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RESEARCH ARTICLE

The Rest-Pause Biceps Curl Exercise Effect on Biceps Brachii Muscle of Women: A Study of Mechanical Responsiveness

HAMID ASADI DERESHGI
Department of Biomedical Engineering, Istanbul Arel University, 34537 Istanbul, Turkey
e-mail: hamidasadi@arel.edu.tr

ABSTRACT The Rest-Pause Biceps Curl (RPBC) exercise generates a physiological response that enhances muscle growth and force in the Biceps Brachii (BB) through increased activation and fatigue. Specifically, the RPBC exercise leads to heightened muscle displacement and stress due to increased activation and fatigue. This stress results in muscle strain, and contracting of the muscle fibers, which causes microtrauma. The repair and adaptation process in response to this microtrauma can result in increased muscle size and force. This scrutiny purposed to explore the influence of isometric, concentric and eccentric contractions on the mechanical behavior of the BB muscle in the RPBC exercise at 2 kg, 3 kg and 5 kg dumbbell weights. In this study, ten healthy women aged 20 to 30 years, with a training background and no history of cardiovascular, neurological, or upper extremity disorders, were studied as subjects. This research was innovative in that it evaluated the collective effect of contractions on mechanical changes in BB muscle behavior during the exercise, without having physical contact with the muscle. In conclusion, the maximum displacement (37.56 μm), stress (355.89 Pa), and strain (3.06×10^{-4} %) was achieved in the BB muscles as the subjects lifted 5 kg dumbbells. In addition, a linear correlation between muscle force and mechanical behavior in the muscle was observed for three different weights of the dumbbell. The results of this study evaluates muscle fatigue and recovery during exercise, providing insights into injury risk and prevention, and improves exercise technique and form.

INDEX TERMS Biceps brachii muscle force, elbow joint, joint moment, musculoskeletal model, rest-pause biceps curl exercise.

I. INTRODUCTION

The BB is a muscle located in the upper arm. It has two heads, the short head and the long head, that originate from different parts of the scapula (shoulder blade) and insert on the radius bone of the forearm [1]. It is responsible for flexion of the elbow joint, supination of the forearm, and assisting in shoulder movement [2].

The contraction of the BB muscle, like in all skeletal muscles, sets in motion a highly regulated series of biological events, culminating in the deliberate generation of force [3]. Central to this intricate process is the strategy of motor unit recruitment, involving the selective activation of motor neurons responsible for stimulating specific muscle fibers within the BB [4]. This activation is rigorously governed by the central nervous system to ensure precise alignment between the generated force and the intended mechanical task [5]. Upon the transmission of neural signals from the brain to motor neurons, a sophisticated signaling cascade is initiated [6]. Motor neurons subsequently convey these signals to muscle fibers, triggering the release of calcium ions from the sarcoplasmic reticulum [7]. These calcium ions serve as pivotal initiators, instigating a meticulously coordinated sequence of molecular events that ultimately result

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in the synchronized sliding of actin and myosin filaments, thereby effecting the process of muscle contraction [8]. As a consequence of this muscle contraction, a mechanical force is generated. This force, in turn, induces a rotational moment at the elbow joint, providing the movement of the limb [9]. In the context of sports biomechanics, understanding these physiological intricacies is paramount.

The BB plays an important role in sports biomechanics, as it is heavily involved in a variety of upper body movements [10], [11]. In many sports, such as weightlifting [12], gymnastics [13], and rock climbing [14], the BB is used to generate force and control movements of the upper body. Overall, having a strong BB can help improve performance in many sports, by allowing athletes to generate more force and control their movements more effectively [15]. There are several methods to strengthen the BB muscle, such as resistance training [16], isometric exercises [17], and eccentric training [18]. Resistance training includes exercises such as bicep curls (dumbbell, barbell, or cable) [19], chin-ups [20], and pull-ups [21]. These exercises contract the BB by using resistance to create tension in the muscle, which can help increase muscle strength and size [22]. Isometric exercises involve contracting the muscle without any movement, such as holding a weight in a fixed position for a certain period of time. Isometric exercises can be useful for targeting specific muscle fibers and improving muscle endurance [23]. Eccentric training concentrates on the lowering phase of an exercise, during which the muscle is lengthening. This type of training can help to increase muscle strength and size, and improve muscle endurance [24].

The BB muscle undergoes various mechanical changes during strengthening exercises [25]. These changes happen due to the stress [26] that the muscle is under during weight lifting [27], which causes micro-tears in the muscle fibers, which are then repaired and rebuilt stronger and bigger [28]. It is worth mentioning that investigating the mechanical behavioral changes in the BB muscle is important for maintaining muscle health and function, preventing injuries, and optimizing performance [29]. There have been several studies that have investigated the mechanical changes of the BB muscle during different types of exercise. For example, Blemker et al. [30] investigated the mechanical properties of the BB using the finite element method. In this study, the BB was designed as a fiber-reinforced composite with transverse isotropic material symmetry. It was observed that the strain value in the fiber varied from 0.0-2.4. In addition, the highest strain value was obtained around the distal aponeurosis [30]. Knarr [31] studied inhomogeneous stresses in the BB during isometric, concentric and eccentric contractions using the finite element method. In addition, deformations in the BB muscle of eight subjects were visualized by magnetic resonance imaging technique and statistical analysis of the results was performed. Consequently, the maximum stress was obtained as -110.67 kPa at the eccentric motion [31]. Hwang et al. [32] examined the fatigue and force of the BB muscle for dumbbell curl exercise using electromyography signals. In this study, subjects repeated the dumbbell curl exercise twenty times. It should be noted that electromyography signals of weights corresponding to 20%, 35%, 50% and 75% maximum voluntary contraction levels were recorded. Consequently, it was obtained that the average integrated electromyography signal during fatigue equals approximately 250 μV [32]. Kawczyński [33] investigated the force and electromyographic responses of the BB during eccentric exercise on twenty-four subjects. This study was performed on equal numbers of athletes and non-athletes subjects. Each subject performed the eccentric exercise 25 times with dumbbells in the 50° to 180° range of motion. Thus, electromyography signals were achieved during this scenario. In addition, force measurements were obtained by means of a dynamometer. Consequently, 24% and 8% of maximum voluntary isometric and isokinetic contractions were observed in athletes and non-athletes, respectively [33]. Li et al. [34] determined the local muscle fatigue of the BB in dynamic and static contraction using numerical and experimental methods. In this study, firstly, the electromechanical behavior of the three-dimensional model of skin, fat, muscle and bone layers for the human upper arm was investigated by finite element analysis. Secondly, local muscle fatigue was evaluated on ten volunteers with the novel developed non-invasive electrical impedance myography system. Finally, it was obtained that there is a linear correlation between muscle fatigue and resistance [34]. Dereshgi et al. [35] investigated the displacement, stress and strain behavior of the BB muscle fiber using the finite element method by applying static forces between 2.5 N and 100 N in 5 N steps [35]. In another study, the same researchers examined the mechanical behavior of this muscle fiber with the dynamic forces derived from the biceps curl exercise [36]. In these studies, a linear correlation was obtained between the magnitude of the force applied to the BB muscle fiber and the displacement, stress, and strain.

