Analysis of Human Arm Movement During Vehicle Steering Maneuver

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The analysis of human arm motion during steering maneuver is carried out for investigation of man-machine interface of driver and steering system Each arm is modeled as interconnection of upper arm, lower arm, and hand by rotational joints that can properly represents permissible joint motion, and both arms are connected to a steering wheel through spring and damper at the contact points. The joint motion law during steering motion is determined through the measurement of each arm movement, and subsequent inverse kinematic analysis. Combining the joint motion law and inverse dynamic analysis, joint stiffness of arm is estimated. Arm dynamic analysis model for steering maneuver is setup, and is validated through the comparison with experimentally measured data, which shows relatively good agreement. To demonstrate the usefulness of the arm model, it is applied to study the effect of steering column angle on the steering motion.

Key Words : Steering Motion, Multibody Dynamics, Joint Motion Law, Muscular-Skeletal Motor Action, Man-Machine Interface

1. Introduction

Steering motion for controlling vehicle motion is a typical man-machine system between the driver and vehicle. Recently, active researches have been done for developing advanced steering systems, such as speed sensitive steering systems, steering by wire systems, etc. However, these efforts are mainly focused on the design of electric and/or mechanical hardware and control logic, not much emphasis on the human driver. Any steering system designed without considering man-machine interface can hardly be driver friendly, which is very important factor for the safety of vehicle.

Man-machine interaction during steering maneuver is initiated with information from in-vehicle instruments and environments. The driver senses and analyzes this information, and determines actions to take. Once the decision is made, muscular-skeletal motor action of arms to control the steering wheel is carried out to achieve desired vehicle motion. Thus, the basic task to model human arm motion is how to represent muscular-skeletal motion of human arm.

Morasso and Mussa-Ivaldi (1986) assumed human arm as a manipulator consisting of rigid bodies, multi-joints and biological actuators. Although muscle forces are inherently non linear, they assumed that muscle forces can be regarded as linear when muscle displacements are small. Then the relationship between the force at hand

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F and small hand displacement **X** can be given as

$$\mathbf{F}=\mathbf{KX} \quad (1)$$

where **K** is the task stiffness of hand. The stiffness of hand can be transformed into the stiffness at the joint, $\mathbf{K}_J$, once the Jacobian of arm $\mathbf{J}_A$ is known.

$$\mathbf{K}_J=\mathbf{J}_A^T\mathbf{K}\mathbf{J}_A \quad (2)$$

Perreault et al. (1996) also performed study on the stiffness of arm in 2-dimensional space based on the linear relationship assumption between arm force and displacement. They represented human arm as a MIMO (Multiple-Iinput Multiple-Output) system with force as input and displacement as output, and divided the MIMO into several SISO (Single-Input Single-Output) subsystems to find the relationship between force and displacement for each SISO. Park (1999), in his effort to investigate the phenomenon of stepping away from the brake pedal in reaction to sudden brake vibration when an anti-lock brake system is activated, carried out study on estimating leg motion stiffness in two dimensional space.

In order to setup a mathematical model for dynamic analysis of steering maneuver, torque at each joint should be known. If a joint torque is assumed to be proportional to a joint displacement with joint stiffness as the proportional coefficient, then joint stiffness can be calculated once joint torque and displacement are known through some measurements and inverse dynamic analysis.

Since arm joints have redundant degrees of freedom, the displacement at each joint cannot be determined analytically. Thus, experiments have to be performed to find joint motion law that determines the relationship between hand movement and corresponding joint displacements. For this purpose, sensors that can pick up three dimensional locations and orientations of upper and lower arms during steering maneuver are used. Once the joint motion law has been established, the stiffness of hand during steering can be transformed into joint stiffness as Eq. (2). The process of finding joint motion law, and setting up the equations of motion require considerable amount of computing task. In this study, LifeMOD, which is a biomechanical analysis software, is used for kinematic, dynamic, and inverse dynamic analysis of human arm motion.

