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Research Article

Investigating the biomechanics of the biceps brachii muscle during dumbbell curl exercise: A comprehensive approach

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Abstract: Investigation of the mechanical behavior of the biceps brachii (BB) muscle at different dynamic forces is essential to improve training techniques, prevent sports injuries and optimize rehabilitation results. In previous studies, researchers studied mechanical changes during muscle contraction using various mathematical methods and simulation models. The models adopted by the majority of these studies assumed a constant value for muscle force. However, variable muscle force has different effects on muscle mechanics. In this study, an inverse dynamic simulation model was initially utilized to determine the dynamic muscle forces generated in the BB while performing the dumbbell curl exercise with 5 kg and 10 kg weights. Subsequently, the finite element method (FEM) was used to calculate the stress and strain changes experienced by BB as a consequence of the applied forces. Moreover, simultaneous analysis through electromyography (EMG) was carried out to investigate muscle contraction during the dumbbell curl exercise. Consequently, it was concluded that the average BB force during the dumbbell curl exercise with 5 kg and 10 kg weights was 433.9 N and 695.0 N, respectively. The maximum stresses in the BB during exercise were calculated to be 960.5 Pa and 1484.9 Pa, respectively. Additionally, the maximum displacements were determined to be 102.30 μm and 158.28 μm, respectively. According to the findings of muscle force 100% increase in dumbbell weight increases the maximum muscle force by 83.13% and the average muscle force by 60.17%. Therefore, it is understood that there was no linear correlation between weight gain and muscle force.

Keywords: Joint moment, Biceps Brachii muscle force, musculoskeletal model, elbow joint, EMG

1. Introduction

The biceps brachii (BB) is a skeletal muscle located in the upper arm, composed of a long and short head that originate from the scapula and is inserted on the radius bone [1]. It is responsible for flexing the elbow joint, supinating the forearm, and is innervated by the musculocutaneous nerve [2]. The muscle is made up of both fast-twitch and slow-twitch muscle fibers, allowing for both explosive power and sustained contraction [3]. The muscle is also considered a synergist for other muscles involved in elbow flexion, such as the brachialis and brachioradialis muscles [4]. In general, the BB muscle plays an important role in many aspects of upper body movement and is a key muscle for daily activities as well as athletic performance [5, 6]. Therefore, strengthening the BB muscle can provide numerous benefits, including improved arm strength, better aesthetics, and improved grip strength [7]. There are several effective methods to strengthen the BB muscle, including resistance training [8, 9], isometric training [10], plyometric training [11], and eccentric training [12]. Resistance training involves using weights or resistance bands to perform exercises that target the BB muscle [13], whereas isometric training involves holding a static contraction of the muscle without any joint movement [14]. Plyometric training involves performing explosive movements that involve rapid stretching and contracting of the muscle [15], and eccentric training involves focusing on the lowering phase of a movement [16]. The literature surveyed indicates that resistance training is a highly effective way to strengthen the BB muscle, and has several advantages over other types of exercise for achieving this goal [17, 18]. By providing specificity, progressive overload, high muscle activation, and flexibility, resistance training is a key tool for building strength and hypertrophy in the BB muscle [19, 20]. It is worth mentioning that dumbbell curls are a common exercise in resistance training programs aimed at strengthening and hypertrophying the BB muscle, and can be performed as part of a full-body workout or as a targeted exercise in isolation [21, 22]. Therefore, researchers are studying the effects of dumbbell curls on the BB muscle to understand the mechanisms of muscle hypertrophy, improve athletic performance, and potentially develop rehabilitation programs for individuals recovering from injury or surgery

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[23, 24]. Additionally, insights into the optimal training strategies for enhancing bicep strength may be useful for individuals with musculoskeletal disorders [25, 26].

