

Repair of tendon injury in Taekwondo by nanobiotics

Dilong An*, Shun Jiang, Tongtong Cai and Wei Tian

Department of Physical Education, Chang'an University, Xi'an 710064, Shannxi, China

(Received February 4, 2022, Revised September 10, 2022, Accepted September 19, 2022)

Abstract. In the present study, capability of nanobiotics in repairing tendon injuries commonly occur in Taekwondo sport is investigated and some approaches are proposed. In this regard, a brief review on the types and application of nanobiotics is presented. Their capabilities and limitation are discussed. Next, different type of tendon injuries in Taekwondo athletes are discussed along with their treatment approaches. Based on the presented data, a nano-scale feasible robot model carrying nanobiotics is proposed for repairing tendons. Finite element simulations is also conducted to show the effectiveness of the repairing process using nanorobots equipped with nanobiotics. This repairing procedure is a combination of mechanical and chemical treatments. The results indicated that using nanobiotics on nanorobots arms in the repair of tendon injuries has many benefits. First, drug delivery is directly injected to the target section. Second, Due to the nanorobots small sizes more acute treatment is possible. Finally, since the control of the nanorobots are assisted with computers, the possibility of human error reduces significantly. The proposed method of the present study could be utilized by other scientists and technological industry in developing final nanorobots with nanobiotics carrying capacity.

Keywords: nanobiotics, nanorobots, tendon repair, taekwondo, achilles tendon, nanotechnology

1. Introduction

Nanotechnology has affected almost every aspects of early lives. From drug-delivery systems to motions sensors have been changed to small-scale nanostructure-based systems (Habibi *et al.* 2016, 2018a, b, 2019b, d, e, Ebrahimi *et al.* 2019a, Esmailpoor Hajilak *et al.* 2019, Pourjabari *et al.* 2019, Safarpour *et al.* 2019a, Zhu *et al.* 2022, Dai *et al.* 2023, Zheng *et al.* 2023). Besides drug delivery systems, other aspects of nanotechnology have found applications in health care systems. Nanocomposites are numerously utilized in tendon injury repair as both bio-degradable scaffolds and screws (Fazaeli *et al.* 2016, Habibi *et al.* 2017, 2019a, c, Safarpour *et al.* 2018, 2019b, 2020, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Ghazanfari *et al.* 2020, Chen *et al.* 2022). These materials have astonishing strengths with customizable properties for different situations. On the other hand, these nanoscale materials could be equipped with nano-medicine for precise delivery to the damaged section. Moreover, nanorobots, as another nanotechnology achievement, could perform operations in cell-size scale to confront diseases like cancer (Ebrahimi *et al.* 2019b, c, 2020b, Hashemi *et al.* 2019, Habibi *et al.* 2020, Moayedi *et al.* 2019, 2020a, b, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Oyarhossein *et al.* 2020, Shariati *et al.* 2020a, b, Shokrgozar *et al.* 2020). There are many other applications of nanotechnology-based systems which are widely used in the health care systems.

Nanobiotics are novel nanotechnology drugs against antimicrobial resistance (Chakraborty *et al.* 2022). Their

small scale and capability of surface modification put a suitable pathway in the treatment of mycobacterial infections (Batalha *et al.* 2019). Batalha *et al.* (2019) showed that using polymer nanobiotics it is possible to encapsulate antibiotic drug delivery. The nanobiotics in their study were used to improvement in killing Mycobacterium tuberculosis and to deliver drugs accurately. Mohamed *et al.* (2018) formulated a nanobiotic drug to confront Staphylococci which is resist against antibiotic drugs. They showed that nanosystem drug delivery with their innovative method could enhance the antimicrobial effects of three type of antibiotics (Hashemi *et al.* 2019, Al-Furjan *et al.* 2020e, o, q, s, Bai *et al.* 2020, Cheshmeh *et al.* 2020, Li *et al.* 2020a, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020c, Xiong *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021a).

