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Sport and exercise impact on the therapy with nanomedicine in drug delivery

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Abstract. Nanomachines can be pretty helpful in curing diseases. Nanomototors, thanks to their self-propelled feature, are one of the best structures to be utilized as drug delivery devices. These devices have been employed in biomedical application as they can improve the efficiency of drug delivery. In this study stability of a designed nanomotor in the bloodstream is investigated when the physical activities have been done considering the physical activities. Sports training, as well as exercise enhance the bloodstream, and this factor can significantly impact the drug-delivery quality. The mathematical simulation of nanomotor movement in the condition of the sports is done based on the mechanical sciences, and the impact of various essential parameters is discussed in detail.
Keywords: drug-delivery; dynamic stability; physical activities; sport training

1. Introduction

Because of their various designs and shapes, nanostructures have been utilized in diverse devices in engineering and science. One of the uses of these structures is their biological usage, such as drug delivery to a specific cell and with the right amount to prevent the whole body poisoning and heightening up the efficiency of the drugs. It is crucial to remember that the theoretical studies on the abovementioned small-scale structure must be carried out to design and manufacture these devices and structures. One of the most significant characteristics and structures is their mechanical behavior (Fakher *et al*. 2020). In the past few years, researchers have put a large amount of effort into formulating and studying nanostructures by utilizing different theories like strain gradient theory (Lim *et al*. 2015), local/nonlocal elasticity (Naderi *et al*. 2021), nonlocal theory (Eringen and Wegner 2003), modified couple stress (Park and Gao 2006), and nonlocal strain gradient theory (Barretta and Marotti de Sciarra 2018).

Nonlocal strain gradient, which is the combination of nonlocal elasticity and strain gradient theory, has been the topic of many pieces of research in which the behavior of small-scale structures, such as nanobeams (Şimşek 2016), nanoplates (Arefi *et al*. 2019), and nanoshells (Moayedi *et al*. 2021), were investigated. one of the studies in which the size-dependent theory is nonlocal strain gradient theory, aka NSGT, is the paper by Esmailpoor Hajilak *et al*. (2019) in which they studied the wave propagation associated with an FG plate by utilizing higher-order shear deformation and NSGT. Also, the flexural as well as axial vibration behavior of a nanobeam were investigated through NSGT and Euler-Bernoulli beam theory (Apuzzo *et al*. 2018). In addition, by incorporating weighted residual method, the static bending and vibrational response related to beams in small-scale was presented (Apuzzo *et al*. 2018). The formulations related to the vibrational analysis of a nanobeam were extracted by using NSGT, higher-order beam theory, as well an energy method and solved by means of Navier’s method (Lu *et al*. 2017a). Based on Kelvin–Voigt model and NSGT, the wave propagation corresponded to a conveying fluid nanotube was carried out by Li and Hu (2016). Additionally, the buckling and static bending of nanobeams which are modeled via NSGT in addition to various beam theories was analyzed (Lu *et al*. 2017b). Thai *et al*. (2020) managed to present a study on the bending behavior related to nanobeams made of functionally graded materials. The beam theory in the abovementioned article was higher-order beam model, and the size-dependent model was NSGT. By developing NSGT for double-curved shells, Karami *et al*. (2018) explored the wave propagation of shells on a small scale. By utilizing NSGT along with higher-order beam theory, the nonlinear form of vibrational as well as static response of a nanotube which is made of FG porous materials was examined (She *et al*. 2018). The analytic solution for the wave propagation associated with FG nanobeams placed on the elastic foundation was presented through NSGT (Ebrahimi and Barati 2017). The critical speeds of a flow which is conveyed via a microtube which is modeled based on NSGT and Euler-Bernulli beam theory were extracted by Li *et al*. (2016). The wave dispersion in a carbon nanotube which is filled with a fluid was conducted on the basis of Timoshenko theory along with NSGT (Yang *et al*. 2018). In addition, the wave propagation of a nanoplate made of fiunctionally graded material was examined by utilizing NSGT and higher-order plate theory (Ebrahimi and Dabbagh 2017).

Two of the most vital behavior of any structure, vibration and dynamic stability, has to be explored before

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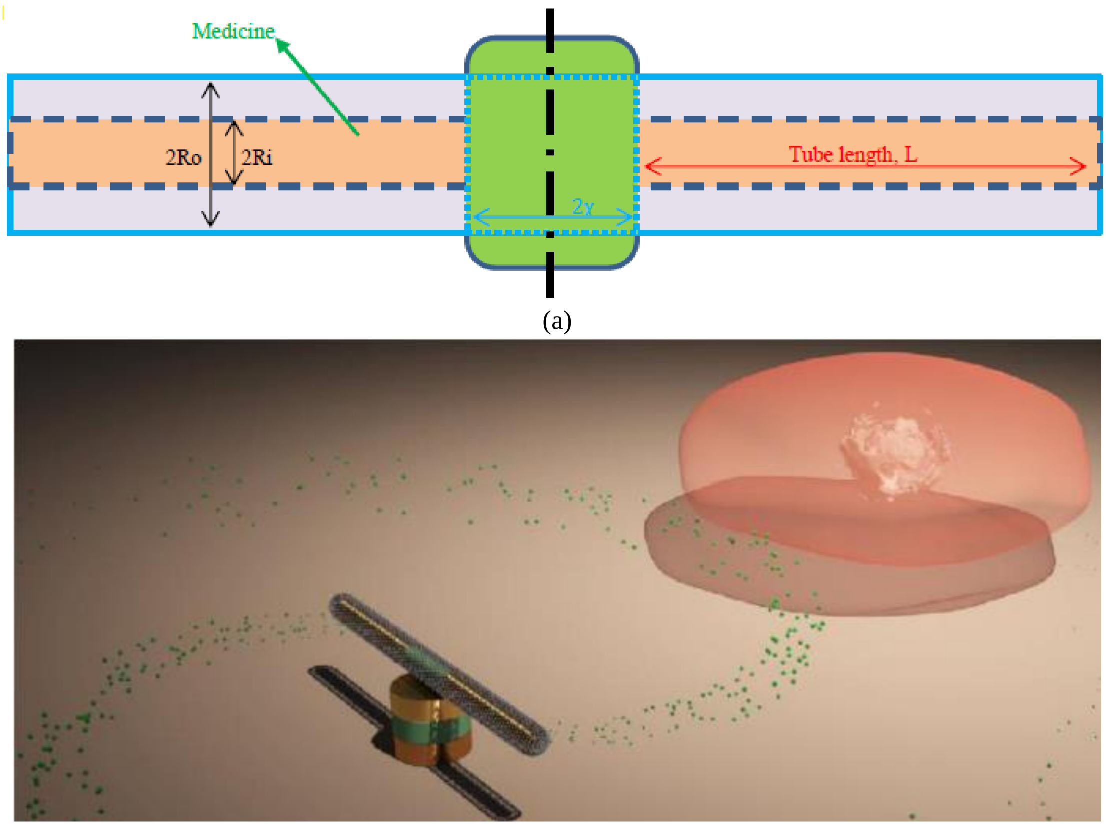

(a)

(b)

