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Modeling and Dynamic Simulation of Super-redundant Musculo-skeletal System

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ABSTRACT
Development of human friendly robots that can cooperate with us in our every day life is highly expected. For these robots, it is important to realize not only diversities of motions, softness, but also dexterities and adaptability to complex environment. As one solution to realize such a robot, in this research we study super-redundant human musculo-skeletal system. We describe on how to model the dynamics as well as redundant D.O.F. of the musculo-skeletal system, and we will show our results of dynamic simulation. The significance of this research is not only to develop a new robot but also to clarify the underlying human motor control mechanisms.

KEY WORDS
musculo-skeletal model, bio-mimetic robots, redundancy

1 Introduction

It is well known that a musculo-skeletal body has basically two kinds of redundancy. One is the number of D.O.F. of all joints that are larger than the number of D.O.F. of task space. It means that human body has many kinds of superiority from the point of view of kinematics between the task space and joint space. Another is that one joint is driven by many muscles. It means that human can change internal force in order to control impedance property. These kinds of redundancy make it possible for human to perform many kinds of tasks dexterously in unknown environment. To obtain these dexterous and skillful motions as human movements has become one of the most important subjects in bio-mimetic research. The purpose of this research is not only for developing a robot which can interact directly with human but also for clarifying the problem on how human controls many limbs by the brain motor control mechanism. To achieve this objective, a dynamic motion analysis platform which can 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. To analyze human movement, many motion capturing systems are used widely. These systems are consist of few optical position makers and some sheet of force plates. By using these systems, each joint torques can be easily calculated by optical measurement and force measurement [1][2]. In the following sections, we describe our dynamic motion capturing system. Unlike present motion capturing system, our platform can measure the acceleration information directly using accelerometers instead of 2nd numerical differentiation of angle information. In addition, it can also measure the EMG signals synchronizing with motion capturing system or force plates.

To reconstruct dynamic human movements in real-time, a dynamics simulator is developed for the real-time 3D dynamic motion simulation of a whole body human musculo-skeletal system model. This model is constructed by 100 segments of born, 105 D.O.F., and 300 muscles which consist of damping, stiffness and generating contraction force.
To verify practical effectiveness of this system, one experiment is carried out which measure the acceleration of the human arm movement and derive the joint torques and then reconstruct the human movement. Finally, we apply this model into 3D virtual space of CAVE so as to interaction with real human.

2 3D Motion Capturing System

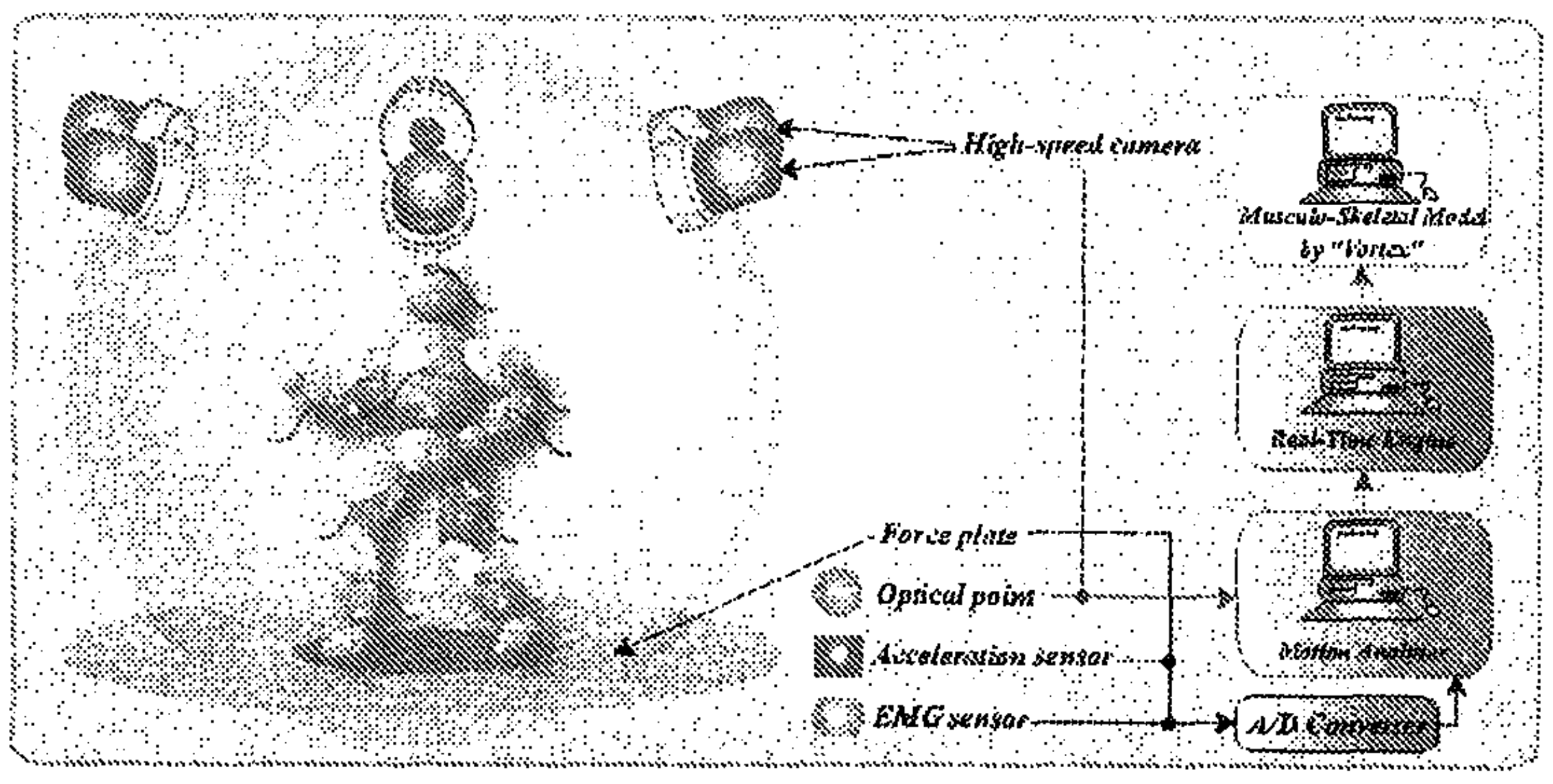

Figure 1: A 3D motion capturing system

The whole motion capturing system developed in this research is shown in Fig. 1. This system constructs of 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 are obtained approximately only by 2nd numerical differentiation of the measured position information, but there is a large numerical error in these results especially in quick 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 following section.

