

A Biomechanical Analysis of Dumbbell Curl and Investigation of the Effects of Increasing Loads on Biceps Brachii Using A Finite Element Model

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Abstract

Dumbbell curl is one of the most important strengthening exercises for the upper extremity. This exercise trains especially biceps brachii. Exercise load is increased to achieve more muscle strength for the biceps brachii. Researchers are usually focused on electromyography (EMG) in order to examine the effects of load increasing on muscle contraction. However, only the muscle force can be predicted with EMG measurement. Structural analysis of the muscles cannot be performed. In this study, the effects of load increasing on biceps brachii were investigated by mechanical analysis. The inverse dynamic model was simulated according to the motion analysis of dumbbell curl exercises performed with 6 kg and 10.7 kg. The muscle force of the biceps brachii was calculated from the elbow joint reaction moment. A simplified finite element model of biceps brachii was created and stress-strain response was examined. Although the muscle force increases by 78.3%, the rate of increase of elbow peak moment is 57.7% and the rate of increase of peak muscle force is 38.3%. Similarly, the rate of increase of maximum strain and maximum stress are 44.4% and 37.3%, respectively. According to these results, it is understood that increasing the dumbbell load does not increase the muscle force at the same rate.

Key words: Increasing training load, muscle force, MATLAB, ANSYS

1. Introduction

Dumbbell curl or biceps curl is a basic exercise to strengthen upper extremity muscles. The movement pattern of this exercise, which can be performed in different posture positions or with different equipment, is generally the same. The movement is started when the elbow joint is in full extension and the forearm is flexed until dumbbells reach the top of the shoulders. Then arms return to the starting position. The elbows keep close to the body during the movement. The forearm and upper arm muscles are strengthened with repeated movements. The most contraction occurs in biceps brachii during the dumbbell curl exercise [1].

Exercises are done with dumbbells of different weights and different repetitions to strengthen the biceps brachii. It is necessary to know the effects of dumbbell curl movement on biceps brachii to prevent muscle damage and to provide an effective exercise. Hwang et al. [2] used electromyography (EMG) to determine muscle fatigue during dumbbell curl exercise. Garcia-Manso et al. [3] examined the effects of biceps curl exercises on muscles with 10 kg and 30 kg loads by tensiomyography method. Cha et al. [4] predicted muscle activation and muscle moments in different dumbbell load using EMG signals.

There are different simulation models and software for biomechanical analysis of exercise

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movements and prediction of muscle force [5, 6]. In addition, finite element models are used for structural analysis of skeletal muscles such as stress, strain and deformation. Oomens et al. [7] studied the anterior tibialis strain of a rat under constant load using a 2D continuum model. Blemker et al. [8] investigated non-uniform strain on a 3-dimensional model of biceps brachii. Martins et al. [9] analysed the continuum deformations in skeletal muscles using 2D and 3D finite element models according to the Hill-type muscle model. Webb et al. [10] calculated the moment arm distance of the muscles with a 3D finite element model. Rohrle et al. [11] studied the stress and displacement in the muscles using the continuum-mechanical forward simulation method.

The intensity of muscle contraction can be calculated in analysis using EMG [5]. Additionally, muscle force can be estimated during contraction. However, the deformation on the muscle and the tendon cannot be determined clearly. Finite element models give useful results in determining the muscle deformation. It is shown that muscle force is held constant in previous studies on finite element models. The peak stress or the deformation of the muscle can be calculated in the analysis using the peak muscle force. However, muscle force is variable during the exercises. Therefore, the force applied to the muscles should vary according to the movement pattern for accurate analysis.

This study aimed to investigate the mechanical effects of the dumbbell curl exercise performed with different loads on the biceps brachii. In addition, it is aimed to understand whether the relationship between dumbbell load increase and muscle force is linear. First of all, the dynamic muscle force during the dumbbell curl exercise was calculated via an inverse dynamic simulation model. Then, the effects of dynamic muscle force on the biceps brachii were investigated with a simplified 3D finite element model. As a result of the analyses, the strain and stress on biceps brachii were calculated.

