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Effect of exercise on the stability of protein tissues

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Abstract. This study investigates the stability of protein tissues regarding the vibration analysis based on the classical beam theory coupled with the nonlocal elasticity theory concerning the exercise impact. As reported in the previous research, four different types of protein tissues are supposed, and the influence of sports training is investigated. The protein tissues are made of protein fibers surrounded by an elastic foundation. The exercise enhances the muscle area and plays an essential role in the stability and strength of protein and muscle tissues. The results are examined in detail to examine the impact of different parameters on the stability of nano protein fibers.

Keywords: fiber protein beam; frequency response; protein tissues. stability analysis; vibration analysis

1. Introduction

As shown, the muscles are made of four different proteins and are in the shape of a small-scaled fiber (Ma *et al.* 2021, Hou *et al.* 2021, Huang *et al.* 2021c, Liu *et al.* 2021c, Yu *et al.* 2022). Thus, since the muscles can be affected by various phenomena, such as exercises (Zhao *et al.* 2021, Huang *et al.* 2021b, Jiao *et al.* 2021, Moradi *et al.* 2021, Xu *et al.* 2021), it is essential to study such muscle fibers' mechanical behavior (Kazior *et al.* 2016). Also, it should be remembered, due to the shape of these fibers (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), they can be approximated as a small-scaled beam (Liu *et al.* 2020b, 2021b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Zhang *et al.* 2021). Additionally, the critical fact that should be considered is that in exploring small-scaled—nano or micro—the typical classical elasticity cannot be utilized (Naderi *et al.* 2021). Hence, the new types of elasticities are introduced by which the impact of the small size of the structures can be taken into account (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b). Some of the theories by which the impact of small size are considered are Nonlocal elasticity (Reddy 2007), Two-phase elasticity (Behdad *et al.* 2021), modified couple stress theory (Park and Gao 2006), strain gradient theory (Lim *et al.* 2015), etc (Al-Furjan *et al.* 2020c, d, f, Bai *et al.* 2020, Li *et al.* 2020a, Zhang *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021a).

As one of the most significant theories in studying small-scaled structures, the nonlocal elasticity has been the choice of many researchers for investigating nano- along with micro-sized beams (Hashemi *et al.* 2019, Al-Furjan *et al.* 2020e, Cheshmeh *et al.* 2020, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020c), plates (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, 2020b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020b), shells (Ebrahimi *et al.* 2019a, b, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Ebrahimi *et al.* 2020, Liu *et al.* 2020a, Shariati *et al.* 2020a, Shokrgozar *et al.* 2020b), and so on. In this regard, Aydogdu (2009) presented the investigation on the vibration, bending as well as buckling of beams which are modeled with various beam theories. By utilizing shear deformation theory and nonlocal elasticity, the vibration analysis of a beam made of functionally graded material and subjected to thermal and mechanical loading was studied Ebrahimi and Reza Barati (2016). In addition, the vibration, static bending, and buckling related to a thin beam modeled via Euler-Bernoulli and nonlocal elasticity were carried out by employing the Ritz method (Ghannadpour *et al.* 2013). In the framework of nonlocal elasticity, the stability together with vibrational behavior associated with small-sized tubes, which were used as conveying fluid systems, was investigated (Wang 2011). Behera and Chakraverty (2017) presented a survey on the dynamic characteristics related to nano-tubes made of carbon on the basis of nonlocal theory. By using nonlocal theory as well as DQM as the solution method, the vibration and bending associated with a rotating clamped-free nanobeam were explored (Pradhan and Murmu 2010). Based on Timoshenko beam theory along with Kelvin–Voigt scheme, a model for vibrational analysis of a viscoelastic nanobeam was presented (Lei *et al.* 2013). In the article mentioned above, nonlocal elasticity was utilized to capture the effect related to nanosize. Uymaz (2013) managed to present a study on the forced vibrational response of a nanobeam modeled via nonlocal elasticity. In this article, the material of the beam was considered to be FG. Aslo, the vibration associated with hcarbon nano-tubes under thermal loading was explored based on Timoshenko beam theory and differential form of nonlocal elasticity (Benzair *et al.* 2008). The critical flow velocities for micro- and nano-tubes was attained in a paper by Wang (2009) in

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which the tubes were formulated with the aid of nonlocal elasticity. By utilizing nonlocal elasticity, the nonlinear vibration analysis of carbon nano-tubes was presented by Ansari *et al*. (2012).

