

Sport impact on the strength of the nanoscale protein tissues under the thermal condition

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Abstract. The stability of protein tissues and protein fibers in the human muscle is investigated in the presented paper. The protein fibers are modeled via tube structures embedded in others proteins fibers like the elastic substrate. Physical sport and physical exercise play an important role in the stability of synthesis and strength of the protein tissues. In physical exercise, the temperature of the body increases, and this temperature change impacts the stability of the protein tissues, which is the aim of the current study. The mathematical simulation of the protein tissues is done based on the mechanical sciences, and the protein fibers are modeled via wire structures according to the high-order theory beams. The thermal stress due to the conditions of the sport is applied to the nanoscale protein fibers, then the stability regarding the frequency analysis is investigated. Finally, the impact of temperature change, physical exercise, and small-scale parameters on the stability of the protein tissues are examined in detail.

Keywords: thermal impact; small-scale tissues; stability analysis; protein tissues

1. Introduction

The study of various parameters affecting the muscle tissue in the human body can enhance the understanding of the characteristics of these parts of humans. It is vital to mention that the muscle fiber, the accumulation of which builds the whole muscles, can be modeled as a nanotube (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020a). Therefore, by modeling the fiber, various types of mechanical behavior of these fibers can be carried out. One of the essential characteristics of any structure is stability analysis (Ghadiri and Shafiei 2016b, Ghadiri *et al.* 2016a, b, c, d, Shafiei *et al.* 2016b).

One of the parameters that can affect the structure's stability is the temperature effect, which can be found as body temperature in muscle fiber cases (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Fakher *et al.* 2020, Li *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b, Tahir *et al.* 2021). Given this, it can refer to a paper by Mudhaffar *et al.* (2021) that studied the static bending associated with a functionally graded plate which is placed on a viscoelastic medium. The structure is considered to be in the Hygro-thermal surrounding. Also, the vibrational characteristics of a three-layered beam made of FG composites under thermal loading were investigated (Zaitoun *et al.* 2021). By employing higher-order theories, the three-layered plate whose core is FG porous and face sheets are piezoelectric was modeled in order to present its vibrational analysis (Arshid *et al.* 2021). It is assumed that the plate is on an elastic foundation and under thermal load. Additionally,

Merazka *et al.* (2021) conducted research on the static bending of FG plates placed on a substrate and in a Hygro-thermal environment. The thermally affected beams made of functionally graded porous material were formulated to investigate its buckling and stability response (Bellifa *et al.* 2021). By considering the effects related to Hygro-thermal surroundings, the static analysis associated with an FG plate was carried out (Tounsi *et al.* 2020). Refrafi *et al.* (2020), by taking into account the impact of the thermal environment, studied the buckling characteristics of a three-layered plate which placed on an elastic medium.

Recently, the use of a numerical solution procedure, the Generalized differential quadrature method (GDQM), has been raised in mechanical studies as it can solve various problems with high complexity (Al-Furjan *et al.* 2020c, d, f, Bai *et al.* 2020, Li *et al.* 2020a, Naderi *et al.* 2020, Zhang *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021a, Naderi *et al.* 2021). In this regard Al-Furjan *et al.* (2021) investigated the static analysis associated with a reinforced composite disk with the help of DQM and higher-order theory. Also, the dynamic stability associated with a disk which is rotating was presented through DQM as well as modified couple stress (Huang *et al.* 2021b). Next, it can refer to a work investigating the vibrational behavior related to a three-layered structure placed on a two-parameter foundation whose core was made of the honeycomb structure (Al-Furjan *et al.* 2020g). The solution procedure in the abovementioned article was DQM. Additionally, another paper that utilized DQM is the paper by Shariati *et al.* (2021) studied the vibration along with the dynamic stability of viscoelastic nanotubes. Also, by employing Von Karman theory and DQM, the buckling behavior of a disk made of reinforced composites coupled with a piezo layer was presented (Al-Furjan *et al.* 2022b). In addition, by incorporating the perturbation approach as well as GDQM,

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the nonlinear vibration of a disk which is subjected to thermal loading and made of reinforced composites was analyzed (Al-Furjan *et al.* 2022a).

Investigation of the structures in nanostructures has been at the center of researchers' attention in the past few years (Balubaid 2019, Hashemi *et al.* 2019, Al-Furjan *et al.* 2020e, Cheshmeh *et al.* 2020, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020b, Kumar *et al.* 2021). By using the Donnell shell theory, the vibrational behavior of a nanotube was investigated through nonlocal elasticity (Asghar *et al.* 2020). On the basis of the integral nonlocal model, the Bucklin analysis associated with graphene sheet which is placed in a viscoelastic medium was presented (Bellal *et al.* 2020). The formulation corresponded to the buckling behavior of a graphene sheet, which is placed in a viscoelastic medium, was obtained based on FSDT (Rouabhia *et al.* 2020). Also, Heidari *et al.* (2021) carried out an investigation on the mechanical behavior of reinforced composite with carbon nanotubes. Additionally, by utilizing HSDT, the bending analysis associated with reinforced nanocomposites was investigated through the rule of the mixture (Zerrouki *et al.* 2021). With considering the flexoelectricity effect, Soleimani-Javid *et al.* (2021) examined the vibrational behavior of a three-layered plate with a honeycomb core. In addition, the static stability of a panel which is curved in two directions and made of reinforced composites was explored by Huang *et al.* (2021e). Next, it can refer to a paper in which the vibration of functionally graded multilayer nanoplates was presented through nonlocal elasticity (Van Vinh and Tounsi 2021).

