A STUDY ON THE BEHAVIOR ANALYSIS OF HUMAN RIGHT ARM UNDER IMPACT CONDITION

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1 General Introduction

In this study, the behavior analysis of human right arm under impact condition was performed by creating the human model of Korean young men and both the impact force and the applied load of the specific joint through a simulation of occurred condition with hammering impact was obtained. The right arm was modeled by muscle-skeleton elements to obtain the behavior of right arm of human under impact condition, where physical and geometrical properties of human body such as Young's modulus, shear modulus, cross sectional area, length, density, moment of inertia and position were defined. Based on the numerical model of the right arm, the impact response of the right arm was obtained. By the comparison with the experimental results, the model of the right arm was verified.

The behavior of human right arm under impact condition is affected by the characteristic of the human muscle-skeleton model. The behavior of human right arm affects the further research activity in biomechanics and survivability study. The impact by hammering is transferred to the segment of the human right arm. The finite element model and the analysis method were needed to analyze and compare with experimental results.

2 Characteristics of Analytical Model

2.1 Biomechanical Model of Human Right Arm

The biomechanical model is based on the finite element method to the different aspects of biomechanical human body movement, which is kinematical and dynamical analysis of spatial movements of human body. The characteristics of human muscles are determined by the sensitivity analysis method. [1-4]

Table 1. Physical condition of Korean young men

<table>
<thead>
<tr>
<th>Model</th>
<th>Stature (cm)</th>
<th>Weight (kg)</th>
<th>Forearm (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical</td>
<td>174</td>
<td>70</td>
<td>32</td>
</tr>
<tr>
<td>Experimental</td>
<td>174</td>
<td>70</td>
<td>32</td>
</tr>
<tr>
<td>Size Korea</td>
<td>174</td>
<td>69</td>
<td>33</td>
</tr>
</tbody>
</table>

In this study, physical condition of basic model of 50 percentile Korean young men is referred to the report of Size Korea 2005 [5] as Table 1. In case of human modeling for operating the maintenance tool and shooting the small arms, perpendicular posture of forearm and upper arm is modeled basically [6]. Forearm is horizontal and upper arm is vertical as Fig. 1.
2.2 Kinematics and Dynamics

Kinematics is described as follows. The major equation of generalized displacement \( \{ \Delta \} \) of skeleton-muscle system depends on static application of forces \( \{ P \} \)

\[
[K] \cdot \{ \Delta \} = \{ P \} \tag{1}
\]

Where, \([K]\) is a global matrix of system stiffness, \(\{ \Delta \}\) is a generalized displacements vector and \(\{ P \}\) is a generalized external forces vector. The elements of the global stiffness matrix \([K]\) are calculated by common rules of the finite element method and can be represented as;

\[
K = \sum_{e=1}^{n} \tilde{k}_{ij}^{e} \tag{2}
\]

Where, \(k_{ij}^{e}\) is elements of local stiffness matrix oriented in global coordinate system, \(i\) and \(j\) are the numbers of generalized displacements in local system, and \(n\) is the number of finite elements.

![Fig. 2. Rod element and degree of freedom of node of human body](image)

The structural mechanical displacements of bar elements are represented in Fig. 2.

Connection between local stiffness matrix of bar element and arbitrary oriented in global \(X\ Y\ Z\) stiffness matrix of the same element in local \(x\ y\ z\ [k']\) is carried out by way of guide cosine matrix \([L]\). And \([L]\) is matrix of direction cosines.

\[
[k'] = [L]^T [k'] [L] \tag{3}
\]

where,

\[
[L] = \begin{bmatrix}
[\{l\}] & 0 & 0 & 0 \\
0 & [\{l\}] & 0 & 0 \\
0 & 0 & [\{l\}] & 0 \\
0 & 0 & 0 & [\{l\}]
\end{bmatrix}, [l] = \begin{bmatrix}
l_{xX} & l_{xY} & l_{xZ} \\
l_{yX} & l_{yY} & l_{yZ} \\
l_{zX} & l_{zY} & l_{zZ}
\end{bmatrix} \tag{4}
\]

Each element of local stiffness matrix \(k'_{ij}\) represents a force or reaction appearing in \(i\) direction for unit displacement along \(j\) direction. Full stiffness matrix is are represented in Fig. 3

![Fig. 3. Stiffness matrix considering force N](image)

Where, \(L\) is length of element, \(E\) and \(G\) are modulus of elasticity and rigidity, \(F\) is an area of cross-section, \(J_{o}\) is polar moment of inertia, \(J_{1}\) and \(J_{2}\) are inertia moments of elements on cross-section area about main central axis. Moment of human right arm is described by the following equation.

