POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

Stress-strain response of muscle fibers in biceps brachii under dynamic force: an analysis of biceps curl exercise

Pazu kası lifinin dinamik kuvvet altındaki gerilme-gerinme davranışı: bir ön kol bükme egzersizi analizi

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Bu makaleye şu şekilde atıfta bulunabilirsiniz(To cite to this article): Asadi Dereshgi H., Serbest K., Balık B. ve Şahin S. N., "Stress-strain response of muscle fibers in biceps brachii under dynamic force: an analysis of biceps curl exercise", Politeknik Dergisi, 25(4): 1777-1783, (2022).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.1025328

Stress-Strain Response of Muscle Fibers in Biceps Brachii under Dynamic Force: An Analysis of Biceps Curl Exercise

Highlights

- *Mechanical model of the biceps brachii*
- *Finite element analysis with COMSOL Multiphysics 5.5*
- *Dumbbell curl analysis*
- *Dynamic muscle response*

Graphical Abstract

A finite element model was developed and mechanical behaviors in the biceps muscle fiber during exercise were investigated.

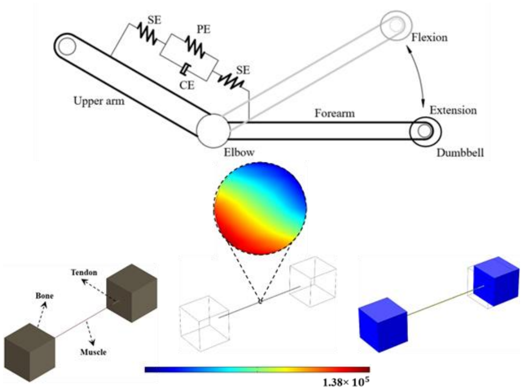

Figure. An illustration of the study

Aim

The aim of this study was to investigate the mechanical behaviors resulting from the application of dynamic forces that occur during the dumbbell curl exercise on muscle fibers.

Design & Methodology

Fibers in the biceps brachii were modelled as a Hill-type muscle. A finite element model of the muscle was created on COMSOL Multiphysics software. Dynamic analysis was performed with two different weights (5 kg and 10 kg).

Originality

It was thought that when the exercise weight is increased, the muscle force will increase at the same rate. However it is understood that weight gain did not increase muscle force as much.

Findings

It was observed that when dumbbell weights were doubled (100%), the maximum muscle force and deformation increased by 83.13% and 84.92%, respectively.

Conclusion

We suggest that training program should be designed according to the needs of the individuals.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Pazu Kası Lifinin Dinamik Kuvvet Altındaki Gerilme-Gerinme Davranışı: Bir Ön Kol Bükme Egzersizi Analizi

Araştırma Makalesi / Research Article

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(Geliş/Received : 18.11.2021 ; Kabul/Accepted : 11.12.2021 ; Erken Görünüm/Early View : 02.02.2022)

ÖZ

Dayanıklılık egzersizlerinin en önemli özelliklerinden biri setler arasında egzersiz ağırlığının artırılmasıdır. Kaslardaki kasılma-kuvvet ilişkisi sayesinde daha yüksek bir kasılma kuvveti elde edilerek kas gelişiminin artırılması amaçlanmaktadır. Önceki çalışmalarda genellikle maksimum yük altındaki kas davranışının incelendiği görülmüştür. Ancak egzersiz ağırlığının artırılması ile kas kasılması arasındaki ilişki tam olarak incelenmemiştir. Bu çalışmada iki farklı ağırlıkla (5kg ve 10kg) yapılan biceps curl egzersizi esnasında meydana gelen biceps brachii kas kuvveti hesaplanmıştır. Daha sonra bir sonlu elemanlar modeli oluşturularak egzersizler esnasında biceps brachii kas lifinde meydana gelen mekanik değişimler incelenmiştir. Sonuçlara bakıldığında egzersiz ağırlığı ile kas kuvveti arasında doğrusal bir ilişki olmadığı görülmüştür. Ağırlığın iki katına çıktığı (%100) durumda maksimum kas kuvveti ve deformasyonun sırasıyla %83.13 ve %84.92 oranında arttığı görülmüştür. Elde edilen sonuçlar egzersizler esnasında aşırı ağırlık artırmanın kas gelişimine beklenildiği kadar fayda sağlamayacağını göstermektedir.