The muscle fiber is at the mercy of exercise, and thus this factor is one of the most crucial parameters in exploring muscle fibers' behavior. In this regard, the effect of strength and endurance exercise on the muscle tissues was investigated by Kazior *et al.* (2016). Also, the impact of daily exercise on the muscles related to the Skelet of the body was presented (Ubaida-Mohien *et al.* 2019). In this paper, specifically, investigated whether exercise can prevent muscle loss from aging. Additionally, the effect associated with two different types of exercises, resistance training in addition to high-intensity interval training, on the hypertrophy as well as strength of muscles was explored (Sabag *et al.* 2018). In addition, the influence related to the duration of endurance exercise on the hypertrophy of muscles was presented by Shirai *et al.* (2021).

The stability of protein tissues and protein fibers in the human muscle is investigated in the presented paper. The muscles are modeled as a nanotube based on nonlocal strain gradient theory as well as higher-order beam theory. The effect of body temperature on the nanotubes' stability is explored. The nanotube is assumed to be embedded in an elastic foundation with two parameters. The formulations are obtained through the energy method, and then solved via the GDQM solution procedure. The results are validated by means of other published articles. The impact of various parameters such as physical activities, temperature change, foundation parameters, nonlocality, and strain gradient parameter on the dynamic stability of the nanotubes is explored.

2. Mechanical simulation of protein tissues

The chain made of amino-acid, $-\text{NH}-\text{CHR}-\text{CO}-$, makes the muscle proteins varies in types by changing the succession R. Between $-\text{CO}-\text{NH}-$ groups, Hydrogen bonding can happen (Roslan *et al.* 2017, Hou *et al.* 2021a, Zou *et al.* 2021, Chen *et al.* 2022b, Ji *et al.* 2022).

Proline and are two amino acids which are relevant. Cysteine can make cross-links in the chains, and Proline, by replacing $-\text{H}$ in $-\text{NH}-$ and joining $-\text{CH}_2-\text{CH}_2-\text{CH}_2-$ can make a ring that distorts the chain (Habibi *et al.* 2017, 2019c, Safarpour *et al.* 2018, 2020, Ghazanfari *et al.* 2020).

The molecules can take up two types of crystal lattice. These can be related to ideal forms that would be taken up by simple polypeptides with repetitions of a single simple side-group, such as $-\text{H}$ or $-\text{CH}_3$. The amorphous globular forms are more diverse (Hearle 2007). The three basic forms are:

- While, because of the size in addition to the activity of the side-groups, general deviations as well as bigger local disturbances can occur, Coiled crystals approximate Pauling's ideal α -helix. In such intermediate filaments (IFs) as fibrils which is in the wool, coiled coils form in multiple twisting of pairs from a dimer to the 32 molecules in the IF (Habibi *et al.* 2019a, Safarpour *et al.* 2019b, Alipour *et al.* 2020, Ebrahimi *et al.* 2020, Chen *et al.* 2022a).

- Crystalline β -sheets, whose shape is deformed from the ideal form corresponded to fully extended molecules (Habibi *et al.* 2018a, 2019b, d, e, Pourjabari *et al.* 2019, Safarpour *et al.* 2019a).

- A lots of form related to globular molecules. Although the interaction of particular amino-acid sequences can lead to specific forms, which are irregular but as deterministic as a crystal, in the simplest form, these would be random coils of flexible molecules, which act as typical rubbers (Habibi *et al.* 2016, 2018b, Ebrahimi *et al.* 2019, Esmailpoor Hajilak *et al.* 2019).

One of the phenomenal things happen in nature is the forming of these tissues (Hearle 2007). Fig. 1 shows a protein fiber (lipid nano-tubule), composed of rolling lipid bilayer around a cylinder (Alizadeh-Hamidi *et al.* 2021). Herein, R , h , and L are the radius, thickness, and length of the lipid nano-tubule, respectively. The behavior of this lipid bilayer is a temperature-dependent phenomenon. The muscle cell, muscle fiber, contains protein filaments of actin and myosin that slide past one another, producing contractions that move body parts, including internal organs. Although muscles produce heat energy, they also require energy to perform their functions. Muscles are predominantly powered by the oxidation of fats and carbohydrates, but anaerobic chemical reactions are also used. These chemical reactions produce adenosine triphosphate (ATP) molecules that are used up by myosin filaments during muscle contractions (Liu *et al.* 2020b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Liu *et al.* 2021b, Zhang *et al.* 2021).

The thermo-mechanical dynamic behavior of lipid nano-carriers is a function of temperature, and the temperature variations play an important role in stability of protein