3 Dynamic Musculo-skeletal System Model

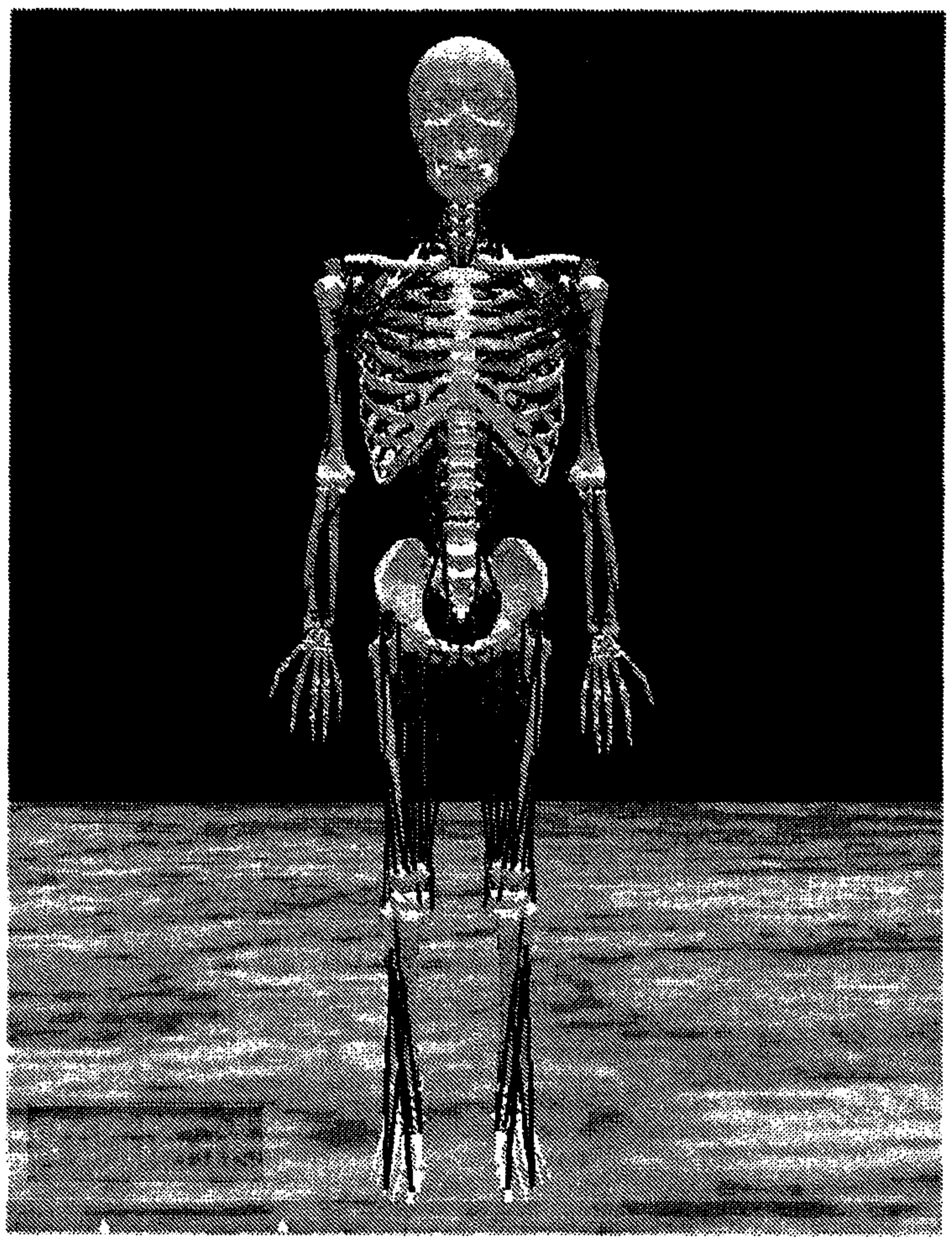

Figure 2: Whole body musculo-skeletal system

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" [3]. By input muscle forces, this simulator can easily calculate collision between each body parts as well as dynamic body movements within real time. In this musculo-skeletal model, bones of the whole body are classified into 100 segments. The total motion degrees of freedom of the whole body have 105 D.O.F., which connect each body segments and drive the joint motions. The detailed 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 but have linear actuator element, passive spring and dumping element. The present models only include main outer muscle and omitted the inner muscle.