Here, it is essential to be mentioned that, as the slenderness of the fiber is so low, the Euler-Bernoulli beam theory can be utilized in studying the vibration of muscle fibers (Ebrahimi and Shafiei 2017, Ghadiri *et al*. 2017e, Mirjavadi *et al*. 2017a, Shafiei and Kazemi 2017a, Shafiei *et al*. 2017d, Azimi *et al*. 2018). Based on this theory, Ebrahimi *et al*. (2016) probed the vibrational characteristics of a beam whose material was FG and was under thermal loading. The differential transform method was incorporated as the solution method in the paper cited above. Also, the buckling along with the vibration of an Euler-Bernoulli nanobeam embedded in an elastic foundation was conducted (Fakher *et al*. 2020). Additionally, the vibration frequency associated with a beam modeled via Euler-Bernoulli and resting on soil which was considered to be Pasternak elastic foundation, was studied (De Rosa and Maurizi 1998). In addition, on the basis of the Euler-Bernoulli beam theory, the vibration of a piezo-magnetic nanobeam which is placed on a viscoelastic foundation was investigated through GDQM (Naderi *et al*. 2022). By utilizing the exact transfer matrix procedure, Lee and Lee (2017) carried out an investigation of the vibration analysis of Euler beams. The material of the beam was considered to be FG. The vibration associated with beams which are subjected to changing axial load was examined by Naguleswaran (2004).

The dynamic stability as well as vibration analysis have been one of the most significant areas of study in the pursuit of investigating the mechanical characteristics of the structures (Ehyaei *et al*. 2017, Ghadiri *et al*. 2017c, d, Mirjavadi *et al*. 2017d, Shafiei and Kazemi 2017b, Shafiei *et al*. 2017c). There have been quite a few studies in which the dynamic stabilities of plates (Liu *et al*. 2020a), beams (Simo and Vu-Quoc 1986), shells (Sheng and Wang 2018, Shokrgozar *et al*. 2020a), and panels (Sahu and Datta 2003) are examined. One of these articles is the work by Kane *et al*. (1987) in which they explored the dynamic stability of a clamped-free beam. Also, based on nonlocal strain gradient elasticity, the dynamic stability associated with a plate under axial loading from two directions and made of FG porous material was conducted (Jalaei and Thai 2019). Ilyasov and Aköz (2000) carried out the dynamic as well as static stability analysis for viscoelastic plates. The buckling, vibration, and stability response for a microbeam made of bidirectional FG material was investigated by means of GDQM and modified couple stress theory (Chen *et al*. 2019).

In this investigation (Habibi *et al*. 2017, 2019, Safarpour *et al*. 2018, 2020, Ghazanfari *et al*. 2020), on the basis of Euler-Bernoulli and nonlocal theory, the dynamic stability and vibration analysis associated with small-scaled wire, which represents the fibers in the muscle, is explored. It has been considered that muscle fibers are made of four different types of protein. Also, the other assumed factor is that these fibered are embedded in an elastic medium. Then GDQM is utilized to extract the results of the current problem. The obtained results' validity is examined through a comparative study. Lastly, the impacts of engaged parameters are investigated.

2. Mathematical simulation

2.1 Generation of motion equations

In this paper, the small-scale tissues are mathematically simulated according to the classical beam theory coupled with the nonlocal elasticity theory. The protein tissues are schematically assumed in Fig. 1 based on the wire structures embedded in the elastic substrate (Abd Samad *et al*. 2017, Shamsudin *et al*. 2017, Chen *et al*. 2021, Tang *et al*. 2021, Zou *et al*. 2021, Chen *et al*. 2022).

The following governing equations and corresponding boundary conditions will be conveyed according to the Euler-Bernoulli beam theory linked with the nonlocal Eringen elasticity for the protein tissues based on an elastic foundation (Ghadiri *et al*. 2017a, b, Mirjavadi *et al*. 2017b, Mirjavadi *et al*. 2017c, Shafiei *et al*. 2017a, b).