Anahtar Kelimeler: Hill-tipi kas modeli, kas-iskelet modeli, kas kuvveti, sonlu elemanlar yöntemi, COMSOL Multiphysics.

Stress-Strain Response of Muscle Fibers in Biceps Brachii under Dynamic Force: An Analysis of Biceps Curl Exercise

ABSTRACT

One of the most important features of endurance training was to increase the weight of the dumbbells between sets. According to the relationship of the contractile force in the muscles, the porpuse was to increase muscle growth by gaining more contractile force. Previous studies had generally examined muscle behavior under maximum force. However, the relationship between increased dumbbell weight and muscle contraction was not fully investigated. The aim of this study was to investigate the mechanical behaviors resulting from the application of dynamic forces that occur during the dumbbell curl exercise on muscle fibers. In this study, biceps brachii muscle force during biceps curl exercise performed with two different weights (5kg and 10kg) was calculated. Then, a finite element model was developed and mechanical behaviors in the biceps muscle fiber during exercise were investigated. It was achieved that there was no linear correlation between dumbbell weight and muscle force. It was observed that when dumbbell weights were doubled (100%), the maximum muscle force and deformation increased by 83.13% and 84.92%, respectively. The results showed that increasing excessive weight during exercises will not be as beneficial for muscle development as expected.

Keywords: Hill-type muscle model, musculoskeletal model, muscle force, finite element method, COMSOL Multiphysics.

1. INTRODUCTION

The musculoskeletal system consists of bone, cartilage, muscle, tendon and connective tissue that provide the forces needed to move. Skeletal muscles consist of muscle fibers with a thickness of 10 μm to 100 μm with 1 cm to 30 cm length, it forms a layer on the bones and is connected to the bones by tendons. There are over 430 skeletal muscle groups in the muscular system, which constitutes 40% to 45% of body weight [1-2].

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Contractions that cause the muscles to show complex mechanical properties, occurs in the muscle fiber as a result of neural excitations [3-4]. The mathematical notations used to analyze the complex mechanical properties of contractions were based on Hill and Huxley muscle models [5-8]. Hill's muscle model described the dynamics of the combination of muscle and tendon using interconnected mechanical elements and the mechanism of force generation [9-10].

The mechanical behavior of the musculoskeletal system is investigated by the finite element method, the boundary element method and the finite volume method [11-15]. Finite element models were used to study the active behavior of skeletal muscle, which was composed of contractile muscle fibers in connective tissue [16]. It is worth noting that finite element models are preferred because they provide advantages in studying the functions of complex structures in the musculoskeletal system, nonlinear material properties, complex geometries and biological structures with boundary conditions [17]. Literature survey shows that there are many studies about the contractions of the muscles in different situations. For example, Chao et al. (1993) investigated the force analysis of human muscle, bone, tendon, joint and ligament structures by performing exercises and simulations [18]. Johansson et al. (2000) determined the muscle properties with the finite element method. Moreover, muscle modeling was performed by nonlinear continuum mechanics method [19]. Bayraktar et al. (2004) investigated the properties of femoral cortical and trabecular bone structure using mechanical tests and nonlinear finite element method [20]. Bourne et al. (2004) modeled the mechanical variability of trabecular tissue with homogeneous and inhomogeneous finite element methods [21]. Teran et al. (2005) modeled the musculoskeletal system using the degenerate and reversible finite element method. Thus, the upper extremity musculoskeletal model was created [22]. Blemker et al. (2005) performed a 3D model focusing on the main features of the muscle. Thus, the structure of the muscle that is effective in tension and the cause of non-uniform tensions are indicated by the finite element method [23]. Lu et al. (2010) based on the Helmholtz free energy function to characterize under tension skeletal muscle behavior, they developed a three-dimensional visco-hyperelastic skeletal muscle model using the finite element method [24]. Silva et al. (2011) presented a muscle fatigue model that can be correlated with Hill-type muscle models based on the force production of each muscle according to the previous literature [25]. Żuk et al. (2018) investigated the effect of variability of lower extremity musculoskeletal model parameters on muscle force. Thus, muscle models were compared with simulation method using inverse dynamics based static optimization and hybrid approach [26]. Kuravi et al. (2021) studied the effects of different conditions on mechanical behavior using three-dimensional finite element models which were from a series of histological sections of skeletal muscle tissue by performing numerical simulations [27].