2. Materials and Method

Firstly, the motion analysis of the dumbbell curl exercise was performed in this study. The displacement of the upper extremity joints was determined using two different dumbbell load on a volunteer subject. Then, the dumbbell curl exercise was simulated in MATLAB environment using the motion data of the joints. As a result of simulation, the biceps brachii contraction force was calculated. Structural analysis of muscle force on biceps brachii was examined with a finite element model based on muscle and tendon material properties. Figure 1 shows the flowchart of the study. Details of the above are included in the following sections.

2.1. Motion analysis of the dumbbell curl

Dumbbell curl exercises were performed by a male subject (33 years, height 174 cm and mass 73 kg) with a training background. Passive markers were placed on the dumbbell bar, elbow and shoulder joints of the subject. The volunteer performed the dumbbell exercise in standing position according to [1]. The exercise was done with 6 kg and 10.7 kg dumbbells. The subject completed 3 repetitions for each load with a self-selected speed. Markers motion were captured with a digital video camera which has 30 Hz image frequency. Tracker video analysis software was used for

digitization [12]. The angular displacement, angular velocity and angular acceleration of the elbow joint were calculated using the motion data of the markers.

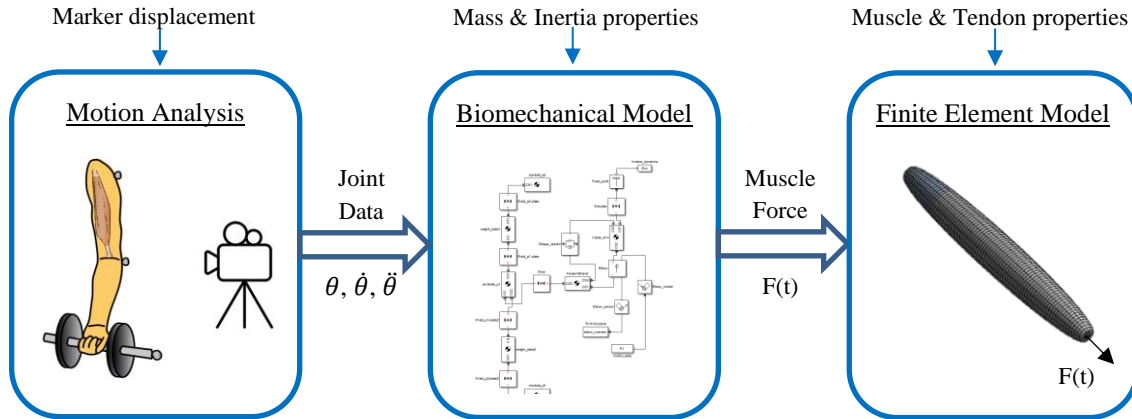


Figure 1. The flowchart of research methodology.

2.2. Simulation model of the dumbbell curl

An inverse dynamic joint limb model has been created to simulate the dumbbell curl exercise. The model consists of dumbbell, forearm, upper arm, elbow and shoulder joints. In addition, the biceps brachii is modelled as a spring-damper element according to the Hill-type muscle model [13]. The joint limb model is shown in Figure 2.

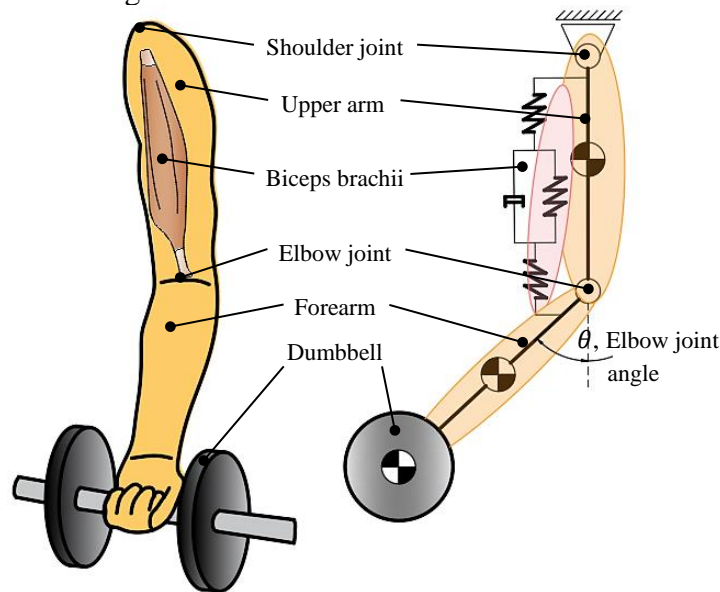


Figure 2. Left; physiological model, right; mechanical model of the dumbbell curl.