Fig. 1 (a) The schematic of the drug delivery mechanism based on mechanical modeling, (b) A real simulation of the drug-delivery mechanism (Guo *et al*. 2015; Ghadiri *et al*. 2017e)

designing and building a device based on that specific structure. With this in mind, scholars have conducted many a study on the vibration of different structures of various sizes, i.e., plates (Putcha and Reddy 1986) (Hashemi *et al*. 2019, Moayedi *et al*. 2019, 2020a, b, Oyarhossein *et al*. 2020, Shariati *et al*. 2020b), shells (Sofiyev *et al*. 2006, Ebrahimi *et al*. 2019a, b, 2020b, Mohammadgholiha *et al*. 2019, Mohammadi *et al*. 2019, Habibi *et al*. 2020, Shariati *et al*. 2020a, Shokrgozar *et al*. 2020), beams (Habibi *et al*. 2017, 2019c, Safarpour *et al*. 2018, 2020, Ghazanfari *et al*. 2020, Naderi *et al*. 2020), and tubes (Fu *et al*. 2006, Esmailpoor Hajilak *et al*. 2019, Habibi *et al*. 2019a, Alipour *et al*. 2020, Ebrahimi *et al*. 2020a, Chen *et al*. 2022). Regarding this, the vibrational analysis associated with nanobeams which have a crack and resting on a two-parameter medium was studied (Behdad *et al*. 2021). Also, based on Von-Kármán theory, the nonlinear vibrational analysis of an elastic nanobeam which is coupled via an elastic medium with a piezoelectric nanobeam was conducted through GDQM solution procedure (Ghorbanpour Arani *et al*. 2015). In addition, the vibrational chrachtristcs associated with a nanobeam made of axially FG composites resting on a viscoelastic foundation were investigated (Zeighampour and Tadi Beni 2015). The solution procedure which is utilized in the above paper was DQM. The piezo-magnetoelctric nanobeams, which are placed on a viscoelastic foundation, were formulated based on local/ nonlocal elasticity along with the Euler-Bernoulli beam theory to investigate the vibrational response of the nanobeams (Naderi *et al*. 2022). Also, by using NSGT and Von-Kármán theory, the nonlinear vibrational behavior related to FG nanobeam was investigated by Liu *et al*. (2019). The formulations of a curved nanobeam which is made of FG composites and placed on an elastic substrate were obtained by means of NSGT (Allam and Radwan 2019). The dynamic stability as well as vibrational response of a nanoplate subjected to bi-directional stress was studied based on NSGT (Shen *et al*. 2020). Additionally, Nami and Janghorban (2015) presented an investigation on the vibrational analysis of nanoplates modeled via NSGT and higher-order theory. In this article, they utilized an analytic approach to extract their results. A nanoplate made of porous materials was modeled as a mass nanosensor by Barati and Shahverdi (2018). They studied the different parameters affecting the vibrational behavior of the nanoplate.

Given the above paragraphs, the current paper investigates the dynamic stability and vibration of a rotating nanotube which can be utilized as a drug delivery system. The formulations for this problem are extracted by using higher-order beam theory, NSGT, and energy method. Then, by using GDQM in conjunction with the Newmark method, time-dependent results are obtained. The validity as well as accuracy of results are proven by means of a comparison study. The effect of various parameters on the dynamic stability of the nanotube is examined.

2. Mechanical simulation of drug delivery mechanism

The drug-delivery mechanism in this paper is made of a nanomotor that is spun the nanotube carrying the nanomedicine, and the nanotube is the blade of this intelligent nanomedicine. In this type of drug-delivery mechanism, the nanomedicine is released into the blood flow, and in precisely defined conditions, the medicines are leaked to the target cells (Yan *et al*. 2020, Chen *et al*. 2021, Choi *et al*. 2021). As shown in Fig. 1, the nanotube is both a medicine capsule and a nanomotor blade. Based on the physical sciences, the conditions for drug release can be defined regarding the resonant behavior, for example, the frequency of cancer cells is higher than that of normal cells, so the resonant frequency of nanodevices can play an essential role in drug delivery (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). It means that in the production of nanodevice, the resonant frequency is predicted equally to the frequency of cancer cells, when the released nanomedicine reaches these cancer cells, according to the resonant science, the drugs are leaked into the target cells. Before the mathematical simulation of these nanodevices, as displayed in Fig. 1, the tube length is 'L', and inner and outer tube radiuses are 'Ri' and 'Ro', and the nanotube is spun around the nanomotor by 'ϕ' as rotation speed, furthermore, the hub radius is 'χ'.

2.1 Mathematical formulation

The high-order tube theory introduced by Zhang and Fu (2013) is used for mathematical simulation of nanodevice for the drug-delivery purpose. For this aim, the Hamilton principle is utilized in order to generation of governing equation and associated boundary conditions according to the following equation (Al-Furjan *et al*. 2020c, d, f, Bai *et al*. 2020, Ma *et al*. 2020, Zhang *et al*. 2020, Guo *et al*. 2021b, Liu *et al*. 2021a).

$$\int_{t_1}^{t_2} \delta \Pi dt = 0 \tag{1}$$

where

$$\Pi = S - K + W \tag{2}$$

In which, 'W', 'S' and 'K' represented the external energy of external forces, the strain energy and the kinetic energy, respectively (Adamian *et al*. 2020, Al-Furjan *et al*. 2020a, b, Li *et al*. 2020, Zare *et al*. 2020, Dai *et al*. 2021b). The strain energy can be expressed as:

$$S = \iiint \frac{1}{2} \sigma : \varepsilon dv \tag{3}$$

"ε" and "σ" meant the strains and the stress tensors. Based on the Zhang and Fu (2013) theory the displacement elements along x-axis (u_x), y-axis (u_y), and z-axis (u_z) have been recognized as follows (Habibi *et al*. 2018, 2019b, d, e, Pourjabari *et al*. 2019, Safarpour *et al*. 2019):

$$\begin{aligned} u_x(x,y,z,t) &= \vartheta(y,z)\left[\psi(x,t) + \frac{\partial w(x,t)}{\partial x}\right] - z\frac{\partial w(x,t)}{\partial x} + u(x,t) \\ u_z(x,y,z,t) &= w(x,t) \\ u_y(x,y,z,t) &= 0, \end{aligned} \tag{4}$$

where 'w' as well as 'u' represents the transverse and axial deflection. Additionally, 't' and 'ψ' denote time and rotation. Also, 'ϑ' is a function that is obtained Ref. (Zhang and Fu 2013) as follows.

$$\vartheta(y,z) = z + z\left({R_e}^2 {R_i}^2 r^{-2} - \frac{r^2}{3}\right)\left({R_e}^2 + {R_i}^2\right)^{-1} \tag{5}$$

where

$$\begin{aligned} z &= r\,sin(\theta) \\ y &= r\,cos(\theta) \\ r^2 &= y^2 + z^2 \end{aligned} \tag{6}$$

Also, the strains relations are (Liu *et al*. 2020b, 2021b, Habibi *et al*. 2021, He *et al*. 2021, Huang *et al*. 2021a, Zhang *et al*. 2021):

$$\begin{aligned} \varepsilon_{xz} &= \frac{1}{2}\left(\frac{\partial u_1}{\partial z} + \frac{\partial u_3}{\partial x}\right) = \frac{1}{2}\frac{\partial \vartheta(y,z)}{\partial z}\left(\frac{\partial w}{\partial x} + \psi\right) \\ \varepsilon_{xy} &= \frac{1}{2}\left(\frac{\partial u_1}{\partial y} + \frac{\partial u_2}{\partial x}\right) = \frac{1}{2}\frac{\partial \vartheta(y,z)}{\partial y}\left(\frac{\partial w}{\partial x} + \psi\right) \\ \varepsilon_{xx} &= \frac{\partial u_1}{\partial x} = \frac{\partial u}{\partial x} - z\frac{\partial^2 w}{\partial x^2} + \vartheta(y,z)\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial \psi}{\partial x}\right) \end{aligned} \tag{7}$$