The effect of dumbbell curls exercise on the BB muscle has been investigated through the use of different methodologies in various studies. These include electromyography (EMG) [27] to assess muscle activation levels, muscle biopsies [28] to analyze changes in muscle fiber size and composition, ultrasound imaging [29] to measure muscle thickness and cross-sectional area, and strength testing [30] to evaluate changes in muscular strength and endurance. Additionally, some studies have utilized different variations of the dumbbell curl exercise, such as altering the resistance [31], range of motion [32], and grip type [33], to investigate the effects of these factors on BB muscle activation and hypertrophy. In general, these diverse methods provide a comprehensive understanding of the physiological [34] and biomechanical [35] responses of the BB muscle to dumbbell curls exercise. In the open literature, several studies have been conducted to investigate the biomechanical modifications occurring in the BB muscle during different forms of physical exercise. For example, Watanabe et al. (2015) studied EMG changes in the BB muscle during resistance training and detraining in 10 male subjects. They performed 6 weeks of resistance training on one arm followed by 8 weeks of detraining, measuring EMG using a 64-channel surface system during dumbbell curls. The researchers found that EMG amplitude increased during training, but returned to baseline during detraining. However, the spatial distribution of EMG potentials did not significantly change during either phase [36]. Hwang et al. (2016) developed a new method for predicting muscle fatigue and force during isokinetic dumbbell curl exercise using EMG signals. The method involved investigating the relationship between biceps fatigue and EMG signals at different maximum voluntary contraction levels and co-plotting them in a global EMG index map. An algorithm based on this map was developed to predict muscle fatigue and force in real-time EMG signals with arbitrary maximum voluntary contraction levels [37]. Fu et al. (2018) investigated the impact of exercise intensity on electrical impedance changes of biceps tissue during a fatiguing isotonic exercise. Resistance and reactance measurements were collected from 18 participants before and after execution of a fatiguing protocol at two different intensities. This study found that exercise intensity did not significantly affect changes in electrical impedance of biceps tissue during a fatiguing isotonic exercise. This has important implications for the use of electrical impedance measurements in monitoring exercise-related changes and injury [38]. Li et al. (2020) utilized numerical and experimental methods to investigate the local muscle fatigue of the BB during dynamic and static contractions. Firstly, the electromechanical behavior of the human upper arm's skin, fat, muscle, and bone layers was investigated using the finite element method (FEM) to construct a three-dimensional model. Secondly, local muscle fatigue was evaluated using a non-invasive electrical impedance myography system on ten volunteers. Finally, the study revealed that there is a linear correlation between resistance and muscle fatigue [39]. Coratella et al. (2023) investigated the impact of different handgrip positions on the activation of the BB and brachioradialis muscles during dumbbell curl exercises. EMG measurements in 10 resistance-trained male subjects revealed that the supinated grip resulted in higher BB activation, while the pronated grip yielded greater brachioradialis activation [40]. Typically, the techniques utilized for investigating the mechanical behavior of the BB muscle are contingent upon the particular kind of physical information that researchers seek to acquire. The open literature includes several investigations that primarily examine the mechanical behavior of the BB muscle during different exercises and movements, but there are no studies supporting each other.

The purpose of this study was to investigate the influence of different dumbbell weights on the BB muscle during dumbbell curl exercises, with a particular emphasis on the assessment of the associated dynamic forces. In this context, a multifaceted methodology was utilized, encompassing motion analysis, FEM, and EMG techniques, to unveil the concealed biomechanical intricacies governing muscle behavior during the dumbbell curl exercise. The initial approach entailed motion analysis, which encompassed the utilization of cameras and markers to monitor the kinematics of the link during exercise. This facilitated the quantification of link angle, angular velocity, and acceleration, thereby affording insight into the muscle's biomechanical activity during exercise. The subsequent approach utilized force and torque measurement, which enabled the determination of the magnitudes of forces and torques evoked during exercise. This data was critical for assessing the muscle's load and work output, consequently affording valuable insight into the resultant mechanical stresses on the muscle. The tertiary methodology comprised FEM, which entailed utilizing computerized models to emulate the dynamics of the musculotendinous-bony complex during exercise. This method allowed for the prediction of the stresses and strains placed on the muscle, tendons, and bones during exercise, providing a way to analyze the internal stresses and strains that occur in the muscle during exercise. Finally, the acquisition of EMG signals during exercise was utilized. EMG involved measuring the electrical activity in the muscle during exercise, providing insight into the activation patterns of the muscle during exercise and how the muscle functioned during activity. Together, these methods provided a comprehensive understanding of the changes that occur in the BB muscle during dumbbell curl exercises with different weights. These techniques provided complementary information on the mechanical stresses placed on the muscle, the internal stresses and strains occurring within the muscle, and the activation patterns of the muscle during exercise.

This study is potentially novel in the field of biomechanics as it combines several methods to examine changes in the BB muscle during dumbbell curl exercise. In general, the study has the potential to provide valuable insights into the biomechanics of dumbbell curl exercise and could contribute to the development of more effective exercise programs for individuals looking to strengthen their BB muscle. These methodologies can also be applied to effectively engage the BB muscle during rehabilitation processes and monitor the recovery progress. Therefore, this research holds the potential to offer benefits in the biomedical and healthcare domains. The organization of the paper is as follows. The methods of the study are described in Section 2. In Section 3, the results of motion analysis, muscle force, FEM simulations, and EMG analysis are presented and discussed. Finally, the concluding remarks are reviewed in Section 4.

2. Materials and Methods

Investigating the effects of the dumbbell curl exercise on the BB muscle using a combination of motion analysis, FEM, and EMG signals was the central focus of this study. A simulation model was created to encompass the forearm, upper arm, elbow joint, and shoulder joint for this purpose. The mass properties of the body segments were adapted from previous studies, and the motion analysis of the dumbbell curl exercise was performed with a male participant. The Link Segment Model (LSM) and body mass properties were modeled with MATLAB Simscape Multibody block diagrams, and the dumbbell curl exercise was simulated using motion analysis data with the Simscape Multibody model. In addition, EMG signals were used to measure the electrical activity of the muscle during the exercise. The following sections provide a detailed description of these methods and their application in this study.