Modeling and simulation of contractions of muscles in different situations is mainly used to analyze human movement within the framework of the musculoskeletal system. Additionally, musculoskeletal models play an active role in the treatment process of various disorders. Examination of dynamically changing muscle forces during exercise movements and performing analyzes according to changing muscle forces increase the accuracy of the models created by providing an understanding of muscle mechanics. The purpose of this study was to investigate the mechanical behaviors resulting from the application of dynamic forces that occur during the dumbbell curl exercise on muscle fibers. It is predicted that by examining the displacement and stretching behavior of the differenet force in the muscle, it will be possible to understand the muscle contraction-force relationship in people with different physical characteristics.

2. MATERIAL and METHOD

Dumbbell curl is a basic exercise for upper extremity. The exercise starts with positions of full extension of the elbow and ends with forearm flexion. Biceps brachii is the most contracted muscle during this exercise. At the beginning of the study, a biomechanical model of the forearm, upper arm and elbow joint was performed to simulate the dumbbell biceps curl exercise. Motion analysis of the dumbbell curl exercise was performed with a male participant by placing passive markers on the limbs and dumbbells. Biceps curl exercise was implemented using 5 kg and 10 kg dumbbells. The movement was started with the forearm parallel to the ground, then the bending process was performed, and the movement was finished with the forearm parallel to the ground. The movement was recorded by a camera with a sensitivity of 30 frames/second. Thus, displacements in the joint limbs were obtained. Additionally, the mass properties of the limbs were adapted from studies in the open literature [28]. The biceps brachii muscle was modeled using spring and damping elements according to the Hill muscle model [29]. Figure 1 shows the biomechanical model of the biceps brachii, upper arm, forearm, and elbow joint. CE refers to contractile component of the actin, myosin and myofibril. PE represents epimysium, endomysium, perimysium and sarcolemma which are the components located to parallel to the CE. SE refers to tendons which are spring-like elastic components.

The maximum contraction force of the biceps brachii muscle according to the Hill muscle model was expressed in Equation 1.

$$[\vec{F}(x) + a][\vec{v}(t) + b] = [\vec{F}(x)max + a]b \quad (1)$$

where, F was muscle force, v was muscle contraction velocity, F_{max} was maximum isometric force, t was time, "x" was muscle tension, a and b were contraction constants. a and b are dimensionless shape parameter. Muscle force also can be described in a simpler manner as Equation 2.

$$\frac{dF}{dx} = K_1 F + K_2 \quad (2)$$

where K_i are constants. Muscle force can be calculated solving the Equation 2 with boundary conditions as Equation 3.

$$F = K_3(e^{K_1 \Delta_x - 1}) \quad (3)$$

The displacement and mass properties of the muscle were inserted into Equation 1 to obtain the torque values. Thus, the forces that the biceps brachii muscle could produce when lifting 5 kg and 10 kg dumbbells have been achieved.