The stresses tensors are considered as follows:

$$\begin{aligned} \sigma_{ij} &= E\varepsilon_{ij} i = j \\ \sigma_{ij} &= G\varepsilon_{ij}, i \neq j \end{aligned} \tag{8}$$

where, "$G=E/(2+2\nu)$". The virtual Kinetic energy of the higher-order theory of tubes are taken as follows:

$$\delta K = \int_V \rho\left[\frac{\partial u_x}{\partial t}\delta\left(\frac{\partial u_x}{\partial t}\right) + \frac{\partial u_z}{\partial t}\delta\left(\frac{\partial u_z}{\partial t}\right)\right] dV \tag{9}$$

Furthermore, the virtual energy of external forces due to the rotation of the tubes and the external harmonic loads are considered as follows (Zhao *et al.* , Huang *et al*. 2021b, Jiao *et al*. 2021, Moradi *et al*. 2021, Xu *et al*. 2021):

$$\begin{aligned} \delta W &= \delta\left[\frac{1}{2}\int_0^L N^R \left(\frac{\partial w}{\partial x}\right)^2 dx\right] + \int_V N^{BF} dV\, \delta(w) = \\ &-\int_0^L \frac{\partial}{\partial x}\left(N^R \frac{\partial w}{\partial x}\right) dx\, \delta(w) + N^R \frac{\partial w}{\partial x}\Big|_0^L \delta(w) \\ &+ \int_V N^{BF} dV\, \delta(w) \end{aligned} \tag{10}$$

In which 'N^R' is the external force due to the rotation can be expressed as:

$$N^R = \int_x^L \int_A \rho \phi^2 (\chi + x) dA dx \tag{11}$$

where 'ϕ' is angular velocity and 'χ' is hub radius (Ebrahimi and Shafiei 2017, Ghadiri *et al*. 2017e, Mirjavadi *et al*. 2017a, Shafiei and Kazemi 2017a, Shafiei *et al*. 2017d, Azimi *et al*. 2018). Furthermore, 'N^{BF}' is the external bending harmonic loads due to the blood flow that is presented as follows:

$$N^{BF} = F_{BF} \sin(n\frac{\pi x}{L}) \sin(\varpi t) \tag{12}$$

In which 'F_{BF}' is the external load, and the 'ϖ' is the external excitation frequency (Ma *et al*. 2021, Hou *et al*. 2021, Huang *et al*. 2021c, Liu *et al*. 2021c, Yu *et al*. 2022). The general stress field contains both nonlocal elastic stress in addition to strain gradient stress fields according to the nonlocal strain gradient theory (Shafiei and She 2018, Shafiei *et al*. 2019, 2020).

$$[1-(ea)^2\nabla^2]\sigma_{ij} = (1-l^2\nabla^2)C:\varepsilon_{ij} \tag{13}$$

where '∇' is the Laplace operator, '*ea*' is the nonlocal parameter, '*l*' is the strain gradient parameter, and '*C*' is the elastic modulus tensor (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). To attain the formulations and related boundary conditions, based on the Hamilton principle, we substitute the Eqs. (3), (9) and (10) into Eq. (1), finally, for the higher-order theory of tubes, the Euler-Lagrange equations are provided as:

$$A_{11}u_{,xx} - l^2A_{11}u_{,xxxx} = m_0\ddot{u} - (ea)^2 m_0\ddot{u}_{,xx} \tag{14a}$$

$$\begin{aligned} &Qw_{,xxx} - l^2Qw_{,xxxxx} - B_{11}(w_{,x}+\psi) + E_{11}\psi_{,xx} \\ &-l^2\left(E_{11}\psi_{,xxxx} + B_{11}(\psi_{,xx}+w_{,xxx})\right) = \\ &I_2\ddot{w}_{,x} + m_3\ddot{\psi} - (ea)^2(I_2\ddot{w}_{,xxx} + m_3\ddot{\psi}_{,xx}) \end{aligned} \tag{14b}$$

$$\begin{aligned} &Dw_{,xxxx} + Q\psi_{,xxx} - l^2(Dw_{,xxxxxx} + Q\psi_{,xxxxx}) \\ &-B_{11}(w_{,xx}+\psi_{,x}) + l^2B_{11}(w_{,xxxx}+\psi_{,xxx}) \\ &+N^{BF} - (ea)^2N^{BF}{}_{,xx} - N^R{}_{,x}w_{,x} - N^Rw_{,xx} \\ &+(ea)^2\begin{pmatrix} N^R{}_{,xxx}w_{,x} + N^Rw_{,xxxx} \\ +3N^R{}_{,xx}w_{,xx} + 3N^R{}_{,x}w_{,xxx} \end{pmatrix} \\ &= I_1\ddot{w}_{,xx} - m_0\ddot{w} + I_2\ddot{\psi}_{,x} \\ &-(ea)^2(I_1\ddot{w}_{,xxxx} - m_0\ddot{w}_{,xx} + I_2\ddot{\psi}_{,xxx}) \end{aligned} \tag{14c}$$

Moreover, the related boundary conditions:

$$\delta(u): A_{11}u_{,x} = 0 \tag{14d}$$

$$\delta(\psi): E_{11}(\psi_{,x}+w_{,xx}) - C_{11}w_{,xx} = 0 \tag{14e}$$

$$\delta\left(\frac{\partial w}{\partial x}\right): Dw_{,xx} + Q\psi_{,x} = 0 \tag{14f}$$

$$\begin{aligned} &\delta(w): -Dw_{,xxx} + N^Rw_{,x} - Q\psi_{,xx} \\ &+B_{11}(\psi + w_{,x}) = 0 \end{aligned} \tag{14g}$$

In which

$$\begin{aligned} &(A_{11}, C_{11}, D_{11}, E_{11}) \\ &= \int_A E\,(1, z\vartheta, z^2, \vartheta^2)dA \end{aligned} \tag{15a}$$

$$B_{11} = \int_A K_S G(x,r)\left(\left(\frac{\partial\vartheta}{\partial y}\right)^2 + \left(\frac{\partial\vartheta}{\partial z}\right)^2\right)dA \tag{15b}$$

Here, 'K_S' is the shear correction factor which can be obtained as follows (Fakher *et al*. 2020):

$$K_S = K_{S1}/K_{S2} \tag{16a}$$

where

$$K_{S1} = 6(1+\xi^2)^2(1+\nu)^2 \tag{16b}$$

$$\begin{aligned} K_{S1} = (7+14\nu+8\nu^2)(1+\xi^2)^2 \\ +4\xi^2(5+10\nu+4\nu^2) \end{aligned} \tag{16c}$$

$$\xi = R_i/R_e \tag{16d}$$

Also,

$$Q = E_{11} - C_{11} \tag{17a}$$

$$D = E_{11} + D_{11} - 2C_{11} \tag{17b}$$

$$I_1 = m_3 + m_1 - 2m_2 \tag{17c}$$

$$I_2 = m_3 - m_2 \tag{17d}$$

2.2 Solution procedure

The generalized differential quadrature method (GDQM) is utilized to obtain the results. The r-th order derivative of function $f(x_i)$ is defined in GDQM as bellow (Ghadiri *et al*. 2017a, b, Mirjavadi *et al*. 2017b, c, Shafiei *et al*. 2017a, b):

$$\left.\frac{\partial^r f(x)}{\partial x^r}\right|_{x=x_P} = \sum_{j=1}^{n} C_{ij}^{(r)} f(x_i) \tag{18}$$