4 Definition of Muscle's Via Point

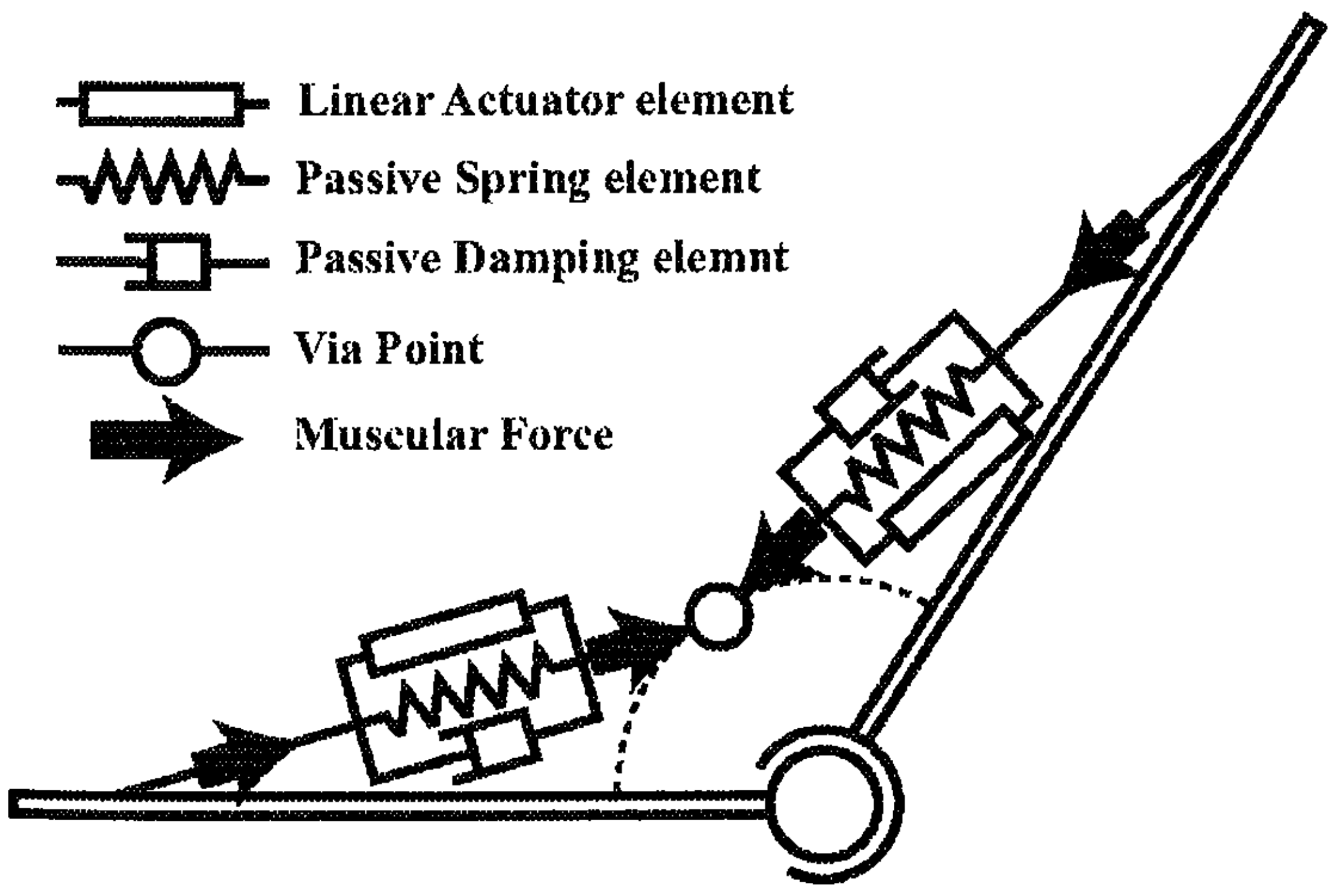

Figure 3: Definition of muscle's via point

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, then, reaches the insertion point of another segment, the muscle's via points should be defined 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.