Governing equations:

$$\delta(u): A_x u_{,xx} + m_0 \ddot{u} - (ea)^2 m_0 \ddot{u}_{,xx} = 0 \tag{1a}$$

$$\begin{aligned}\delta(w)&: D_x w_{,xxxx} - K_w w + K_P w_{,xx} - m_0 \ddot{w} \\ &+ m_1 \ddot{w}_{,xx} + (ea)^2 \begin{pmatrix} K_w w_{,xx} - K_P w_{,xxxx} \\ + m_0 \ddot{w}_{,xx} - m_1 \ddot{w}_{,xxxx} \end{pmatrix} = 0\end{aligned} \tag{1b}$$

Boundary conditions:

$$\delta(u): A_x u_{,x} - (ea)^2 m_0 \ddot{u} == 0 \tag{1c}$$

$$\delta(w): D_x w_{,xxx} - (ea)^2 \begin{pmatrix} K_W w_{,x} - K_P w_{,xxx} \\ + m_0 \ddot{w}_{,x} - m_2 \ddot{w}_{,xxx} \end{pmatrix} = 0 \tag{1d}$$

$$\delta\left(\frac{\partial w}{\partial x}\right): D_x w_{,xx} - (ea)^2 \begin{pmatrix} K_W w - K_P w_{,xx} \\ + m_0 \ddot{w} - m_2 \ddot{w}_{,xx} \end{pmatrix} = 0 \tag{1e}$$

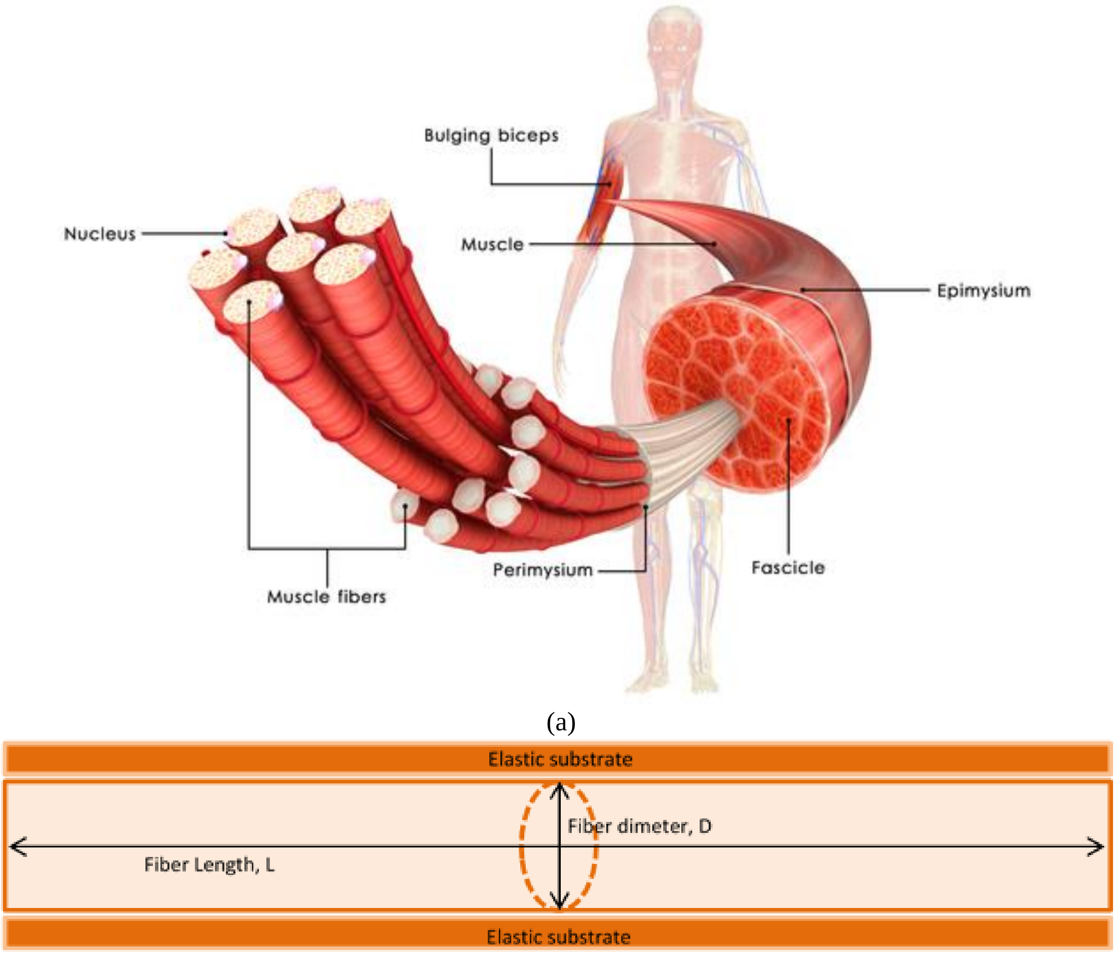
where 'A_x', 'D_x', 'm_0' and 'm_2' are defined as follows:

$$\begin{aligned}&(m_0, A_x, m_2, D_x) \\ &= \iint_A (\rho, E, \rho(r\sin(\theta))^2, E(r\sin(\theta))^2) dA\end{aligned} \tag{2}$$

In which 'ρ' and 'E' represents Density as well as Young's modulus of protein tissues. 'Kp' and 'Kw' are the Winkler and Pasternak elastic foundation constants, and '*ea*' is the nonlocal elastic constant. Furthermore, 'u' and 'w' are the axial and transverse deflection (Ebrahimi and Shafiei 2016, Shafiei *et al*. 2016c, d, f, Ebrahimi *et al*. 2017, Shivanian *et al*. 2017).

2.2 Solving methodology

The generalized differential quadrature method (GDQM) is employed to obtain the results (Azimi *et al*. 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al*. 2016a, e, g). Based on this procedure the r-th order derivative of function $f(x_i)$ is defined in GDQM as below:



(a)

(b)

Fig. 7 Influence of exercise on the dynamic analysis concerning the Winkler parameter (Kw×Dx/L^4) for different kinds of protein tissues surrounded with Winkler substrate for clamped fiber protein tissues, *ea*=1e-4, Kp=1

$$\left.\frac{\partial^r f(x)}{\partial x^r}\right|_{x=x_P} = \sum_{j=1}^{n} C_{ij}^{(r)} f(x_i) \tag{3a}$$

where n denotes the number of grid points in the x-direction.

The fundamental results of the eigenvalue problem of the modal analysis will be obtained via substituting the Eqs. (3) into Eqs. (1), then the following equations will be conveyed to calculate the natural frequency (ω) and mode shapes (λ) (Ghadiri *et al*. 2016a, b, c, d, Ghadiri and Shafiei 2016b, Shafiei *et al*. 2016b).

$$\omega^2 = \frac{\begin{bmatrix} A_x \sum_{s=1}^{n} C_{rs}{}^{(2)} & 0 \\ 0 & D_x \sum_{s=1}^{n} C_{rs}{}^{(4)} - K_w + K_P \sum_{s=1}^{n} C_{rs}{}^{(2)} + (ea)^2\left(K_w \sum_{s=1}^{n} C_{rs}{}^{(2)} - K_P \sum_{s=1}^{n} C_{rs}{}^{(4)}\right) \end{bmatrix}}{\begin{bmatrix} -m_0 + (ea)^2 m_0 \sum_{s=1}^{n} C_{rs}{}^{(2)} & 0 \\ 0 & m_0 \ddot{w} - m_2 \ddot{w}_{,xx} - (ea)^2\left(m_0 \sum_{s=1}^{n} C_{rs}{}^{(2)} - m_1 \sum_{s=1}^{n} C_{rs}{}^{(4)}\right) \end{bmatrix}} \begin{Bmatrix} \lambda(u) \\ \lambda(w) \end{Bmatrix} \tag{4}$$

Additionally, C_{ij} can be defined as follows (Shafiei and She 2018, Shafiei *et al*. 2019, 2020).