2. Arm Modeling

In order to analyze arm motion, mass properties of arms, such as mass, mass center location, inertia for each arm segment, as shown in Fig. 1, have to be known. Since the mass properties of arm depend on age, sex, and many other factors, LifeMOD provides anthropometric data base that can estimate mass properties of every arm segment depending on basic data of sex, age, height, body weight, and body specific data of arm length, sitting height, shoulder width. Table 1 shows the mass properties of the test driver, who is 177 cm, 71 Kg, and age of 28.

In general, joint of arm can have 3 degrees of freedom, flexion-extension, abduction-adduction, internal-external rotation. As shown in Fig. 1, x-y-z axis system is attached to each joint to represent axis of rotation. Each arm has 3 joints, shoulder, elbow, and wrist, and if every joint has 3 degrees of freedom, the total degrees of freedom is 9. However, since the internal-external rotation of wrist and abduction-adduction of elbow is hardly possible, these two joint rotations are not allowed. Fig. 2 shows standing position of the driver, and Fig. 3 shows sitting position for steering maneuver, and Table 2 shows x-y-z

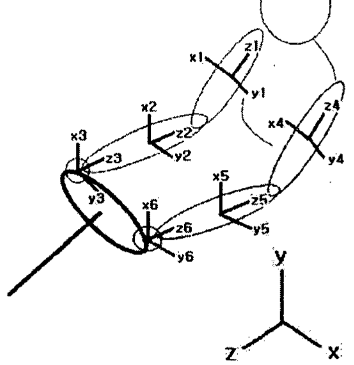

Fig. 1 Driver and coordinates of arm

Table 1 Right arm's mass properties of test driver

		Shoulder	Upper arm	Lower arm	Hand
Location (mm)	x	−8.582E+002	−9.224E+002	−9.224E+002	−9.224E+002
	y	8.982E+002	8.064E+002	7.151E+002	7.151E+002
	z	−1.109E+003	−1.317E+003	−1.098E+003	−8.949E+002
Orientation (degree)	z	180	180	90	90
	x	90	135	180	180
	z	90	90	0	0
Mass (kg)		2.019	1.807	1.440	0.419
Inertia (kg-mm^2)	Ixx	6.661E+003	1.232E+004	9.064E+003	4.648E+002
	Iyy	3.217E+003	1.232E+004	9.064E+003	4.648E+002
	Izz	6.661E+003	1.621E+003	1.069E+003	2.526E+002

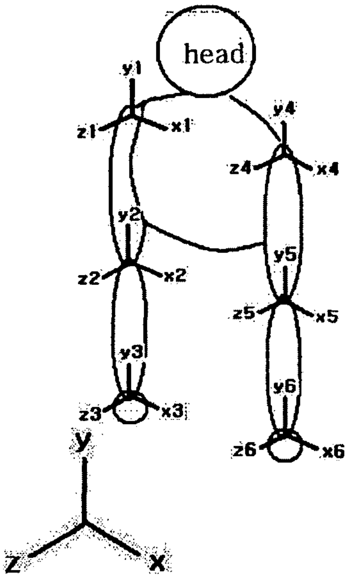

Fig. 2 Arm joint coordinate in standing

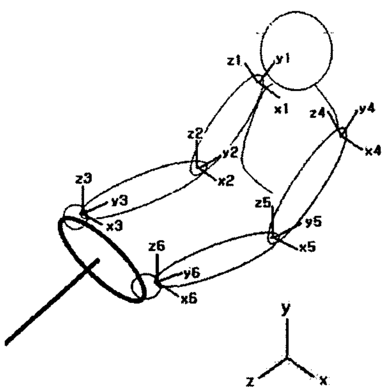

Fig. 3 Arm joint coordinate in driving

Table 2 Arm joint angle in driving posture a standard of joint coordinates

[degree]

		X	Y	Z
Right Arm	Shoulder	−45.0	0.0	0.0
	Elbow	−45.0	0.0	0.0
	Wirst	0.0	0.0	0.0
Left Arm	Shoulder	−45.0	0.0	0.0
	Elbow	−45.0	0.0	0.0
	Wrist	0.0	0.0	0.0

rotation angles for each joint at driving posture.

