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Dynamic Control and Simulation of Human Musculo-Skeletal Model

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Abstract: In this paper, we propose a dynamic human motion simulator to clarify and obtain the natural movement as human carries out. This system consists of a 3D motion capturing system, which has 6 high-speed cameras, 8 force plates, 10 3-axis accelerometers and 32 EMG sensors. To reconstruct the human ’s complex movement in VR space, a dynamic simulation model of human muscle-skeletal body is constructed. This model has 100 segments of born and has totally 105 D.O.F. in whole body, and also 300 muscles are included in this model. These muscles have the properties of stiffness, damping and contractive force generation. This platform makes it possible for construct human dynamic motion control functions more precisely and is thus useful for bio-mimetic robots. By using the super-redundant human body model, we are studying the brain motor control functions through the dynamic simulations.

Keywords: motion capture, musculo-skeletal model, redundancy, bio-mimetic research

1. Introduction

Human can easily perform various kinds of tasks by using many redundant limbs and muscles. To obtain these dexterous and skillful motion abilities by a robot as human movements in everyday life has become one of the most important subjects in bio-mimetic research. The objective of this research is not only limited to develop a robot that can interact directly with human but also important to clarify the control mechanism of the brain motor control system. To achieve this objective, a dynamic motion analysis platform that can be used to measure and reconstruct many kinds of dynamic human motions more precisely is highly expected.

This research aims to develop a novel analyzing platform for studying dynamic human motions. Motion capturing systems are used widely to measure and analyze the human motions. Usually, the system uses optical position makers and some sheet of force plates to calculate each joint torques. 1, 2). In the following sections, we describe our dynamic motion capturing system. Unlike present motion capturing technologies, our platform can measure the acceleration information directly using accelerometers instead of 2nd numerical differentiation of angle information. In addition, our system can also measure the EMG signals synchronize with motion capturing and force measurements from the force plates.

In order to reconstruct the dynamic human movement within real time, a dynamics simulator of a whole body human musculo-skeletal system model is developed, and the immersion type dynamic simulation technology is applied so that the human subject can realize interaction with the virtual human model.

2. Dynamic Motion Capturing System

The whole motion capturing system developed in this research is shown in Fig. 1. This system constructs 6 high-speed cameras, 8 force plates, 10 3-axis accelerometers and 32ches EMG sensors. As the most advantage of this system, the system measures the acceleration information directly using accelerometers and also the myoelectric activities using EMG sensors synchronized with the high-speed cameras. Usually, the human acceleration information for calculating joint torques is obtained approximately only by 2nd numerical differentiation of the measured position information. There is a large numerical error in these results especially in quickly motions. In this system, it can be expected to obtain joint torques more precisely by measuring the acceleration information directly even for the fast dynamic human motions. This advantage will be important for the dynamic simulation described in the next section.

3. Dynamic Musclo-Skeletal System Model

In order to simulate and analyze the human motions, a dynamic simulator of whole body musculo-skeletal system is developed as shown in Fig. 2 using programming library "Vortex" 4). By input muscle forces, this simulator can easily calculate collision between each body parts as well as dynamic body movements within real time. Fig. 2 shows a musculo-skeletal model, in which bones of the whole body are classified into 100 segments. The total motion degrees of freedom of the whole body