2.1. Biomechanical Model of the Dumbbell Curl Movement

The LSM consisting of the forearm, upper arm, elbow joint, shoulder joint, BB, and dumbbells is shown in Figure 1. It was determined that the forearm and upper arm were solid bodies. The movement of the shoulder and wrist joints remained constant since no examination was conducted on them. In accordance with the Hill muscle model, the BB was modeled using spring and damping elements [41]. The composition of this model consists of a contractile element (CE), a series element (SE), and a parallel element (PE). CE is surrounded by passive connective tissue. In this model, PE refers to connective tissues, and SE refers to the force produced by tendons.

The maximum contraction force of the BB according to the Hill muscle model could be expressed in Equation 1.

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

where, F was the muscle force, v was the muscle contraction velocity, F_{max} was the maximum isometric force, t was the time, x was the muscle strain, a and b were the contraction constants. The moment generated on the elbow joint during the dumbbell curl exercise due to the force exerted on the BB is mathematically represented by Equation 2.

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

The moment of reaction, denoted as M, was exerted at the elbow joint while the distance between the connection point of the BB and the forearm and the elbow joint's center of rotation was represented by d in Equation 2. Because Equation 1 was structured non-linearly [41], determining muscle force from joint moment was more straightforward.

Based on previous studies, the mass, moment of inertia, length of the segment, center of mass location, BB stiffness, damping constant, and distance from bone attachment point to joint center (d) were determined. Additionally, the male participant's weight and height (70 kg, 174 cm) were measured and utilized as parameters for the motion analysis study. It is important to note that the male participant included in the analysis had no reported health issues and had a background in sports activities. The anthropometric characteristics of the LSM are listed in Table. It is worth noting that 5 kg and 10 kg dumbbells were modeled as thin discs in this study.

2.2. Motion Analysis

The characteristics of a male participant mentioned in the previous section were subjected to motion analysis. In this regard, passive markers were placed on the shoul-

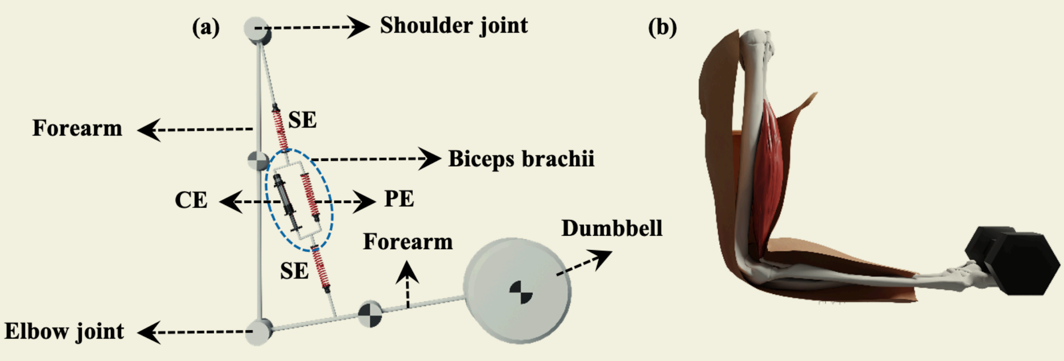

Figure 1. Musculoskeletal model of the dumbbell curl exercise. a) LSM, and b) physiological model.

der joint, the elbow joint, and the dumbbell. The participant performed the exercise using 5 kg and 10 kg dumbbells. The motion analysis was initiated with the forearm placed parallel to the ground, followed by a curling motion of the forearm, and terminated with the forearm assuming its original position, completing the analysis process. The participant stood and moved at the self-selected speed during the motion analysis. Meanwhile, the images were captured using a digital video camera that recorded 30 frames per second. The calculation of the angular displacement of the elbow joint was carried out using camera images, with the assistance of the Open Source Physics video analysis software.

2.3. MATLAB Simscape Structure of the LSM

In this study, the Simscape Multibody tool was used to prepare the joint model, as presented in Figure 2. Simscape Multibody is a robust and versatile simulation environment within MATLAB, specifically designed for modeling and simulating multi-domain physical systems. The elbow joint was actuated by the "Joint Actuator" block. The values obtained as a result of motion analysis were transferred to the model from the file named 'R1' (displacement, velocity, acceleration, time) in MATLAB Workspace. The solution of the Simscape Multibody model was done with the inverse dynamics method (fixed-step, sample time: 0.033) [47]. The moment of reaction that occurred in the elbow joint was calculated using the 'Joint Sensor' block. Subsequently, muscle force was calculated according to Equation 2.

2.4. EMG Analysis of BB

In this study, EMG was utilized to assess the biomechanical effects of dumbbell curl exercise on the BB muscle. EMG measurement [48] was performed to determine the level of muscle contraction during exercises with different dumbbell weights. The Delsys Bagnoli amplifier, manufactured by Delsys Inc. and featuring 8 channels

Table. Anthropometric properties. k; spring stiffness, b; damping constant, l; BB length.