There are a variety of methods that have been used to study the mechanical behavior of the BB muscle. Some studies use an isokinetic dynamometer to measure muscle force, length and velocity during isokinetic contractions [37], [38]. Others use an isometric force transducer to measure muscle force during isometric contractions [39]. Some studies use ultrasound imaging [40] to measure muscle length changes, or use electromyography (EMG) [41], [42] to measure muscle activation. Additionally, many studies have used a combination of different methods to measure muscle behavior, with the aim of obtaining a more complete understanding of muscle function. For example, a study might use an isokinetic dynamometer to measure muscle force and an EMG to measure muscle activation [43], or use ultrasound imaging to measure muscle length changes and an isometric force transducer to measure muscle force [44]. Some study also use in vivo methods to measure muscle mechanical behavior [45], which often involve surgically exposing the muscle and attaching it to a force transducer [46], or implanting

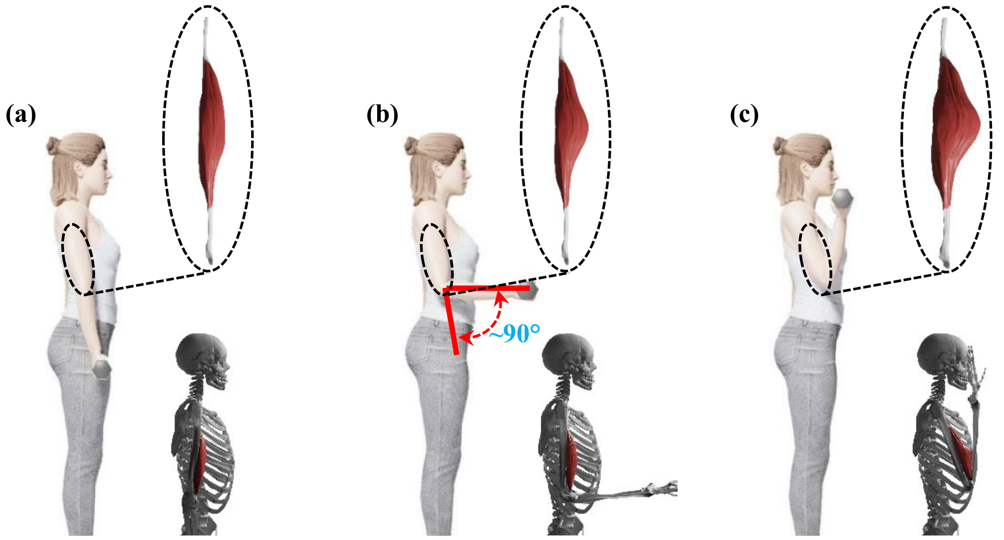

FIGURE 1. Schematic of RPBC at a) 0°, b) 90°, and c) 135°.

electrodes to measure muscle activity [47]. In general, the methods used to study the mechanical behavior of the BB muscle depend on the specific type of physical information the researchers require to obtain. In the open literature, there are many studies that typically focus on the mechanical behavior of the BB during various exercises and movements, but there are no studies supporting each other.

The purpose of this paper was to investigate the mechanical behavior changes (e.g. muscle force, muscle displacement, muscle stress, and muscle strain) in the BB muscle caused by isometric, concentric and eccentric contractions during the RPBC exercise. This study was performed on ten healthy volunteer women aged 20 to 30 years with no history of cardiovascular, neurological or upper extremity disorders. The hypothesis of this study was to simulate and accurately predict the displacement and stress distribution of the BB muscle during the RPBC exercise using the finite element method and data from reflective markers. The prominent innovation of the research was to examine the effects of isometric, concentric and eccentric contractions together on behavior change in the BB muscle during this exercise. In addition, another innovation was to obtain the desired parameters without physical contact (e.g. EMG System, dynamometer test and in vivo methods) with the muscle. The research process briefly included the following steps. First, small reflective markers were attached to the dumbbell, elbow, and shoulder joints, and then the movement of these marks was tracked as the arm moved. The positions of these markers at different time points were analyzed with the Tracker Video Analysis and Modeling Tool. It is important to note that this method require a precise setup, good lighting, and a robust calibration process to ensure the accuracy of the measurements. Second, a musculoskeletal model was performed in MATLAB Simscape Multibody program, thus muscle force and muscle activation were calculated during the exercise. Third,

TABLE 1. The demographic details of women subjects.

Subject	Age (Year)	Height (cm)	Weight (kg)	Dominant Arm
S1	28	168	58	Right
S2	24	168	60	Right
S3	23	163	63	Right
S4	28	168	60	Right
S5	21	175	76	Left
S6	26	175	75	Right
S7	29	170	57	Right
S8	23	165	54	Right
S9	22	172	90	Right
S10	20	170	60	Right

a three-dimensional model of muscle, tendon and bone tissues was provided. Finally, loads and boundary conditions were applied to the proposed model, and then equilibrium equations were calculated using the finite element analysis (FEA) to determine the stress-strain distribution. The organization of the paper is as follows. The methods of the study are described in Section II. In Section III, the results of motion analysis, muscle force and FEA simulations are presented and discussed. Finally, the concluding remarks are reviewed in Section IV.