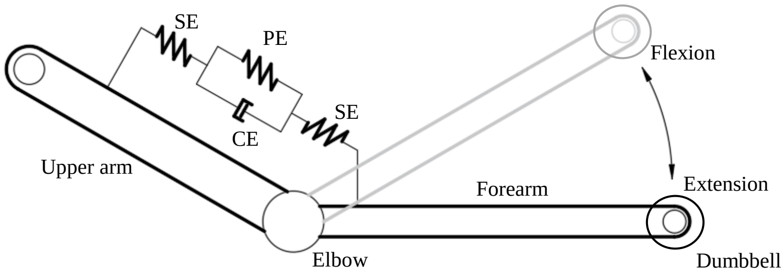

Figure 1. Hill-type muscle of the biceps brachii. CE; contractile element, PE; parallel elastic element, SE; serial elastic element

Biceps brachii muscle fiber was a finite element model consisting of bone, muscle fiber and tendon structures. Muscle and tendon were designed as cylinders and bone as cubes (see Figure 2). In the model, the side lengths of the bone were 100 mm, the length of the muscle fiber was 250 mm, the length of the tendon was 25 mm, and the diameter of the muscle fiber and tendon was 1 mm. The physical properties of the joints were given in Table 1.

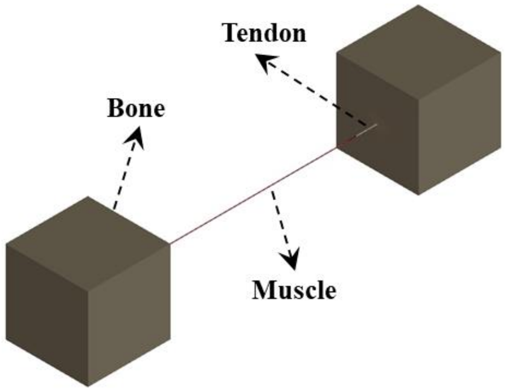

Figure 2. The structure of the bone, muscle and tendon for finete element analysis

Table 1. Physical properties of the muscle, bone and tendon

Joints	Young's modulus (Pa)	Poisson's ratio	Density ($^{kg}/_{m^3}$)
Muscle	1.162×10^{6}	0.4	1056
Tendon	1.6×10^{6}	0.497	1670
Bone	1×10^{10}	0.3	2570

The first Piola Kirchhoff stress tensor relates the Cauchy stress tensor to the stress in the deformed space. This is not a symmetric tensor and is for computational convenience [30]. Therefore, Equation 4 was used to study the mechanical behavior of the biceps brachii by the Finite Element Method (FEM).

$$\rho\frac{\partial^2 u}{\partial t^2} = \nabla . s + F_V \quad (4)$$

where, ρ is the density, "$\frac{\partial^2 u}{\partial t^2}$" is the acceleration and $\nabla.s$ is the gradient of First Piola-Kirchhoff stress and F_V is the volume forces.

In addition, Mesh Convergence Analysis (MCA) was used to prove the accuracy of the analysis. The analysis was performed in three steps with a sensitivity of 0.001 in the COMSOL Multiphysics 5.5 (see Figure 3). The number of meshes used in the first step (Normal) was less than the second step (Fine), and this was repeated until the third step (Finer). The properties of the meshes were given in Table 2.

There was a linear correlation between the number of elements and sensitivity. The error rate between Normal and Fine meshes was ~0.34%, and between Fine and Finer meshes was ~0.05% (see Figure 4). Eventually, Fine meshes were considered the ideal mesh because the error rate between meshes was very low and the processing time raised as the number of elements increased. It is worth mentioning that with this method it is possible to investigate any parameter such as displacement, strain and stress. The results of the mechanical behavior of the link-segment model were presented in the Results and Discussions Section.