\[
[M][\Delta_{t+\delta t}] + [H][\Delta_{t+\delta t}] + [K][\Delta_{t+\delta t}] = \{ P_{t+\delta t} \} \tag{5}
\]

Where, \([H]\) is a dissipation matrix in terms of experimental coefficients \(\alpha\) and \(\beta\) as follows;

\[
[H] = \alpha[K] + \beta[M] \tag{6}
\]
If experimental data is absent, \([H]\) is described by the following equation, approximately according to Arsenev et al. [7],

\[
[H] = 0.15 \cdot 4\pi \nu [M] \quad (7)
\]

where, \(\nu\) is the lowest natural frequency of the system. \(P_{\tau+\delta\tau}\) is a generalized exterior force vector with arbitrary law of change.

To determine natural frequencies and modes of vibration, the human right arm FEM (bar element system) is provided by modified solution of values ([K]-\(\omega^2\)[M]). \{U\}, where \([M]\) is equal to \([M]_1 + [M]_2\), \([M]_1\) is the diagonal mass matrix of system taking into account mass and their moment of inertia, \([M]_2\) is the mass matrix of the system taking into account distributed mass of elements; \(\omega\) is the spectrum of natural frequencies \((i=1…n)\), and \{U\}_i is the natural vector (normalized form of vibrations of the system on \(i\)-th frequency).

\(\hat{\Delta}_{t+\tau}\) in Equation (5) can be described as Equation (8) by considering very short time \(\delta t\) and arbitrary time variation \(\tau\) and applying linear acceleration principle.

\[
\{\hat{\Delta}_{t+\tau}\} = \{\hat{\Delta}_t\} + \left(\frac{\Delta_{t+\tau}}{\delta t}\right) \cdot \tau \quad (8)
\]

Where, by applying the boundary conditions \((C_1 \parallel_{\tau=0} = \{\hat{\Delta}_t\})\) and \((C_2 \parallel_{\tau=0} = \{\Delta_t\})\) considering \(\delta t = \tau\) in Equation (8), Equation (5) can be formulated as Equation (9).

\[
\begin{bmatrix}
\frac{6}{\delta t} \cdot [M] + \frac{3}{\delta t} \cdot [H] + [K] \\
\{P_{\tau+\delta t}\} + [M] \cdot \left(\frac{6}{\delta t^2} \cdot \{\Delta_t\}_i + \frac{6}{\delta t} \cdot \{\dot{\Delta}_t\}_i + 2 \cdot \{\ddot{\Delta}_t\}_i\right)
\end{bmatrix} \cdot \{\Delta_{t+\delta t}\} =

\begin{bmatrix}
\{P_{\tau+\delta t}\} + [M] \cdot \left(\frac{6}{\delta t^2} \cdot \{\Delta_t\}_i + \frac{6}{\delta t} \cdot \{\dot{\Delta}_t\}_i + 2 \cdot \{\ddot{\Delta}_t\}_i\right) \\
\{H\} \cdot \left(\frac{6}{\delta t} \cdot \{\Delta_t\}_i + 2 \cdot \{\dot{\Delta}_t\}_i + \frac{\delta t}{2} \cdot \{\ddot{\Delta}_t\}_i\right)
\end{bmatrix}
\quad (9)
\]

If initial conditions are given, the dynamic response of human system can be calculated by Equation (9).

### 3 Behavior Analysis of Human Right Arm

#### 3.1 Biomechanical Model Analysis

From a biomechanical point of view, the support locomotors apparatus of human is controlled by a biomechanical system consisting of chains, links and their joints with a group of muscles. A number of movable elements, movement degrees of freedom, nomenclature muscles groups and their interactions vary with the current human body position. The human skeleton represents a complex spatial construction by using different kinds of muscles and skeletons. The complexity of the human body structure necessitates using the development of mathematical model and finite element approach.

The muscle-skeleton analysis is only performed in FEM model of human right arm because it is the major effect among human behavior. It is designed as a rod element for each muscle and skeleton. The primary muscle elements and skeleton elements of FEM model are showed in Fig. 1. Table 2 presents the data of geometric characteristics. Table 3 shows mechanical properties of the elements. When the nodal point F got the shock as shown in Fig 4, the behavior of that point was analyzed. It was used input data of B&K 8201 force sensor. Maximum impact forces are 418N, 424N and 431N and their durations are about 0.01 sec.

![Fig. 4. Force history of right arm analysis on the wrist by experiment](image-url)
that time, the movement of the marker on the wrist is calculated as Fig. 5.