In which the grid points number is denoted by *n* / Additionally, C_{ij} can be extracted as (Ehyaei *et al*. 2017, Ghadiri *et al*. 2017c, d, Mirjavadi *et al*. 2017d, Shafiei and Kazemi 2017b, Shafiei *et al*. 2017c):

$$C_{ij}^{(1)} = \frac{\widetilde{M}(x_i)}{(x_i - x_j)\widetilde{M}(x_j)} \tag{19}$$

where $\widetilde{M}(x)$ is:

$$\widetilde{M}(x_i) = \prod_{j=1, j\neq i}^{n} (x_i - x_j) \tag{20}$$

The higher-order $C^{(r)}$, are obtained according to the following equation (Ebrahimi and Shafiei 2016, Shafiei *et al*. 2016c, d, f, Ebrahimi *et al*. 2017, Shivanian *et al*. 2017).

$$C_{ij}^{(r)} = r\left(C_{ij}^{(r-1)}C_{ij}^{(1)} - \frac{C_{ij}^{(r-1)}}{(x_i - x_j)}\right) \tag{21}$$

The greed points are dispersed nonuniformly as follows.

$$x_i = 0.5L\left(1 - \cos\left(\frac{(\pi i - \pi)}{(N-1)}\right)\right) \tag{22}$$

Based on the modal analysis, the following time-independent equation will be obtained:

$$\begin{bmatrix} [K_{dd}] & [K_{db}] \\ [K_{bd}] & [K_{bb}] \end{bmatrix} \begin{Bmatrix} \{\lambda_d\} \\ \{\lambda_b\} \end{Bmatrix} = \omega^2 \begin{bmatrix} [M_{dd}] & [M_{db}] \\ [M_{bd}] & [M_{bb}] \end{bmatrix} \begin{Bmatrix} \{\lambda_d\} \\ \{\lambda_b\} \end{Bmatrix} \tag{23}$$

where, 'ω' is the natural frequency, *b* and *d* indexes are related to the boundary and domain, respectively and λ is the mode shape. Also, according to the following assumption, the time-independent equations will be obtained (Azimi *et al*. 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al*. 2016a, e, g).

$$\begin{aligned} u &= \bar{u}\, exp(\, i\omega t) \\ \psi &= \bar{\psi}\, exp(\, i\omega t) \\ w &= \bar{w}\, exp(\, i\omega t) \end{aligned} \tag{24}$$

'*K*' and '*M* are the stiffness and mass matrices. Utilizing the Eq. (14), stiffness-matrices (*K*) and mass-matrices (*M*) are coupled as:

$$\begin{aligned} &A_{11}\sum_{s=1}^{n} C_{rs}{}^{(2)}\, u_s - l^2 A_{11}(x)\sum_{s=1}^{n} C_{rs}{}^{(4)}\, u_s \\ &= \omega^2\left(m_0 u_s - (ea)^2 m_0 \sum_{s=1}^{n} C_{rs}{}^{(2)}\, u_s\right) \end{aligned} \tag{25a}$$

$$\begin{aligned} &Q\sum_{s=1}^{n} C_{rs}{}^{(3)}\, w_s + E_{11}\sum_{s=1}^{n} C_{rs}{}^{(2)}\, \psi \\ &-B_{11}\left(\sum_{s=1}^{n} C_{rs}{}^{(1)}\, w_s + \psi_s\right) \\ &-l^2\left(Q\sum_{s=1}^{n} C_{rs}{}^{(5)}\, w_s + E_{11}\sum_{s=1}^{n} C_{rs}{}^{(4)}\, \psi\right) \\ &+l^2\left(B_{11}\left(\sum_{s=1}^{n} C_{rs}{}^{(2)}\, \psi_s + \sum_{s=1}^{n} C_{rs}{}^{(3)}\, w_s\right)\right) = \\ &\omega^2\left[\begin{array}{l} I_2\sum_{s=1}^{n} C_{rs}{}^{(1)}\, w_s + m_3\psi_s \\ -(ea)^2\left(I_2\sum_{s=1}^{n} C_{rs}{}^{(3)}\, w_s + m_3\sum_{s=1}^{n} C_{rs}{}^{(2)}\, \psi\right) \end{array}\right] \end{aligned} \tag{25b}$$

$$\begin{aligned} &D\sum_{s=1}^{n} C_{rs}{}^{(4)}\, w_s + Q\sum_{s=1}^{n} C_{rs}{}^{(3)}\, \psi_s \\ &-N^R\sum_{s=1}^{n} C_{rs}{}^{(2)}\, w_s + (ea)^2 3\frac{dN^R}{dx}\sum_{s=1}^{n} C_{rs}{}^{(3)}\, w_s \\ &-\frac{dN^R}{dx}\sum_{s=1}^{n} C_{rs}{}^{(1)}\, w_s + (ea)^2 3\frac{d^2N^R}{dx^2}\sum_{s=1}^{n} C_{rs}{}^{(2)}\, w_s \\ &-B_{11}\left(\sum_{s=1}^{n} C_{rs}{}^{(2)}\, w_s + \sum_{s=1}^{n} C_{rs}{}^{(1)}\, \psi_s\right) \\ &-l^2\left(D\sum_{s=1}^{n} C_{rs}{}^{(6)}\, w_s + Q\sum_{s=1}^{n} C_{rs}{}^{(5)}\, \psi_s\right) \\ &+l^2 B_{11}\left(\sum_{s=1}^{n} C_{rs}{}^{(4)}\, w_s + \sum_{s=1}^{n} C_{rs}{}^{(3)}\, \psi_s\right) \\ &+(ea)^2\left(\frac{d^3N^R}{dx^3}\sum_{s=1}^{n} C_{rs}{}^{(1)}\, w_s + N^R\sum_{s=1}^{n} C_{rs}{}^{(4)}\, w_s\right) \\ &= \omega^2\left(I_1\sum_{s=1}^{n} C_{rs}{}^{(2)}\, w_s - m_0 w_s + I_2\sum_{s=1}^{n} C_{rs}{}^{(1)}\, \psi_s\right) \\ &-(ea)^2\omega^2\left(\begin{array}{l} I_1\sum_{s=1}^{n} C_{rs}{}^{(4)}\, w_s - m_0\sum_{s=1}^{n} C_{rs}{}^{(2)}\, w_s \\ +I_2\sum_{s=1}^{n} C_{rs}{}^{(3)}\, \psi_s \end{array}\right) \end{aligned} \tag{25c}$$

Finally, using the Newmark-beta technique (Singh and Pal 2021), the time-dependent results will be calculated (Ghadiri *et al*. 2016a, b, c, d, Shafiei *et al*. 2016b).