II. MATERIALS AND METHODS

In this paper, the mechanical behavior of the BB muscle during RPBC exercise of ten women subjects with a training background was investigated. In line with ethical guidelines, informed consent was obtained from the ten women study subjects. The demographic data (see Table 1) for the young

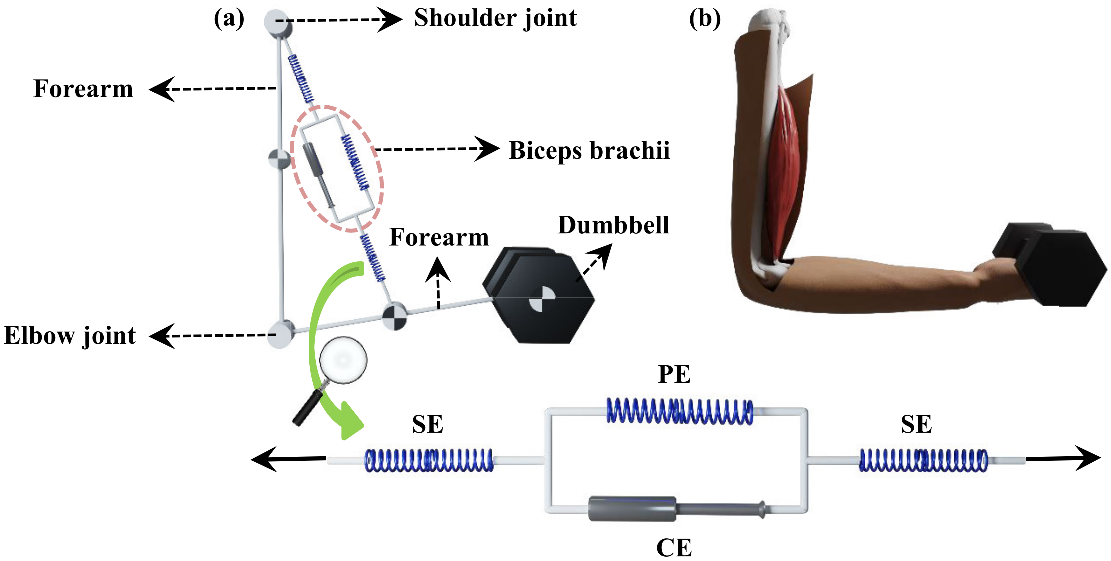

FIGURE 2. Musculoskeletal model of the RPBC. a) Link-segment presentation of the upper limb and BB, b) illustration of the RPBC.

women subjects showed a mean age of 24.4 ± 3.16 years, mean height of 169.4 ± 3.89 cm, and mean weight of 65.3 ± 11.34 kg.

In RPBC exercise, isometric, concentric and eccentric contractions occur due to range of motion and pause in rotation, respectively. In the current study, the RPBC exercise was performed in three steps (see Figure 1) to simultaneously examine the effect of these contractions on the BB muscle. In order to examine the isometric contractions of the muscle, 5-second pauses were actualized at 0° (first pause), 90° (mid pause) and 135° (final pause) range of motion. Additionally, it should be noted that the motion between 0°-90° and 90°-135° caused concentric contraction. Moreover, the reverse of this scenario was effective for eccentric contraction.

The sequence of this section is as follows. The mechanical model of the upper extremity is described in Section A. In Section B, the motion analysis of the RPBC is presented. Finally, the calculation of BB muscle force and the finite element modeling procedure are presented in Section C.

A. MUSCULOSKELETAL MODEL OF THE UPPER EXTREMITY

An inverse dynamic link-segment model was created for the RPBC dynamic analysis. The components of the model included dumbbells, forearms, upper arms, elbow joints, and shoulder joints. In addition, BB was modeled as a spring and damper element in accordance with the Hill muscle model [48]. The link-segment model is presented in Figure 2.

In this paper, the mechanical behavior of the BB muscle was simulated using the Hill type muscle model. In Hill's model, there is a contractile element that represents the active part of the muscle that produces effective force through the interaction between actin and myosin. In addition, there are two series and parallel spring elements, which represent the connective tissues of the tendon and fascia, respectively, carrying passive tension. In other words, the active force of the muscle is caused by its innervation and the occurrence of chemical processes between actin and myosin and its conversion into mechanical force. The length of the sarcomere containing actin and myosin decreases due to contraction, while the passive force is caused by the elasticity of the connective tissues of the muscle in stretching [49]. There are computational relationships for the active and passive parts of Hill's model, in which the effect of length change, contraction and activation rates of muscle fibers have been applied.

The Hill muscle model expresses muscle contraction force via Equation 1. In this equation, the muscle force is represented by "F_m", the velocity of muscle contraction is denoted as "v", "F_{max}" stands for the maximum isometric force, "a and b" are the contraction constants in this expression. The BB force that occurs during the RPBC exercise also generates a moment on the elbow joint as expressed in Equation 2. In Equation 2, the reaction moment in the elbow joint is represented by "M", and "d" signifies the distance between the connection of the BB to the forearm and the elbow joint rotation center.

$$(\vec{F_m} + a)(\vec{v} + b) = \left(\vec{F}_{max} + a\right) b \tag{1}$$

$$\vec{M} = \vec{F_m} \bullet d \tag{2}$$

The procedure of finding muscle force with Equation 1 is rather labor-intensive. In this study, the calculation of muscle force was performed using Equation 2.

The RPBC motion was simulated utilizing the MATLAB Multibody tools (see Figure 3). Here, the limbs were considered as solid bodies. The elbow was modeled as a single-degree-of-freedom rotary joint. The shoulder and wrist