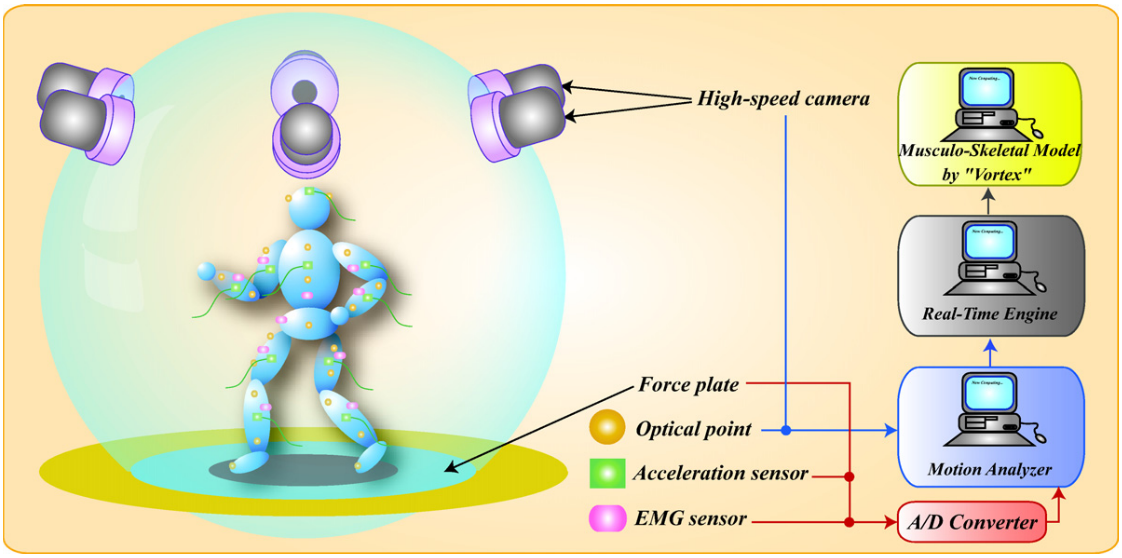

Figure 1: A 3D motion capturing system

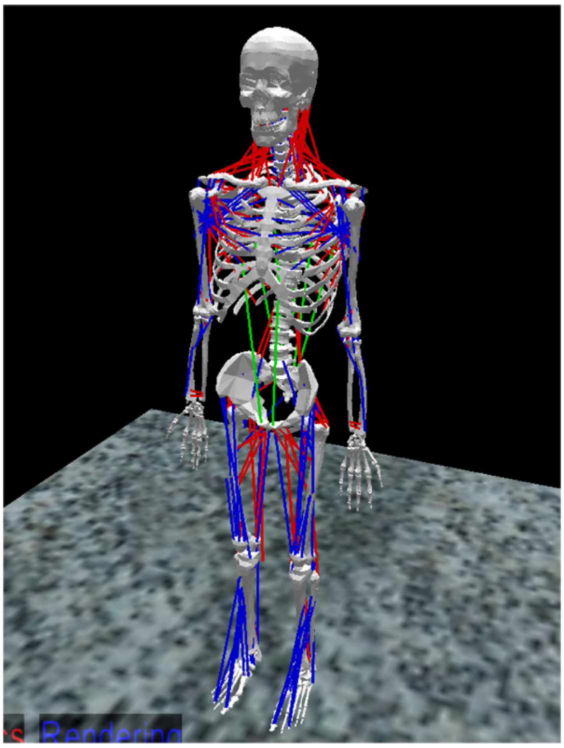

Figure 2: Whole body skeletal system

are 105 D.O.F., which connect each body segments and drive the joint motions. The motion degrees of freedom between each segment are defined as follows:

1) Shoulder, hip and wrist joint have 3 D.O.F., respectively.
2) Elbow, knee and ankle joint have 2 D.O.F., respectively.
3) Waist is defined as a 3 D.O.F. joint about each segment from a sacrum to the 5th lumbar vertebrae, therefore, the waist joint has a total of 15 D.O.F..
4) Neck is also defined as a 3 D.O.F. joint about each segment from a skull to the 7th cervical vertebrae, means that the neck joint has a total 21 D.O.F..
5) For simplicity, the thoracic vertebra, sternum and rib are made into one segment.
6) For each hand, there are 5 fingers, each finger has 4 D.O.F. which makes one hand with totally 20 D.O.F.. The toe joint makes the 5 fingers to one segment and has 1 D.O.F..

In this model, 300 muscles are defined to attach between each bone segments. These muscles do not have mass property and have linear actuator element, passive spring and dumping element. The present model has only main outer muscle and inner muscles are not included.

4. Definition of Muscle's Via Point

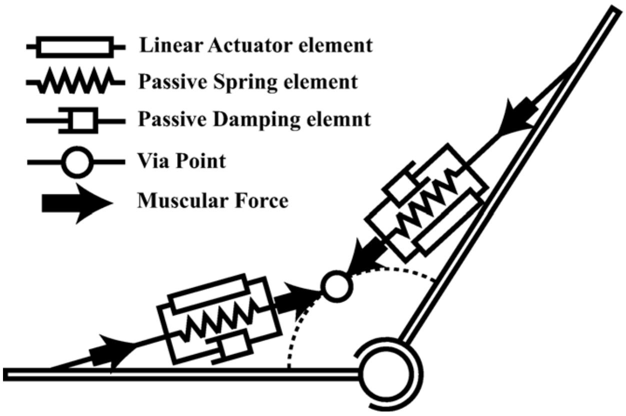

Figure 3: Definition of muscle's via point

Since each muscle is defined as a line model, which starts from the origin point on some body segment, through a number of via points and joints, and finally reaches the insertion point of another segment. The muscle via points should be defined correctly in the model so as to realize more exact motion. As an example, we define the muscle via point about elbow joint as shown in Figs. 3∼4. These via points only transmit the muscular force and change the force directions.