Segment Parameters

Body	Length (cm) [42]	Mass (kg) [42]	Moment of inertia (g·cm²) [43] I_{xx}	I_{yy}	I_{zz}	Centre of mass from proximal end (cm) [42]
Upper arm	30.52	1.965	132×10^3	22×10^3	133×10^3	13.3
Forearm	26.3	1.123	64.5×10^3	88.8×10^3	66.9×10^3	11.31

BB parameters

k = 196 N/m [44]	b = 49 Ns/m [41]	l = 25 cm [41]	d; variable [45, 46]

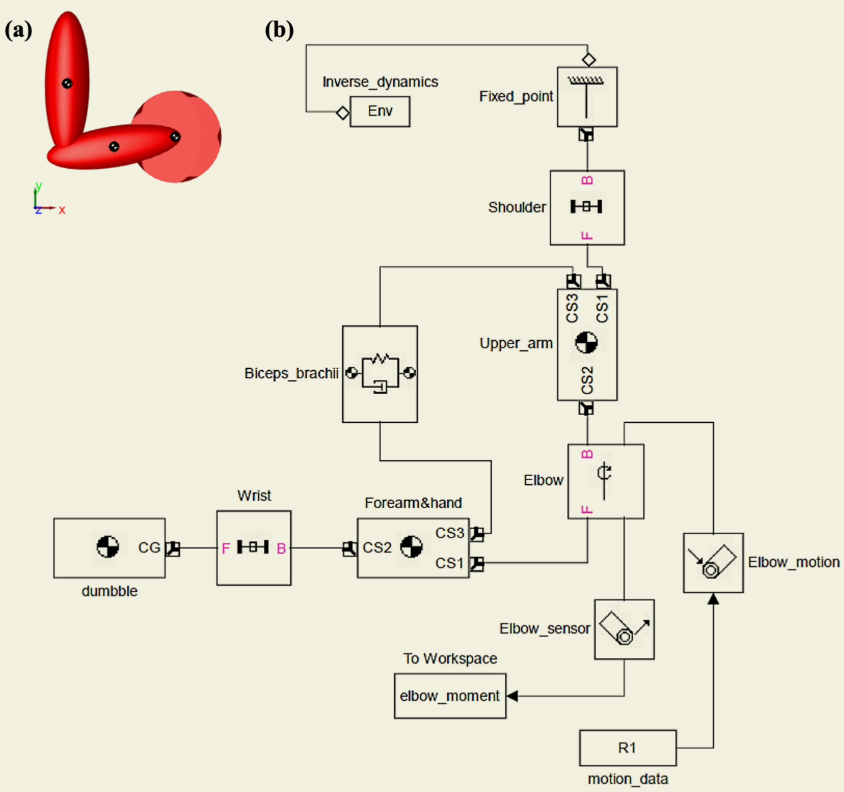

Figure 2. Dynamic analysis of the dumbbell curl exercise. a) Simulation view. b) Simscape block diagram.

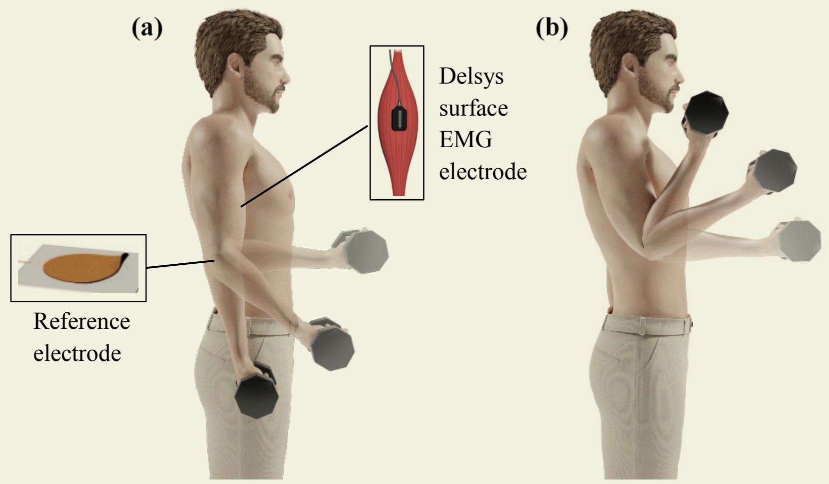

Figure 3. Representation of dumbbell curl exercise and EMG measurement.

with a total gain of 1000, was used for the measurement. A Delsys DE surface electrode was placed on the BB muscle belly on the anterior surface of the upper arm. The reference electrode is placed in the elbow area of the upper arm. Figure 3 illustrates the placement of the reference electrode in the elbow area of the upper arm. During the measurements, the participant was prevented from following the EMG measurement screen in order to focus only on the exercise movements. The EMG signals recorded during exercises performed with 5 kg and 10 kg dumbbells were analyzed using Delsys EMG-Works software. In general, this study utilized state-of-the-art EMG techniques to provide a detailed and accurate assessment of muscle activation during dumbbell curl exercises, which could be useful in designing effective exercise programs for individuals seeking to improve biceps strength and hypertrophy. In section 3, a detailed analysis and evaluation of the EMG results was presented.