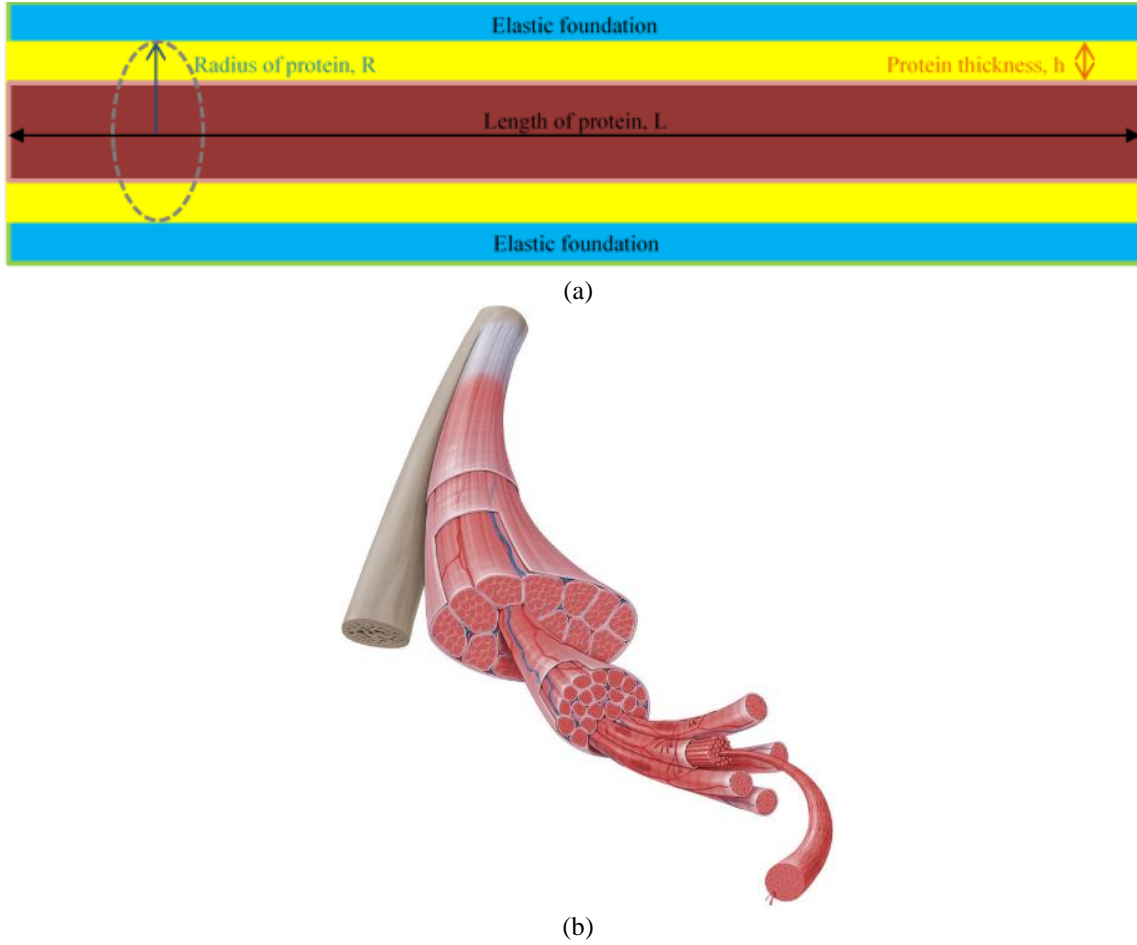


Fig. 1 (a) Schematic of protein tissue modeled in this study, (b) Schematic of protein fiber in the muscle (Aghoghovwia 2020).

tissues. This study modeled a fiber protein embedded in an elastic foundation via tube structures made of protein nanotubules (Liu *et al.* 2020a, Wang *et al.* 2020, Zhou *et al.* 2020, Dai *et al.* 2021a, Guo *et al.* 2021a, Shao *et al.* 2021, Wu and Habibi 2021).

2.1 Generation of motion equations

In order to derive the motion equations of cylindrical protein tissue, the principle of Hamilton is employed, which is exemplified in follows (Zhao *et al.* 2021, Huang *et al.* 2021c, Jiao *et al.* 2021, Moradi *et al.* 2021, Xu *et al.* 2021)

$$\int \delta H dt = \int \delta K + \delta W - \delta S dt = 0 \quad (1)$$

where ‘K’ is the kinetic energy, ‘S’ is the strain energy, and ‘W’ is the energy of the external work. In the presented research, the high-order theory of tube is utilized in order to mathematical modeling of the protein tissues behavior, that the strain energy due to the supposed theory is obtained as follows (Ma *et al.* 2021, Hou *et al.* 2021b, Huang *et al.* 2021d, Liu *et al.* 2021c, Yu *et al.* 2022):

$$S = \frac{1}{2} \iiint \sigma : \epsilon dv \quad (2)$$

where ‘ε’ is the strains which are defined as follows:

$$\epsilon_{xx} = \frac{\partial u_1}{\partial x} = u_{,x} - zw_{,xx} + \vartheta(y, z)(w_{,xx} + \psi_{,x}) \quad (3a)$$

$$\epsilon_{xy} = \frac{1}{2}(u_{1,y} + u_{2,x}) = \frac{1}{2}\vartheta_{,y}(w_{,x} + \psi) \quad (3b)$$

$$\epsilon_{xz} = \frac{1}{2}(u_{1,z} + u_{3,x}) = \frac{1}{2}\vartheta_{,z}(w_{,x} + \psi) \quad (3c)$$

Here, on the basis of the high-order tube theory, ‘u₁’, ‘u₂’, and ‘u₃’ are defined as follows:

$$u_1(x, y, z, t) = -zw_{,x} + u + \vartheta(z, y)(\psi + w_{,x}) \quad (4a)$$

$$u_2(x, y, z, t) = 0 \quad (4b)$$

$$u_3(x, y, z, t) = w \quad (4c)$$

Moreover,

$$\vartheta = z + z \left(R_0^2 R_i^2 r^{-2} - \frac{r^2}{3} \right) / (R_0^2 + R_i^2) \quad (5)$$

where

$$z = r \sin(\theta), y = r \cos(\theta) \quad (6)$$

Also, stresses are represented as follows:

$$\sigma_{ij} = E\varepsilon_{ij}, i = j \tag{7a}$$

$$\sigma_{ij} = G\varepsilon_{ij}, i \neq j \tag{7b}$$

$$G = \frac{1}{2}E(1 + \nu)^{-1} \tag{7c}$$

The virtual strain energy is obtained via substituting Eqs. (7) and (3) into Eq. (2). The Kinetic energy of a protein tissues on the basis of the high-order tube theory is represented as follows (Shafiei and She 2018, Shafiei *et al.* 2019, 2020):

$$\delta K = \int_V \rho (\dot{u}_1 \delta(\dot{u}_1) + \dot{u}_3 \delta(\dot{u}_3)) dV + \int_0^L \left\{ \begin{aligned} & m_3 \left(\dot{w}_x \delta(\dot{w}_x) + \dot{\psi} \delta(\dot{w}_x) \right) \\ & + \dot{w}_x \delta(\dot{\psi}) + (\dot{\psi}) \delta(\dot{\psi}) \\ & - m_2 (\dot{\psi} \delta(\dot{w}_x) + 2\dot{w}_x \delta(\dot{w}_x) + \dot{w}_x \delta(\dot{\psi})) \\ & + m_1 \dot{w}_x \delta(\dot{w}_x) + m_0 (\dot{u} \delta(\dot{u}) + \dot{w} \delta(\dot{w})) \end{aligned} \right\} dx \tag{8}$$

where

$$(m_0, m_1, m_2, m_3) = \int_A \rho(x, r) (1, z^2, z\vartheta, \vartheta^2) dA \tag{9}$$