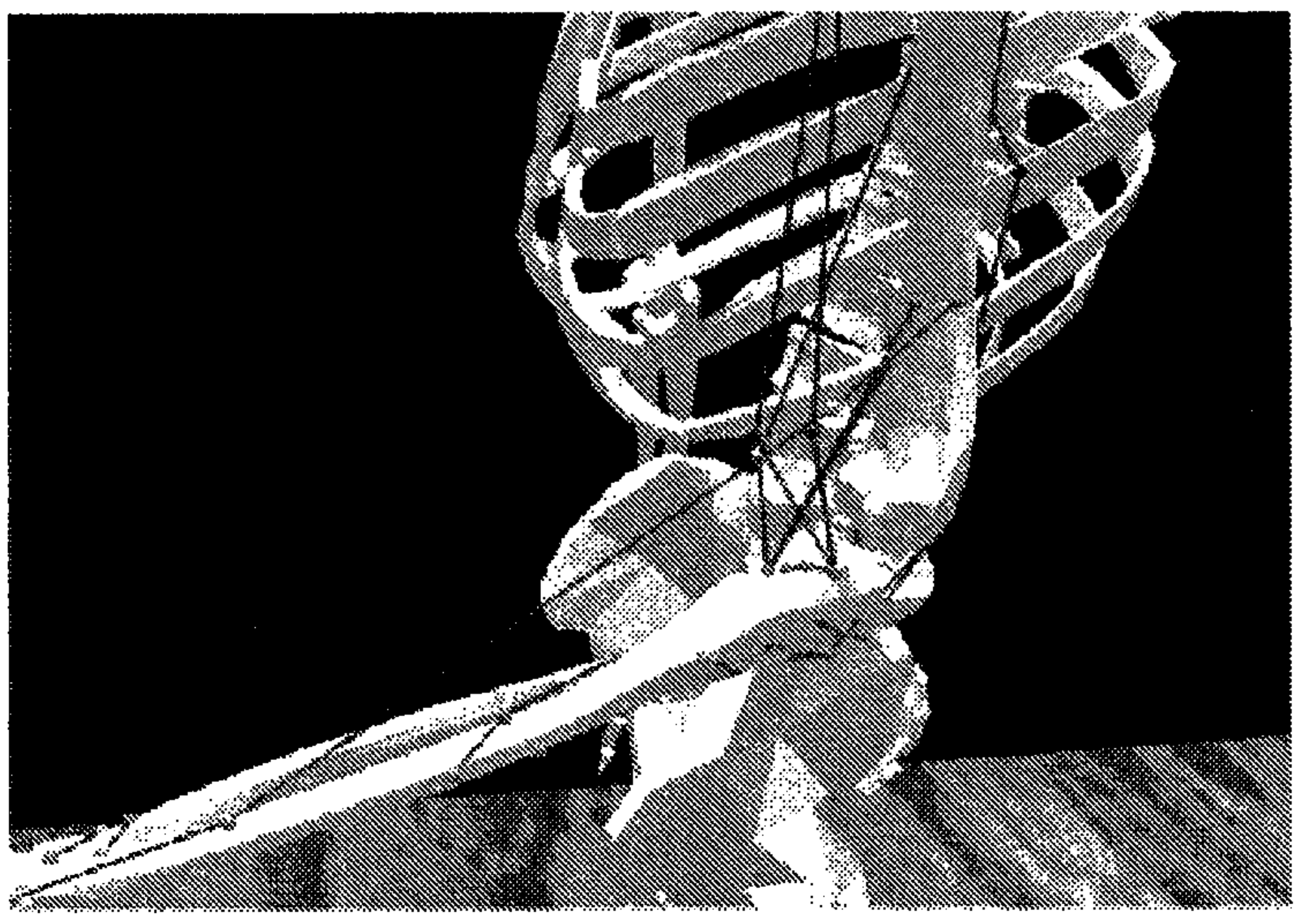

Figure 4: The left elbow joint which defined muscle's via points

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

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

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

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

$$\ddot{X} = -l_1 \dot{q}_1^2 \sin q_1 + l_1 \ddot{q}_1 \cos q_1$$

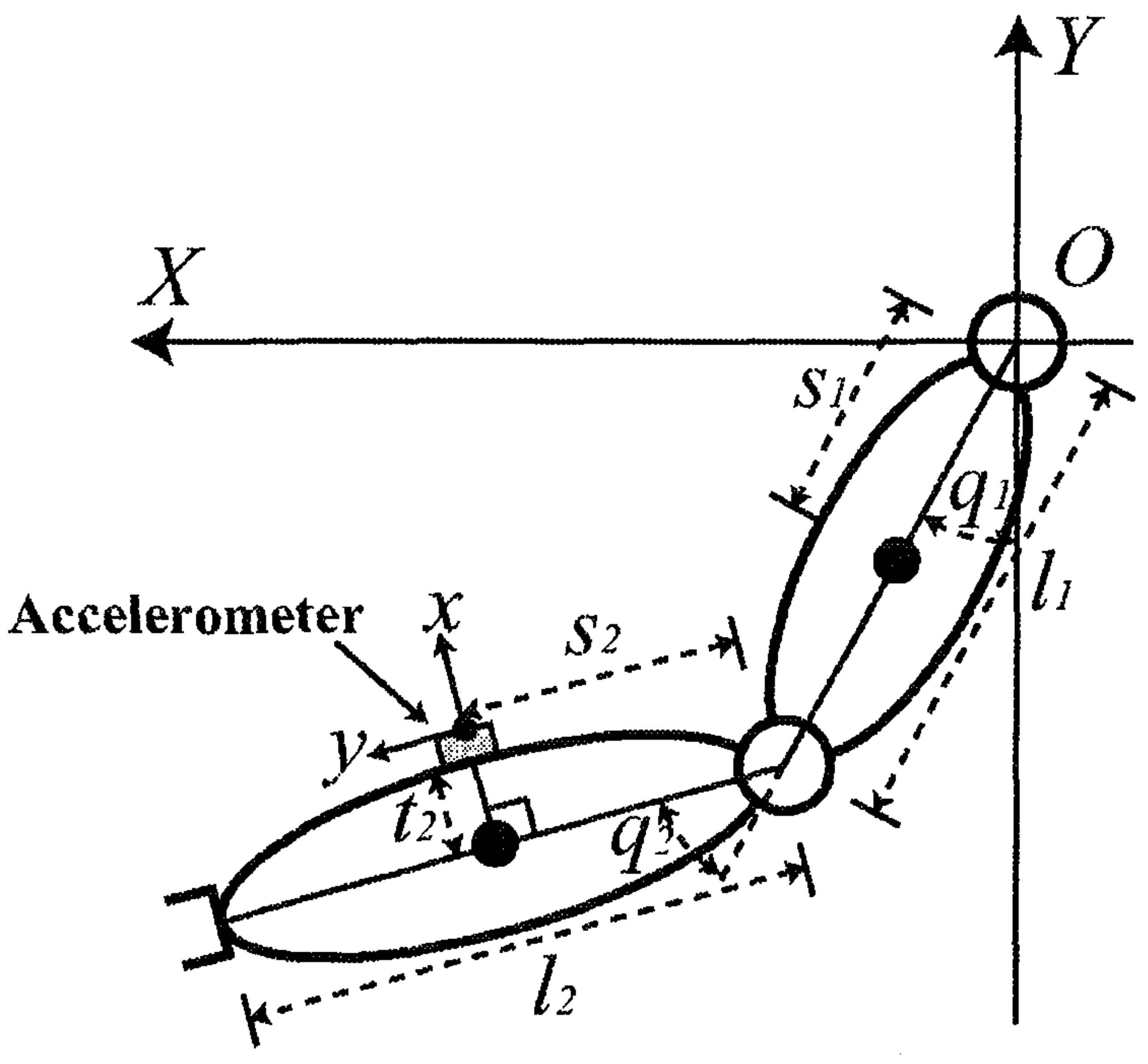

Figure 5: The coordination of 2-link arm

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

The information from accelerometer is transformed from the local sensor's frame to inertia frame as follows:

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

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 $\boldsymbol{R}(q,\ \dot{q}) \in \Re^{2\times2}$ is rotational matrix. Therefore, angular acceleration $\ddot{q} \in \Re^{2\times1}$ can be calculated by substituting eq. (3) for eq. (2) as follows:

$$\ddot{q} = \boldsymbol{Q}(q, \dot{q}, \ddot{x}, \ddot{y}) \tag{4}$$

In this equation, the detailed contents of $\boldsymbol{Q}$ are omitted due to space limitation. Here, the dynamics of this model are as follows:

$$\begin{aligned}
&\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\left(\frac{1}{2}\dot{\boldsymbol{H}}(\boldsymbol{q})+\boldsymbol{S}(\boldsymbol{q},\dot{\boldsymbol{q}})\right)\dot{\boldsymbol{q}}\\
&\qquad+\boldsymbol{C}\dot{\boldsymbol{q}}+\boldsymbol{G}(\boldsymbol{q})=\boldsymbol{\tau}
\end{aligned} \tag{5}$$

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 Coriori and centrifugal forces and it is known to be 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 $(\ddot{\boldsymbol{q}},\ \dot{\boldsymbol{q}},\ \boldsymbol{q}) \in \Re^{2\times1}$ into eq. (5).