$$C_{ij}^{(1)} = \frac{\widetilde{M}(x_i)}{(x_i - x_j)\widetilde{M}(x_j)}, i,j = 1,2,\ldots,n \tag{3b}$$

$$\widetilde{M}(x_i) = \prod_{j=1, j\neq i}^{n} (x_i - x_j) \tag{3c}$$

3. Results

There are quite a few researches has been carried out in which the impact related to endurance exercise on an anabolic response to strength training was investigated. one of the works is the paper by Kazior *et al*. (2016). In this article, they studied the influence of exercise on the degradation in addition to synthesis. To do so, they considered two groups of men, one group just has done

Table 1 Geometrical parameters and material properties of different types of protein tissues (Zhao *et al*. 2009, Sahmani and Aghdam 2018)

Type of tissues	Young's modulus (Pa)	Radius (nm)
A	610e6	66
B	715e6	52.8
C	960e6	39.6
D	1440e6	24.4

Table 2 Comparison of findings for dimensionless frequency $(\omega L^2\sqrt{\frac{A_x}{\pi D_x}})$ of simply-supported Euler-Bernoulli beam theory with results of Zhao and Yu (2021)

	$(ea)^2=0$	$(ea)^2=0.5$	$(ea)^2=1$	$(ea)^2=2$	$(ea)^2=3$	$(ea)^2=4$
Present study	5.56837515	5.435884664	5.312456182	5.088798176	4.891206238	4.714935446
Zhao and Yu (2021)	5.56832	5.43583	5.3124	5.08875	4.89116	4.71489

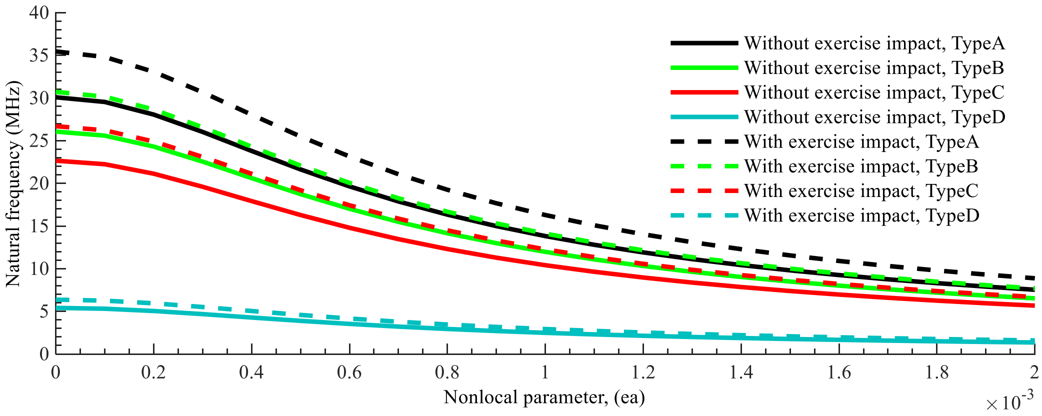


Fig. 2 Stability analysis of the pinned fiber protein tissues due to the frequency analysis versus the nonlocal parameter (*ea*) for different types of protein tissues along with the impact of exercise

resistance exercise for seven weeks—R, n = 7—and the other group did continuous and interval cycling after the endurance exercise—ER, n = 9. To carry out the research, they took Muscle biopsies both before and after the exercises. It has been seen that maximal oxygen uptake was intensified (8%, $P<0.05$) only in the ER, while the elevation in leg-press one repetitions maximum (30%, $P<0.05$) was observed in both of the groups. Additionally, type 1 in addition to 2 fibers has gotten bigger in ER group. However, in the group who had done R training, only enlargement of type 1 was apparent. In addition, it was seen in ER people that the mean fiber area was intensified up to 28% ($P<0.05$), while the was no increase in the other group. Furthermore, two types of protein, mTOR along with Akt, was expressed in people who have done ER training, which was limited to only mTOR in R group. The vital point in this study is that exercise was able to change the level related to mTOR along with Akt, which are corresponded to alternation in mean fiber area ($r = 0.55–0.61$, $P<0.05$) and type 1 fiber area ($r = 0.55–0.61$, $P<0.05$). Thus, this study has shown the significance of the proteins in muscle hypertrophy. Also, both types of trainings diminished MAFbx protein ($P<0.05$) and increased MuRF-1. The results of this study exhibit that the larger hypertrophy seen in the group who has done ER exercises is because of pronounced stimulation of anabolic and not 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 (Zhao *et al*. 2009, Sahmani and Aghdam 2018). Furthermore, '$\rho=1470(Kg/m3)$' (Baninajjaryan and Tadi Beni 2015).

