Subject Specific Modeling of Bodies for Muscle Activity Estimation Based on Geometric Morphing

（幾何学的モーフィングに基づいた筋活動推定のための被験者固有身体モデリング）

池上 洋介　　指導教員　中村 仁彦 教授

Yosuke Ikegami　　(Professor Yoshihiko Nakamura)

Key Words : Geometric morphing, Musculoskeletal Modeling, Contact force estimation, Mouse motion analysis

1. Introduction

This dissertation studies the modeling of the subject-specific musculoskeletal systems based on the geometric and/or kinematic parameters for dynamic whole body muscle tension analysis. A model of musculoskeletal system is necessary for analysis of musculoskeletal motion analysis. Muscle model can be mapped onto skeletal system using geometric information.

The skeletal model manage two types of parameters, the geometric parameter representing joint and marker position, and dynamic parameter representing mass, inertia tensor and center of gravity. The geometric parameter identification technique, the calculation of the link length by the inverse kinematics solver using motion capture data is simple way to the measurement[1]. For the identification method of the dynamic parameters, the real-time identification method using visual feedback has been proposed [2]. However, method of the high-DOF musculoskeletal model is absent so far, a simple and practical modeling techniques are required.

Nakamura et al. developed the whole body model of the human musculoskeletal system that is appropriate and consistent with the algorithms of robotic kinematic and dynamic computation[3, 4, 5] and proposed an optimization algorithm to estimate muscle activities based on the information from a motion capture system and the other sensory systems. This motion analysis simulator is used for applications in various fields. Conventionally in the field of sports, physical skills obtained from long time training had to be transmitted through the try and error to the next generation. This is due to a problem that it is difficult to quantify the movement. Introducing the method of motion analysis, quantitative skill can be transmitted to the others.

In the medical field, there is a trend to try to apply the simulator to assess the disease progress. There is also an example doing the motion analysis of a mammals. A running horse or walking rat motion analysis is studied [6] through the capturing motion, however neither of them did not carried out the estimation of muscle tension analysis. Laboratory mice played an important role on biomedical studies. Mice are classified to early mammalian in toxicology and have close biological relationship with human. However, there is no practical musculoskeletal dynamics simulator. Oota et al.[7, 8] developed the model of skeletal system of laboratory mouse based on the X-ray CT scanning, while modeling of the whole musculotendinous system is still a future problem. With respect to the muscle modeling of the mouse, practical and convenient modeling technique is a required. Mouse musculoskeletal system is model using geometric information and walking motion analyzed using newly developed force measurable staircase.

2. Subject Specific Musculoskeletal Modeling Based on Geometric Morphing of Skelton

In this Chapter, the method for mapping muscle model using bone geometry information. The world coordinate

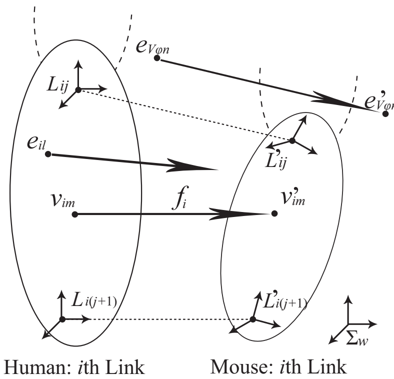

Fig.1 Morphing by the skeletal subspace deformation (SSD): anatomical landmarks and element points

system Σ_w is defined and used to describe the coordinates of all the points. The set of landmarks of the ith link is given by Li. We picked up the landmarks according to Anatomy reference book[9]. A pair of landmarks are defined in one-to-one relationship and on the corresponding pair of links. The mth vertex of the ith link is described by the extended expression such as $\boldsymbol{v}_{im} = [\boldsymbol{p}_{im} \ \ 1]^{\mathrm{T}} \in \boldsymbol{R}^4$. The mth vertex of the ith link, $\boldsymbol{v'}_{im}$, is transferred by mapping function f_i to

$$f_i(\boldsymbol{v}_{im}) = \sum_{j \in L_i} w_{ij} \boldsymbol{T}_{H'_{ij}} (\boldsymbol{T}_{H_{ij}})^{-1} \boldsymbol{v}_{im} \tag{1}$$