3. Discussion of the results

Nanomototors, thanks to their self-propelled feature, are one of the best structures to be utilized as drug delivery devices. it was exhibited that using these structures can increase the efficiency of drug delivery and reduce systemic toxicity. These structures, as they can be in various shapes, sizes, and materials, and also since they can be propelled with different forces such as magnetic, acoustic, and catalytic, they can be an excellent choice to be employed in drug delivery devices. Now, the various ways, designs, and applications related to drug delivery systems are described. In the current study, the use of nanomotor as a drug-delivery system is explored. The nanomotor is made of a carbon nanotube carrying the drug into the tube, spun in the blood vessel. In order to have a clearer representation of the finding's discussion, it is necessary to introduce the following non-dimensional forms of parameters:

Nonlocal parameter (β):

$$\beta^2 = (ea)^2/L \tag{26a}$$

Rotation speed (Φ):

$$\Theta^2 D_{11} = m_0 L^4 \phi^2 \tag{26b}$$

Hub radius (Δ):

$$\Delta L = \chi \tag{26c}$$

Natural frequency (ϑ):

$$\vartheta^2 \pi D_{11} = \omega^2 L^4 m_0 \tag{26d}$$

Strain gradient parameter (κ):

$$\kappa = l/\,R\,o \tag{26e}$$

Deflection (Γ):

$$\Gamma = wD\pi/F_{BF}L^4 \tag{26f}$$

An essential emphasis of this research was on the influence of physical and training activities on the stability of drug-delivery nanodevices, as explained. This study examined the impact of sports on nanomotors and other nanodevices released into the bloodstream. It is clear that sports training and exercise improve the blood flow and bloodstream in the body, and also, physical activities lower blood pressure in individuals with hypertension (Börjesson *et al*. 2016). Sport, as previously said, increases blood flow, and therefore the following measure, dubbed "effect of physical activities (EPA)" is defined in order to investigate this claim:

$$EPA = \varpi \times \omega^{-1} \tag{26e}$$

EPA may be a sign of sports activities in the bloodstream, which implies raising the intensity of sports activities improves the EPA. So, in the following, the exercise effects are displayed by EPA, and a rise in the EPA signifies raises the intensity of sports activities.

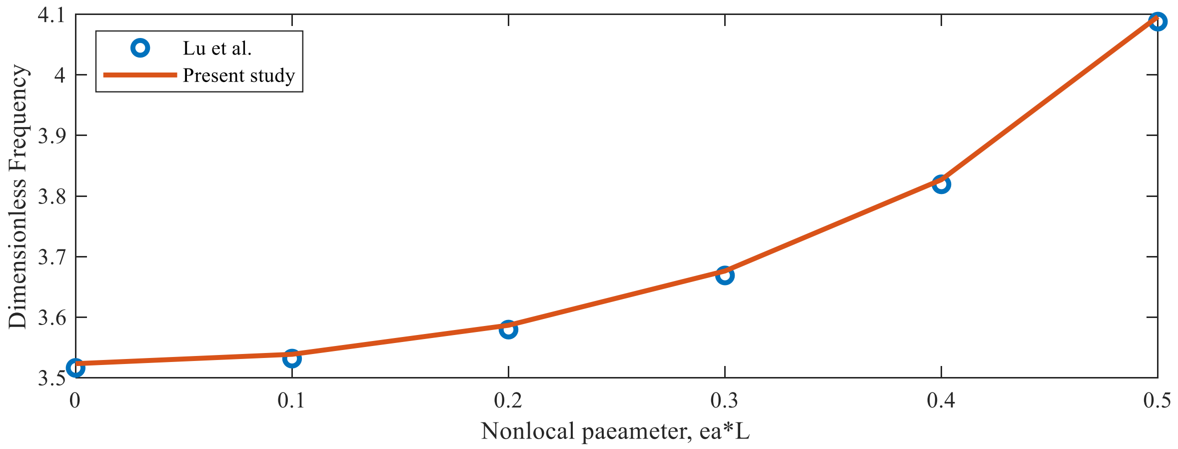

Fig. 2 The reported dimensional frequency ($\omega L^2\sqrt{m_0/D_{11}}$) of a nonlocal classic cantilever beam is compared to Lu *et al*. (2006) published findings

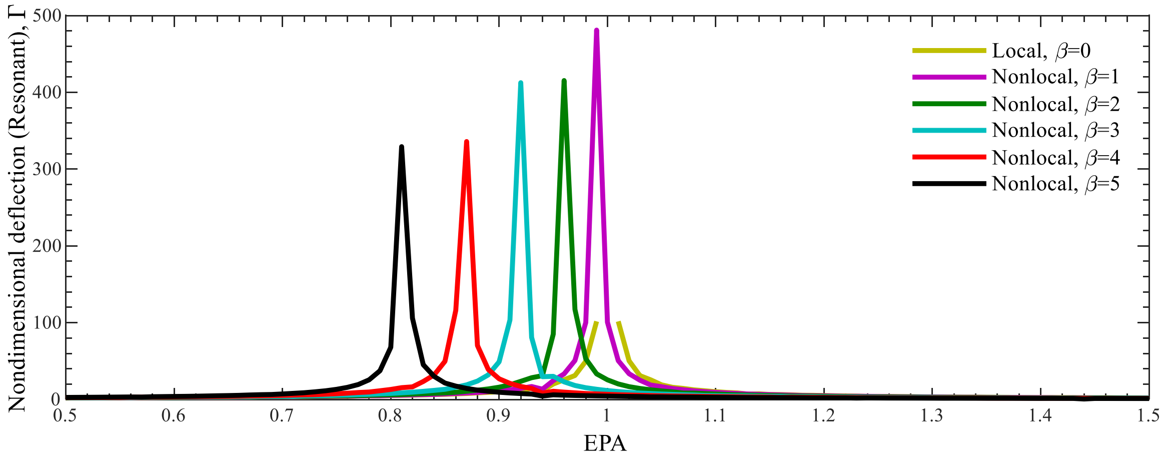

Fig. 3 Impact of the nonlocal parameter (β) on the resonant frequency and deflection of nanomotor's blade versus the intensify the physical exercise parameter (EPA), Θ=1

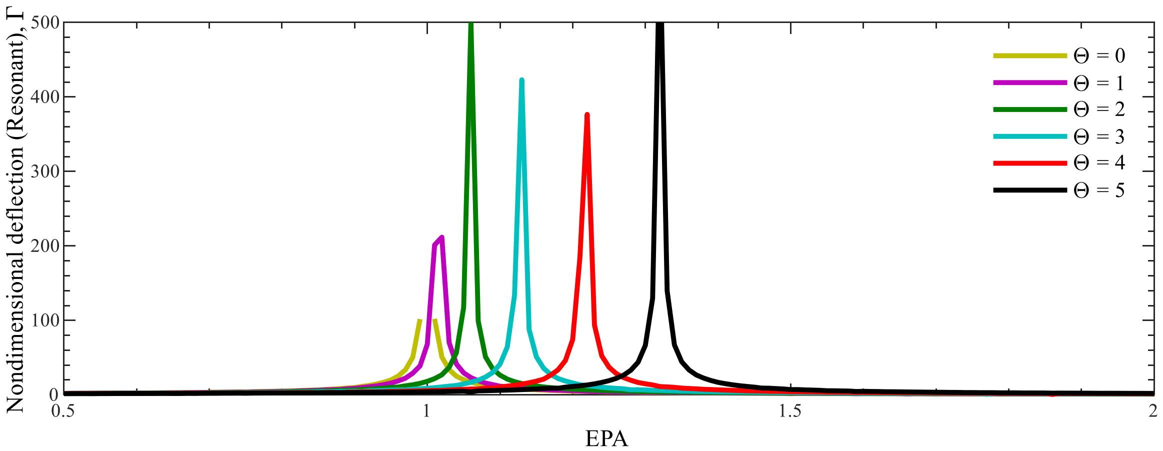

Fig. 4 Influence of rotation speed (Θ) on the resonant frequency and maximum deflection of the drug-delivery mechanism for different parameters of physical exercise (EPA), β=1

Firstly, to validate the results of this study Fig. 2 is presented. In this figure the first nondimentional vibration frequency related to a Clamped-Free nonlocal nanobeam are obtained and compared with those of Lu *et al*. (2006). It can be seen from this figure that the current results has little difference with the results of reference, which proves the accuracy along with the credibility of these results to investigate the vibrational response of a nanomotor modeled via NSGT.