3. Joint Motion Law and Estimation of Joint Stiffness

The joint motion law that describes the relationship between the steering motion and joint displacement should be determined. As shown in Fig. 4(a), two sensors that can pick up 3-dimensional position $\mathbf{r}(t)$ and orientation $\boldsymbol{\phi}(t)$, are attached to upper and lower arm, and measurements are carried out during steering wheel rotation of $\pm 15°$ with rotational speed of 8.3°/sec. To guarantee constant steering motion for each measurements, more than 20 times of steering wheel turning exercises have been done before the actual measurements of 5 times, which are averaged. Steering wheel torque $\boldsymbol{\tau}_{sw}$ is also recorded for later use.

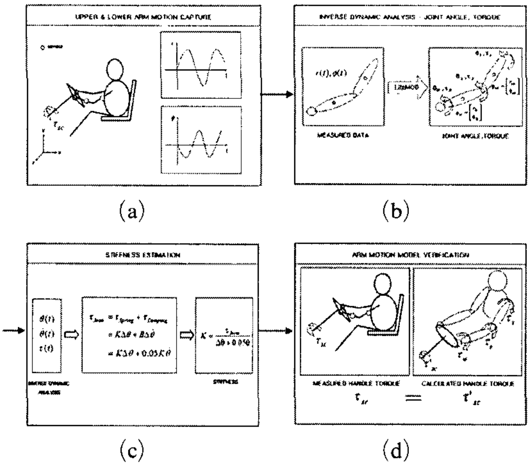

Fig. 4 Steering motion analysis procedure

The upper and lower arm position $\mathbf{r}(t)$ and orientation $\boldsymbol{\phi}(t)$ are put into lifeMOD. Then through inverse kinematic analysis, as shown in Fig. 4(b), joint angular displacements $\boldsymbol{\theta}(t)$, and angular velocities $\dot{\boldsymbol{\theta}}(t)$, and angular accelerations $\ddot{\boldsymbol{\theta}}(t)$ can be computed, which determines the joint motion law during steering motion.

Biologically, muscle motion is a very complicated process, however, for analysis purpose, muscle force can be regarded as a simple spring element where muscle force is proportional to muscle displacement. Flash (1987) and Won (1993) proposed that joint torque be represented as rotational spring and damper,

$$\tau = \mathbf{K}\boldsymbol{\theta} + \mathbf{B}\dot{\boldsymbol{\theta}} \tag{3}$$

where $\mathbf{K}$ and $\mathbf{B}$ are joint stiffness and damping coefficient, respectively, and $\boldsymbol{\theta}$ are joint angles. Also Flash (1987) and Won (1993) assumed that the relationship between $\mathbf{K}$ and $\mathbf{B}$ can be given as $\mathbf{B} = \boldsymbol{\alpha}\mathbf{K}$, and the value of $\boldsymbol{\alpha} = 0.05$ is applicable to general arm joint motion. Applying these relationship gives

$$\boldsymbol{\tau} = \mathbf{K}\boldsymbol{\theta} + \mathbf{B}\dot{\boldsymbol{\theta}} = \mathbf{K}\boldsymbol{\theta} + 0.05\mathbf{K}\dot{\boldsymbol{\theta}} \tag{4}$$

Eq. (4) can be solved for joint stiffness $\mathbf{K}$ as

$$\mathbf{K} = \boldsymbol{\tau}(\boldsymbol{\theta} + 0.05\dot{\boldsymbol{\theta}})^{-1} \tag{5}$$

Once the joint displacements and angular velocities and joint torques are known, joint stiffness can be calculated according to Eq. (5).