Muscle contraction force according to the Hill-type muscle model can be expressed in Eq. (1). where F is muscle tensile force, v is muscle shortening velocity, F_{max} is the maximum isometric

force, a and b are constants. Muscle force of biceps brachii also causes a moment on the elbow joint during the dumbbell curl (Eq. 2). where M is joint reaction moment and d is the distance of biceps brachii moment arm.

$$(\vec{F} + a)(\vec{v} + b) = (\vec{F}_{max} + a)b \quad (1)$$

$$\vec{M} = \vec{F} \cdot d \quad (2)$$

Solving Eq. (1) is a challenging process. Instead, muscle force was calculated using Eq. (2) in this study. Here, d changes according to the elbow joint angle. In our study, d is adapted from [14]. Elbow joint moment was calculated by simulating the dumbbell curl exercise. Then, muscle force was found solving Eq. (2).

Simulation process was done using MATLAB Multibody tools (Figure 3). Body segments are modelled as a rigid body in the MATLAB simulation. The elbow joint is modelled as a single degree of freedom revolute joint. The shoulder and ankle joint are each considered as a fixed joint. Biceps brachii is modelled as a spring-damping element between the elbow and the shoulder joints. Stiffness of biceps brachii (k) is adapted from [15] as a 213 N/m. Damper constant (b) and muscle-tendon length of biceps brachii are adapted from [13] as 6.44 Ns/m and 0.312 m, respectively. The moment of inertia of the body segment was calculated according to the equations from [16]. Segment length, mass and centre of mass were calculated from [17]. Table 1 shows mass and inertial parameters.

Table 1. Body and segment parameters of the limbs and dumbbell. The centre of mass is given by the proximal end of the limb. a; forearm and hand are considered together.

Body	Length (m)	Mass (kg)	Moment of Inertia ($\times 10^{-4}$ kg·m ²)			Centre of mass (m)
			I _{xx}	I _{yy}	I _{zz}	
Forearm ^a	0.299	1.606	75.123	11.932	77.409	0.153
Upper arm	0.356	2.044	148.268	27.200	168.577	0.130
Bar part 1	0.145	0.400	7.492	7.492	9.680	Midpoint
Bar part 2	0.105	0.3	3.119	3.119	7.260	Midpoint
Bar part 3	0.145	0.400	7.492	7.492	9.680	Midpoint
Weight plate1	0.022	2.000	0.289	0.289	0.562	Midpoint
Weight plate2	0.022	2.500	0.410	0.410	0.800	Midpoint

The inverse dynamic model (see Figure 2 and 3) can be solved according to the principle of conservation of angular momentum in Eq. (3) below:

$$\sum_{i=1}^{i=3} M_i = I_i \cdot \ddot{\theta}_i \quad (3)$$

where M is joints moment, I is moment of inertia of the segments and θ is angular displacement of the joints. Reaction moment in each joint can be calculated by Eq. (4) below:

$$\begin{bmatrix} I_{1,xx} & I_{1,yy} & I_{1,zz} \\ I_{2,xx} & I_{2,yy} & I_{2,zz} \\ I_{3,xx} & I_{3,yy} & I_{3,zz} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_{1,z} \\ \ddot{\theta}_{2,z} \\ \ddot{\theta}_{3,z} \end{bmatrix} = \begin{bmatrix} M_{1,z} \\ M_{2,z} \\ M_{3,z} \end{bmatrix} \quad (4)$$

where x , y and z are reference axes. Since the shoulder joint is assumed to be a fixed joint and the dumbbell is fixed to the wrist joint, M_1 and M_3 will be zero. As a result of the simulation, the elbow reaction moment M_2 was calculated. Then, muscle force was calculated by Eq. (2) during the dumbbell curl exercise.