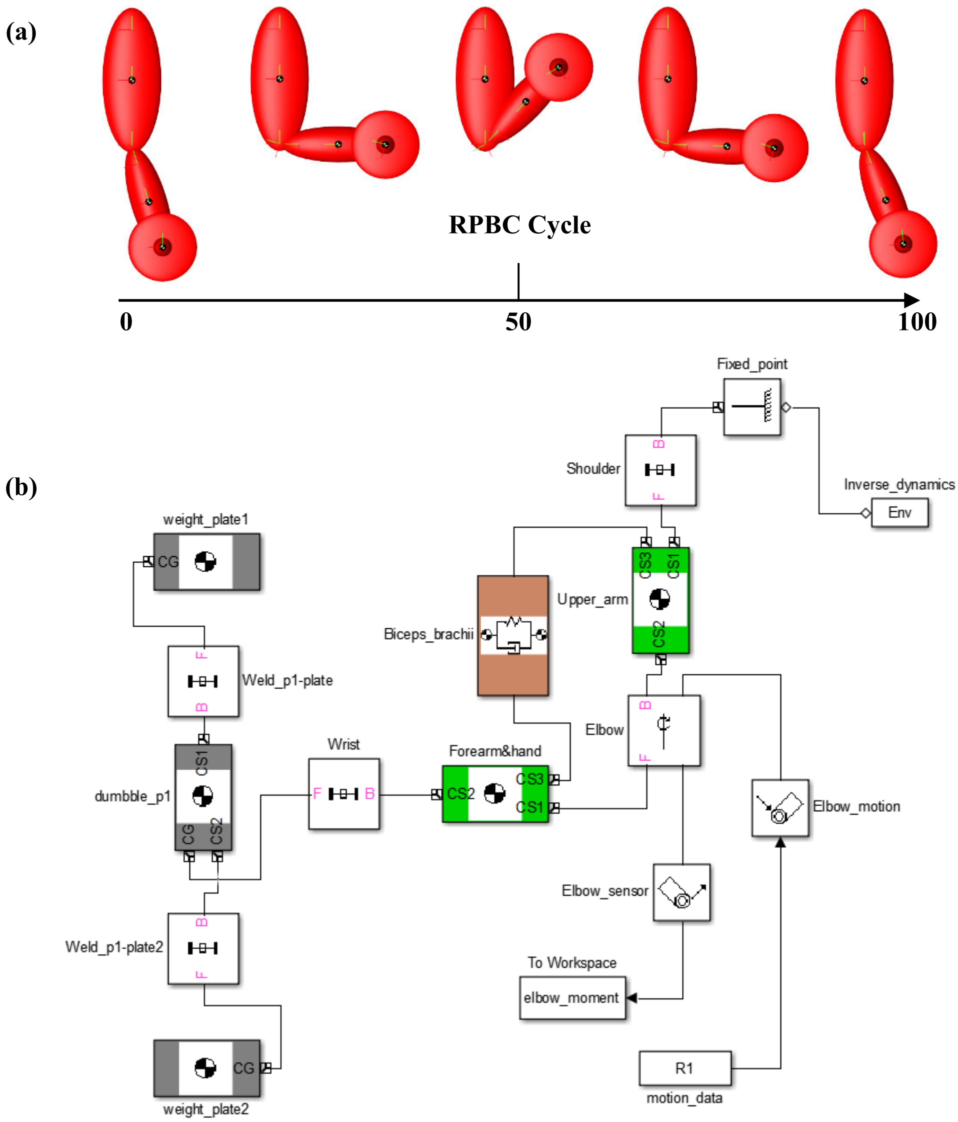

FIGURE 3. Dynamic analysis of the motion. a) Simulation view of the RPBC. b) MATLAB Multibody block diagram of the musculoskeletal model.

joint was modeled as a fixed joint. The BB was modeled as a spring and damper between the elbow and the shoulder. The stiffness of the BB, represented by "k", was 213 N/m [50], its dashpot constant (c) was 6.44 Ns/m; and the muscle-tendon length was 0.312 m [51]. The moment of inertia of the body parts was calculated by referencing the equations in [52]. The limb lengths, masses, and center of mass locations were determined by utilizing the equations described in [53].

B. MOTION ANALYSIS OF THE RPBC

The RPBC exercises were performed by a group of ten women subjects, each possessing a training background. Subjects, aged between 20 and 30, were selected based on their previous experience with resistance training to ensure a consistent fitness level within the group. In order to movement analysis, passive markers were meticulously placed on specific anatomical landmarks, including the subject's elbow and shoulder joints, as well as the dumbbell bar. The placement of markers was done according to the guidelines established by the International Society of Biomechanics [54]. Prior to data collection, a calibration procedure was carried out to ensure the accuracy of marker positions. The exercises were performed in a standing position by the subjects, with an emphasis on maintaining a controlled and consistent range of motion throughout the entire exercise. The exercises were conducted with the use of dumbbells weighing 2 kg, 3 kg, and 5 kg. The pace for the exercise movements was self-determined by the subjects. A 10-minute rest period was enforced between exercises with different weights to minimize fatigue effects. Moreover, it was important to emphasize that all tests were administered to each subject on the same day, with each test being conducted once for every subject. Additionally, as indicated in Table 1, the analysis was specifically conducted on the dominant extremity of the subjects.

The exercises were recorded using a camera with a 30 Hz image capture rate. The motion analysis measurements were calibrated using a calibration stick, and marker positions were digitized with Tracker [55] video analysis software. The software utilized was considered reliable and highly acclaimed by researchers in the field of biomechanics [56], [57]. Additionally, the use of the calibration stick during this research significantly minimized errors that were caused by the recording process. Finally, a 6 Hz low-pass filter was applied to the position data [58]. The position data of the markers was used to calculate the angular displacement, angular velocity, and angular acceleration values of the elbow joint. These values were used as input data for the drive of the elbow joint in the MATLAB blocks seen in Figure 3. The simulation of RPBC with the movement data resulted in the calculation of the elbow joint moment and BB muscle force.

C. FINITE ELEMENT MODEL OF THE BB MUSCLE

The BB, one of the dominant muscles, is a two-joint muscle located in the front of the arm. This muscle provides movement of the shoulder and elbow joints. Therefore, it is the primary muscle used to perform the RPBC exercise. This exercise causes the BB muscle to be loaded beyond its normal capacity. Thus, stress, strain and displacement occur in the muscle. In this particular study, displacement, stress and strain behavior changes in the BB muscles of ten young women subjects during this exercise were investigated using the FEA. It should be noted that despite current advances in computer technology, there are still limitations in the application of FEA for biological models. The intricate and subtle details of anatomical structures cause significant difficulties in FEA. These problems include difficulties in meshing the structure, accurately modeling the material properties, and interpreting the results of the analysis [59]. The elbow joint has a complex anatomical geometry. Therefore, in this research, three-dimensional modeling of the elbow joint with basic geometries was carried out using the COMSOL Multiphysics 5.5 program, as indicated by [35], [36], and [59], to ensure a seamless FEA implementation. The proposed boundary components of this joint are shown in Figure 4. In the illustrated model, the cubic structures, symbolizing bone elements, were intricately joined by a pair of diminutive cylindrical structures, symbolizing tendons, along with a substantial central cylinder, emblematic of the robust BB muscle.

In the analyzes, the density of the representative BB muscle was 1056 kg/m^3, the Young's modulus was 1.162×10^6 Pa, and the poison ratio was 0.4. The density of representative bone was 2570 kg/m^3, the Young's modulus was 1.0×10^{10} Pa and the poison ratio was 0.3. The density of representative tendon was 1670 kg/m^3, the Young's modulus was 1.6×10^6 Pa and the poison ratio was 0.497.