2.5. Finite Element Modelling

In this particular study, the FEM was utilized to simulate the displacement, stress, and strain parameters in the BB muscle during the performance of dumbbell curl exercise. The construction of the model was accomplished through the utilization of COMSOL Multiphysics 5.5 software, a prevalent tool for finite element analysis. It is significant to note that the complex anatomical configuration of the elbow joint was modeled in three dimensions using simple geometries reported in the literature [49]. The boundary components proposed for this joint are depicted in Figure 4. In the presented model, the cubes (bone) were interconnected via two small cylinders (tendons) and a central large cylinder (BB muscle), thereby establishing an integrated system. In the analyses, the representative BB muscle, bone, and tendon displayed respective densities of 1056 kg/m^3, 2570 kg/m^3, and 1670 kg/m^3. Their respective Young's modulus were 1.162×10^6 Pa, 1.0×10^{10} Pa, and 1.6×10^6 Pa, while their respective poison ratios were 0.4, 0.3, and 0.497 [49]. The elasticity and damping constant values of the BB muscle, like many other biological tissues, can vary depending on factors such as age, fitness level, and individual variability. However, in this study, the elastic constant value for the BB muscle, as presented in the open literature for numerical analyses, was assumed to be 3535 N/m, and the damping constant was taken as 6916 Ns/m [50].

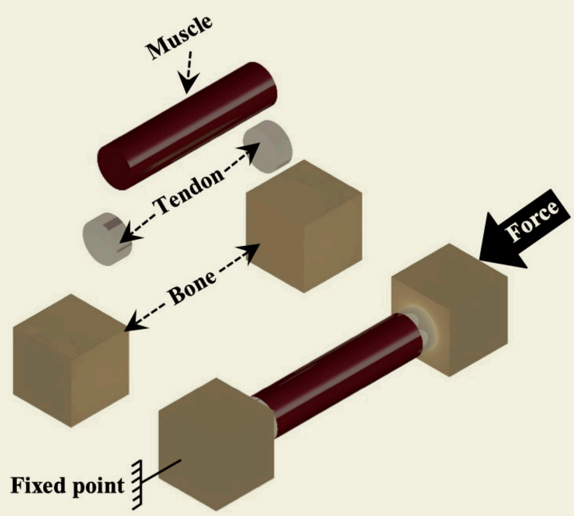

Figure 4. The elbow joint's configuration for FEM.

It is important to point out that the accuracy and validity of analysis depend on the quality of three-dimensional model, material properties, and appropriate finite element selection. In numerical analysis, the proper choice of finite element type is critical as the elements have varying capabilities and limitations. Therefore, it is important to choose the appropriate element type as it can significantly affect the accuracy and efficiency of the analysis. It is worth mentioning that the four-node tetrahedron type hyperelastic element is widely utilized by researchers in simulations of biological soft tissues, such as muscles [51-53]. The geometric shape of the element is a tetrahedron, which consists of four vertices and four triangular faces. In order to approximate the behavior of a small volume of the muscle being analyzed, the element is utilized, and nodal values are used to calculate the stresses and strains within that volume. Thus, this study extensively investigated the nonlinear behavior of the BB muscle using a four-node tetrahedron-type hyperelastic element, which is a nonlinear, continuum-based method. Furthermore, antecedent to commencing the exhaustive analysis, the mesh convergence method was judiciously applied to ascertain the most suitable element and node quantities. Consequently, 3574 and 14296 were identified as the optimal element and node numbers, respectively. Subsequent to the delineation of pivotal parameters, FEM simulations were meticulously executed with a precision threshold of 0.001. By this method, it is possible to investigate any parameter such as displacement, strain, and stress. The results of the mechanical behavior of the LSM are presented in Section 3.

3. Results and Discussions

In our previous study, the elbow joint moment was quantified via Simscape simulation, followed by the computation of the corresponding muscle force that took into account the change in muscle moment arm [8]. The moment arm distance of BB was adapted from Delp et al. [45] in accordance with the angular changes of the elbow joint. The elbow moment and muscle force of the BB during exercise with 5 and 10 kg dumbbells were shown in Figures 5 and 6. It appeared that muscle force occurred more at the beginning and end of the exercise. In the dumbbell curl exercise with 5 kg dumbbells, 925 N of force occurred at the beginning of the exercise, while with 10 kg dumbbells, 1579 N of force occurred at the beginning. The force at the end of the exercise with 5 kg dumbbells was 1103 N, and at the end of the 10 kg exercise, a force of 2020 N had occurred. In addition, the average muscle force during exercise was evaluated, revealing average forces of 433.9 N and 695.0 N for training with 5 kg and 10 kg dumbbells, respectively.