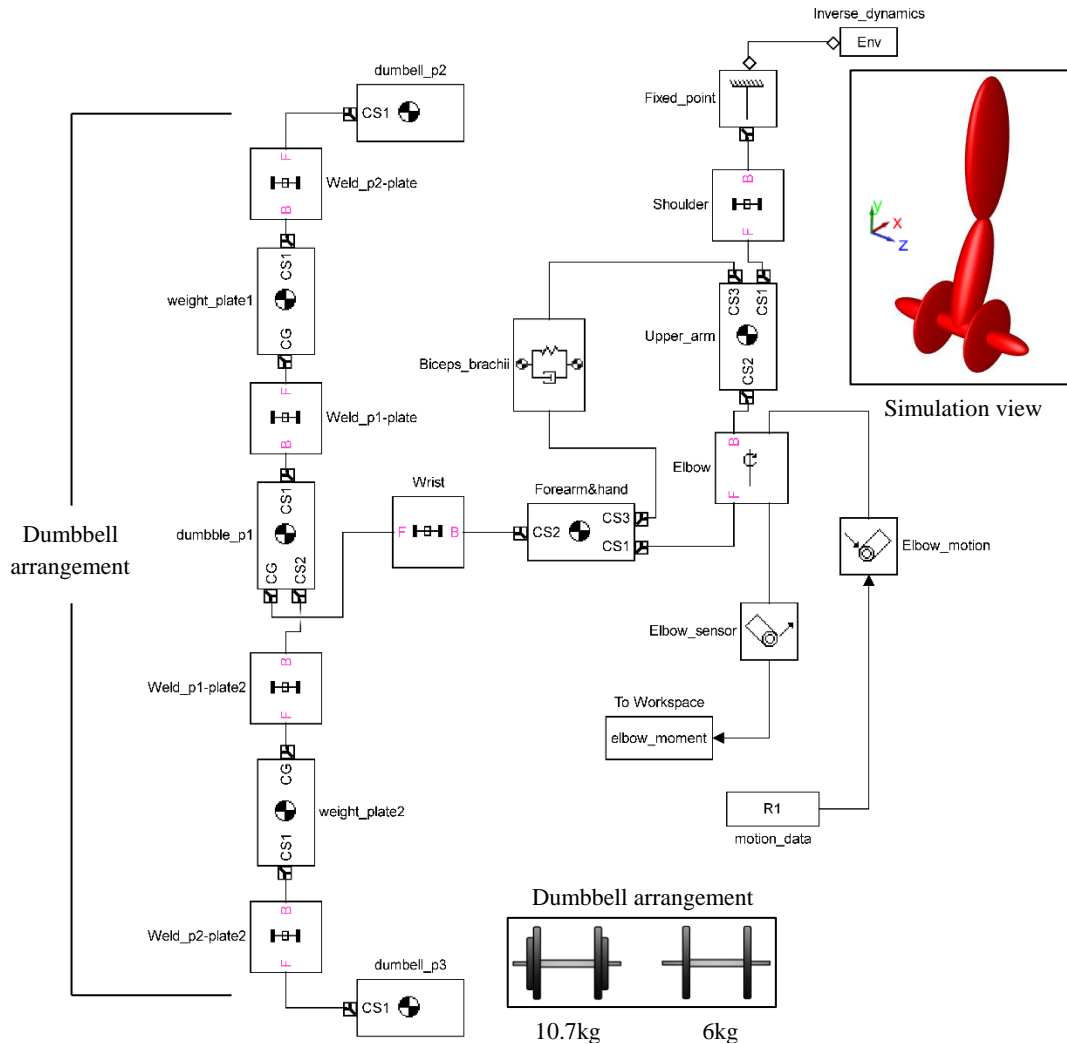


Figure 3. Inverse dynamic model of the dumbbell curl

2.3. Finite element model of the biceps brachii

After calculating the muscle force during the dumbbell curl exercise, the stress and strain response