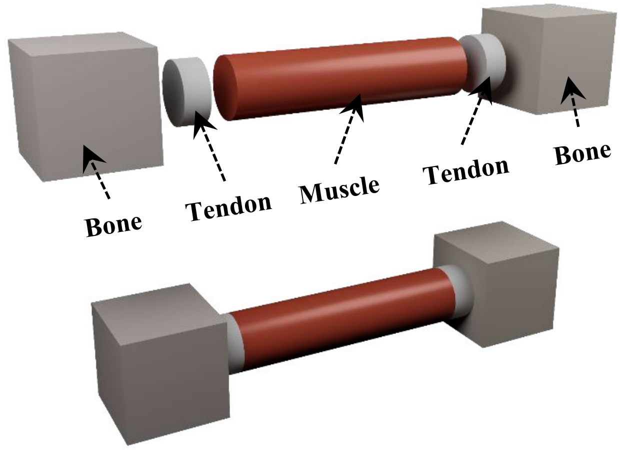

FIGURE 4. The elbow joint's configuration for FEA.

It is worth mentioning that the accuracy and validity of the analysis heavily relies on the quality of three-dimensional model, material properties and the selection of the appropriate finite element. The choice of finite element type is important in numerical analysis because different types of elements have different capabilities and limitations. In the context of modeling soft tissues such as muscle, researchers have historically used various approaches. Historically, researchers utilized simpler elements for biomechanical analyses, such as linear or quadratic elements. However, these traditional elements may not capture the nonlinear behavior of muscle tissue effectively [60]. Therefore, the selection of the appropriate element type can greatly affect the accuracy and efficiency of the analysis. It should be noted that in recent years, the four-node tetrahedron type hyperelastic element is commonly used by researchers in biological soft tissue simulations such as muscle [61], [62]. This element is shaped like a tetrahedron, which is a geometric shape with four triangular faces and four vertices. The element is used to approximate the behavior of a small volume of the muscle being analyzed, and the nodal values are used to calculate the strains and stresses within that volume. Accordingly, in this particular study, the BB muscle's nonlinear behavior was exhaustively examined through the implementation of a four-node tetrahedron-type hyperelastic element (SOLID285 element), which is a nonlinear, continuum-based approach. It is noteworthy to highlight that the stress state within the element can be determined using the Cauchy stress tensor, which relates the stress state to the deformation of the material. The Equation 3 defines the Cauchy stress tensor.

$$\sigma = 2C_1(I_1 - 3) + 2C_2(I_2 - 3) \tag{3}$$

where, "σ" is the Cauchy stress tensor, "C_1 and C_2" are material constants, "I_1 and I_2" are the first and second invariants of the right Cauchy-Green deformation tensor. The first and second invariants are defined in Equations 4 and 5,

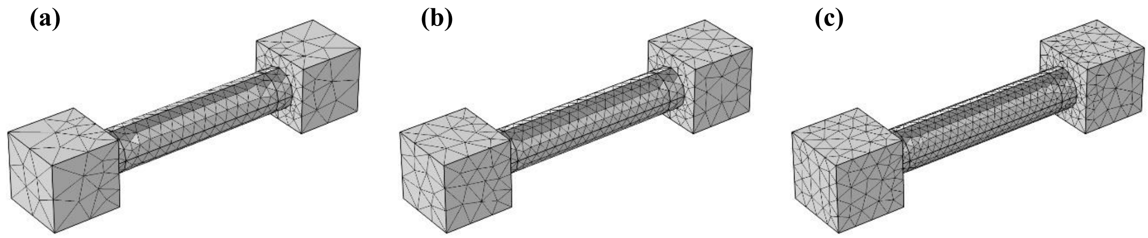

FIGURE 5. Mesh types of the elbow joint, a) Normal, b) Fine, and c) Finer.

TABLE 2. Specifications of BB's finite element model.

Domain element statistics	Number of elements	Minimum element quality	Average element quality	Element volume ratio	Mesh volume (mm^3)
Normal	2509	0.2699	0.6563	0.005855	2814000
Fine	3574	0.2169	0.66	0.01244	2826000
Finer	6770	0.2142	0.6628	0.0125	2834000

respectively.

$$I_1 = tr(C) \tag{4}$$

$$I_2 = (1/2)(tr(C)^2 - tr(C^2)) \tag{5}$$

where, "C" is the right Cauchy-Green deformation tensor and "tr" is the trace operator. It is worth emphasizing that the constants "C_1 and C_2" are material properties that can be determined through experimentation. The strain within the element was determined using the Green-Lagrange strain tensor, which relates the strain state to the deformation of the material. In Equation 6, the Green-Lagrange strain tensor is defined.

$$E = 1/2(F^T \times F - I) \tag{6}$$

where, "E" is the Green-Lagrange strain tensor, "F" is the deformation gradient tensor, and "I" is the identity tensor. The term "$F^T \times F$" represents the outer product of the deformation gradient tensor with its transpose, which gives a symmetric matrix. The subtraction of the identity tensor from this matrix gives the Green-Lagrange strain tensor. The deformation gradient tensor, "F", is a matrix that describes the local deformation of a material. It relates the position vectors of a material point before and after deformation. The identity tensor is a square matrix with 1's along the diagonal and 0's elsewhere. By specifying the geometry, material properties, mesh type and finite element equations for the elbow joint, the mesh convergence method was utilized to identify the most appropriate mesh size in order to validate the assumptions and results of the numerical analysis. In this research, three unique mesh types - Normal, Fine, and Finer - have been implemented for the BB muscle model (see Figure 5). In Table 2, the physical characteristics of the meshes are provided. The Normal mesh was the coarsest of the three meshes and had the fewest number of elements. The Fine mesh had more elements than the Normal mesh and it was

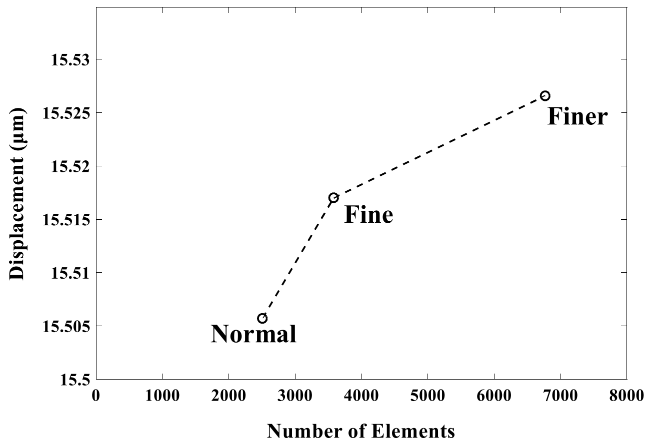

FIGURE 6. Mesh convergence analysis for the model displacement.

refined enough to capture the important details of the muscle. The Finer mesh had the most elements of the three meshes and it had the highest degree of accuracy in analysis. The mesh density, or number of elements, can affect the precision of the analysis results. However, the number of elements used to discretize the model affected the computation time. The Normal and Fine meshes had an error rate of approximately 0.072%, and the Fine and Finer meshes had a rate of about 0.061% (see Figure 6).