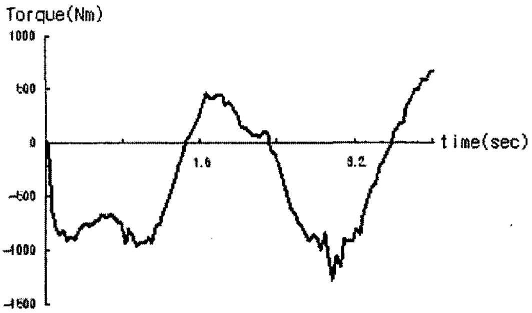

Fig. 5 Torque of wrist flexion-extension motion

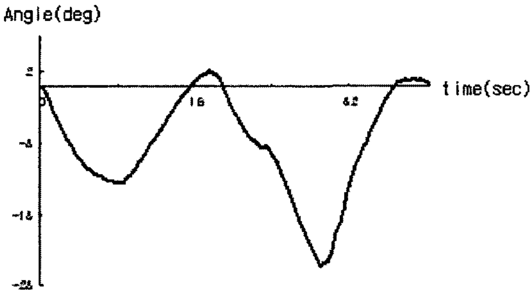

Fig. 6 Angle of wrist flexion-extension motion

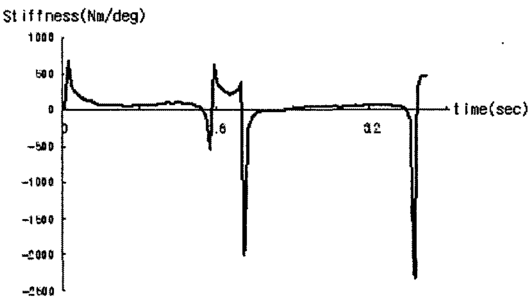

Fig. 7 Stiffness of wrist flexion-extension motion

Figs. 5 and 6 respectively shows right wrist flexion-extension torque and rotation angles, and Fig. 7 represents wrist joint stiffness calculated by Eq. (5). In the Fig. 7, severe change of joint stiffness is observed, which is due to the fact that as the wrist angle becomes 0, stiffness becomes very large since stiffness is obtained through division by very small number. Joint stiffness for relatively constant value ranges in Fig. 7 is chosen. Table 3 shows joint stiffness of each joint. Wrist flexion-extension and shoulder internal-external rotation motions have the largest joint stiffness.

Table 3 Arm joint stiffness (unit : Nm/deg)

	Shoulder	Elbow	Wrist
X-axis Joint	4.73	5.56	48.13
Y-axis Joint	0.587	5.14	—
Z-axis Joint	64.4	—	0.308

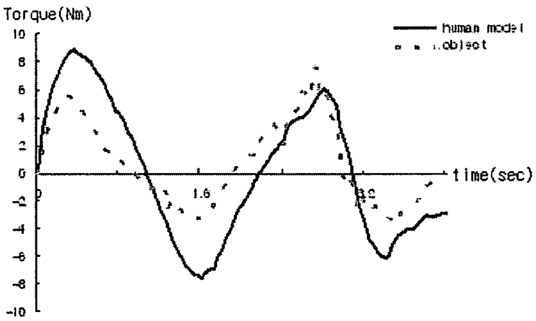

Fig. 8 Comparison of steering torque

Now that joint stiffness is known, joint torques can be generated as Eq. (4) as a function of joint angel and joint angular velocity. With the known mass properties of arm segments, the dynamic equations of arm motion can be setup. To validate the dynamic model of arm, simulation is carried out for the same steering motion as determining the joint motion law, where steering wheel is rotated ±15° with rotational speed of 8.3°/sec. Fig. 8 shows the comparison of steering wheel torques from the simulation and measurement. Even though there is some difference in magnitude due to the inherent errors in motion measurements, estimation of joint stiffness, and mass properties of arms, the tendency of two torque plots show relatively good agreements.