5.1 Experimental Results

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

Table 1: Parameters

	1st Link	2nd Link
Length [m]	0.280	0.250
Center of Mass [m]	0.140	0.125
Mass [kg]	2.05	1.90
Damping [N·s]	3.0	3.0

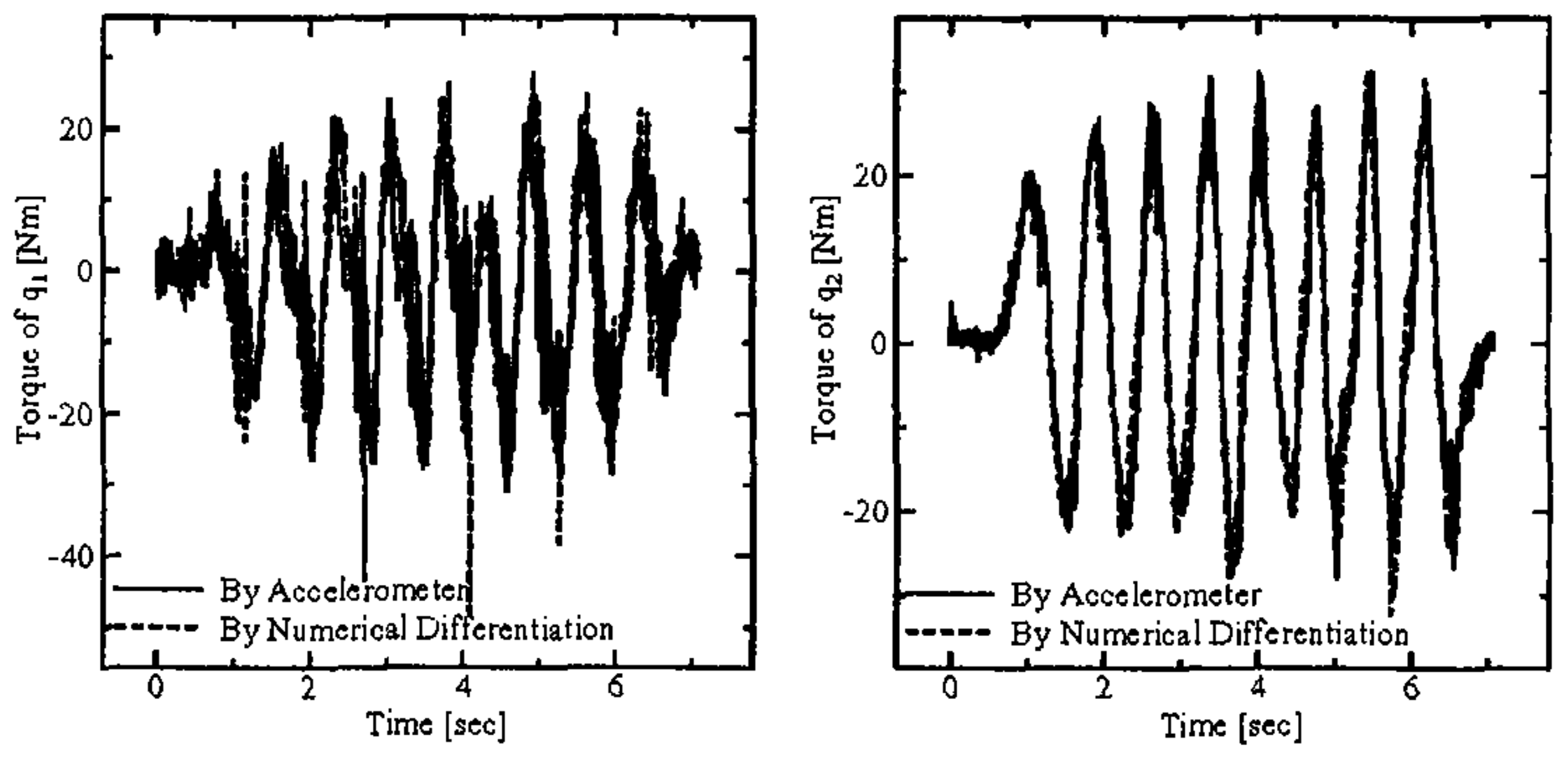

Figure 6: Comparison of joint torques in fast motion calculated from numerical differentiation and from measured acceleration