Possibility of using nanorobots in performing large scale operations has been the focus of researches for years. Small scale applications has been successfully devises and employed (Soto and Chrostowski 2018, Chen *et al.* 2019, Soto *et al.* 2020b). By nano-robot it is meant any system producing mechanical movement and deformation having or using nano-scale structures. Nano-robots have been studied to perform surgeries in small scale. Soto *et al.* (2020b) reviewed the main applications of nanorobots in surgery. Applications were divided into four categories of biopsy, tissue penetration, intercellular drug delivery and biofilm degradation. Tissue penetration for different purposes and achieving access to deep regions of tissues. Jafari *et al.* (2019) utilized magnetic field for controlling microrobots penetrating brain tissue in mouse cadavers. They reported that easier transportation of the microrobot was achieved using combination of rotational and linear movement. The significance of this process is the minimal and insignificant damages to the internal organs and brain.

*Corresponding author, Ph.D.,
E-mail: andy0323@chd.edu.cn

Mair *et al.* (2019) used the same system to penetrate neural net of living mice to observe capability of controlling deep brain structures. The importance of such penetration and control lays in the fact that the deep organs are not simply accessible. Their success in controlling some behaviors of the living mice put a novel way forth to extend the application of such small-scale robots. Xi *et al.* (2013) devised a micro-structure controllable device to incise different tissues using magnetic material. These robots could be utilized in micro-scale surgeries (Adamian *et al.* 2020, Al-Furjan *et al.* 2020c, d, Li *et al.* 2020b, Liu *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Liu *et al.* 2021b, Zhang *et al.* 2021).

Micro/nanorobots could also be employed in sample collection and biopsy operations. Soto *et al.* (2020a) proposed a multilayer spherical structure for collecting pathogens using chemical attractive materials in their structure. This structure is also capable of killing pathogens using Ag⁺ ions. Using a star shape controllable and foldable robot for the aim of single cell biopsy applications and micro-scale incision. This robot is actuated using temperature change to bend its fingers leading to change in shape from a planar structure to a capsule-shape structure containing one or few number of cells (Breger *et al.* 2015). Fusco *et al.* (2014) proposed a micro-scale robot exploiting three features of near infrared light, magnetic alginate micro-beads and 3D structures capable of encapsulating cells for drug delivery purposes. The micro/nano-scale robots have the potential to be utilized in larger scale surgeries using bottom-up repairing strategies. One of the main most challenging repairmen in human body is due to tendon injuries which often occur in athletes.

Taekwondo is among sports in which tendon injury and rupture commonly occurs. Tendon repair technique has well-established procedures based on the level of injury. Lee *et al.* (2009) examined changes in extensor hallucis longus (EHL) tendon in taekwondo athletes in comparison to non-taekwondo athletes. The results indicated that changes in the tendons of taekwondo athletes had a significant difference. The fraction of athletes with change was 20% against 2% in non-taekwondo participants. The results also indicated that the EHL thickness in athletes was greater than other group of participants. Houshian *et al.* (1998) reported a statistics of Achilles tendon rupture in a course of 13 years in Danish county. They found that the number of Achilles injuries occurrence in men and women were different with a ratio of 3:1. Moreover, the frequency of the rupture had increased over years from 18.2 per hundred thousand in 1984 to 37.3 in 1996. The rupture in the younger group was related to the sport activity while in the elderlies it was independent from level of exercises. Son *et al.* (2020) statistically studied injuries occurrence in Taekwondo elite athletes to unravel the type, frequency and healing duration of the injuries with respect to age, sex and type of exercise during which injury occurs. The results showed that the frequency of injuries were higher in younger athletes in comparison to adults.

Repair of tendon injuries differs based on the level and type of injury. In the cases with low injuries self-healing is

the best practice for complete recovery of the tendon. For complete rupture in tendons, surgical intervention is inevitable in most cases. Surgical operations comes with cutting and damaging to nearby organs. Docheva *et al.* (2015) reviewed common procedure in repairing tendon injuries. These practices includes autografts, allografts, suture and synthesis prostheses. They discussed each method in detail and concluded that none of these methods could completely heal the tendon injuries. Therefore, new feasible technology and procedure needs to be conceived in this specific area of healthcare system.