In the present research, the external force is due to the thermal forces of the exercise activities, since the physical activities increases the blood flow and temperature in the body and muscle and protein tissues, so the Energy of the external work regarding to the thermal impact is computed as follows.

$$W = \int_0^L \left(\left(\iint E\alpha\Delta T dA - K_p \right) w_x \right) dx + K_w \delta(w) + \left(\iint E\alpha\Delta T dA - K_p \right) w_x \Big|_0^L \delta(w) \tag{10}$$

where, ‘ α ’ is thermal expansion coefficient, ‘ K_w ’ and ‘ K_p ’ are the Winkler and Pasternak foundation constant.

2.2 Applying the small-scale theory

Nonlocal strain gradient theory (NSGT) is one of the most accurate size-dependent theory which includes both softening and hardening phenomena is used in the present research. The presented theory which is introduced by Lim *et al.* (2015) impacts the stresses in the following form:

$$[1 - (ea)^2 \nabla^2] \sigma_{ij} = (1 - l^2 \nabla^2) C : \varepsilon_{ij} \tag{11}$$

where the tensor of elastic modulus is denoted by ‘ C ’, ‘ ea ’ is the nonlocal parameter, ‘ l ’ is the gradient strain parameter, and ‘ ∇ ’ is the Laplace operator (Ebrahimi and Shafiei 2017, Ghadiri *et al.* 2017e, Mirjavadi *et al.* 2017a, Shafiei and Kazemi 2017a, Shafiei *et al.* 2017d, Azimi *et al.* 2018). According to the nonlocal strain gradient theory, by substitution of the virtual strain energy (Eq. (3)), the virtual Kinetic energy (Eq. (8)) and virtual energy of external work (Eq. (10)) into the Hamilton principle (Eq. (1)), also, according to the Euler-Lagrange procedure, the following motion equations along with the related boundary conditions are obtained (Ehyaei *et al.* 2017, Ghadiri *et al.*

2017c, d, c, Mirjavadi *et al.* 2017d, Shafiei and Kazemi 2017b):

$$A_{11}u'' - l^2 A_{11}u'''' = m_0 \ddot{u} - (ea)^2 m_0 \ddot{u}'' \tag{12a}$$

$$Qw''' - l^2 Qw'''' - B_{11}(w' + \psi) + l^2 B_{11}(\psi'' + w''') - E_{11}\psi'' - l^2 E_{11}\psi'''' = I_2 \ddot{w}' + m_3 \ddot{\psi} - (ea)^2 (\ddot{w}''' + \ddot{\psi}''') \tag{12b}$$

$$\begin{aligned} & -l^2 [Dw'''' + Q\psi'''' - (B_{11}\psi''' + B_{11}w''''')] \\ & - \left(\iint E\alpha\Delta T dA \right) w'' + (ea)^2 \left(\iint E\alpha\Delta T dA \right) w'''' \\ & - K_w w + K_p w' + (ea)^2 (K_w w'' - K_p w''') \\ & Dw'''' + Q\psi'''' - B_{11}(w'' + \psi') = I_1 \ddot{w}'' - m_0 \ddot{w} + I_2 \ddot{\psi}' \\ & - (ea)^2 (I_1 \ddot{w}'''' - m_0 \ddot{w}'' + I_2 \ddot{\psi}''') \end{aligned} \tag{12c}$$

In which

$$I_2 = -m_2 + m_3 \tag{13a}$$

$$I_1 = -2m_2 + m_1 + m_3 \tag{13b}$$

$$D = -2C_{11} + D_{11} + E_{11} \tag{13c}$$

$$Q = -C_{11} + E_{11} \tag{13d}$$

where

$$(A_{11}, C_{11}, D_{11}, E_{11}) = (1, z\vartheta, z^2, \vartheta^2) dA \tag{14a}$$

$$B_{11} = \int_A K_s G (\vartheta_y^2 + \vartheta_z^2) dA \tag{14b}$$

In which, ‘ K_s ’ is the factor of the geometry correction that is described as follows for the pipes and tube structures.

$$K_s = K_{SA}/K_{SB} \tag{15a}$$

$$\xi = \frac{R_i}{R_o} \tag{15b}$$

$$K_{SA} = 6(1 + \xi^2)^2(1 + \nu)^2 \tag{15c}$$

$$K_{SB} = 4\xi^2(5 + 10\nu + 4\nu^2) + (7 + 14\nu + 8\nu^2)(1 + \xi^2)^2 \tag{15d}$$

Boundary conditions are:

$$(\delta u), A_{11}u' = 0 \tag{16a}$$

$$\delta(\psi), Qw'' + E_{11}\psi' = 0 \tag{16b}$$

$$\delta(w), B_{11}(\psi + w') - Q\psi'' - Dw'''' = 0 \tag{16c}$$

$$\delta \left(\frac{\partial w}{\partial x} \right), Dw'' + Q\psi' = 0 \tag{16d}$$

3. Solution methodology

A numerical approach is used to solve the governing equations of the two-dimensional functionally graded porosity-dependent non-uniform pipe. In this study, the generalized differential quadrature method (GDQM) was employed to handle and generate the numerical results. Based on the GDQM, the eigenvalue problem is solved

according to the following format.