Now, in Figs. 3-5, the effects of the nonlocal parameter

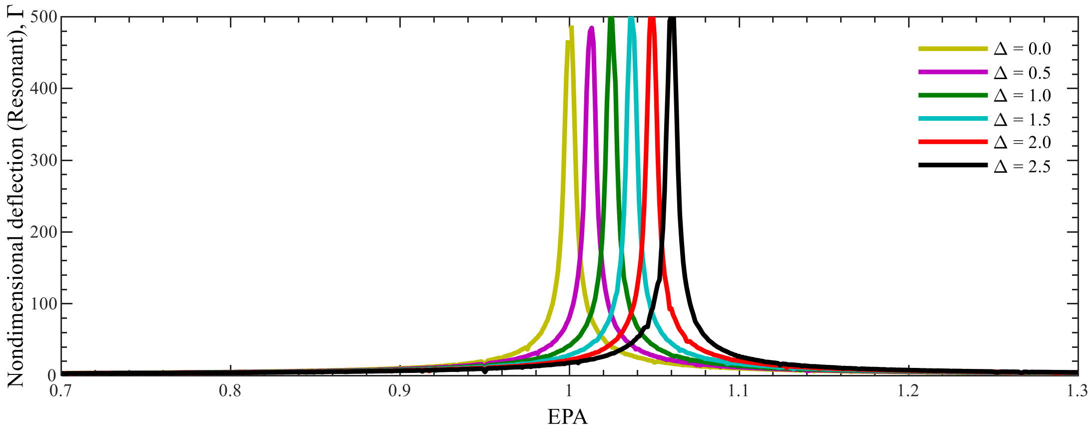

Fig. 5 Influence of hub radius (Δ) on the resonant frequency and maximum deflection of the drug-delivery nanomedicine for various values of physical training intensify (EPA), β=Θ=1

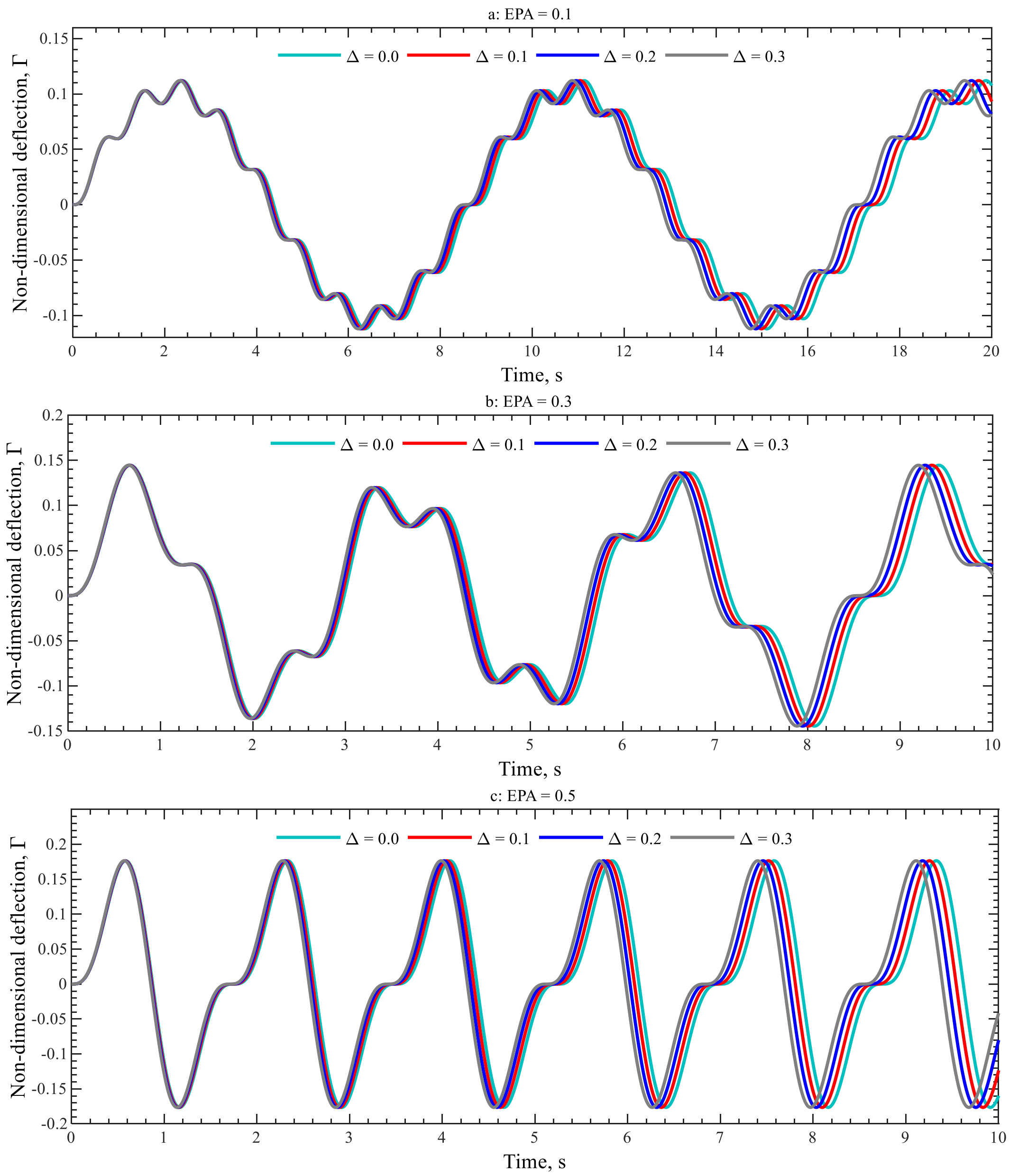

Fig. 6 The time-dependent deflection of nanomedicine blade for different hub radius (Δ) values versus the variable condition of blood flow (EPA) in the conditions of the sport Θ=1.5, β=1