Here, to begin with, the results of the nondimensional vibration frequency of an Euler-Bernoulli beam which are attained by the presented formulation and solution method are extracted and compared with the results from Zhao and Yu (2021) in Table 2 for different values of nonlocality. Also, the end condition in this study is considered to be simply supported. The good agreement between the present results and the results obtained from the reference indicates the reliability and accuracy of the formulation to study the stability and vibrational behavior of a fiber embedded in an elastic foundation.

Now, the impact of various parameters which can affect the vibrational frequency as well as stability of fiber representing the muscle fibers which is modeled via nonlocal elasticity, is investigated. First, in Figs. 2 and 3,

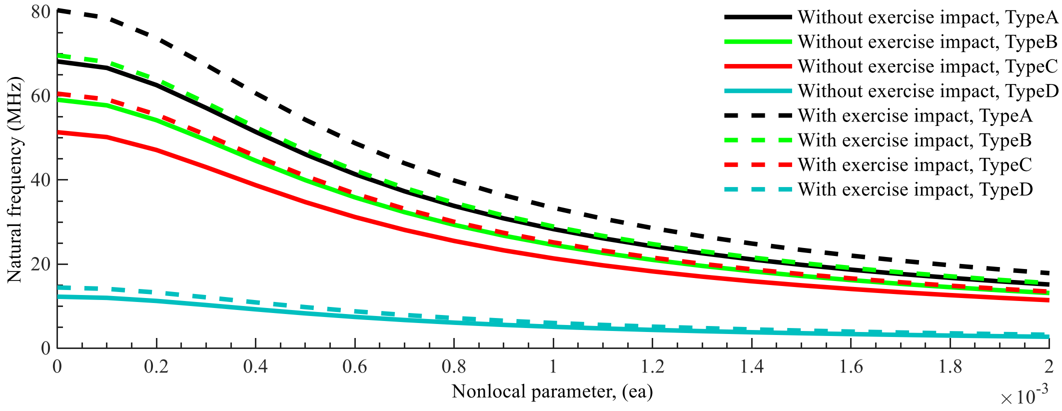


Fig. 3 Dynamic analysis of the clamped fiber protein tissues due to the frequency analysis versus the nonlocal parameter (*ea*) for different types of protein tissues along with the impact of exercise

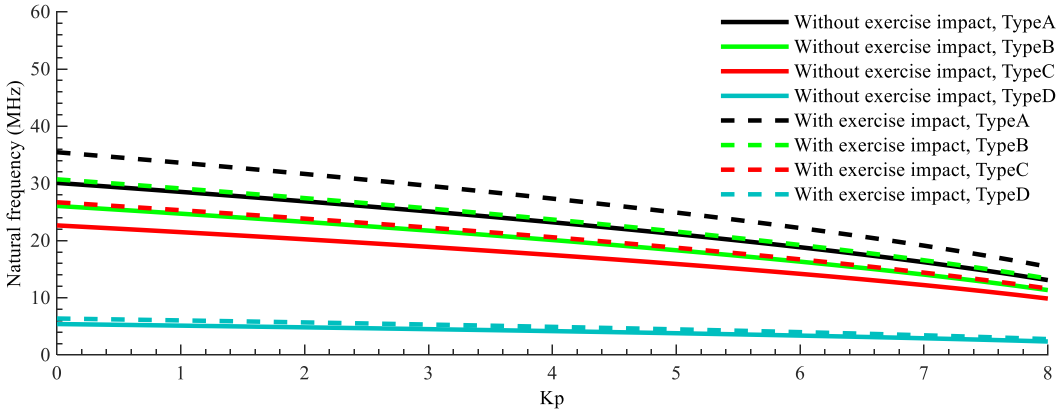


Fig. 4 Impact of exercise on the stability analysis of the pinned fiber protein tissues based on Pasternak substrate regarding the dynamic analysis versus the Pasternak parameter (Kp×Dx/L^2) for different types of protein tissues, *ea*=1e-4