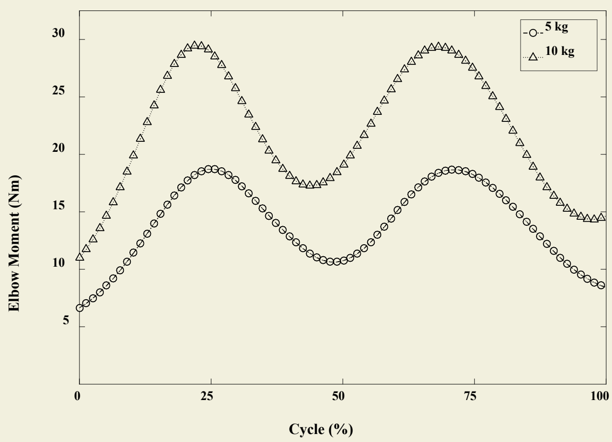

Figure 5. Elbow moment during the dumbbell curl exercise.

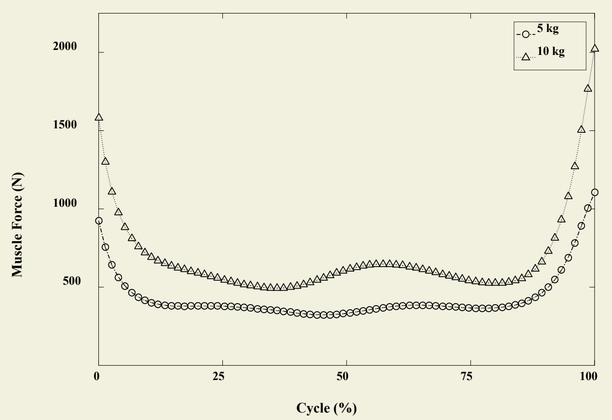

Figure 6. BB muscle force during the dumbbell curl exercise [8].

The results of the EMG measurement, as depicted in Figure 7, indicated that the maximum amplitude of the BB muscle during the forearm dumbbell curl exercise increased with an increase in exercise load. Specifically, the maximum amplitude of the BB muscle in the exercise performed with a 5 kg dumbbell was 0.795×10^{-5} V, and the maximum amplitude increased to 1.30×10^{-5} V when the exercise was performed with a 10 kg dumbbell. Even though the exercise weight increased by 100%, the maximum EMG amplitude increased by 63.5%. Additionally, the minimum EMG amplitude during exercises performed with different dumbbells was measured as 0.513×10^{-5} V and 0.754×10^{-5} V, respectively. There was a 46.9% increase in the minimum EMG amplitude. The results suggested that as the exercise weight increased, the muscle activity also increased, which may have been related to the muscle's ability to generate more force to overcome the resistance. However, this increase appeared to be non-linear in comparison to the increase in exercise weight.

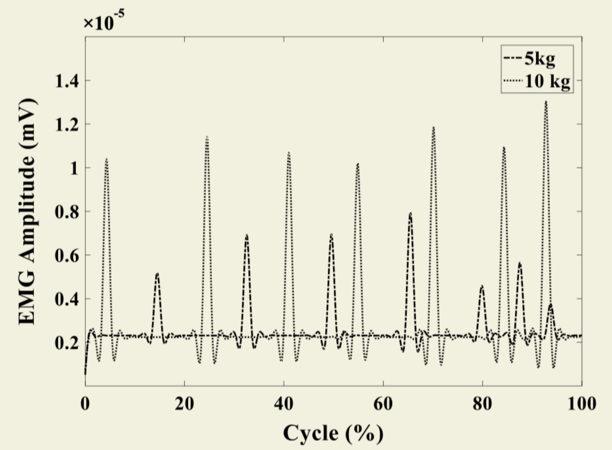

Figure 7. EMG analysis of BB during dumbbell curl exercises.

In the FEM analysis that was conducted (see Figure 8), the difference in the Young's modulus of bone (1×10^{10} Pa), tendon (1.6×10^{6} Pa), and muscle (1.162×10^{6} Pa) tissues

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caused the maximum displacement to occur at the midline of the muscle and the junction surface of the tendon and bone. The concentration of displacement, stress, and strain values observed at the midline were the result of a complex interaction between tissue properties and mechanical loading. Nonetheless, the purpose of this study was to analyze the modifications in the mechanical behavior of the BB. Therefore, the effect of forces was investigated by determining a surface in the midline of the BB.

The results of the numerical analysis revealed that at 2020.80 N (see Figure 9), the maximum displacement, strain, and stress on the midline surface of the BB were 158.28 µm, 1.27×10^{-3} and 1484.97 Pa, respectively. The muscle force-induced displacement in BB was demonstrated in Figure 9a. The average displacement during exercise with 5 kg dumbbells was 34.51 µm, compared to 55.86 µm during exercise with 10 kg dumbbells. Moreover, the maximum displacements achieved were 102.30 µm and 158.28 µm, respectively. In Figure 9b, the stress-strain change in BB was illustrated, and the maximum stresses experienced during exercise movements were calculated to be 960.5 Pa and 1484.9 Pa, respectively.