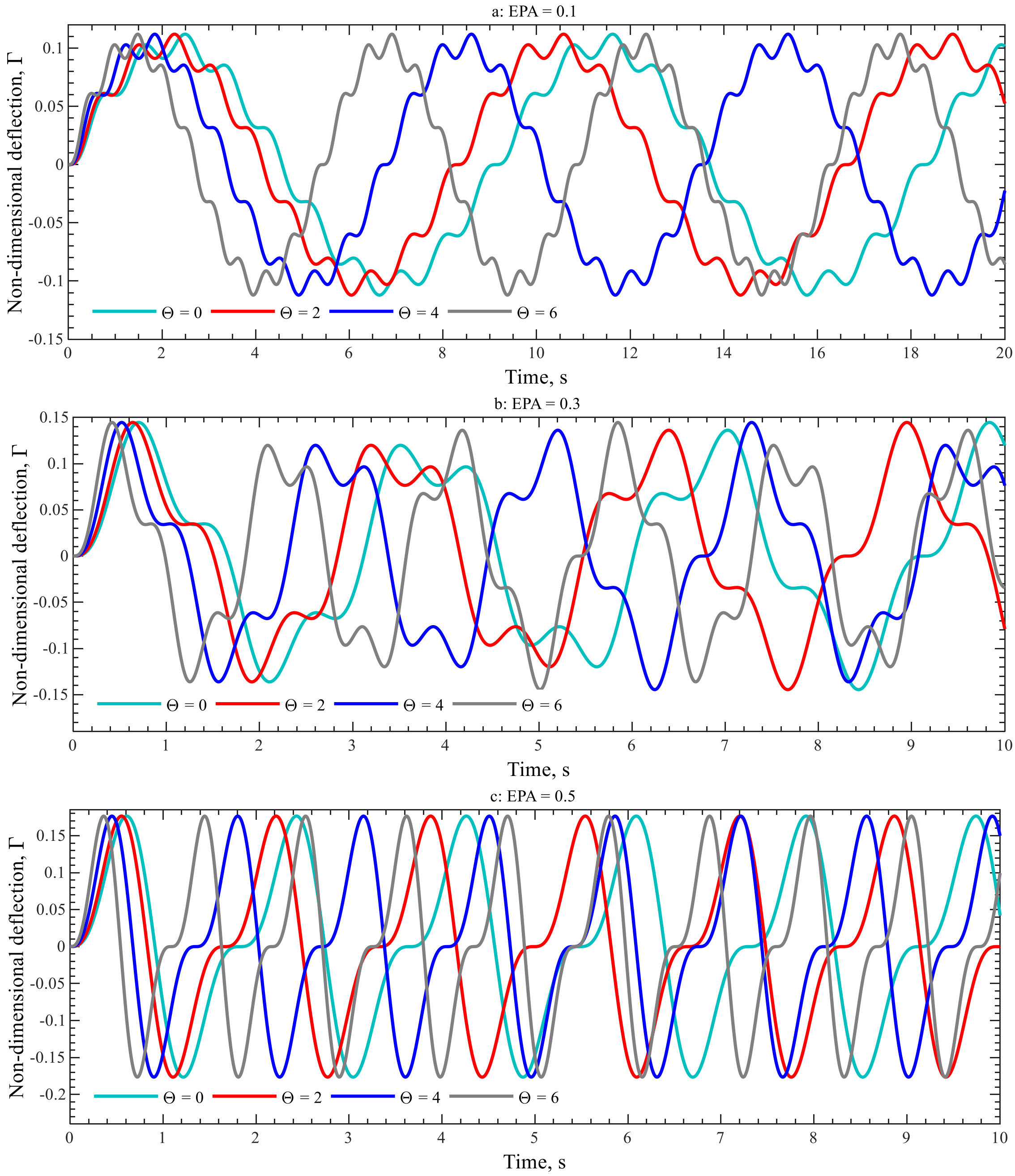

Fig. 7 Impact of velocity (Θ) on the dynamic deflection of nanomotor versus the different intensity of exercise actions (EPA), Δ=0.15, β=1

(β), rotation speed (Θ), and hub radius (Δ) on the effect of physical activities (EPA) is investigated, repectivly. To do so, the varation of effect of physical activities (EPA) versus nondimensional deflection are plotted in these figures for varius values of the abovementioned prameters.

Fig. 3 exhibits that the peak of deflection occurs in lower EPA, providing that the nonlocality of the nanomotor has a higher value. In another word, the peak of the case that nonlocality is zero, local case, the peak is associated with the highest EPA. Also, as a general conclusion, the deflection of the nanomotor intensifies by reducing the value of the nonlocal parameter. Against the results for the nonlocal parameter, the peak of nondimensional deflection is in higher EPA if the rotation speed of the nanomotor has a higher value. Thus, the lowest EPA that can cause the nanomotor to be in the resonant phase is associated with the case whose rotation speed is zero.

Results in Fig. 5 indicate that the resonant phase for nanomotor can be in higher EPA by increasing the value related to hub radius. Additionally, the highest deflection in nanomotor can be seen in the cases with the highest value of Δ.

Next, the impact of hub radius (Δ), rotation velocity (Θ), nonlocal parameter (β), and gradient strain parameter (κ) on the vibrational response of the nanomotor is studied in Figs. 6-9, respectively. In these figures, the time history of the