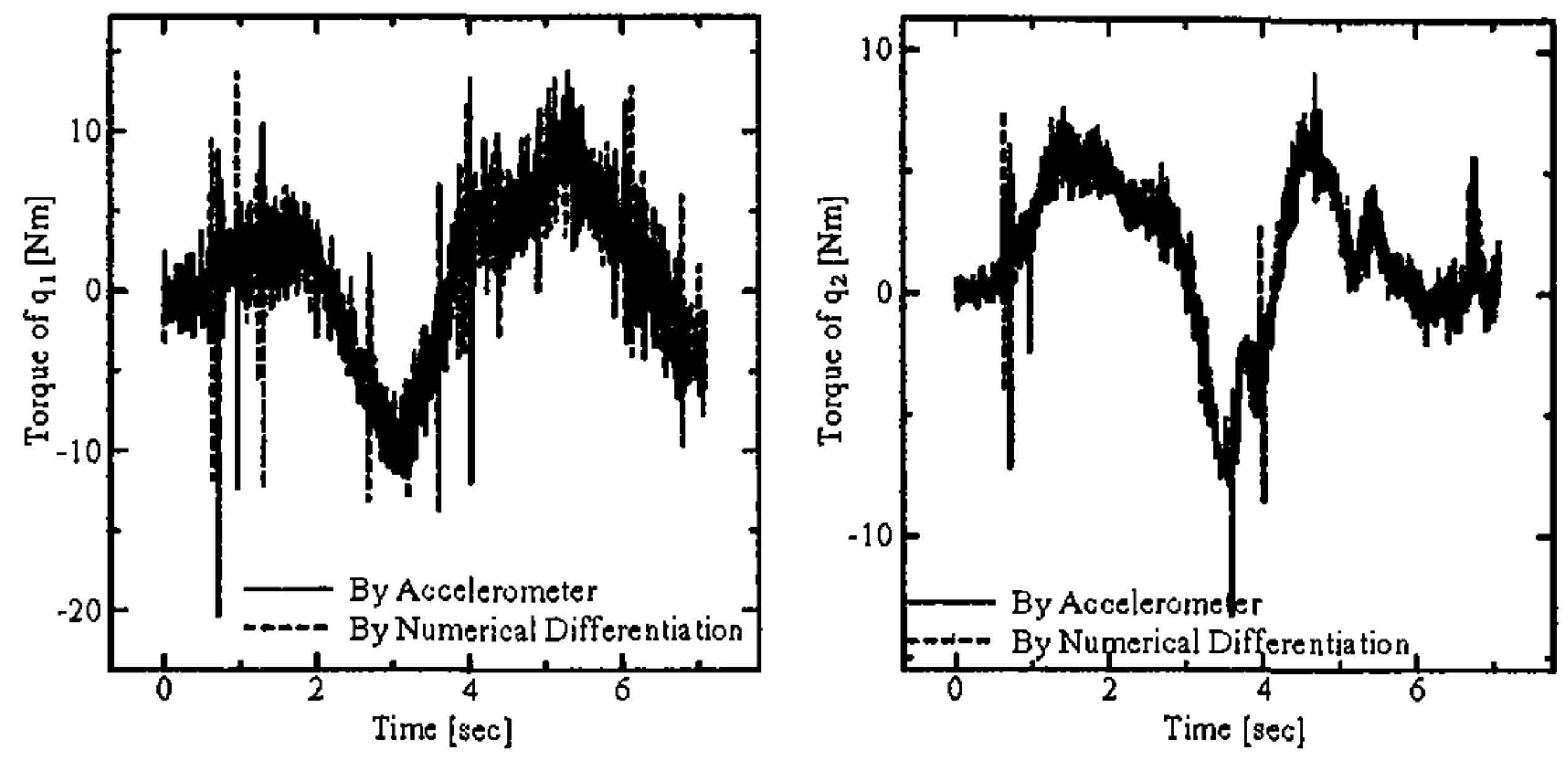

Figure 7: Comparison of joint torques in slow motion calculated from numerical differentiation and from measured acceleration

The blue line is the result of the numerical differentiation, while the red 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.

5.2 Reconstruction of Movement by Forward Dynamics

To confirm torques derived in previous section, we carried out the reconstruction of human arm movement by forward dynamics using derived torques from accelerometers. These results are shown in Fig. 8∼9. Fig. 8 shows a result in case of fast movement. In this figure, there are some errors in the 1_{st} link joint q_1 at first half, but at latter half, there is hardly error between the original and numerical integration and the 2_{nd} link joint angle, too. Fig. 9 shows a result in case of slow movement. In this figure, although there are some errors, it can confirm drawing the almost same trajectory both q_1 and q_2.