of the biceps brachii were analysed using a finite element model. A simplified finite element model according to the muscle and tendon properties of the biceps brachii is shown in Figure 4. Here tendon length (L_t) is 0.0625 m [18], total length of muscle (L_m) is 0.312 m [13], D_1 is 0.014 m and D_2 is 0.042 m [19]. The material properties of the muscle were assumed as follows. Density was 1056 kg/m^3 , Poisson's ratio was 0.4 and Young's modulus was $1.162 \cdot 10^6 \text{ Pa}$ [20]. The material properties of the tendon were assumed as follows. Density was 1670 kg/m^3 , Poisson's ratio was 0.497 and Young's modulus was $1.6 \cdot 10^6 \text{ Pa}$ [21]. A hexahedral mesh consisting of 18428 nodes and 3906 elements was used in the finite element model created in the ANSYS Workbench environment. The model was fixed at the end of the tendon and the dynamic force calculated by dumbbell curl simulation was applied from the tip of the muscle. As a result of the analysis, the strain and stress response of the muscle were calculated.

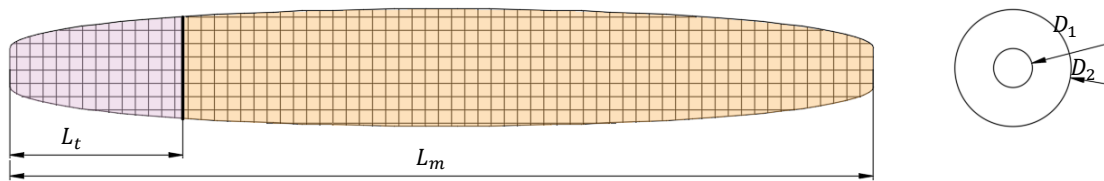


Figure 4. A Simplified finite element model of the biceps brachii.

Due to the different material properties of the muscle and the tendon, total stress (σ_T) can be expressed in Eq. (5) and total strain (ε_T) can be expressed in Eq. (6) where σ_t is tendon stress, σ_m is muscle stress, ε_t is tendon strain and ε_m is muscle strain.

$$\sigma_T = \sigma_t + \sigma_m \quad (5)$$

$$\varepsilon_T = \varepsilon_t + \varepsilon_m \quad (6)$$

3. Results

The maximum displacement in the biceps curl movement performed with 6 kg and 10.7 kg dumbbells was measured at the elbow joint. Shoulder joint has been regarded as fixed because of a small displacement. The angular displacement and angular velocity of the elbow joint with different load can be seen in Figure 5.

The inverse dynamic model was simulated by using the motion data. As a result of the simulation, the joint moment of elbow was calculated. Then, muscle force of the biceps brachii was determined according to changing moment arm. Figure 6 shows the variation of elbow joint moment and biceps brachii force in two different loads.

After calculating the biceps brachii force, the finite element model was analysed. Strain (Figure 7) and stress (Figure 8) responses of the biceps brachii were analysed using variable muscle force.

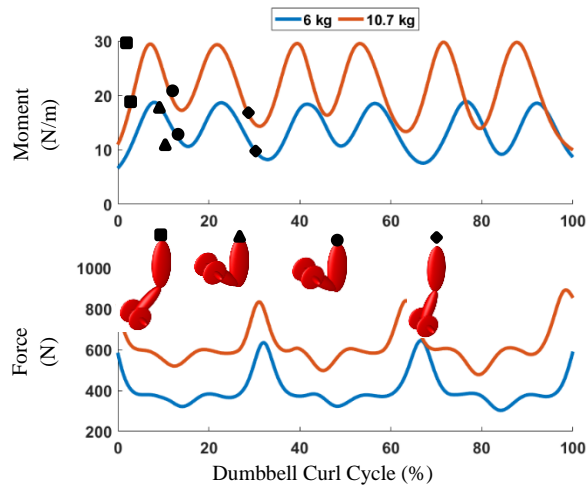


Figure 6. Elbow joint moment and muscle force of biceps brachii with different load.