4. Application of Arm Model

As an application of the arm model, the effect of steering wheel column angle on the arm motion during steering maneuver is to be studied. As shown in Fig. 9, steering column angels of 30°, 45°, 60° are considered, and external steering wheel torque, shown in Fig. 10, is applied. The torque at each joint is to be computed using the arm dynamic model.

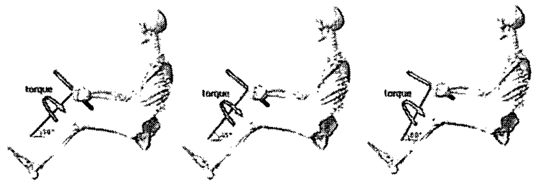

Fig. 9 Driver's posture with steering column angles 30°, 45°, 60°

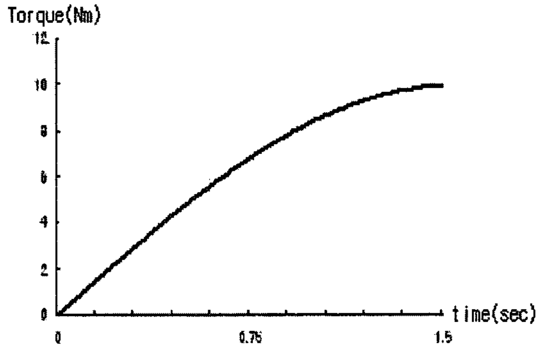

Fig. 10 Torque in handle

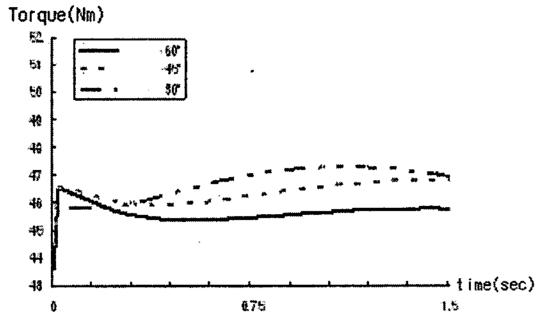

Fig. 11 Joint torque of right shoulder x-axis joint

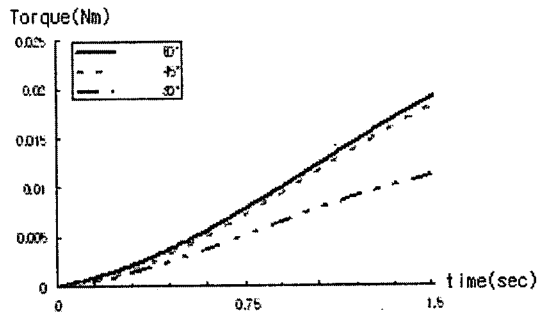

Fig. 12 Joint torque of right shoulder y-axis joint

Joint torques of the right arm are shown in Figs. 11-17. The plots show that the magnitude of