In the present study, In the present study, capability of nanobiotics in repairing tendon injuries commonly occur in Taekwondo sport is investigated and some approaches are proposed. In this regard, a brief review on the types and application of nanobiotics is presented (Fan *et al.* 2022a, Luo *et al.* 2022b, Wang *et al.* 2022a, Xia *et al.* 2022). Their capabilities and limitation are discussed. Next, different type of tendon injuries in Taekwondo athletes are discussed along with their treatment approaches. Based on the presented data, a nano-scale feasible robot model carrying nanobiotics is proposed for repairing tendons. Finite element simulations is also conducted to show the effectiveness of the repairing process using nanorobots equipped with nanobiotics. This repairing procedure is a combination of mechanical and chemical treatments. The benefits of such methods could be at first, drug delivery is directly injected to the target section. Second, Due to the nanorobots small sizes more acute treatment is possible. Finally, since the control of the nanorobots are assisted with computers, the possibility of human error reduces significantly. The proposed method of the present study could be utilized by other scientists and technological industry in developing final nanorobots with nanobiotics carrying capacity.

2. Methodology

2.1 Bendable cantilever nanorobots

Adopting the concept from Ref. (Breger *et al.* 2015), a cantilever nanorobots arm demonstrated in Fig. 1 is proposed for the aim of the gripping tendon. This robot is capable to be bent with change in ambient temperature. The shape of the robot is designed to be pointy so it could simply penetrate into the tendon after straitening. The tendons do not straightened completely so that a bend is exists on each nanorobots. The bend of the nanorobots is in the opposite direction of the tendon movement. Thus, with increase in the tension of the tendon the resistance of the nanorobots increases. Since the tendons composed from parallel fibrous, the nanorobots in the two rows are directed in opposite directions to make fibrous bend and endure a wavy path. This approach cause increase in pulling force of the ruptured tendon (Al-Furjan *et al.* 2020a, b, g, f, h, i, j, k, l, m, n, p, r, t, u, v, 2021a, c).

One another feature of this system in biodegradability of the nanocomposite cage structure and nanorobots. This scheme of the gripping system eliminate the need for

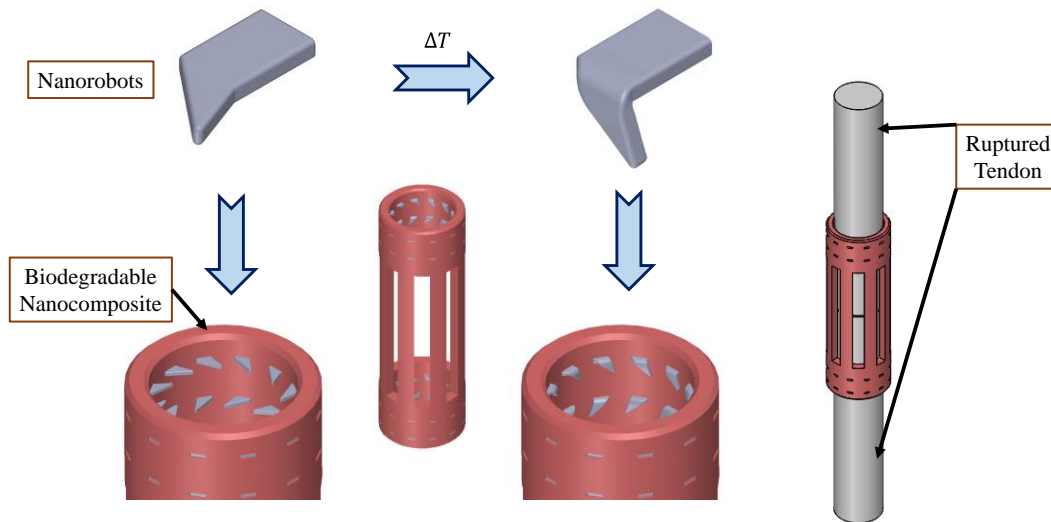


Fig. 1 Nanobiotics carrying nanorobot arms and their mount on the ruptured tendon