Eventually, Fine mesh was considered the ideal mesh to balance the accuracy and the computational cost, and analyzes were performed at a sensitivity of 0.001 depending on time. Thus, the applicability of the proposed method for predicting the mechanical behavior of the BB muscle was confirmed through the simulations and results obtained. Section III contains the results and elaborates on them.

III. RESULTS AND DISCUSSION

The elbow joint moment and BB muscle force calculated as a result of the simulation of the RPBC exercise performed

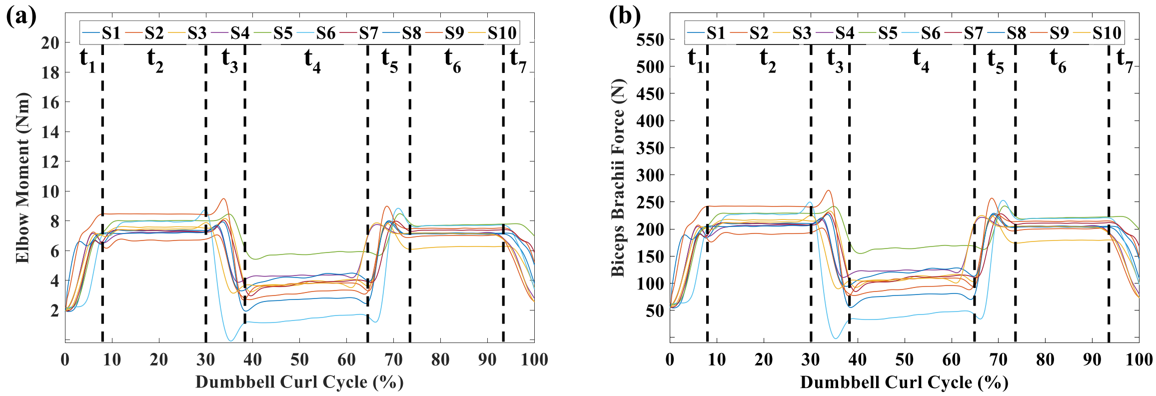

FIGURE 7. Elbow moment (a), and BB muscle force (b) of RPBC exercise at 2 kg.

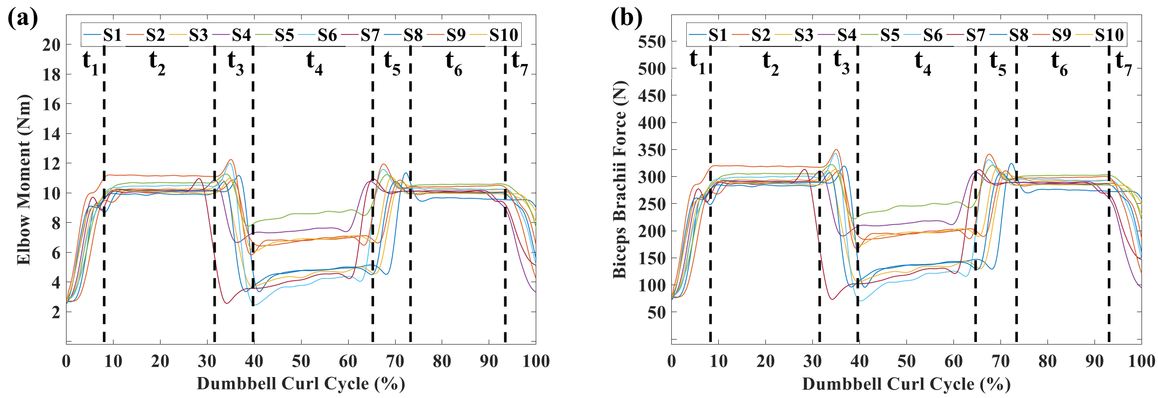

FIGURE 8. Elbow moment (a), and BB muscle force (b) of RPBC exercise at 3 kg.

with 2 kg, 3 kg and 5 kg dumbbells were shown in Figures 7, 8, and 9. The graphs encompass data from every subject. The states of the elbow joint were specified as t_1 (0° to 90°), t_2 (fixed at 90°), t_3 (90° to 135°), t_4 (fixed at 135°), t_5 (transition from 135° to 90°), t_6 (fixed at 90°), and t_7 (transition from 90° to 0°) in this study. The elbow joint performed flexion between t_1 and t_4 and extension between t_5 and t_7. The examination of the exercises performed with weights of 2 kg, 3 kg, and 5 kg revealed that the highest joint moment and muscle force were observed in the t_3 and t_5 intervals. The joint moment and muscle force in the t_2 and t_6 intervals were found to be nearly equivalent to the maximum level. Therefore, it was determined that the most arduous situations for the BB muscle occurred with a fixed elbow joint angle at 90° and during movement between 90° and 135°. The subjects' maximum muscle force during the exercises with 2 kg, 3 kg, and 5 kg weights were approximately 200-250 N, 300-350 N, and 450-500 N respectively. The mean forces generated by the BB muscle were calculated to be 169.04 N, 242.63 N, and 362.14 N in that order. Considering the maximum muscle force during RPBC, it was observed that the mean was 233.33 N at 2 kg, 319.06 N at 3 kg, and 478.80 N at 5 kg. The increase in exercise weight from 2 kg to 3 kg resulted in a 50% increase in weight. Similarly, the exercise weight increase from 3 kg to 5 kg results in a weight increase rate of 66.6%. However, an examination of the same scenarios showed that the increase in mean muscle force rate was 43.5% and 49.2%, respectively. The rate of increase in maximum muscle force was 36.7% and 50.0%. It becomes clear that the rate of increase in exercise weight and muscle force was not linear. An evaluation of the results based on different types of contractions reveals that maximum muscle force was attained at the onset of the t_3 movement phase, where the angle of the elbow joint increased from 90° to 135°, and at the onset of the t_5 movement phase, where it decreased from 135° to 90°.