$$\{[K] - \omega^2[M]\}\{\lambda\} = 0 \tag{17}$$

$[K]$ is the stiffness matrix, and $[M]$ is the mass matrix, ‘ ω ’ is the natural frequency, and ‘ λ ’ is the mode shape (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b). By applying the GDQM, the eigenvalue problem is changed to the following format:

$$-l^2 A_{11} \sum_{s=1}^n C_{rs}^{(4)} u_s + A_{11} \sum_{s=1}^n C_{rs}^{(2)} u_s = \omega^2 m_0 \left(-(ea)^2 \sum_{s=1}^n C_{rs}^{(2)} u_s + u_s \right) \tag{18a}$$

$$\begin{aligned} & -B_{11} \left(\sum_{s=1}^n C_{rs}^{(1)} w_s + \psi_s \right) + Q \sum_{s=1}^n C_{rs}^{(3)} w_s \\ & \quad + E_{11} \sum_{s=1}^n C_{rs}^{(2)} \psi_s \\ & + l^2 \left(B_{11} \sum_{s=1}^n C_{rs}^{(3)} w_s + B_{11} \sum_{s=1}^n C_{rs}^{(2)} \psi_s \right) \\ & - l^2 \left(Q \sum_{s=1}^n C_{rs}^{(5)} w_s + E_{11} \sum_{s=1}^n C_{rs}^{(4)} \psi_s \right) \\ & = \omega^2 \left(I_2 \sum_{s=1}^n C_{rs}^{(1)} w_s + m_3 \psi_s \right) - \\ & \omega^2 (ea)^2 \left(I_2 \sum_{s=1}^n C_{rs}^{(3)} w_s + m_3 \sum_{s=1}^n C_{rs}^{(2)} \psi_s \right) \end{aligned} \tag{18b}$$

$$\begin{aligned} & (ea)^2 \left(\iint E \alpha \Delta T dA - K_p \right) \sum_{s=1}^n C_{rs}^{(4)} w_s \\ & \quad + Q(x) \sum_{s=1}^n C_{rs}^{(3)} \psi_s \\ & + l^2 B_{11} \left(\sum_{s=1}^n C_{rs}^{(3)} \psi_s + \sum_{s=1}^n C_{rs}^{(4)} w_s \right) - B_{11} \sum_{s=1}^n C_{rs}^{(1)} \psi_s \\ & - l^2 \left(Q(x) \sum_{s=1}^n C_{rs}^{(5)} \psi_s + D \sum_{s=1}^n C_{rs}^{(6)} w_s \right) \\ & \quad - B_{11} \sum_{s=1}^n C_{rs}^{(2)} w_s \\ & + D \sum_{s=1}^n C_{rs}^{(4)} w_s - \left(\iint E \alpha \Delta T dA - (ea)^2 K_w \right) \sum_{s=1}^n C_{rs}^{(2)} w_s \\ & \quad - K_w w \\ & = \omega^2 \left(I_2 \sum_{s=1}^n C_{rs}^{(1)} \psi_s - m_0 w_s + I_1 \sum_{s=1}^n C_{rs}^{(2)} w_s \right) \\ & \quad + K_p w_{,xx} \\ & \omega^2 (ea)^2 \left(I_2 \sum_{s=1}^n C_{rs}^{(3)} \psi_s - m_0 \sum_{s=1}^n C_{rs}^{(2)} w_s \right. \\ & \quad \left. + I_1 \sum_{s=1}^n C_{rs}^{(v)} w_s \right) \end{aligned} \tag{18c}$$

where ‘ n ’ is the number of grid points, and on the basis of

Table 1 Geometrical parameters and material properties of different types of protein tissues (Alizadeh-Hamidi *et al.* 2021)

Type of tissues	Young’s modulus (Pa)	Thickness (nm)	Radius (nm)
A	610e6	66	257.5
B	715e6	52.8	249.3
C	960e6	39.6	246.3
D	1440e6	24.4	236.2

Table 2 The density (ρ), heat conductivity coefficient (k), and specific heat capacity (c_p) for protein tissues (Alizadeh-Hamidi *et al.* 2021)

	Density (ρ)	1100(Kg/m ³)
Heat conductivity coefficient (k)	0.25 (W/m.K)	
Specific heat capacity (c_p)	2.3(KJ/Kg.K)	

Table 3 Comparison of the dimensionless frequency ($\omega L^2 Ro^{-1} \sqrt{(\rho E^{-1})}$) of high-order nanotube structure of current study with results of Shafiei and She (2018) versus the different boundary conditions in the thermal environment, $L=40nm$, $Ro=1nm$, $Ro=30Ri$, $ea/L=1$, $1/L=0.25$, $\Delta T=30$

	Current study	Shafiei and She (2018)
Fully clamped nanotube	25.25538529	25.25286
Fully simply supported nanotube	10.60196009	10.6009
Clamped-Simply supported nanotube	17.20092992	17.19921

the GDQM, $\frac{\partial^p f}{\partial x^p} = \sum_{s=1}^n C_{rs}^{(p)} f$ is the definition of an q -th order derivative function of ‘ f ’, which is defined as follows (Ebrahimi and Shafiei 2016, Shafiei *et al.* 2016c, d, f, Ebrahimi *et al.* 2017, Shivanian *et al.* 2017):

$$\begin{aligned} C_{ii}^{(p)} &= - \sum_{j=1, i \neq j}^n C_{ij}^{(p)}, i = j \\ C_{ij}^{(p)} &= p \left[- \frac{C_{ij}^{(p-1)}}{(x_i - x_j)} + C_{ij}^{(1)} C_{ij}^{(p-1)} \right], i \neq j \end{aligned} \tag{19}$$

where

$$\begin{aligned} C_{ij}^{(1)} &= - \sum_{j=1, i \neq j}^n C_{ij}^{(1)}, i = j \\ C_{ij}^{(1)} &= \tilde{M}(x_j) [(x_i - x_j) \tilde{M}(x_j)]^{-1}, i \neq j \end{aligned} \tag{20}$$