3.1. Mechanical Considerations of LSM

In this study, the mechanical effects of different dumbbell weights on the BB were investigated. The muscle force was determined by means of the MATLAB Multibody tool. Although the MATLAB Multibody tools are developed for mechanical analysis of solid bodies, musculoskeletal systems can be examined in terms of mechanical aspects [54, 55]. Subsequently, the finite element model developed in the COMSOL Multiphysics 5.5 was utilized to study the stress-strain behavior of the BB, depending on muscle force. The muscle force findings showed that doubling the dumbbell weight resulted in an 83.13% increase in maximum muscle force and a 60.17% increase in average muscle force. The maximum and minimum EMG amplitudes experienced an increase of 63.5% and 46.9%, respectively, mirroring the pattern observed in muscle force. Therefore, it was understood that there was no linear relationship between weight gain and muscle force. This situation arose because the muscle moment arm distance was dependent on the angle of the joint. It can be concluded from these findings that further increases in exercise weight would not result in a similar effect on muscle contraction. The research

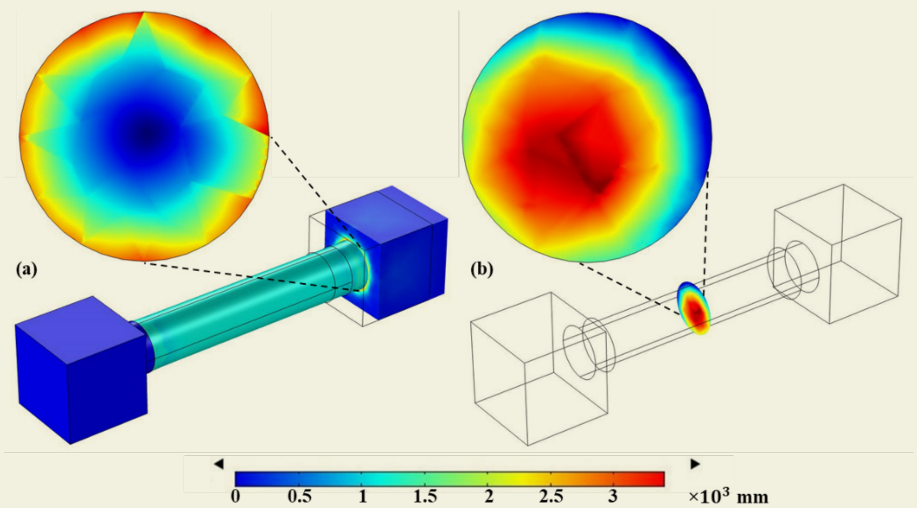

Figure 8. Displacement analysis of LSM at a) the junction surface of the bone-tendon tissues, and b) the midline of the BB.

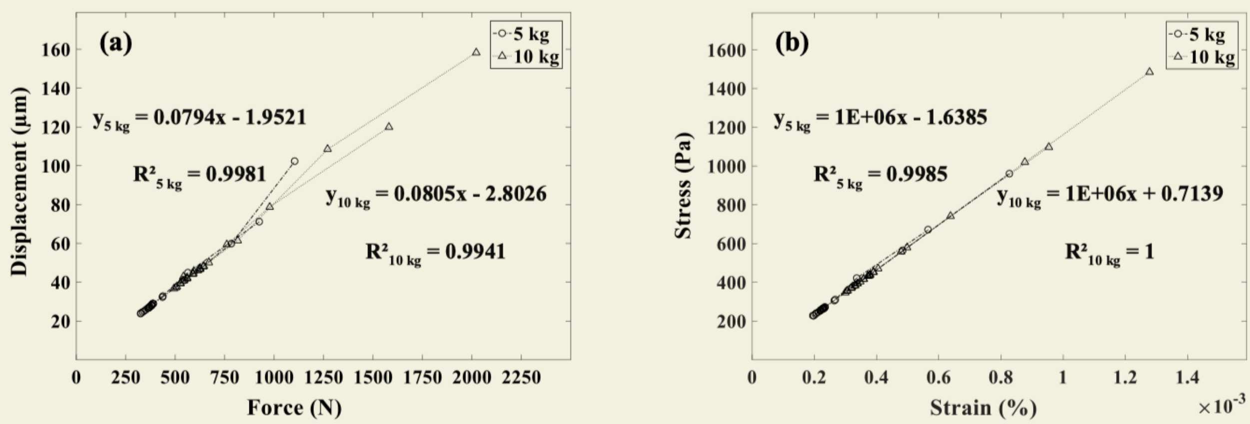

Figure 9. Mechanical behavior of the BB as a function of a) the force-displacement relationship, and b) the stress–strain curve.

conducted by Bryanton et al. [56] on Scott demonstrated that increasing barbell load had no discernible impact on muscle effort with measuring EMG. The results of our study mirrored this finding.