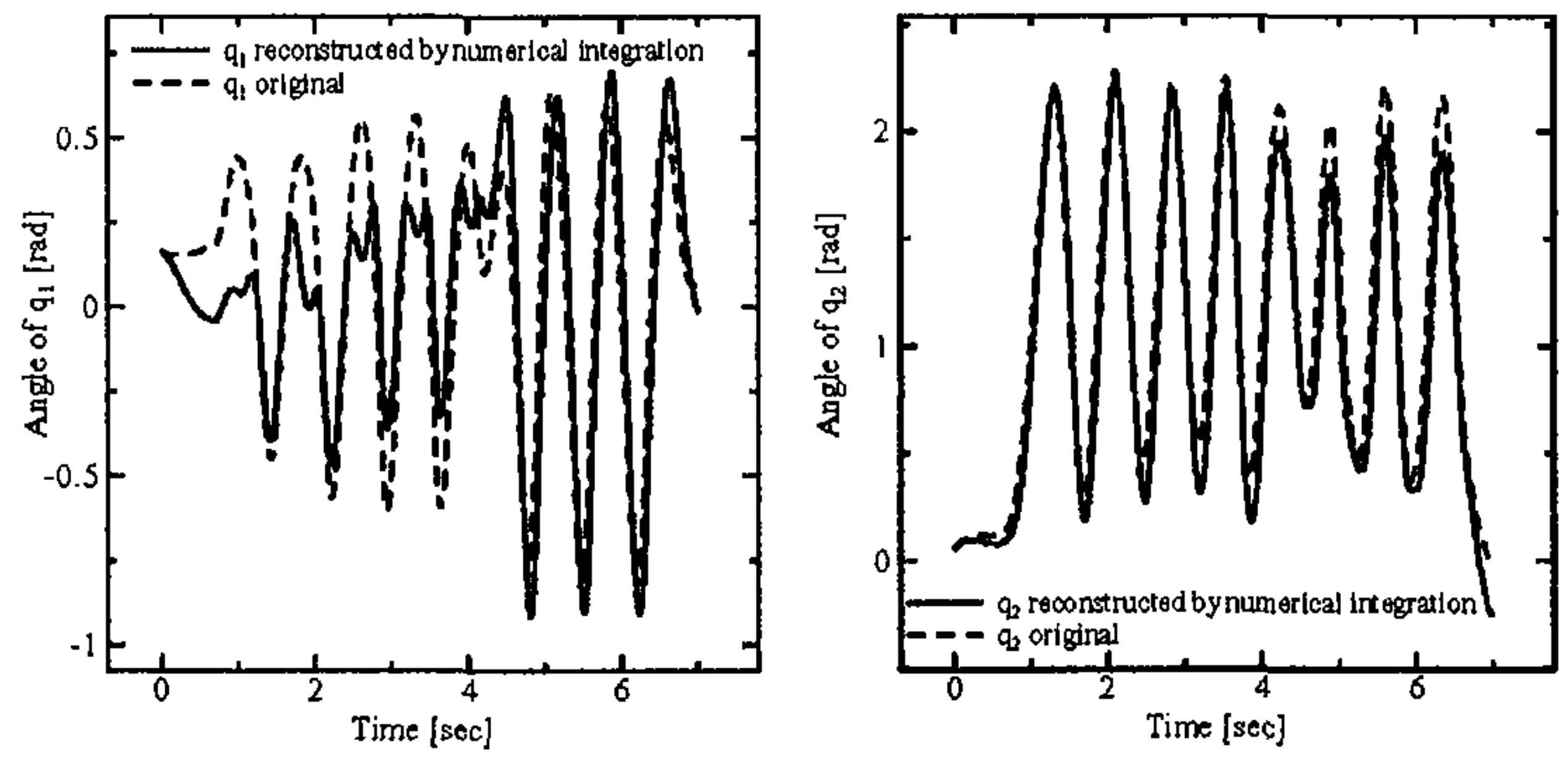

Figure 8: Reconstruction of a fast movement by numerical integration

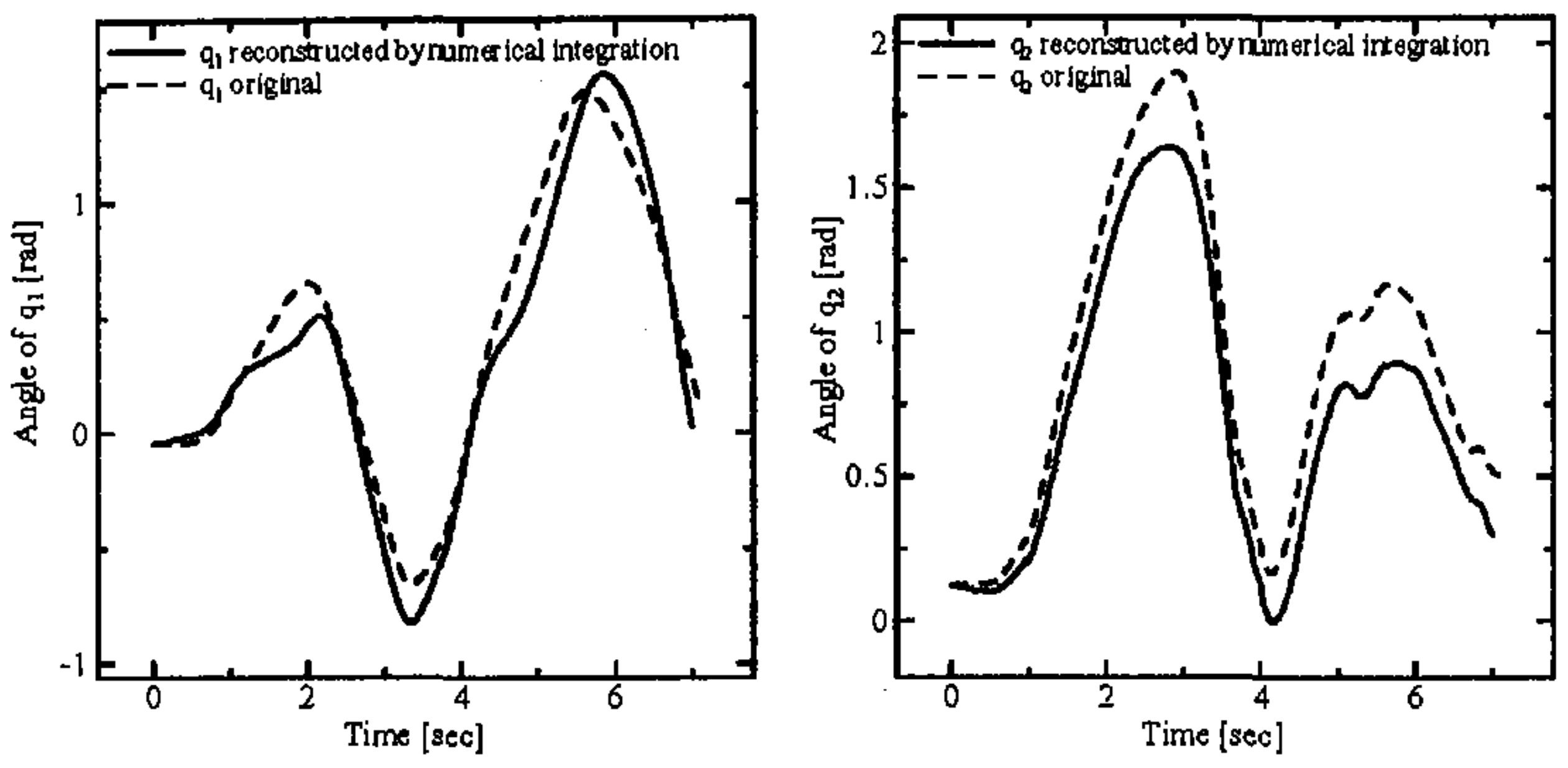

Figure 9: Reconstruction of a slow movement by numerical integration

6 Interaction within a 3D VR Space

In this section, we propose and attempt to apply our musculo-skeletal model into a 3D virtual space of CAVE [4] so as it interacts with real human at real time. This immersion type VR system consists of parallel graphic processing PC units, four sheets of surrounding screen (left, right, front and under), auditory effect generator by using 8 speakers and some position sensors to recognize the position of human head and hands. In addition, physical interaction between a human and a robot can perform in this system. This immersion display system makes it possible to perform various interactive experiments between a human and such robot in various situation as shown in Figs. 10 ∼ 11.