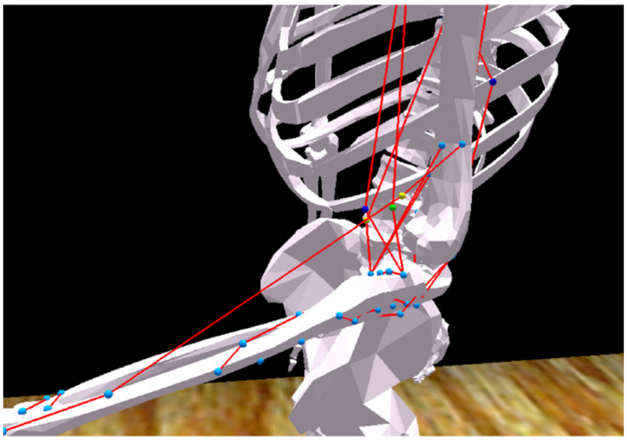

Figure 4: The left elbow joint which defined via points of muscles

5. Measuring of Acceleration by 2 D.O.F Planer Arm

In this section, the way of simplified measurement to calculate joint torques by means of 2 D.O.F. planer arm model are shown. The coordination of 2-link arm model is shown in Fig. 5. The kinematics from origin to accelerometer position is as follows:

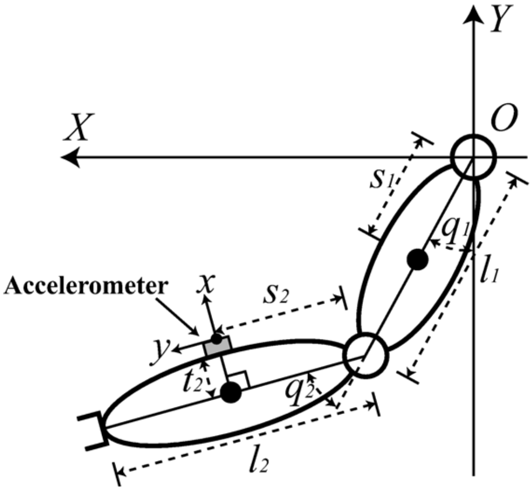

Figure 5: The coordination of 2-link arm

$$
\begin{aligned}
X &= l_1 \sin q_1 + s_2 \sin(q_1+q_2) + t_2 \cos(q_1+q_2) \\
Y &= -l_1 \cos q_1 - s_2 \cos(q_1+q_2) + t_2 \sin(q_1+q_2)
\end{aligned}
\quad (1)
$$

and the 2nd differentiation of above equations are as follows:

$$
\begin{aligned}
\ddot{X} &= -l_1 \dot{q}_1^2 \sin q_1 + l_1 \ddot{q}_1 \cos q_1 \\
&\quad -s_1(\dot{q}_1+\dot{q}_2)^2 \sin(q_1+q_2) + s_2(\ddot{q}_1+\ddot{q}_2)\cos(q_1+q_2) \\
&\quad -t_2(\dot{q}_1+\dot{q}_2)^2 \cos(q_1+q_2) - t_2(\ddot{q}_1+\ddot{q}_2)\sin(q_1+q_2) \\
\ddot{Y} &= l_1 \dot{q}_1^2 \cos q_1 + l_1 \ddot{q}_1 \sin q_1 \\
&\quad +s_1(\dot{q}_1+\dot{q}_2)^2 \cos(q_1+q_2) + s_2(\ddot{q}_1+\ddot{q}_2)\sin(q_1+q_2) \\
&\quad -t_2(\dot{q}_1+\dot{q}_2)^2 \sin(q_1+q_2) + t_2(\ddot{q}_1+\ddot{q}_2)\cos(q_1+q_2)
\end{aligned}
\quad (2)
$$

The information from accelerometer is transformed from local coordination to inertia coordination as follows:

$$
\begin{pmatrix} \ddot{X}_a \\ \ddot{Y}_a \end{pmatrix} = \boldsymbol{R}(\boldsymbol{q},\ \dot{\boldsymbol{q}}) \cdot \begin{pmatrix} \ddot{x}_a \\ \ddot{y}_a \end{pmatrix} \quad (3)
$$

