple fibers is generally defined as a unit. Based on this concept of muscle unit, we constructed Joint Muscle Force Function(JMFF) in this section.

To calculate a muscle force based on the characteristic of muscle activity, we need to define a maximum muscle force \( F_m \) varied with both length \( l_M \) and contraction velocity \( V \). By using Hill [2] model which define the relation between muscle force and contraction velocity, we can calculate the maximum muscle force in equation(1).
\[ F_m(l_M, V) = \frac{b\bar{F}_{iso}(l_M) + Au}{V + b} - au \] (1)

In equation (1), we define \( A \) as a cross sectional area. The constant \( b \) is the dimension of velocity and \( F_{iso}(l_M) \) is a muscle force with only muscle length \( l_m \). \( u \) is a parameter which controls a muscle force.

In this paper, we modelled a joint muscle force by using Zajac [7] model based on the theory of Hill [2]. As Zajac[7] model has not the dimension between units, his model is better than Hill model in the efficiency of calculation. He also applied many biomechanical characteristic of muscle to simulate more precise muscle characteristic than Hill model.

To apply Zajac[7] model, we need the normalization of muscle length in equation (2).

\[ l_M = \frac{l^M}{l_0^M} \] (2)

\( l_0^M \) is the length in case of muscle generating the maximum force and muscle length \( l^M \) is normalized as \( l_M \) by \( l_0^M \). The maximum force with normalized length is shown a thin line in Figure 2(a). The contraction velocity of muscle is another factor which effects the maximum muscle force as given in section 3. To define the relation between muscle force and contraction velocity from joint movement, we apply Hill [2] model to calculate the muscle force in equation 3.

\[ F_{CE} = \frac{b\bar{F}_{iso}(l_M) + ag}{(\dot{\theta}^C + b)} - ag \] (3)

Equation 4 below is a function for calculation of passive force. Total maximum muscle \( \dot{F}_m \) force is calculated by adding the active force \( \dot{F}_{CE} \) to the passive force \( \dot{F}_{PE} \) in equation 5.

\[ \dot{i}^M \geq 1 \quad \dot{F}_{PE} = 4(\dot{i}^M - 1)^3 \text{ else } 0 \] (4)

\[ \dot{F}_m = (\dot{F}_{CE} + \dot{F}_{PE}) \cdot \cos \alpha \] (5)

where \( \alpha \) is Pennation Angle. A detail explanation about \( \alpha \) is given in [6]. The activity level \( CL_m \) is defined as the ratio of desired force \( F_m \) to \( \dot{F}_m \). We can calculate the desired force \( F_m \) of each muscle by applying \( CL_m \) to maximum muscle force \( \dot{F}_m \) in equation (6).

\[ F_m = CL_m \cdot \dot{F}_m \quad 0.0 \leq CL_m \leq 1.0 \] (6)

where \( m \) is the index of each joint muscle. We define these overall mechanism for calculation of the desired joint muscle force as Joint Muscle Force Function.

\[ \tau_j = a_j^{m_{mx}} \cdot F_j^{mx} + a_j^{m_{mg}} \cdot F_j^{mg} \] (7a)

\[ \tau_j^{m_{mx,mg}} = \sum_{m=1}^{N} \tau_j^m \] (7b)

To calculate joint angular movement generated by \( \tau_j^{m_{mx,mg}} \), we need to use inverse dynamics based on Newton-Euler method in equation (8).

\[ \tau(\Theta, \dot{\Theta}, \ddot{\Theta}) = M(\Theta)\ddot{\Theta} + V(\Theta, \dot{\Theta}) + G(\Theta) \] (8)

where \( M(\Theta) \) is a mass term of torque, \( V(\Theta, \dot{\Theta}) \) is a centrifugal and coriolis term, and \( G(\Theta) \) is a gravity term. Precise explanation about dynamic equation is introduced in [12] and [13]. We can calculate a mass terms of equation(8) in equation(9) below.

\[ M(\Theta) = \frac{\tau(\Theta, \dot{\Theta}, \ddot{\Theta}) - (V(\Theta, \dot{\Theta}) + G(\Theta))}{\dot{\Theta}} \cdot \dot{\Theta} = 1 \] (9)

By applying \( M(\Theta) \) to forward dynamic in equation(10), we can calculate the angular acceleration \( \ddot{\Theta}_j \) generated by all muscles which control joint \( j \).

\[ \ddot{\Theta}_j = \frac{i_j^{m_{mx,mg}} + V(\Theta_j, \dot{\Theta}_j) + G(\Theta_j)}{M(\Theta_j)} \] (10)
6 Muscle-skeleton model and applying anthropometry to human Figure

To generate a realistic human walking, we need precise data about a skeleton and muscle. In this paper, we construct muscle-skeleton model based on the data of Delp[17]. By using Delp data, we designed the graphical muscle-skeleton model which consists of 70 muscles separated as Single Joint Muscle and Double Joint Muscle as shown in Figure 4. Single Joint Muscle means one joint is controlled by a muscle and Double Joint Muscle means one joint is controlled by multiple muscles.