In which

$$\tilde{M}(x_i) = \prod_{j=1, j \neq i}^n (x_i - x_j) \tag{21}$$

where the Chebyshev-Gauss-Lobatto method is used to determine the mesh point distribution as follows (Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al.* 2016a, e, g):

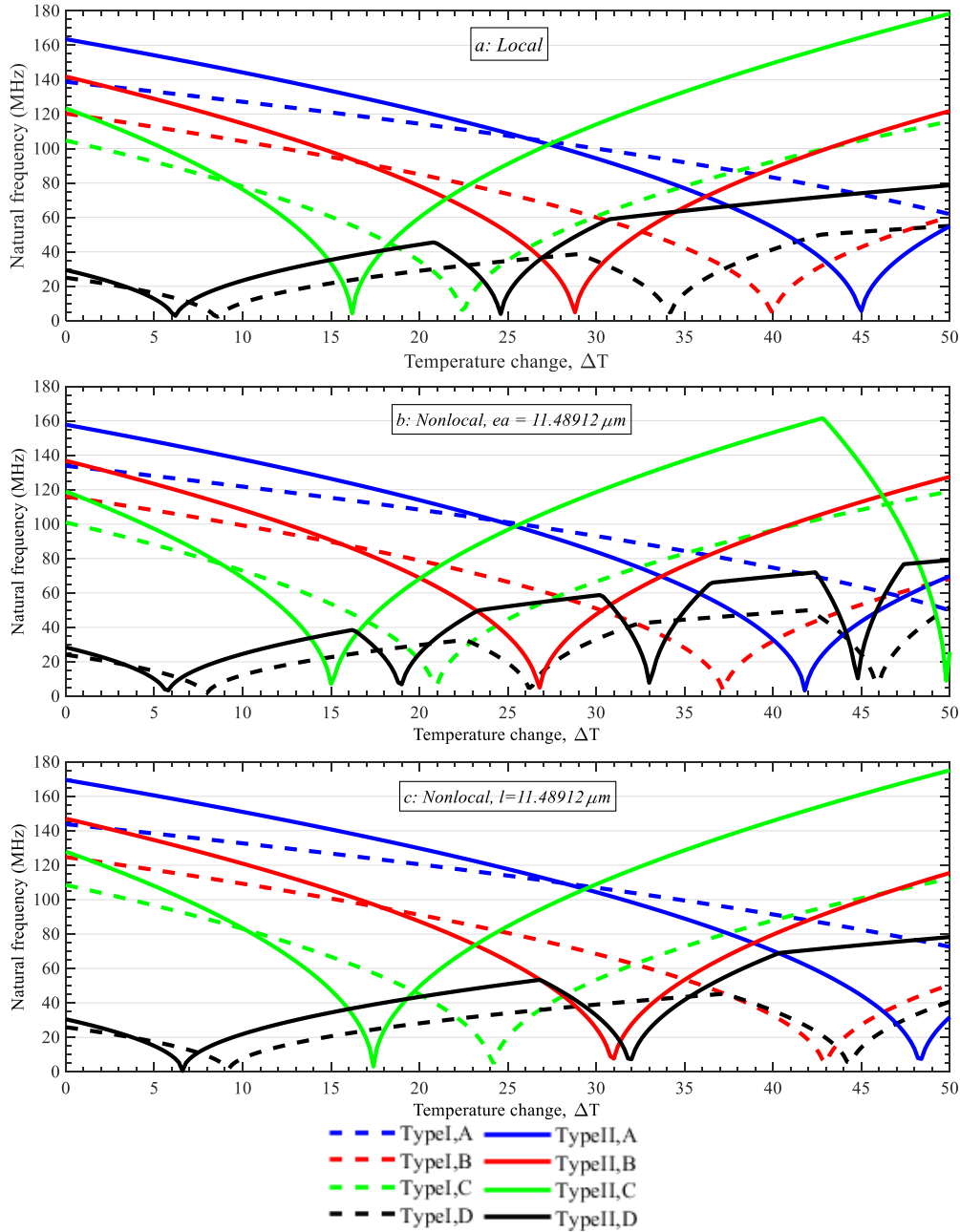


Fig. 2 Effect of the small-scale parameters, including the nonlocal (ea) and gradient strain (l) parameters, on the frequency of protein tissues for different types of protein tubules versus the temperature change (ΔT) in the natural muscle size (typeI) and while they are enhanced by physical activities (typeII), $L/R=25$

$$2x_i = L(1 - \cos(\pi(i - 1)(n - 1)^{-1})) \quad (22)$$

4. Discussion of results

As it was shown that the effect of strength exercise and endurance one is different on the anabolic response Kazior *et al.* (2016) by taking two groups, one only performed resistance exercise for 7 weeks (R, $n = 7$) and the other did this in addition to continuous and interval cycling (ER, $n = 9$). Investigation showed that leg-press with 30%, $P < 0.05$ was observed for both groups, while ER showed an

increase in oxygen uptake (8%, $P < 0.05$). type 1 and 2 of muscle fibers got bigger in ER group, while only type one was subjected to change in E. Also, only in ER, the mean fiber area increase by 28% ($P < 0.05$). mTOR protein was the only type to be increased in E group, whereas ER enhanced Akt and mTOR protein. Also, it was exhibited that variation in Akt and mTOR is dependent on mean fiber area ($r = 0.55 - 0.61$, $P < 0.05$) as well as type 1 fiber area ($r = 0.55 - 0.61$, $P < 0.05$), which proves the crucial role of proteins in muscle hypertrophy. The level of MAFbx protein ($P < 0.05$) is diminished in both groups, while they elevate MuRF-1. Furthermore, It is exhibited that the bigger hypertrophy related to ER group is because of pronounced stimulation