$\boldsymbol{T}_{H_{ij}}$ implies the homogenous transformation matrix representing the position and orientation of the link coordinates of the jth landmark on the ith link and the scale

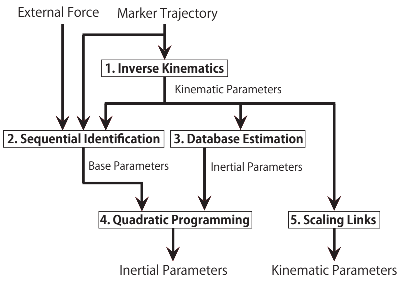

Fig.2 Outline of the proposed method to identify kinematic and inertial parameters

factor, where the orientation and the scale factor are manually adjusted for closer matching of polygonal surfaces. The weight function w_{ij} is defined according to the distance between a landmark and the mth vertex of the ith link, and satisfies the following constraints:

$$\sum_{j \in L_i} w_{ij} = 1, \quad w_{ij} = \frac{(P_{ij} - P_{v_{im}})^{-\alpha}}{\sum_{j \in L_i} (P_{ij} - P_{v_{im}})^{-\alpha}} \tag{2}$$

In this dissertation, the α is set as 4. Muscles, tendons, ligaments are modeld as wires. Wire can describe using points, which are starting point, end point, and via point. Those elements points can be mapped to the new position using same mapping function.

3. Subject Specific Inertia Modeling Based on Geometric Morphing of Skin

Identification of kinematic and inertial parameters for subject-specific model using body shape information was proposed. Figure 2 shows outline of the proposed method to identify kinematic and inertial parameters. Time series of marker data and floor reaction force measured by motion capture system are the input of the proposed method, and then kinematic and inertial parameters are obtained. This method consists of five steps below. 1. Identification of kinematic parameters by solving inverse kinematics. 2. Identification of base parameter by sequential identification method. 3. Estimation of the inertial parameters using statistical data. Assume that a rigid body is constituted by mass points which are closest to COG of the link. Operating parameters to form the body shape was determined by principal component analysis based on the scanned and measured data at digital Human Research Center National Institute of Advanced Industrial Science and Technology. 4. Calculation of the inertial parameters by least square method. 5. Applying the kinematic parameters of the lower DOF model to the large DOF musculoskeletal mode.

Base parameters are obtained by sequential identification method. Subject-specific inertial data can be estimated by the sum of the mass point arranged at regular intervals to the body shape data obtained from database. Inertial parameters are obtained by solving least square method satisfying the conditions of base parameters and inertial parameters, respectively. An identification result of each link is dependent on the accuracy of a discrete mass point in the body shape. By comparison with the reference, the effectiveness of this method was stated. Cross-validation on measured force and force which was calculated by identified inertial parameter was done. Recreation of the reaction force was confirmed by using identified parameters. Since the subject-specific model can be obtained from just one motion, simplicity was achieved.

4. Motion Analysis with Contact Force Estimation

For the dynamic computation, to estimate whole body muscle tension, the following three types of optimization problem is solved in order. A) In inverse kinematics, generalized coordinates is obtained to reproduce the trajectory of the marker measurement while satisfying the wire constraints. B) In contact force estimation external forces to reproduce all external force calculated from the generalized coordinates and the known inertial model, and to reproduce the measured value of the total floor reaction force simultaneously. C) In inverse dynamics, the tensile strength of each wire to reproduce the joint torque calculated with the generalized coordinates, contact forces and known inertial model, and to reproduce the measured values from the EMG data. The motions for dynamics simulator is classified based on the treatment of the contact state. In case of multi-point contact situation, the method to solve the optimization problem of both all muscle tensions and multipoint contact forces simultaneously can estimate more natural way. Generalized coordinate including an external force term $\boldsymbol{\tau}_g$ can be described using equation of motion, as follows.