![Figure 4: Pattern of joint muscle](image)

Figure 4: Pattern of joint muscle

An individual has an weight and build different from others. When we are also walking, these differences of body makes us walk in individual style. In this model, by considering these difference depending on individual, we applied the algorithm which can calculate approximated data of body part. To realize this concept, we define the length of a lower half body \( l_{\text{real}} \) as normalizing factors to the length of each body part. We also define the weight of a lower half body \( m_{\text{real}} \) as normalizing factors to the weight of each body part. This normalization is based on anthropometry in [14]. We express the normalized values of length and weight as \( \hat{l}_j \) and \( \hat{m}_j \) and calculate approximated length \( l_{\text{real}} \) and weight \( m_{\text{real}} \) of real body in equation (11a) and (11b).

\[
\begin{align*}
    l_{\text{real}} &= \hat{l}_j \cdot l_{\text{real}} \quad (11a) \\
    m_{\text{real}} &= \hat{m}_j \cdot m_{\text{real}} \quad (11b)
\end{align*}
\]

7 Generation of human walking by control of muscle Activity level

As shown in Figure 1, the mechanism of human movement is explained as what each muscle receives a command for the control of each joint from the brain to generate a desired movement. In this paper, we present the system for simulation of human walking as shown in Figure 5 based on human movement mechanism.

Individual control of all muscles on lower limb is too difficult. To simplify the control process of joint muscle, we define 24 joint control functions based on the joint function of Delp data [17]. Based on 24 joint control functions, we define the function of each muscle.

A muscle has generally multiple functions which are separated a main function and assistance functions. A main function is defined as representative function of a muscle. By the main function of individual muscle, we can classify all muscles into 24 muscle groups. Therefore a function of muscle group is identical with the main function of all muscles belong to a group.

We define the activity level sent to muscle group as the group activity level and the function of muscle group as the group function. The group activity level is sent to each group to control the activity of all muscles in group.

As mentioned above, a muscle has multiple functions for joint control. For this reason, a group function which is defined as a only one particular function is not enough to precisely control a individual muscle in a group. To overcome this weak point, we control the group activity level by the difference between the assistance functions and the group function of individual muscle.

Based on the concept as mentioned above, we construct the system as shown in Figure 5. To realize Top Level Command, the group activity level \( L^{g_i} \) is sent to corresponding group \( G_i \) and \( L^{g_i} \) is controlled by the difference between assistance function of each muscle and the group function. This process makes \( L^{g_i} \) change to \( L^{g_i} \) which is sent to individual muscle \( m \).

\( L^{g_i} \) is input into JMFF as mentioned in section 4.

![Figure 5: Human walking generation system](image)
This process output a muscle force $F_m$ as explained in equation (6). By calculating a joint angular movement $\Delta \Theta_j$ from $F_m$, we can generate human walking. The calculation of $\Delta \Theta_j$ is introduced in section 5.

8 Visualization result

We visualized some results of human walking simulation by using the proposed system in this paper. Figure 6(a),(b),(c) show a sagittal view and coronal view, back view of lower limb and 70 supporting muscles. We visualized a muscle as green color line.

![Figure 6: Muscle skeleton model](image1)

Figure 6: Muscle skeleton model

![Figure 8: Human walking simulation in coronal plane](image2)

Figure 8: Human walking simulation in coronal plane

Based on the system as shown in Figure 5, we generated human walking for Single limb support period. Single limb support period is introduced in [6]. Figure 7 and 8 show human walking in this period. Figure 7 is the result which visualize a walking simulation in sagittal plane and Figure 8 is the result which visualize a walking simulation in coronal plane. Both results consist of results (a),(b),(c),(d),(e),(f),(g) in process order as a human walks in forward. These results show that the simulated human walking keeps the balance in both sagittal plane and coronal plane.

In this system, we also visualized the muscle activity by the color of line expressing muscle which changes the activity during walking. In case that activity level is 1.0, we visualized a muscle as pure red. In case that activity level is 0.0, we visualized a muscle as pure green. In case that the activity level between 0.0 and 1.0, we visualize a muscle as color $C$ in equation (12).

$$C = G \cdot (1.0 - CL_j^m) + CL_j^m \cdot R$$

where G is pure green and R is pure red. By using this system, we can observe the changing of individual muscle activity on lower limb during moving. Added to this, we can study multiple functions of individual muscle from this visualization system.

To simulate the walking in Single limb support pe-
period, we use a activating muscle and their activity level for input data of our system. The input data of our system is the activity level pattern of muscle during Single limb support period based on the reference book [6].

9 Conclusion and future work

In this work, we try to construct the system which can apply biomechanical characteristic of a muscle to human walking generation. We can summarize two results of this work below.

- Construct the visualization system for human walking simulation based on muscle skeleton data.
- Realize the simulation with consideration of gravity based on dynamics.

From these results, we can not only realize real walking but also show the possibility what the visualization system using Computer Graphics is applied to sport science and medical science, biomechanical engineering which need to analyze the result of simulation related with human motion. But our system in this paper has many problems still to be solved. Our future works for these problems are introduced below.

- Construct the function that can estimate the difference between group function and individual muscle function belong to group and precisely calculate a individual muscle activity level based on this difference.
- Develop the function which can estimate a result motion and make the system to revise a simulation result based on this function.
- Construct the human walking system with consideration of the upper part of the body.
- Construct the human walking system with consideration of the external force.

References