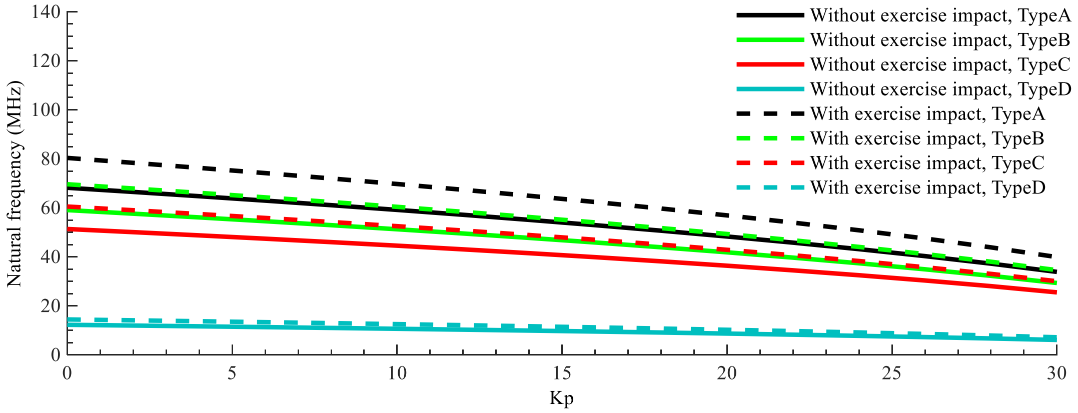


Fig. 5 Impact of exercise on the stability analysis of the clamped fiber protein tissues based on Pasternak substrate regarding the dynamic analysis versus the Pasternak parameter (Kp×Dx/L^2) for different types of protein tissues, *ea*=1e-4

the variation of nondimensional vibration frequency versus nonlocal parameters are plotted for different cases with and without exercise with various tissue types. Figs. 2 and 3, respectively, represent the results for a fiber protein in simply supported and clamped end conditions. The results from this figure show that, regardless of the tissue type as well as exercised or not exercised group, by increasing the nonlocal parameter, the vibration frequency of the fiber is diminished, softening effect. Also, it is observable that the vibration frequency in cases with exercise, considering the the tissue type, is higher than in non-exercised cases in any nonlocality. Also, as a general result, the frequency of the fiber from lowest to highest value regarding the tissue type are as follows, Type A, B, C, and D.

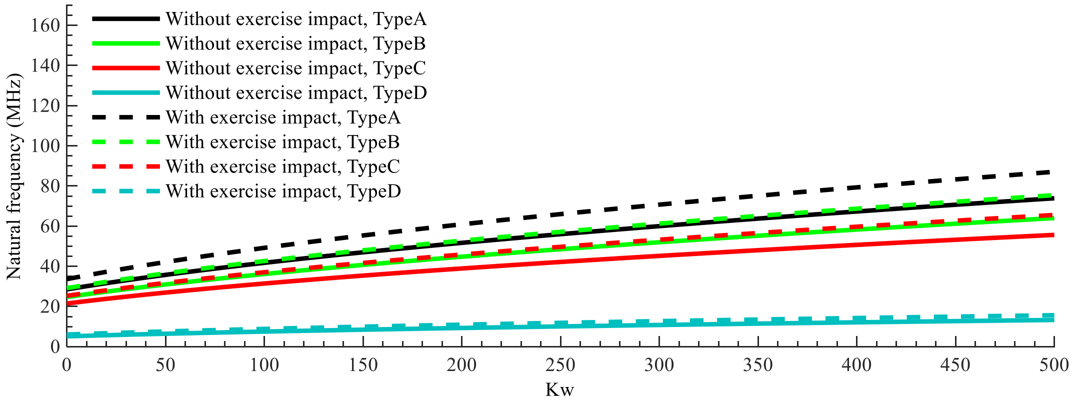


Fig. 6 Influence of exercise on the dynamic analysis against the Winkler parameter ($Kw \times Dx/L^4$) for various kinds of protein tissues surrounded with Winkler substrate for pinned fiber protein tissues, *ea*=1e-4, Kp=1