The maximum muscle force was occurred during the isometric contraction at t_2 and t_6 movement phases, as determined by the mean muscle force evaluation. It was understood that the minimum muscle forces were in the isometric contraction in the t_4 movement phase, where the elbow joint angle was the largest. In addition, the muscle force in concentric contraction [63] was significantly higher compared to that in eccentric contraction. The BB muscle is the one in charge of flexing the elbow joint, and during the RPBC exercise, the muscle contracts to lift the weight and then relaxes to reduce the weight. The muscle's need to generate more force to lift heavier weights results in heightened activation and

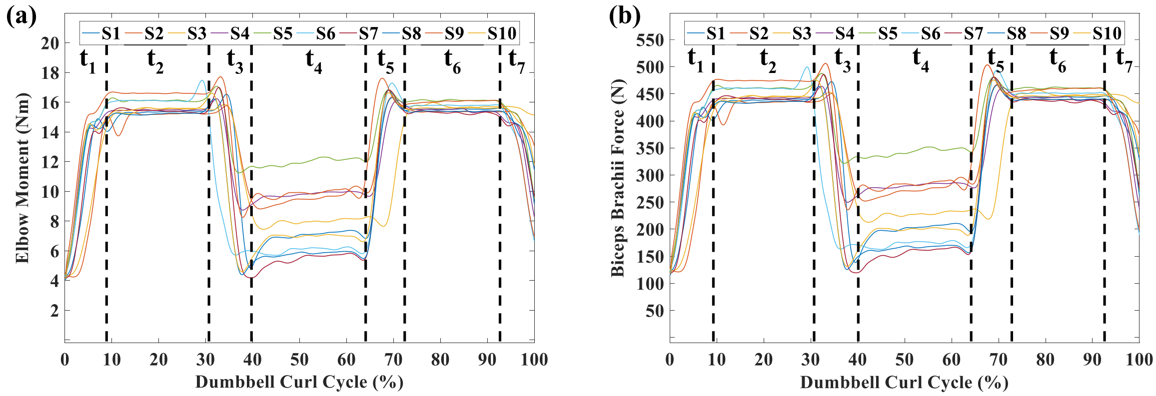

FIGURE 9. Elbow moment (a), and BB muscle force (b) of RPBC exercise at 5 kg.

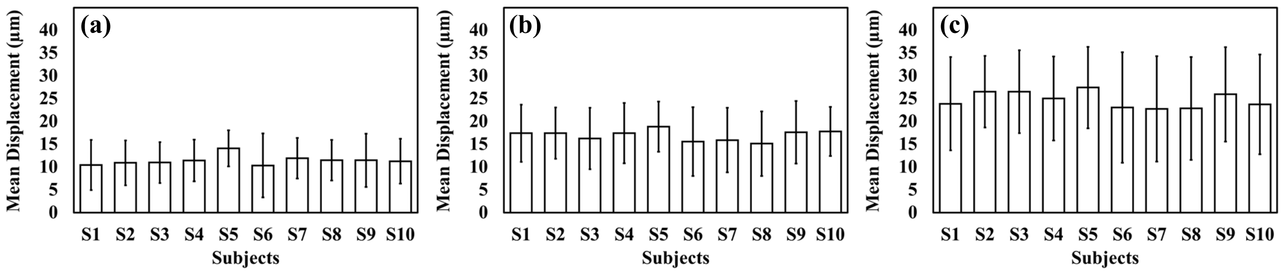

FIGURE 10. BB muscle force and displacement relationships at a) 2 kg, b) 3 kg, and c) 5 kg.

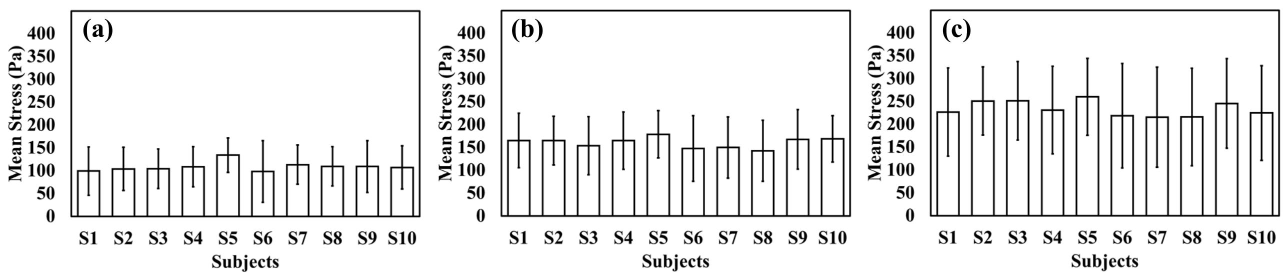

FIGURE 11. BB muscle force and stress relationships at a) 2 kg, b) 3 kg, and c) 5 kg.

contraction. The result of heightened activation and contraction is increased muscle displacement as the fibers are subjected to more demanding work.

The BB muscles of ten women with a training background were analyzed for displacement, stress and strain at 2 kg, 3 kg, and 5 kg weights during the RPBC exercise using the FEA. The mean displacement of the subjects' BB muscles during a supination is given in Figure 10. The BB muscles of the subjects exhibited maximum displacements of 18.90 μm, 25.76 μm, and 37.56 μm, respectively, in response to lifting weights of 2 kg, 3 kg, and 5 kg. The results indicated a 50% and 150% enhancement in the weights lifted by the subjects with dumbbells, accompanied by a ~38% and ~106% increase in the mean of maximum displacements value of the BB muscle. Thus, the study revealed that there was no significant linear correlation between the weight of the dumbbell and muscle displacement. Additionally, the findings showed that lifting 2 kg weights led to a lower mean displacement of the subjects' muscle in comparison to lifting 3 kg or 5 kg weights. This meant that there was a decrease in the activation and contraction of the muscles. Thus, it was comprehended that the BB muscle fibers of the subjects required minimal effort to lift a weight of 2 kg.