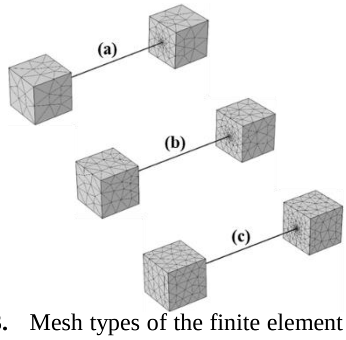

Figure 3. Mesh types of the finite element model, a) Normal, b) Fine, and c) Finer

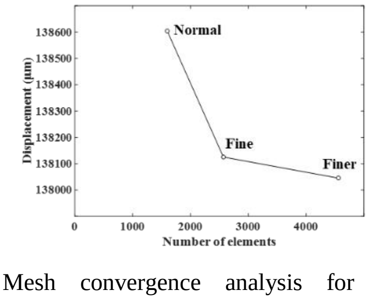

Figure 4. Mesh convergence analysis for the model displacement

Table 2. Specifications of Biceps Brachii's Finite Element Model

Domain element statistics	Number of elements	Minimum element quality	Average element quality	Element volume ratio	Mesh volume (mm^3)
Normal	1599	0.08598	0.6013	0.00002957	2001000
Fine	2570	0.1201	0.6034	0.00005771	2001000
Finer	4559	0.2196	0.6316	0.00003292	2001000

3. RESULTS AND DISCUSSION

Angular displacement of the elbow joint during the exercise was shown in the Figure 5. The joint angles ranged from 40° to 160°. The same movement pattern was performed in both the 5 kg and 10 kg exercises. 160° refers to extension of the elbow and 40° refers to flexion of the elbow joint. The fact that the movement pattern was similar in both exercises made it possible for muscle force to change only depending on the dumbbell weight.

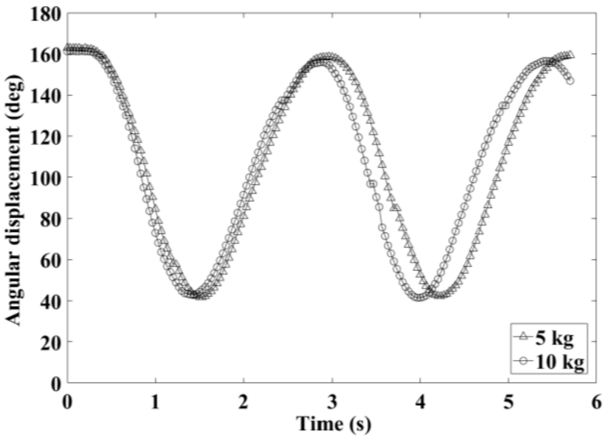

Figure 5. Displacement of the elbow joint

The biceps brachii force calculated as a result of biceps curl exercises performed with two different weights, which was based on motion analysis data, was shown in Figure 6. The maximum muscle force was calculated to be 1103 N in the 5 kg dumbbell exercise and 2020 N in the 10 kg dumbbell exercise. It is seen that the maximum muscle force increases by 83.13% when the exercise weight is doubled.