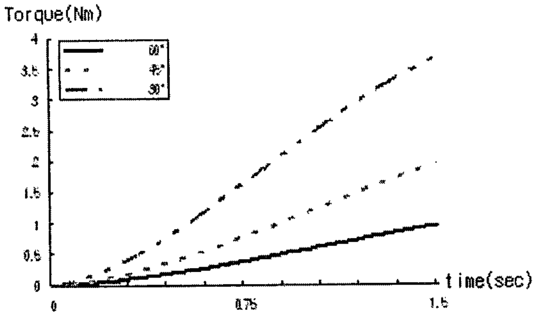

Fig. 13 Joint torque of right shoulder z-axis joint

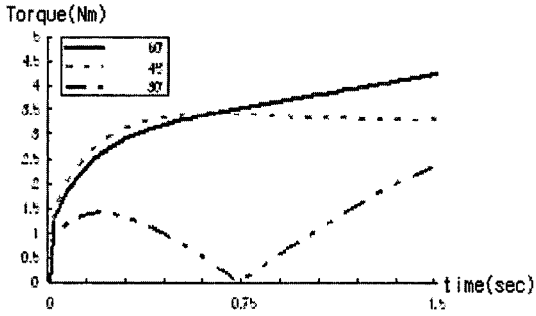

Fig. 16 Joint torque of right wrist x-axis joint

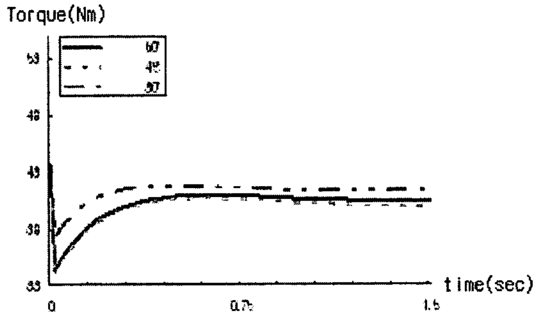

Fig. 14 Joint torque of right elbow x-axis joint

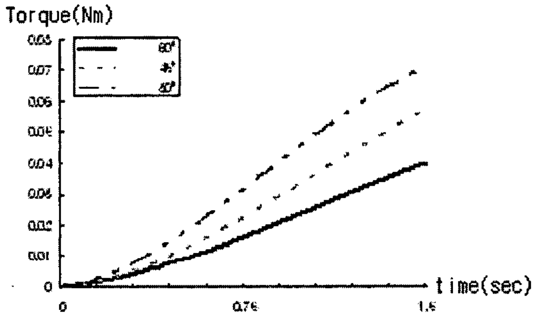

Fig. 17 Joint torque of right elbow z-axis joint

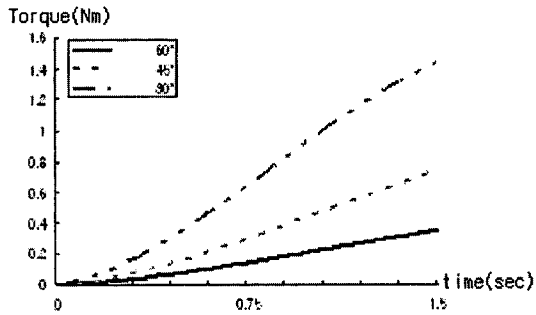

Fig. 15 Joint torque of right elbow y-axis joint

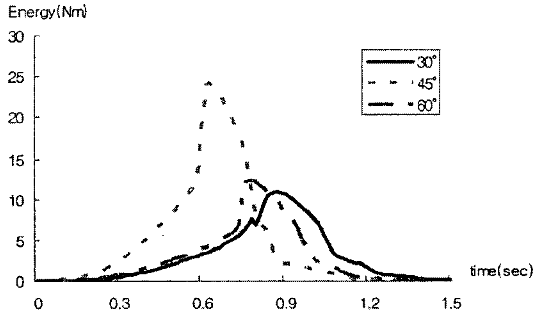

Fig. 18 Kinetic energy of upper arm

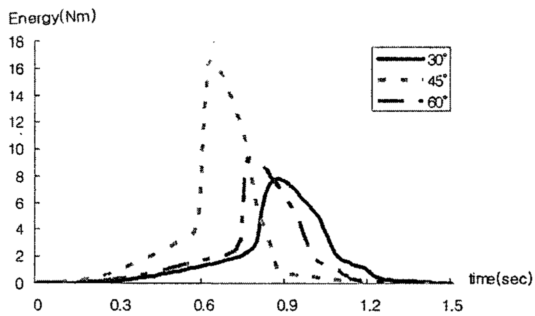

Fig. 19 Kinetic energy of lower arm

joint torques as a function of the steering wheel column angles. Joint torque of shoulder x-axis motion, as shown in Fig. 11, and joint torque at elbow x-axis motion, as shown in Fig. 14, have larger values compared to other joint torques.