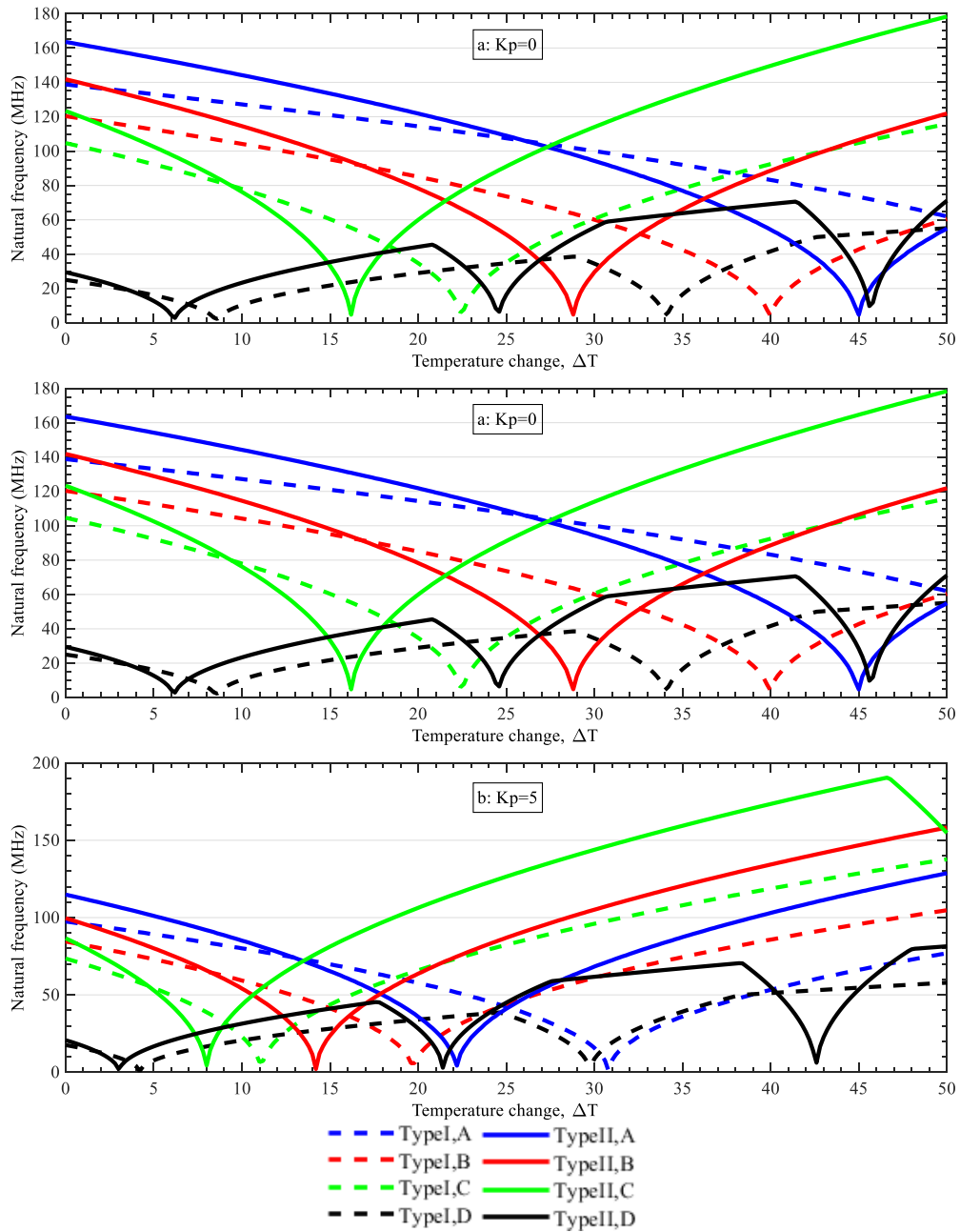
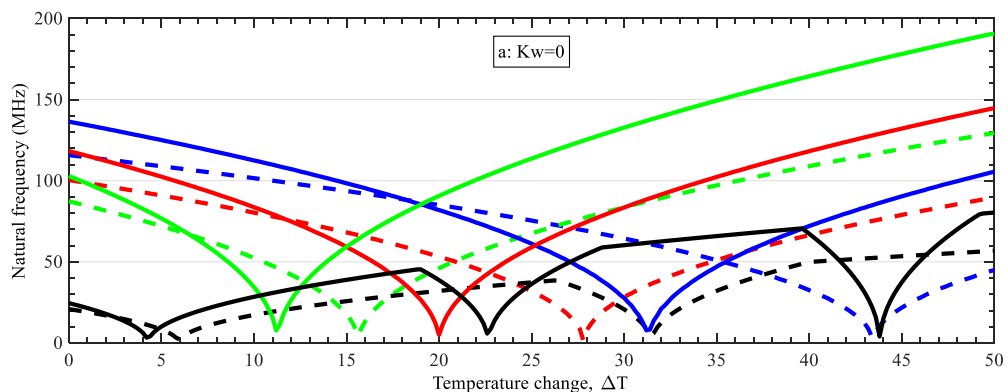


Fig. 3 The impact of elastic foundation regarding the Pasternak type of substrate (K_p) on the frequency of protein structures versus the temperature change (ΔT) as well as different protein types (A,B,C,D) in the natural muscle size (typeI) and while they are enhanced by physical activities (typeII), $ea=l=1.149\mu\text{m}, L/R=25$