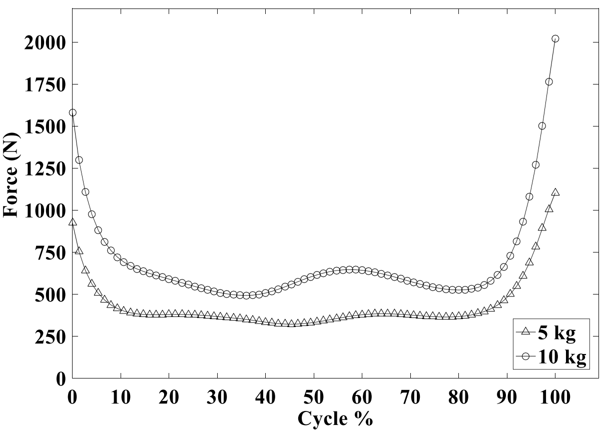

Figure 6. Biceps brachii force of biceps curl exercise

The mechanical behaviors at the midpoint of the muscle fiber were investigated. Figure 7 shows the displacement of the muscle fiber during exercise at 10 kg. The displacement values during the biceps curl exercise with 5 kg and 10 kg dumbbells are given in Figure 8. The relationship between muscle force and displacement was linear. The minimum displacement of muscle fiber was 22.3 mm and the maximum displacement was 6.75 mm in exercises performed with 5 kg dumbbells. In the exercise performed with 10 kg dumbbells, the minimum and maximum displacement were calculated as 34.1 mm and 139.8 mm, respectively. Here was the case where the dumbbell weight was doubled, it was seen that the minimum deformation increased by 52.9% and the maximum deformation by 84.9%.

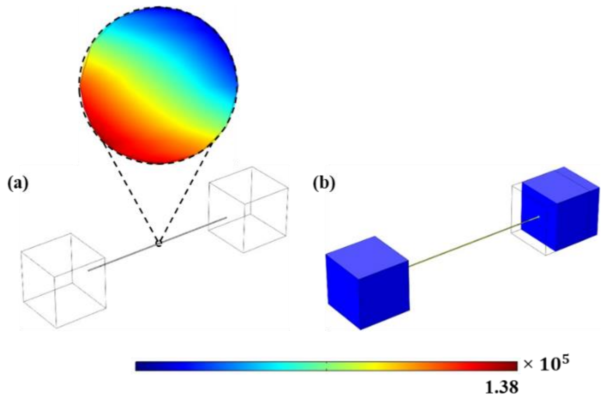

Figure 7. Displacement analysis of the model at 10 kg

Figure 9 shows the stress-strain behavior of the muscle fiber in exercises performed with two different weights. In the exercise performed with 5 kg dumbbells, it was seen that the minimum strain was 0.17% and the minimum stress was 207.8 kPa. At the same weight, the maximum strain was 0.60% and the maximum stress was calculated as 704.2 kPa. In 10 kg dumbbells, it was seen that the minimum strain was 0.27% and the minimum stress was 317.8 kPa. At the same weight, the maximum strain was calculated as 1.12% and the maximum stress as 1301.9 kPa.

It was understood that when the dumbbell weight was doubled, the minimum and maximum strains increase by 58.8% and 86.6%, respectively. Similarly, when the stress values were examined, it was observed that the increase rate of the minimum and maximum stresses were 53.4 and 84.8%, respectively.

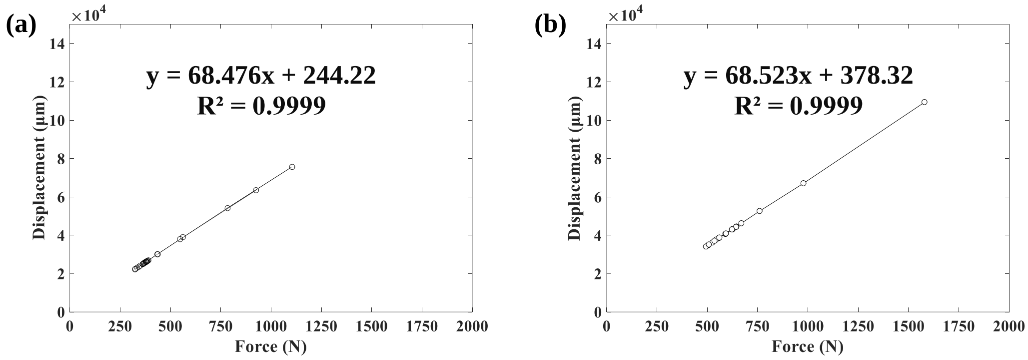

Figure 8. The force-displacement relationship of the biceps brachii at a) 5 kg, and b) 10 kg