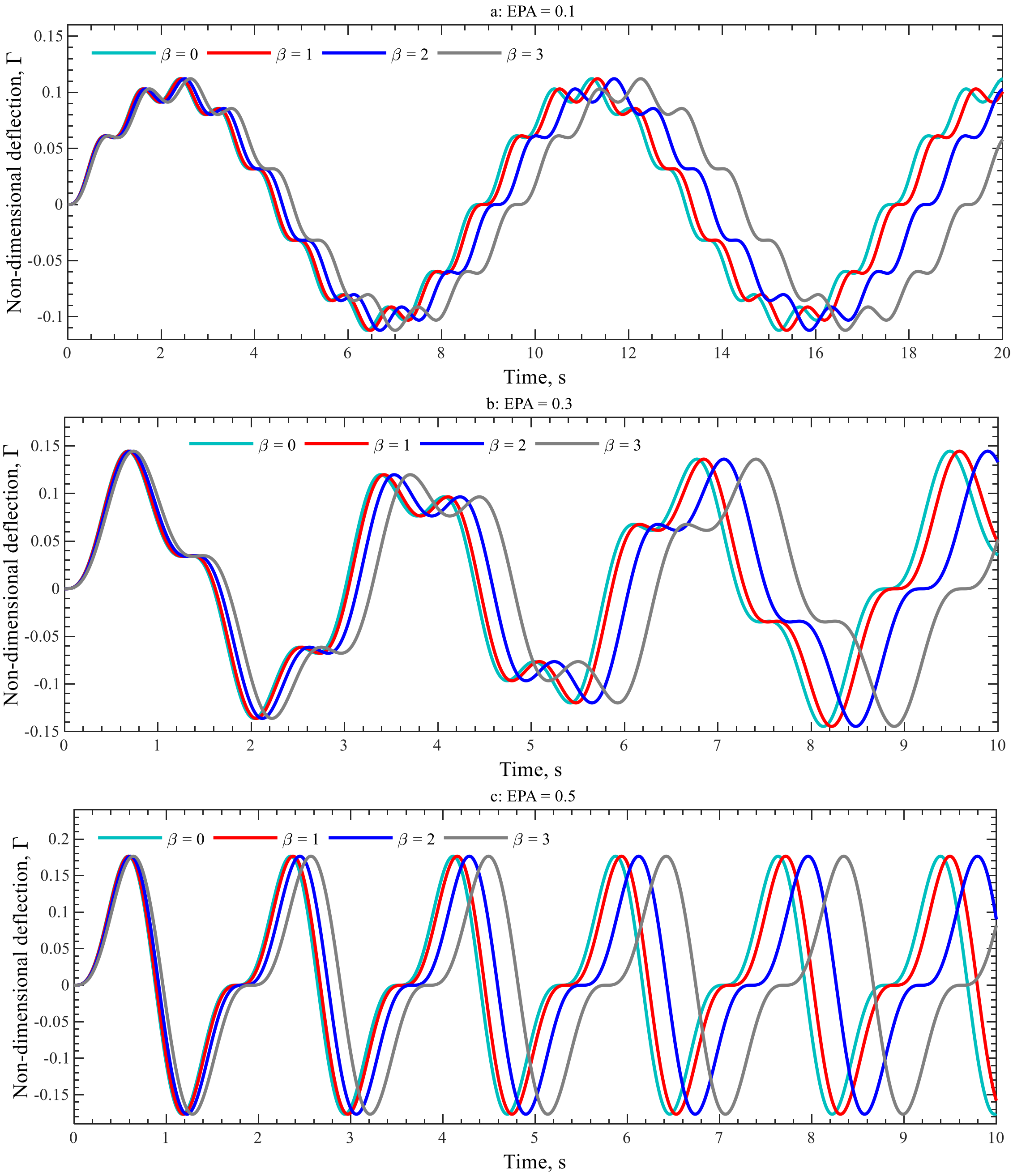

Fig. 8 The time-dependent deflection of nanomedicine blade versus nonlocal values (β) versus the different intensifies the physical exercise (EPA) in the conditions of the sport, Θ=1.0, Δ=0.15

forced vibration associated with the nanomotor modeled via NSGT is plotted for three different values of EPA. Also, the other constants used to extract these results are explained in the caption of the figures.

Fig. 6 shows that the higher the EPA is, the higher the nanomotor deflection, and the lower the period time of the vibration is. Also, the other notable result which can be observed from this figure is that increasing the hub radius does not change the vibration deflection, however, it can reduce the period of the vibration.

In a like manner to the previous figure, it is evident that the cases with higher EPA have higher deflection and lower period time. Additionally, intensifying the nanomotor speed leads to a lower period, regardless of the value of EPA. Additionally, the velocity cannot change the value of vibration deflection.

Against the results for hub radius and rotation speed, increasing the value of the nonlocal parameter can increase the period of vibration, which is due to softening effect of nonlocality. However, this parameter does not vary the vibration deflection regardless of the value of EPA.

The exciting results in Fig. 9 show that, by increasing gradient strain parameter (κ), both period and deflection of the vibration of nanomotor can diminish significantly. Also, like previous figures, the highest frequency and deflection are associated with the cases with a higher value of EPA.

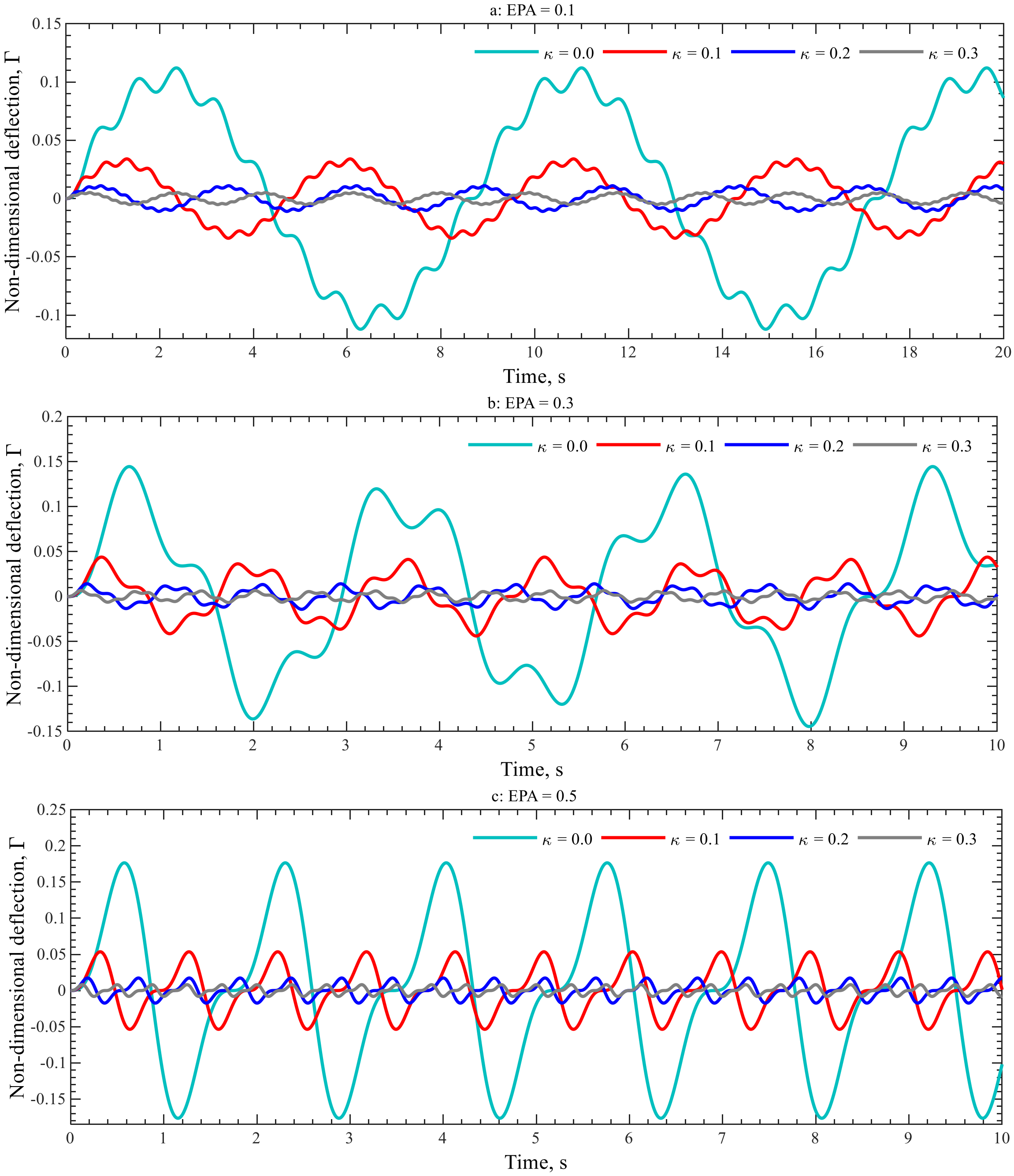

Fig. 9 Effect of gradient strain parameter (κ) on the time-dependent dynamic deflection of nanomotor for various values of EPA, β=1, Θ=10, Δ=1.5

4. Conclusions

The current study investigates the dynamic stability and vibration of a rotating nanotube which can be utilized as a drug delivery system. The formulations for this problem are extracted by using higher-order beam theory, NSGT, and the energy method. Then, by using GDQM in conjunction with the Newmark method, time-dependent results are obtained. The validity as well as accuracy of results are proven by utilizing a comparison study. The effect of various parameters on the dynamic stability of the nanotube is examined. The following are the most significant results of the current study:

- By increasing gradient strain parameter (κ), both the period and deflection of the vibration of the nanomotor can diminish significantly.
- Increasing the value of the nonlocal parameter can increase the period of vibration.
- The cases with higher EPA have higher deflection and lower period.
- The resonant phase for nanomotor can be in higher EPA by increasing the value related to hub radius.
- The peak of deflection occurs in lower EPA, providing that the nonlocality of the nanomotor has a higher value.

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