Table 1 Elastic material properties of components used in the nano-structured tendon gripper system. (whenever some data is not available the rule of mixture is utilized for calculations)

Component	Material	Elasticity modulus (GPa)	Poisson's ratio	Reference
Tendon	Tendon	0.87	0.55	(Lichtwark and Wilson 2005) and (Vergari <i>et al.</i> 2011)
Nanorobots	Graphene oxide	390.9	0.178	
	Matrix	1.2	0.34	
Nanocomposite cage	PLGA	0.341	0.30	(Moffat <i>et al.</i> 2008)

secondary operation to remove the material from the body. The cage holding the nanorobots have openings for access to the ruptured area of the tendon. It may be needed that the two side of the area to be stitched together. However, this stitch endure no load since the majority of the load is applied to the nanorobots grippers (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 2021a, Kong *et al.* 2022).

The insertion of this grip system is a simple practice. First, the temperature of the system is set in the condition so that the nanorobots arms is folded and they are not an obstacle in the way of the tendon through cage structure. After the inserting tendons in their positions the ruptured on the tendons are stitched together to avoid any gap between them. In the next step the temperature is changed to the condition in which the arms of nanorobots are open and penetrate the tendon. This a very simple procedure.

2.2 Material properties

As presented in the precious section, there are several biodegradable materials which are used in the grip nanorobots system (Hou *et al.* 2021, Liu *et al.* 2021c, Luo *et al.* 2022b, Moradi *et al.* 2022, Wang *et al.* 2022b, Wang *et al.* 2022c, Yang *et al.* 2022a, Fang *et al.* 2023, Jin *et al.* 2023, Wang *et al.* 2023). First of all, the materials used in the nanorobots grips are adopted from Peng and De (Peng and De 2013, Smith *et al.* 2019). Next, the biodegradable

nanocomposite materials properties are in accordance with Correia Pinto *et al.* (2017). Finally, the mechanical properties of the tendon are utilized from (Lichtwark and Wilson 2005) and (Vergari *et al.* 2011). All the properties are summarized in Table 1.

2.3 Finite element analysis

The load capacity of the nanorobots-based gripper designed for the purpose of tendon repair was evaluated using finite element method (Dong *et al.* 2022, Fan *et al.* 2022a, b, Hu *et al.* 2022, Huang *et al.* 2022, Luo *et al.* 2022a, Yang *et al.* 2022b, Zhang *et al.* 2022, Zheng *et al.* 2022, Zhou *et al.* 2022a). In this regard, several models with different geometry and number of nanorobots were constructed in SolidWorks software as shown in Fig. 1 and 2. In Fig. 2, the idealized shape and dimensions of the gripper system is shown. The parametric values will be used in the result section to find the effects of geometry ratios and number of nanorobots on the load capacity of the gripper. The diameter of tendon is represented by D_T , diameter of the nanocomposite cage by D_{NC} and length of the cage by L_{NC} . The number of the nanorobot arms is denoted by N .

Finite element numerical calculations (Amelirad and Assempour 2019, 2021) are performed in ANSYS Workbench software. The contacts between nanorobots and the cage is considered to be perfect with no sliding and separation. Connection between nanorobot arm and the