In light of the pressure and strain findings, it was determined that the maximum displacement and maximum strain had increased by 54.72% and 54.59%, respectively, upon doubling the weight of the dumbbell. Once again, it is observed that weight gain and the search for pressure and strain are not linearly related. Nevertheless, an escalation in strain led to an increase in muscle tension. The research conducted by Leedham and Dowling [57] showed that stretching the arm from the BB area resulted in an increase in the maximum muscle force. These results were also supported by our findings. The finite element analysis results indicated that the tendon underwent more substantial changes, primarily because of the unique material properties of the tendon tissue.

This study utilized MATLAB R2018b and COMSOL Multiphysics 5.5 to holistically model muscle, tendon, and bone tissues. The analyses were carried out with a sensitivity of 0.001s. The changes that occur at each point of the model as a result of applying random dynamic forces were investigated. Consequently, it was evident that the FEM analysis conducted in this study yielded accurate mechanical behaviors of LSM, which were consistent with the findings of previous studies.

3.2. Comparison with the State of the Art

In accordance with the investigation, the mechanical behavior of the BB muscle could be compared with those described in other research that utilized different methodologies. In previous research, the biomechanical effects of exercise on the BB muscle were studied using techniques such as EMG [58, 59], ultrasound imaging [60, 61], and magnetic resonance imaging (MRI) [62]. In comparison to EMG analysis, the study provided a more complete understanding of the mechanical behavior of the BB muscle during dumbbell curl exercise by utilizing joint motion analysis and finite element analysis. In contrast to EMG analysis, joint motion analysis and finite element analysis provided extensive insights into muscle force, moment, and activation patterns. The supplementary data can assist researchers in comprehending the interaction between the BB muscle with other muscles and joints during exercise. Similarly, ultrasound imaging and MRI were useful for evaluating muscle structure and activation patterns. However, these techniques were often expensive and time-consuming compared to joint motion analysis and finite element analysis. Additionally, ultrasound imaging and MRI did not provide information on muscle force and moment, which were critical in understanding the biomechanics of muscle function during exercise. Therefore, the joint motion analysis and finite element analysis methods used in the study provided several advantages over other techniques in terms of comprehensively evaluating the biomechanical effects of exercise on the BB muscle. These methods offered a cost-effective and time-efficient way to examine muscle force, moment, and activation patterns, which were essential for understanding muscle function during exercise. In our previously referenced study [8], these techniques were applied to a single fiber of the BB muscle, resulting in significant findings. Furthermore, in the present investigation, an additional EMG approach was incorporated to scrutinize the biomechanical dynamics exhibited by the entirety of the BB muscle. Finally, the study provided valuable insights into the mechanical behavior of the BB muscle during dumbbell curl exercise, and the joint motion analysis and finite element analysis methods used in the research offered several advantages over other techniques used in previous studies.

4. Conclusion

It is necessary to perform continuous exercises and strengthen muscles to achieve high performance levels in different types of sports. The BB muscle can also grow with different exercises depending on the position of the forearm. The BB muscle is a long muscle that sits anteriorly to the humerus, characterized by an easily palpable, oval-shaped bump. It is one of the flexor group muscles of the forearm and, as the only flexor of the arm, it extends from the shoulder joint to the elbow joint and acts on both joints. Therefore, it is particularly important to strengthen this muscle based on the correct principles. This is because BB injury is associated with pain and inflammation and causes limitations in daily activities. An important point to make is that injuries and pain in this muscle are usually caused by excessive pressure and overuse. The techniques used in this paper are crucial for addressing BB muscle injuries and pain because they provide a comprehensive understanding of the underlying biomechanics. Moreover, the conclusions of this study have found that the mechanical behavior of dynamic muscle force generated during a dumbbell curl exercise was investigated using MATLAB R2018b and COMSOL Multiphysics 5.5. It was evident from that research that specialized software programs like OpenSim, AnyBody, and LifeModeler, developed exclusively for muscle mechanics analysis, were not mandatory for carrying out muscle mechanics studies. The findings of the study were consistent with the previous literature, as revealed by the results. Additionally, it was found that the correlation between muscle force increase and muscle contraction is not linear and that the proposed model can be easily expanded and applied to other muscles and exercise movements. This research can help to improve our understanding of muscles' response to different loads and can aid in exercise prescription, muscle training, and injury prevention. Therefore, the methodologies used in the study show promise for applications in the biomedical and healthcare fields. These approaches can be adapted to design more effective rehabilitation programs, monitor progress, and contribute to the overall well-being of individuals with specific muscle-related conditions.

It is important to acknowledge certain limitations in this study. Firstly, this study involved tests on a single participant, who was a healthy individual without any preexisting medical conditions. Future studies could explore the applicability of findings to a broader population, including individuals with various fitness levels and clinical conditions. Secondly, the study focused solely on the BB muscle, and future research could extend its scope to other muscle groups involved in similar exercises to provide a more comprehensive understanding of exercise biomechanics. Additionally, this study primarily examined short-term effects, and longitudinal investigations could elucidate the long-term adaptations of the BB muscle to different training regimens. Furthermore, technological advancements may offer new avenues for more precise data collection and analysis.

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