Where $(\ddot{x}_a,\ \ddot{y}_a)$ is acceleration information on local frame from accelerometer, $(\ddot{X}_a,\ \ddot{Y}_a)$ is acceleration information on inertial frame from accelerometer and $\boldsymbol{R}(\boldsymbol{q},\ \dot{\boldsymbol{q}}) \in \Re^{2\times2}$ is rotational matix. Therefore, angular acceleration $\ddot{\boldsymbol{q}} \in \Re^{2\times1}$ can be calculated by substituting eq. (3) for eq. (2). Here, the dynamics of this model are as follows:

$$
\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \left(\frac{1}{2}\dot{\boldsymbol{H}}(\boldsymbol{q}) + \boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}})\right)\dot{\boldsymbol{q}} + \boldsymbol{C}\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau} \quad (4)
$$

Where $(\ddot{\boldsymbol{q}},\ \dot{\boldsymbol{q}},\ \boldsymbol{q}) \in \Re^{2\times1}$ are joint acceleration, velocity and angle respectively. $\boldsymbol{H} \in \Re^{2\times2}$ is inertia matrix and $\boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}}) \in \Re^{2\times2}$ is a coefficient matrix whose term includes Coriolis and centrifugal forces and is a skew-symmetric matrix. $\boldsymbol{G}(\boldsymbol{q}) \in \Re^{2\times1}$ means gravity terms. Each joint torques $\boldsymbol{\tau} \in \Re^{2\times1}$ is obtained by substituting $(\ddot{\boldsymbol{q}},\ \dot{\boldsymbol{q}},\ \boldsymbol{q}) \in \Re^{2\times1}$ for eq. (4).

5.1 Experimental results

In this section, some experimental results of the calculated torques for human shoulder and elbow joints movement are shown in Figs. 6∼7. Some parameters in this experiment are shown in Table. 1.

Table 1: Parameters

	1^{st} Link	2^{nd} Link
Length [m]	0.280	0.250
Center of Mass [m]	0.140	0.125
Mass [kg]	2.00	1.90
Damping [N·s]	3.0	3.0

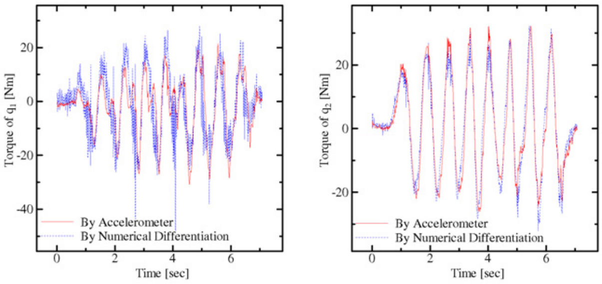

Figure 6: The comparison of joint torques with fast motion calculated from numerical differenciation and from measured acceleration

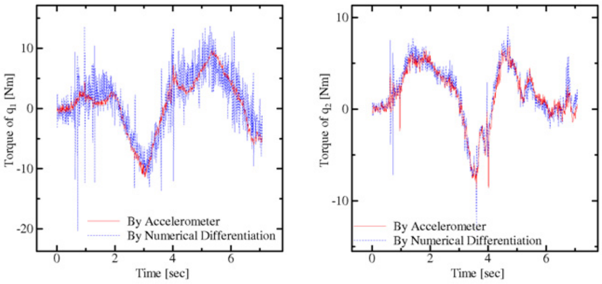

Figure 7: The comparison of joint torques with slow motion calculated from numerical differentiation and from measured acceleration

The red line is the result of the numerical differentiation, while the blue line is the result from directly measured acceleration. As seen from these figures, obviously, the torque data calculated from the numerical differentiation of the position has high frequency noise. However, the torque from the acceleration data is smoother especially in the case of fast movements.

6. Interaction with human subject within PC-CAVE

In this section, we apply immersion type dynamic simulation technology to study the real time human interactions. The results are given in Fig. 9 5).

Figure 8: Human interactions

7. Conclusions

In this paper, a dynamic motion capturing system and a dynamic human motion simulator are developed. Accelerometers may increase the accuracy when calculating the human joint torques for the fast dynamic motions.

In the future, to approach a redundancy problem between a muscle space and joint space from the point of view of mechanical impedance, the information of myoelectric activity should be applied. By this platform, we hope to clarify the mystery motor control mechanism of the brain in controlling such redundant and complex musculo-skeletal system.

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Figure 9: The interaction between human subject and human musculo-skeletal model in VR space