$$\boldsymbol{\tau}_g \triangleq \boldsymbol{H}\ddot{\boldsymbol{q}} + \boldsymbol{b} = \boldsymbol{Y}^{\mathrm{T}}\boldsymbol{x} \tag{3}$$

$$\boldsymbol{Y}^{\mathrm{T}} = [\boldsymbol{J}^{\mathrm{T}} \quad \boldsymbol{J}_{CF}^{\mathrm{T}} \quad \boldsymbol{J}_{CI}^{\mathrm{T}}\boldsymbol{n}] \in \boldsymbol{R}^{N \times N_S} \tag{4}$$

$$\boldsymbol{x} = [\boldsymbol{f}^{\mathrm{T}} \quad \boldsymbol{F}_{CF}^{\mathrm{T}} \quad \boldsymbol{e}_{CI}^{\mathrm{T}}]^{\mathrm{T}} \in \boldsymbol{R}^{N_S} \tag{5}$$

$$N_S = N_W + 6N_{FP} + N_{CI} \tag{6}$$

$\boldsymbol{x}$is consists of muscle tension vector, floor reaction force vector, and coefficient vector of vector norm.

The following optimization problem is calculated in each sample frame to minimize evaluation term Z.

$$\begin{aligned} \min_{\boldsymbol{x}} \ Z = & \frac{1}{2}||\boldsymbol{W}_{dyn} \ (\boldsymbol{\tau}_g - \boldsymbol{Y}^{\mathrm{T}}\boldsymbol{x})||^2 \\ & + \frac{1}{2}||\boldsymbol{W}_{msd} \ (\boldsymbol{F}^* - \boldsymbol{H}\boldsymbol{x})||^2 + \frac{1}{2}||\boldsymbol{W}_{stb} \ \boldsymbol{x}||^2 \\ \text{subject to} \quad & \boldsymbol{f} \leq 0, \quad \boldsymbol{C}_Z\boldsymbol{F}_{CF} \geq 0, \quad \boldsymbol{e} \geq 0 \end{aligned} \tag{7}$$

where, $\boldsymbol{C}_Z$ is the projection matrix to extract Z components of the floor reaction forces. $\boldsymbol{W}_{dyn} \in \boldsymbol{R}^{n \times n}$ is the weighted diagonal matrix whose diagonal elements are positice.$\boldsymbol{f}_C^{ref}$ is the force reference value in which can be calculated from Hill-Stroeve type muscle models [10, 11] and measured force plate data.

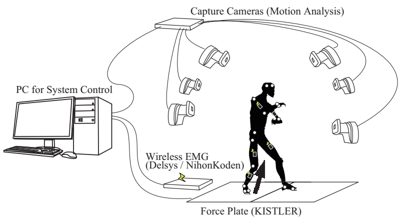

Fig.3 Motion capture system

5. Analysis of Masters' Skills from Musculoskeletal Estimation

We discuss the computation of human motion dynamics and its analysis of the experts' motion skills. Figure 3 shows the overview of the motion capture system. As examples of analysis, we measured and analyzed experts ’ motion patterns, and obtained following considerations.

1. In Tai Chi dance performance, height of the COG is relatively low and movement is stable. Regardless of the orientation of the trunk during movement, the COG has periodicity of the Y-axis direction. Muscles of the lower limbs are working actively, and muscles in upper body works less compare to the muscles in lower limb.
2. For the tap dancing, the COG has oscillatory motion to the vertical direction. The height of COG is lower than standing posture in average. Muscles of the whole body actively involved, in particularly upper limb muscles. Hip and knee joint does not move so hard from upright position in tap dancing. Motion of the ankle joint has an important role to play for tap dance.
3. As for the drum playing, the COG does not change much. Muscle activity is dependent on the musical instruments. Z-axis direction movement of COG, it is correlated with the performance of the bass drum on the right foot and the snare drum in the left hand.
4. Proposed contact force estimation method that optimize multi-point contact force and muscle tension simultaneously can provide more natural value in Judo Uchimata analysis and independent estimation force vectors by using vector space of muscle Jacobian.