In Fig. 16, it is observed that when the steering column angle is 30°, the wrist flexion-extension torque becomes 0, which is due to the change of direction from flexion to extension, and would give driver uncomfortable feeling. Figs. 18-21 respectively represents the kinetic energy of the

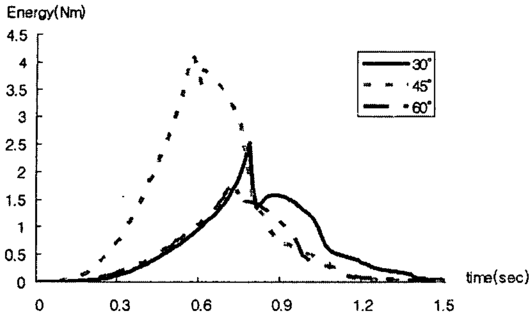

Fig. 20 Kinetic energy of hand

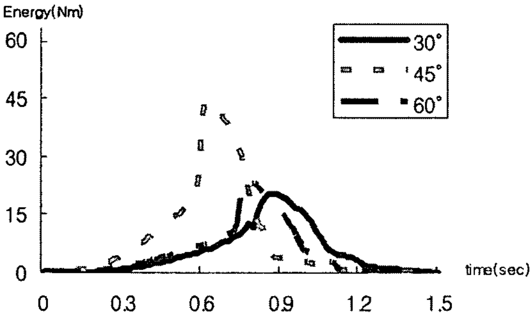

Fig. 21 Total kinetic energy of arm

Table 4 Work done by arm

[N-mm]

	30°	45°	60°
Shoulder x-axis	576.99	619	519.07
Shoulder y-axis	36.74	48.81	32.51
Shoulder z-axis	5170	4420	4050
Elbow x-axis	30913.32	29031.33	227.97
Elbow y-axis	285.72	369.12	255.93
Wrist x-axis	259.39	1030	51.1
Wrist z-axis	3360	8020	2020
sum	40602.16	39560.26	7156.51

upper arm, lower arm, hand, and the total kinetic energy. When the steering column angle is 45°, the kinetic energy is the biggest, which implies that the joint velocity is highes, and it is relatibely easy to turn the wheel.

In Table 4, work done by joints of arm and the total work are computed. The larger the amount of work is, the harder to perform the steering operation. In Table 7, when the steering column angle is 30°, the total work done is the greatest, and when the steering column angle is 60°, the work done is the smallest. Also from Table 7, it is shown that shoulder flexion-extension, abduction-adduction, 3 rotations of elbow, and wrist flexion-extension motion do the relatively large amount of work depending on the steering column angle.

5. Conclusions

The research can be summarized as follows. The human arm mass properties are estimated through anthropometric data base in LifeMOD. The joint motion law during steering motion is determined by measurement of upper and lower arm motion and by subsequent inverse kinematic analysis. Once joint motion law is determined, joint torques of arm joint is calculated through inverse dynamic analysis. Using the known values of joint angles and torques, joint stiffness of arm joint can be assessed based on the linear relationship between joint displacement and torque. The joint stiffness enables modeling of joint torque generating mechanism during steering motion, thus the equations of motion for arm movement can be setup.

Arm dynamic model is applied to investigate the effect of steering wheel column angle on the steering motion. Joint torques are calculated, and kinetic energy of each arm segments and work done by each joint is computed. Comparison in joint torque, kinetic energy, and work done by joint, does not show any consistent indication that which steering column angle is better for human driver. That is mainly due to the lack of information on the relationship between the physical quantities of arm motion, such as torque and displacement, and human perception in steering motion, which will be the major research area for further knowledge of man-machine interface during steering motion.

Acknowledgment

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