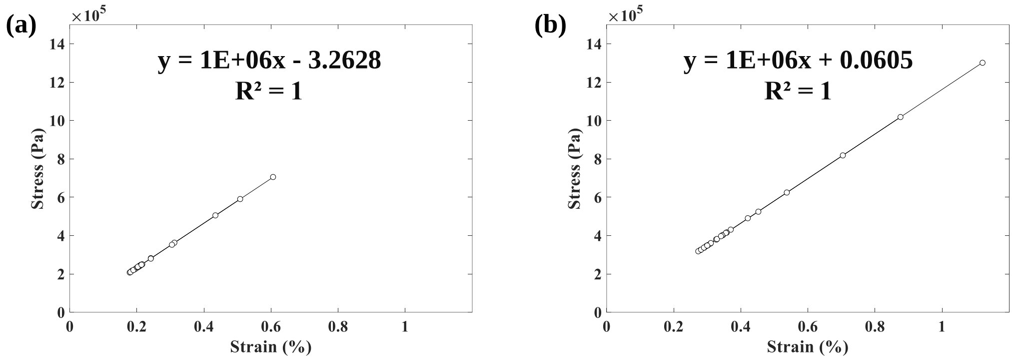

Figure 9. The stress–strain relationship of the biceps brachii at a) 5 kg, and b) 10 kg

In this study, the muscle forces that occur during biceps curl exercises performed with two different dumbbell weights, by constructing a finite element model of the biceps brachii muscle fiber, the effects of exercise weight gain on muscle mechanics were investigated. According to the motion analysis data, as a result of the calculation made using the mass and inertia properties of the limbs and the Hill-type muscle model, the muscle force of the biceps brachii during the exercise movements was calculated. During the examining the results of muscle force, it was seen that the highest muscle forces occur at the beginning and end of the exercise movement as 925 N and 1103 N. Since the inertia effects on the limbs were large at the beginning of the movement, a highest force was required to activate the elbow joint. In addition, at the end of the movement, a high muscle force was applied to balance the elbow joint flexion. Maximum muscle force values in this study were similar to the results of Nolte et. al (2011) study [31]. In this study, where the average body weight was 85 kg, the highest muscle force in the biceps curl exercise was calculated as 1180.7 N.

It is a common approach to increase exercise weight to accelerate muscle growth in endurance exercises. It was thought that when the exercise weight is increased, the muscle force will increase at the same rate. However, when the results of this study were examined, it is understood that weight gain did not increase muscle force as much. When the dumbbell weight was doubled, the increase in muscle force varied between 51.2% and 83.13%. Given that deformity and stress increase with weight, it has been proven that excessive weight gain was not a good strategy for muscle growth. One of the factors affecting force production in the muscles was the force-speed relationship. Therefore, instead of increasing weight for muscle development, performing the exercise movement in the right pattern may give a better result.

6. CONCLUSION

A starting point is needed to start a fitness program. Therefore, it requires the formation of the right rules to achieve resistance training exercises. Thus, the objectives should be designed according to the needs of the individual on the basis of the training program. In this study, the forces performed by the biceps brachii and its mechanical behavior were invasively investigated when an adult lifts 5 kg and 10 kg. Consequently, this study demonstrated that increasing weight during exercise did not provide efficacy to muscle hypertrophy as expected. In future studies, the electrical behavior of the biceps brachii and the role and importance of each of the above-mentioned structures will be examined in detail. Additionally, biceps brachii can be modelled as a viscoelastic material. Thus, stress relaxation and creep behavior of the muscle can be analyzed.

ACKNOWLEDGEMENT

This work was supported by Research Fund of the Sakarya University of Applied Sciences. Project Number: 2021-01-04-055.

DECLARATION OF ETHICAL STANDARDS

This article does not contain any studies with human participants or animals performed by any of the authors.

AUTHORS' CONTRIBUTIONS

Hamid ASADI DERESHGI: Performed the experiments, analyse the results and wrote manuscript.

Kasım SERBEST: Performed the experiments, analyse the results and wrote manuscript.

Büşra BALIK: Analyse the results and wrote manuscript.

Sema Nur ŞAHİN: Analyse the results and wrote manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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