6. Musculoskeletal Morphing Between Different Spieces of Mammals, from Human to Mouse

In this chapter we discuss a systematic method to construct the musculotendinous model of mouse, through geometric morphing between the human skeletal system and the skeletal system of mouse. The musculotendinous model of mouse is constructed from that of human using the method presented in Chapter 2 based on the homology of the two species.

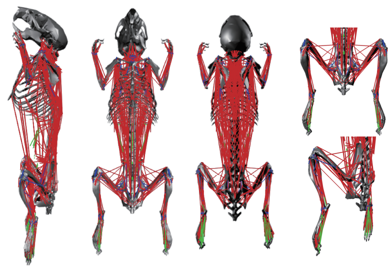

Fig.4 Mapped musculotendinous system

The muscle length analysis is conducted using the motion capture data.

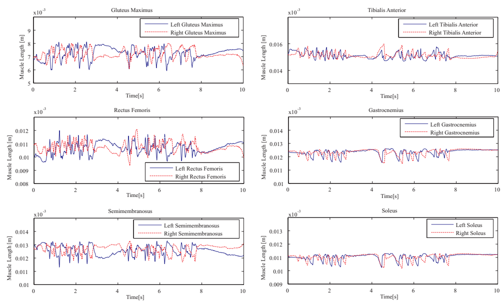

Fig.5 Muscle length analysis of gait

7. Muscle Force Estimation for the Behavioral Analysis of Mutant Mice

We develop the simple stairs to measure reaction force for mouse walking motion, and did calibration. Figure 6 shows the developed stairs.Each stage consists of base, load cell, color to give a constraint, struts and plates. One load cell can measure the axial force Z. The width of each plate is 100mm, and 10mm depth, and pitch is 20mm. This is obtained by calculating the pitch of gait analysis in the reference[12]. We conducts the motion

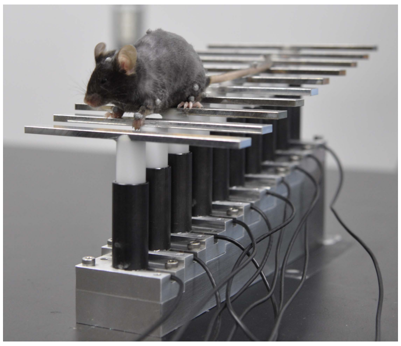

Fig.6 Outline of the stairs for mouse force measurement

capture experiment on B6 mice using force stairs. Using inertial model of the mouse obtained separately, muscle tension estimation of mouse walking motion can be done with the calculation of inverse dynamics. Result shows any specific evidence of strong abnormal gain pattern of homo hugger mouse in sample motion.

8. Conclusion

This dissertation studies the subject-specific modeling of bodies and the modeling of contacts with environment, which are required for the estimation of muscle forces from noninvasive measurement data on the basis of geometric characteristics for the individuals'.

In this dissertation, the useful important findings to model the subject-specific musculoskeletal systems are to be provided as follows: (1) The fundamental and simple-manner techniques of muscle modeling and inertial parameter modeling for large-DOF musculoskeletal systems on the basis of geometric characteristics of bodies are to be developed. Not only for the humans, but also through the modeling of heterogeneous mammals, especially for the mice, the wide range of applicability of developed techniques are to be perceived. (2) Through the development of the contact modeling, the method of practical motion analysis combined with multiple people are to be proposed. Especially, practical contact force estimation in multipoint become possible by solving the optimization problem for contact forces and muscle forces simultaneously considering force directions and somatosensory electromyography signals even if the contact forces can not be measured directly. (3) The quantitative assessment techniques for the large-DOF whole-body motor functions of the laboratory mice are to be newly developed ahead of the world through the presentation of the measurement techniques and the analysis results, which include the time-series data of the muscle tensions, joint torques, and joint trajectories.