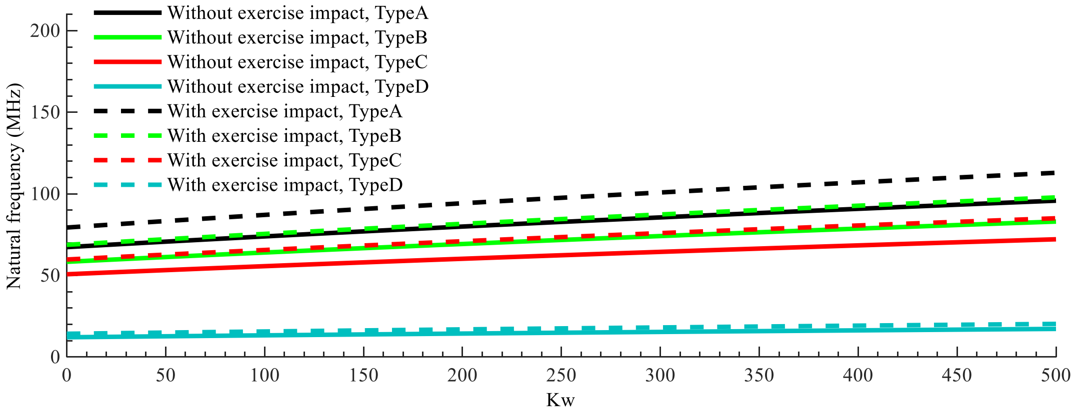


Fig. 7 Influence of exercise on the dynamic analysis concerning the Winkler parameter ($Kw \times Dx/L^4$) for different kinds of protein tissues surrounded with Winkler substrate for clamped fiber protein tissues, *ea*=1e-4, Kp=1

Fig. 3, representing the variation of vibration frequency against the nonlocality for clamped cases, shows the same trend for the vibrational frequency as in the previous figure. However, it should be mentioned that, generally, the vibration frequency has higher values in clamped conditions.

Next, in Figs. 4 and 5, the vibration frequency variation against the value of the Pasternak coefficient related to the elastic medium for simply-supported and clamped boundary conditions are plotted, respectively. Also, the value of nonlocality in these figures is set to be *ea*=1e-4.

The exciting results from these figures show that the vibration frequency of the system is reduced provided that the foundation has a higher value of the Pasternak factor. Also, again, it is observable, concerning the type which is used for the tissue, the vibrational frequency of cases without exercised cases are higher than those of non-exercised. Additionally, the fact that the frequency of the fiber is higher in clamped end conditions can be seen as well.

Lastly, the impact of the other coefficient of the elastic medium, the Winkler coefficient, on the vibration frequency of Simply-supported and clamped fibers made of different tissue types are examined in Fig. 6 and Fig. 7. Also, the nonlocality is assumed to be *ea*=1e-4, and the value for the Pasternak coefficient is Kp=1. Against the results for the Pasternak coefficient, the higher the value of Kw is, the higher the vibration frequency of the fiber can be, and this effect is not dependent on either of the parameters such as tissue type, exercise history, or boundary conditions of the fiber. Additionally, it is observable that the vibration frequencies of the fiber are succession from higher to lower in the following format: Type A, B, C, and D, with respect to whether the cases are exercised or not.

4. Conclusions

This paper investigates the stability of protein tissues regarding the vibration analysis based on the Euler-Bernoulli beam theory in addition to the nonlocal elasticity theory concerning the exercise impact. It was shown that four different types of protein are considered for the fibers, which can affect the vibrational frequency as well as stability of the fibers. The protein tissues are made of protein fibers surrounded by an elastic foundation. The exercise enhances the muscle area and plays an essential role in the stability and strength of protein and muscle tissues. The formulation of the current study is solved via the GDQM solution procedure. The different parameters which can play a role in the stability of protein fibers are examined, and here is the highlight of this paper:

- The higher the value of Kw is, the higher the vibration frequency of the fiber can be.
- The vibration frequency of the system is reduced provided that the foundation has a higher value of the Pasternak factor.
- The frequency of the fiber is higher in clamped end conditions.
- By increasing the nonlocal parameter, the vibration frequency of the fiber is diminished, softening effect.
- The vibrational frequency of cases without exercised cases are higher than those of non-exercised.

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