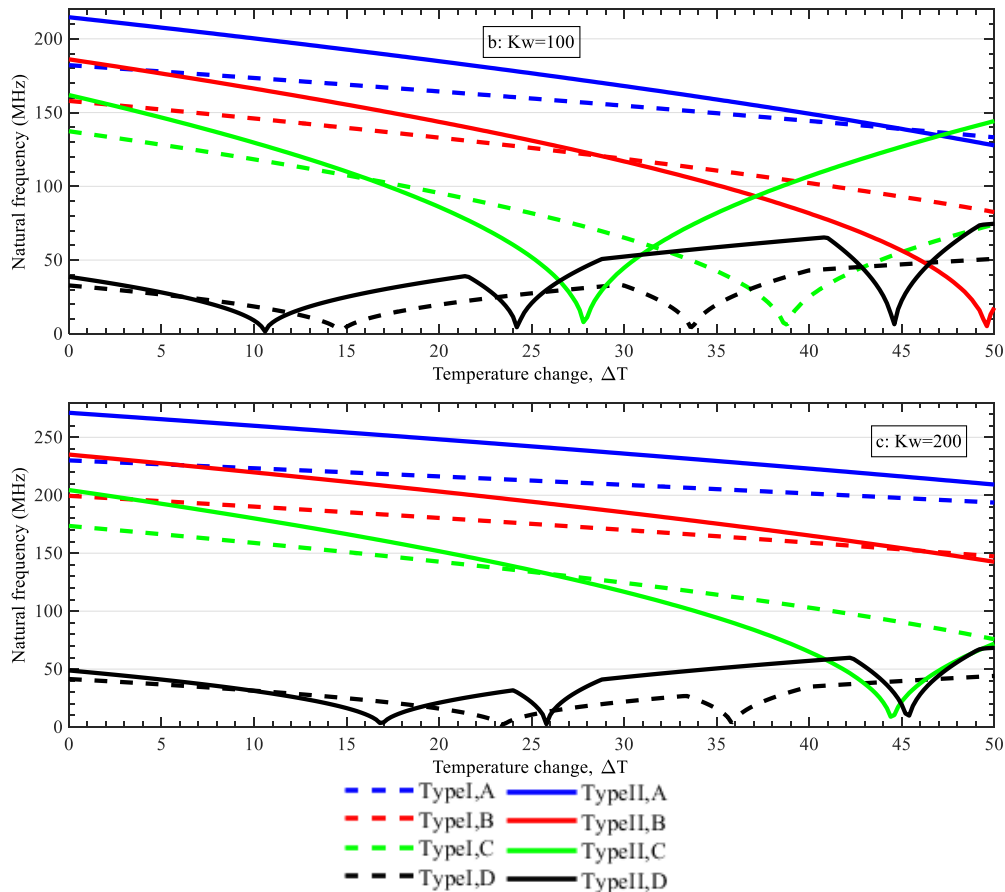


Fig. 4 Influence of physical activities on the thermal frequency response of different types of protein fibers founded in elastic proteins substrate along with temperature change (ΔT) due to the exercise in both natural muscle size (type I) and also in the sport condition of physical activities (type II) versus the various Winkler parameter (K_w) of the elastic substrate, $ea=l=1.149\mu\text{m}$, $K_p=3$, $L/R=25$

of anabolic rather than inhibition of catabolic processes (Kazior *et al.* 2016). According to the presented report, this paper focused on the stability of the protein tissues in the natural size (type I) and also while they are enhanced by training for 28% in the area (type II). Also, four types of protein tissues are assumed for this study listed in Table 1 to investigate the mechanical and geometric properties. Furthermore, the density (ρ), heat conductivity coefficient (k), and specific heat capacity (c_p) for protein tissues presented in Table 2.

Now, firstly, the nondimensional vibration frequency associated with a nanotube under thermal loading is obtained for different boundary conditions and compared with the result extracted from the reference in Table 3. This table reveals that the current results are accurate enough to investigate the stability of nanotubes that are under thermal loadings.

By validating the results, in the following, the effect of various parameters which can affect the dynamic stability of protein tubules is explored. Firstly, in Fig. 2, the impact of nonlocality and gradient strain parameters on tubes' vibrational frequency and dynamic stability is studied. In this figure, the variation of vibration frequency versus temperature change is plotted for different types of protein tissues considering the impact of physical activity on the

tissues. This figure indicates that physical activity can reduce the critical temperature of the system in any case, local and nonlocal. Also, as the nonlocality can soften the device, it reduces the critical temperature and the nanotube's stability. Against the nonlocal parameter, the higher 1 is, the more stable the system can be. Additionally, the nanotube is most stable if the Type A of the tissue is utilized.

Next, the impact of Pasternak and Winkler's parameters related to the elastic foundation on the dynamic stability of the nanotube made of protein tissues is explored in Figs. 3 and 4, respectively. In these figures, the vibrational frequency is plotted against the temperature changes for different foundation parameters and various tissue types concerning being rested or having a physical exercise state. These two figures reveal that the system can be more stable if the foundation is stiffer, the foundation parameters possess a higher value. In other words, the critical voltage of the nanotubes, regardless of the tissue types, can escalate by increasing the foundation factors. Also, the nanotubes are more stable if they are made of type A tissue. Generally, in the following succession, the nanotubes can be more stable: Type A, B, C, and D. Also, it is evident that the exercised tissues are less stable, having a lower critical buckling load.

5. Conclusions

The stability of protein tissues and protein fibers in the human muscle is investigated in the presented paper. The muscles are modeled as a nanotube based on nonlocal strain gradient theory as well as higher-order beam theory. The effect of body temperature on the nanotubes' stability is explored. The nanotube is assumed to be embedded in an elastic foundation with two parameters. The formulations are obtained through the energy method, and then solved via the GDQM solution procedure. The results are validated by means of other published articles. The impact of various parameters such as physical activities, temperature change, foundation parameters, nonlocality, and strain gradient parameter on the dynamic stability of the nanotubes is explored, the highlight results of which can be written in the following:

- The system can be more stable if the foundation is stiffer.
- The exercise improves fiber volume and decreases the protein stability regarding the thermal vibration.
- The exercised tissues are less stable concerning the thermal response due to enhancing the fiber area.
- The thermal buckling is faster in the exercised tissues.
- The nonlocality can soften the device, reducing the critical temperature and the nanotube's stability.
- The elastic substrate regarding the Winkler type delays the thermal buckling while the thermal buckling happens sooner by the Pasternak protein foundation.

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