Furthermore, the findings revealed that the force of the BB muscles caused different displacements as the subjects lifted identical dumbbells. This was due to the linear correlation between muscle force and displacement. In addition, the RPBC exercise generates both stress and strain in the BB muscle. It is of importance to mention that stress is related to the force of the muscle fibers, and strain is related to the deformation of the muscle fibers due to this force. Figures 11 and 12 depict the stress and strain in the BB

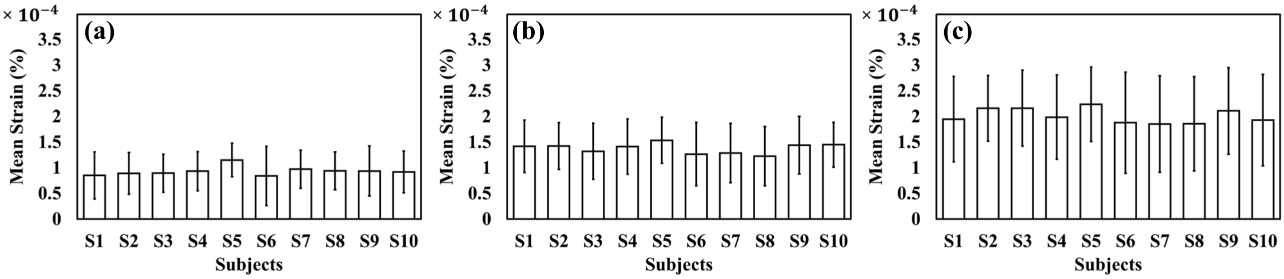

FIGURE 12. BB muscle force and strain relationships at a) 2 kg, b) 3 kg, and c) 5 kg.

muscles of the subjects as a result of lifting dumbbells of varying weights. The results of the study revealed that the maximum stress values, in ascending order of magnitude, were 180.70 Pa, 246.26 Pa, and 355.89 Pa for light (2 kg), medium (3 kg), and heavy (5 kg) dumbbells, respectively. The corresponding maximum strain values were 1.55×10^{-4}, 2.12×10^{-4}, and 3.06×10^{-4}, respectively. The mean of the maximum stress-strain values of the ten subjects increased by ~37% and ~105%, relative to the weight ratios of the dumbbells. Therefore, a non-linear correlation emerged between dumbbell weights and stress-strain behavior. Moreover, the findings indicated that the muscle fibers of the subjects underwent heightened stress and strain as they attempted to lift the weight of the dumbbells. It was understood that there was a linear correlation between stress-strain values and muscle force generation values.

Consequently, it was comprehended that the magnitude of muscle force varies according to potential factors such as muscle fiber type and training status. Individuals with a higher proportion of fast-twitch muscle fibers may experience greater muscle displacement during the exercise, as these fibers have the ability to produce more force than slow-twitch fibers. Furthermore, bicep training over time can lead to greater muscle force, and therefore greater muscle displacement, stress and strain during exercises.

IV. CONCLUSION

The BB is a two-headed muscle located in the upper arm that acts to flex the elbow and supinate the forearm. It originates from the scapula (shoulder blade) and inserts on the radius bone of the forearm. The muscle is innervated by the musculocutaneous nerve and is involved in movements such as lifting objects and arm curl exercises. This muscle can be strengthened through resistance training exercises. The RPBC exercise is a type of high-intensity, resistance training that is designed to increase BB muscle force and hypertrophy (muscle growth). The exercise involves performing a traditional biceps curl, but with a short rest period between each repetition. This allows the muscle to partially recover, allowing for more reps to be performed. In accordance with the objectives of this study, ten women subjects with a mean age of ~24 years and a background of training performed the RPBC exercise. The BB muscle force and the moment of the elbow joints were achieved as the subjects performed lifts with different dumbbell weights. In addition, the mechanical behavior changes of the BB muscles to generate the required force were obtained by the FEA. In conclusion, a linear correlation was obtained between muscle force and mechanical behavior changes. The results of this study can provide valuable insight into muscle behavior under different loads, improving our ability to design effective exercise programs, muscle training regimens, and minimize the risk of injury. The results from FEA can be used to optimize the design of BB muscle models for applications in biomechanics and injury prediction.

The results of the study involving the RPBC exercise and its effect on the BB muscle can provide insights into the use of this training technique for muscle activation and growth. The linear correlation between muscle force and mechanical behavior changes in the BB muscle indicates that the RPBC exercise is an effective way to increase muscle activation and hypertrophy. From these results, we can infer that the RPBC exercise provides an adequate stimulus for the BB muscle to generate the required force and undergo growth. This highlights the potential of the RPBC exercise as a training technique for individuals looking to improve their arm strength and size. Additionally, the results of the FEA provide valuable insights into the mechanical behavior of the BB muscle during the RPBC exercise, which can inform the design of effective training programs. This information can be useful for coaches, trainers, and fitness enthusiasts who are looking to optimize their training regimens for maximum results. In conclusion, the results of the study suggest that the RPBC exercise is an effective training technique for increasing the strength and size of the BB muscle in women. Actually, these results suggest that we could make a similar inference for males. One of the future studies will also aim to conduct a similar examination for male subjects. Finally, the insights gained from this study can be applied to inform the design of more effective training programs, muscle training regimens, and to minimize the risk of injury. Moreover, taking an in-depth look at the research methodology will offer valuable insights into the basis for the findings related to the RPBC exercise.

In future studies, the goal is to extend the model to cover the full upper body, including the hand and fingers, and to delve into more intricate exercise movements. By doing so, we can further improve our understanding of the complex mechanisms involved in resistance training and how to effectively target the BB muscle for optimal results. Moreover, we will initiate clinical investigations to gain a more profound insight into the repercussions of BB muscle behavior within an alternative demographic cohort. These prospective studies will expand our scientific exploration into clinical contexts, thereby complementing the pioneering mechanical analysis presented in this study.

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HAMID ASADI DERESHGI received the Ph.D. degree from the Department of Mechatronics Engineering, Sakarya University. He has been a Faculty Member with the Department of Biomedical Engineering, Istanbul Arel University, since 2019, where he is currently the Director of the Artificial Intelligence Studies, Application and Research Center (ArelMED-I). His research interests include haptics, robotics, mechatronics, biomechanics, implantable medical devices, MEMS scale energy harvesting for self-sustained electronic systems, and integrated microfluidics and personalized medicine.