The proposed methods and results to model the subject-specific musculoskeletal systems are as follows: (A) The musculoskeletal modeling using geometrical morphing scheme from the knowledges of bone geometric characteristics between two subjects are to be proposed. We show that the modeling method is effective between the subjects even in the heterogeneous mammals by creating mapping functions using the homology of the bone geometry, such as a human and a mouse. The obtained mouse musculoskeletal model is to be compared with other model to confirm that the method is practical. (B) Methods for calculations of the kinematic and inertial parameters as the enhancement of lower-DOF identification methods by combining the knowledge of geometric skin shape are to be discussed. Using the subject motion data and the obtained geometric and dynamic parameters, cross-validation is to be performed with respect to the force acting on floating base link, and practicality is to be confirmed from obtained results. (C) The methods for estimating the contact forces and muscle tensions using subject-specific models obtained in (B) are to be discussed. The experts' motions, such as Tai Chi, tap dance, drum performance, and Judo Uchimata motion, are to be measured and analyzed under the contact modeling, and characteristics are to be stated. (D) A quantitative kinematic and dynamic motion analysis is to be performed using the mouse musculoskeletal model obtained in (A). Ten steps staircase capable of sensing the reaction force is to be newly developed. The walking motion capture experiment on mutant hugger mice is to be performed and analyzed. Our initial results are able to provide the motion results in multi-dimensional data.

References

[1] Ko Ayusawa and Yosuke Ikegami and Yoshihiko Nakamura. Simultaneous Geometric Parameters Identification and Inverse Kinematics of Time Series Motion by Fast Optimization Using Decomposed Gradient Computation. *Proc. of the Conf. on Robotics and Mechatronics*, pp. 2P1–O10, 2012 (in Japanese).

[2] K. Ayusawa, G. Venture, and Y. Nakamura. Real-time implementation of physically consistent identification of human body segments. *Proc. of the IEEE Int. Conf. on Robotics and Automation*, pp. 6282–6287, 2011.

[3] Y Nakamura, K Yamane, I Suzuki, and Y Fujita. Dynamic computation of mucsculo-skeletal human model based on efficient algorithm for closed kinematic chains. *Proc. of the 2nd International Symposium on Adaptive Motion Animals and Machines*, pp. SaP–I–2, 2003.

[4] Y Nakamura, K Yamane, I Suzuki, and Y Fujita. Somatosensory computation for man-machine interface from motion capture data and musculoskeletal human model. *IEEE Transactions on Robotics*, 2005.

[5] Yoshihiko Nakamura, Katsu Yamane, and Akihiko Murai. Macroscopic modeling and identification of the human neuromuscular network. *Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 99–105, 2006.

[6] T Lelarda, M Jamonc, J P Gascb, and P P Vidal. Postural development in rats. *Experimental Neurology*, Vol. 202, No. 1, pp. 112–124, 2006.

[7] S Oota, K Mekada, Y Fujita, J Humphpheries, K Fukami-Kobayashi, Y Obata, T Rowe, and A Yoshiki. Four-dimensional quantitative analysis of the gait of mutant mice using coarse-grained motion capture. *Proc. of IEEE Engineering in Medicine and Biology Society*, pp. 5227–5230, 2009.

[8] S Oota, A Yoshiki, Y Fujita, J Humpheries, K Fukami-Kobayashi, Y Obata, T Rowe, and Y Nakamura. Development of a coase-grained skeletal model of laboratory mouse and its application. *Proc. of 1st Int'l Conf. on Applied Bionics and Biomechanics*, 2010.

[9] Carmine D Clemente. *Anatomy A Regional Atlas of the Human Body*. Lippincott Williams & Wilkins, 2007.

[10] A V Hill. The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London*, Vol. 126, pp. 136–195, 1938.

[11] S Stroeve. Impedance characteristic of a neuromusculoskeletal model of the human arm I. posture control. *Biological Cybernetics*, Vol. 81, No. 5-6, pp. 475–494, 1999.

[12] Yoshihiko Nakamura, Yosuke Ikegami, Akihiro Yoshimatsu, Ko Ayusawa, Hirotaka Imagawa, and Satoshi Oota. Musculoskeletal morphing from human to mouse. *IUTAM Symposium on Human Body Dynamics: From Multibody Systems to Biomechanics*, 2011.