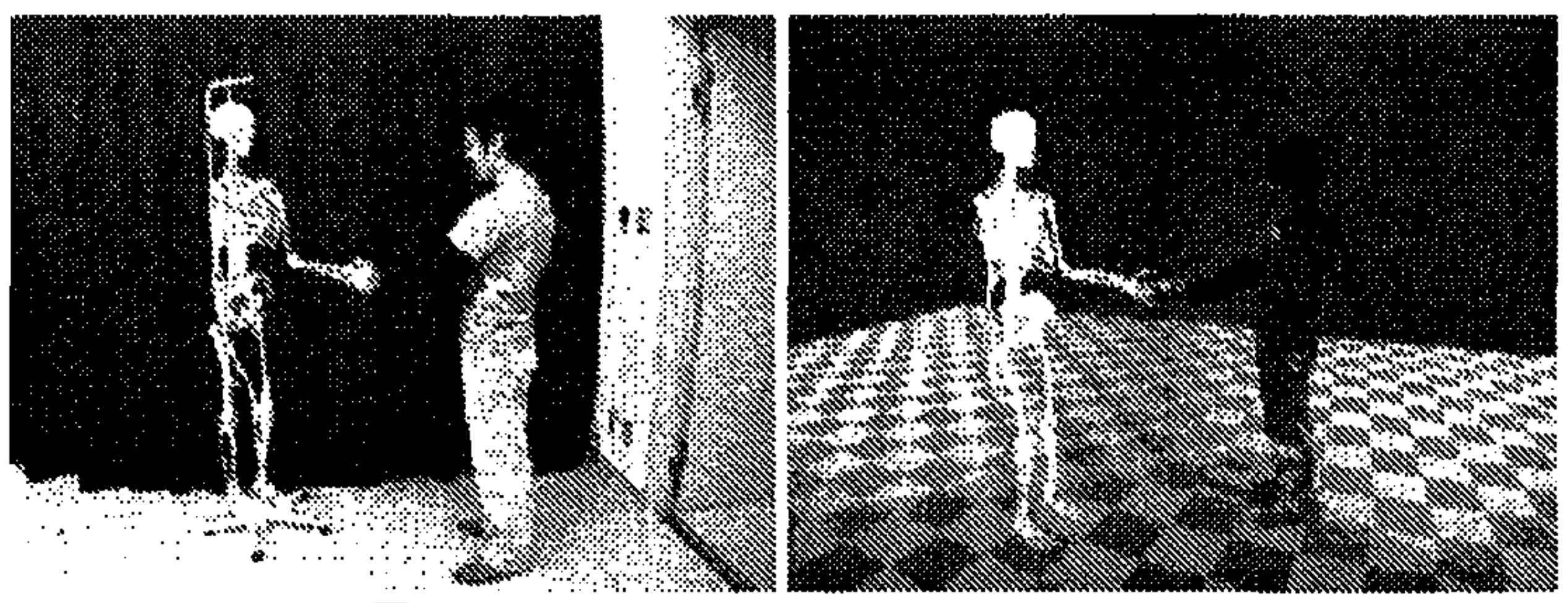

Figure 10: Human interactions

In these figs., a human subject interacts with musculo-skeletal model physically.

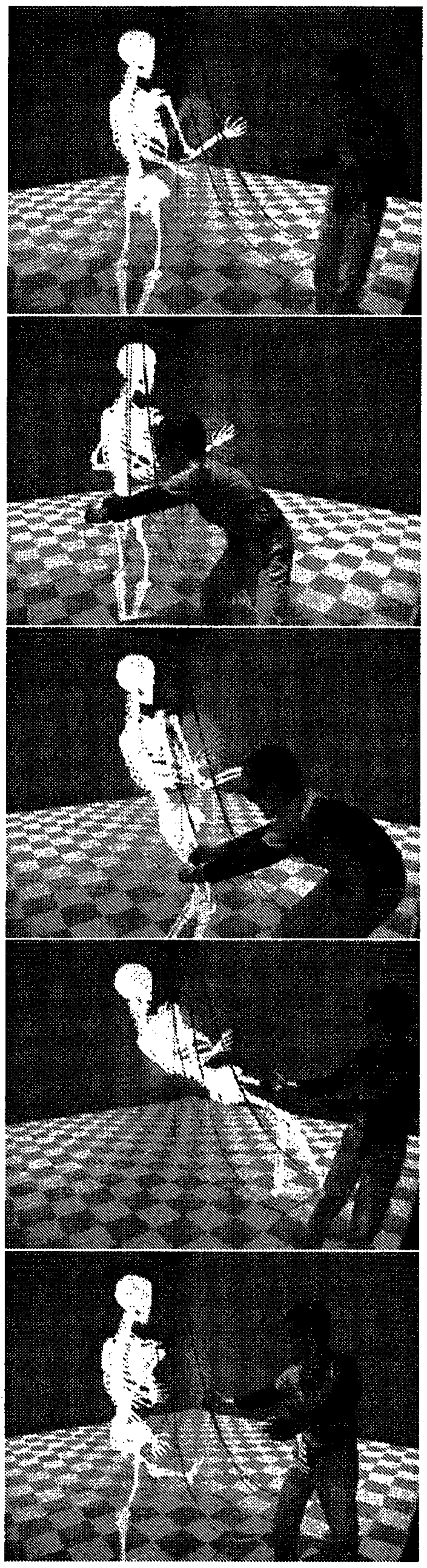

Figure 11: The interaction between real human and musculo-skeletal model in 3D VR space

7 Conclusions

A dynamic human motion simulator that uses dynamic motion capturing system including accelerometers is developed and human subject interacts with musculo-skeletal model in terms of physical dynamics within immersion 3D VR space. Accelerometers may increase the accuracy when calculating the human joint torques. In the future, we will take into account of the information of myoelectric activity and approach a redundancy problem between a muscle space and joint space from the point of view of mechanical impedance. 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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