Table 2. Geometrical information of FEM model of right arm [8]

<table>
<thead>
<tr>
<th>Node</th>
<th>y (cm)</th>
<th>x (cm)</th>
<th>Node</th>
<th>y (cm)</th>
<th>x (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>0</td>
<td>0</td>
<td>E</td>
<td>-2</td>
<td>32</td>
</tr>
<tr>
<td>A</td>
<td>-12</td>
<td>0</td>
<td>F</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>B</td>
<td>-30</td>
<td>0</td>
<td>G</td>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>-2</td>
<td>H</td>
<td>0</td>
<td>38</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Mechanical property of finite element model of right arm [8]

<table>
<thead>
<tr>
<th>No.</th>
<th>Elasticity $E$ (kg/cm²)</th>
<th>Area $A$ (cm²)</th>
<th>Rigidity $G$ (kg/cm²)</th>
<th>Density $\rho$ (kg/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>200,000</td>
<td>2.3</td>
<td>20,000</td>
<td>0.019</td>
</tr>
<tr>
<td>10</td>
<td>200,000</td>
<td>2.3</td>
<td>20,000</td>
<td>0.019</td>
</tr>
<tr>
<td>12</td>
<td>200,000</td>
<td>2.0</td>
<td>20,000</td>
<td>0.0079</td>
</tr>
<tr>
<td>13</td>
<td>200,000</td>
<td>2.0</td>
<td>20,000</td>
<td>0.0079</td>
</tr>
<tr>
<td>14</td>
<td>200,000</td>
<td>3.0</td>
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<td>0.0079</td>
</tr>
<tr>
<td>15</td>
<td>200,000</td>
<td>10.0</td>
<td>20,000</td>
<td>0.0067</td>
</tr>
<tr>
<td>16</td>
<td>200,000</td>
<td>4.0</td>
<td>20,000</td>
<td>0.0067</td>
</tr>
<tr>
<td>31</td>
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<td>12.6</td>
<td>38.0</td>
<td>0.0005</td>
</tr>
<tr>
<td>33</td>
<td>64.1</td>
<td>12.6</td>
<td>38.0</td>
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</tr>
<tr>
<td>35</td>
<td>64.1</td>
<td>10.8</td>
<td>38.0</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

The maximum displacement in y-axis direction occurred at 0.109 sec. The values for each are 121.5 mm, 123.2 mm and 125.3 mm. As the impact value is bigger, the displacement increases more and more in value. The quantitative analysis had to be verified through several tests and evaluation.

Fig. 5. Analytical results of node F (right wrist) behavior along the y direction

3.2 Experimental Setup Analysis

Several tests are conducted to verify the results of behavior of the wrist. While the upper arm is fastened to stay motionless on the table, the forearm is vertical to the upper arm. When the wrist is impacted in y-axis direction with a hammer, the behavior is measured. Fig. 6 shows the experimental setup of this test. Time histories are measured while it is impacted using 0.8 kg rubber hammer. These are used as input data to analyze FEM model in Fig. 4.
3.3 Comparison of Biomechanical Model and Experimental Setup

Fig. 8-10 show similar trend of analytical and experimental results of right wrist behavior along the y direction under 418 N, 424 N and 431 N. Not only quantitative displacement but also maximum behavior displacement time history shows a similar tendency. In the case of maximum behavior displacement 136.6 mm, standard deviation of different is 3.1 mm. The results of comparison verified the behavior analysis of human right arm under impact condition.

Fig. 7. Experimental results of right wrist behavior along the y direction under 418 N, 424 N and 431 N
Fig. 10. Comparison of analytical and experimental results of right wrist behavior along the y direction under 431 N

4 Conclusions

The right arm was modeled by muscle-skeleton elements to obtain the behavior of right arm of human under impact condition, where physical and geometrical properties of human body such as Young's modulus, shear modulus, cross sectional area, length, density, moment of inertia and position were defined. Based on the FEM model of the right arm, the impact response of the right arm was obtained. By the comparison with the experimental results, the model of the right arm was verified. The result of this study shows accuracy of the real behavior and analytical behavior of human right arm. The standard deviation is only 3.1 mm at 418 N, 3.6 mm at 424 N, 1.8 mm at 431 N. Each error percentage is 6-7% in y direction. It can be validated that human right arm research has high accuracy for real behavior as well as influence of muscle-skeleton and hammering interaction. This study can be applied to virtual human modeling, exoskeleton development, anthropology research, biomechanics research, gait analysis and medical science.

References