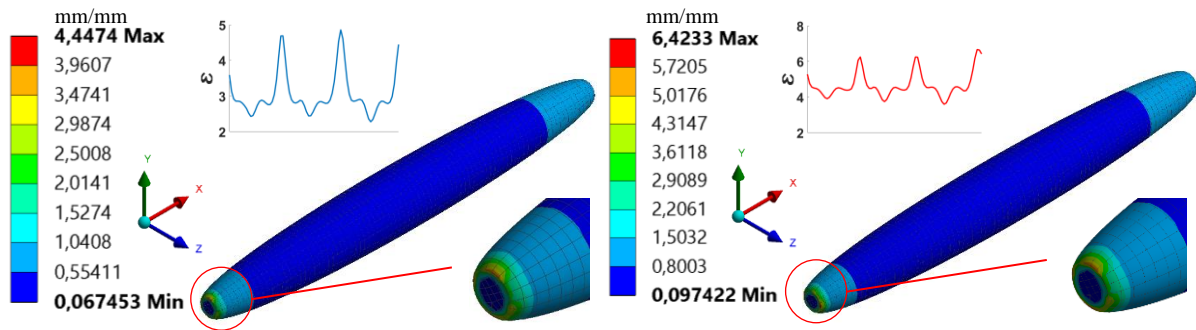


Figure 7. Force-dependent strain behaviour of biceps brachii. Left; 6kg, right; 10.7kg

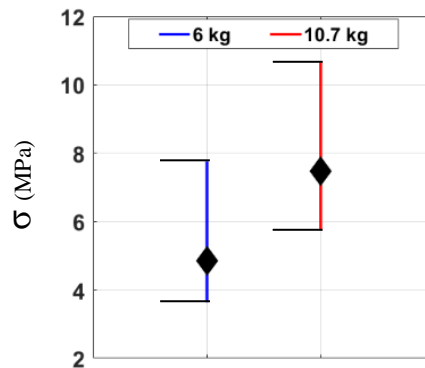


Figure 8. Equivalent stress of biceps brachii.

4. Discussion

It is seen that the behaviour of the displacement and the velocity are almost the same in both dumbbell loads (see Fig. 5). Thus, the only parameter which affects joint moment is increasing dumbbell load.

The peak joint moment was calculated to be 18.88 Nm with 6 kg dumbbell and 29.78 Nm with 10.7 kg dumbbell. The peak muscle force was calculated to be 645.66 N with 6 kg dumbbell and 893.04 N with 10.7 kg dumbbell. It was shown that the rate of increase of load was 78.3%, the rate of increase of peak joint moment was 57.7% and the rate of increase of peak muscle force was 38.3% comparing exercises with 6 kg and 10.7 kg dumbbells.

Maximum strain was calculated as 4.44 mm/mm with 6 kg dumbbell and calculated as 6.42 mm/mm with 10.7 kg dumbbell. Considering the stress, mean of the σ_{max} was 4.85 MPa and 7.46 Mpa, respectively. In addition, peak value of the σ_{max} was 7.76 Mpa and 10.66 Mpa, respectively. When comparing two different load of exercise, the rate of increase of maximum stress was 44.4% and the rate of increase of maximum strain was 37.3%. Considering the strain and the stress results, it is understood that the strain and the stress on the tendon is greater. This is due to the different material properties of the tendon tissue.

It is seen that there is no linear correlation with increasing load (from 6 kg to 10.7 kg) considering the results of muscle force, joint moment, strain and stress. Although the motion analysis results of the two different loads are similar, the mechanical response of the biceps brachii is different for the two dumbbell loads. Peak moment of elbow joint increased by 57.7% while peak muscle force increased by 38.3%. This is because the muscle moment arm distance changes during the dumbbell curl exercise. The percentage increase in strain and stress is also different (44.4% and 37.3% respectively). This is due to the nonlinear characteristics of the muscle-tendon complex.

Conclusions

Firstly, the motion analysis of the dumbbell curl exercise was performed in this study. The inverse dynamic model was simulated according to the motion data and the joint moment was calculated. Then, the biceps brachii force was calculated considering the muscle moment arm change. After that, structural analyses of the biceps brachii were examined with a simplified finite element model. It is understood that there is no linear correlation between dumbbell load and the mechanical response of the muscle considering the results of muscle force, strain and stress. Therefore, it could be said that increasing load in strength exercise does not have a significant impact on muscle growth. A simplified finite element model is used in the study. However, this model is considered to be sufficient since the two dumbbell loads are examined relatively.

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