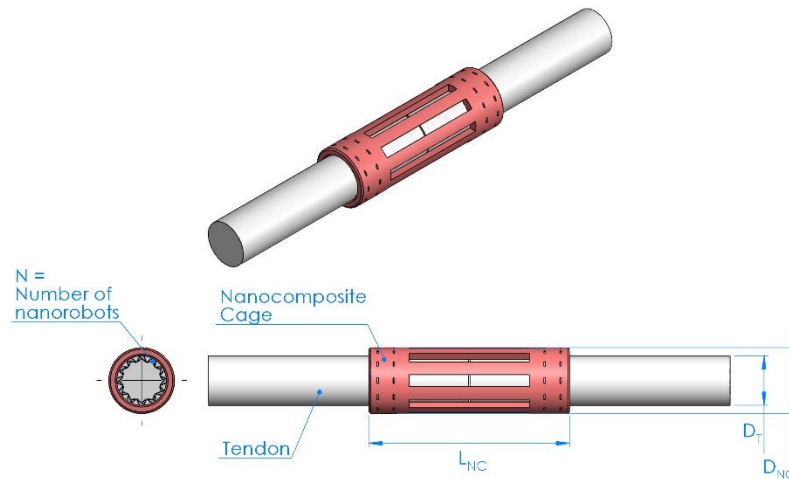


Fig. 2 Dimensions of the nanorobots-based gripper system

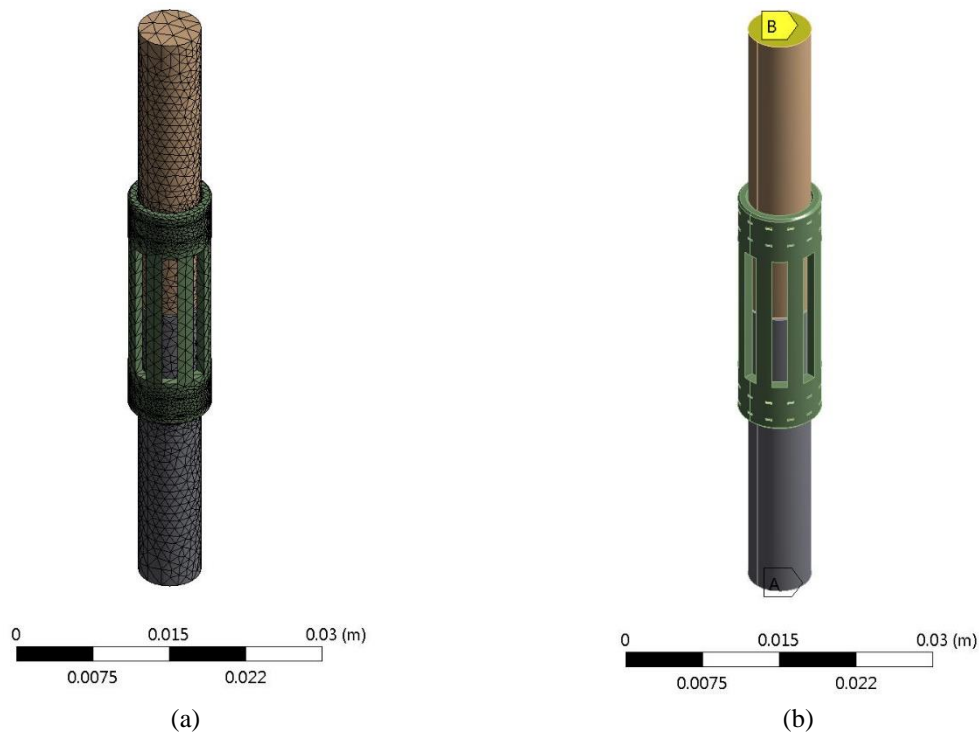


Fig. 3 (a) finite element discretization (b) displacement loading at B and fixed end at A

tendons surfaces after penetration is considered to be frictional with friction coefficient μ . The discretized model with boundary and loading condition is shown in Fig. 3. The quadratic quadrilateral elements were used for analysis (Huang *et al.* 2021b, Jiao *et al.* 2021, Ma *et al.* 2021, Moradi *et al.* 2021, Xu *et al.* 2021, Zhao *et al.* 2021, Michael *et al.* 2022, Yu *et al.* 2022, Zhou *et al.* 2022b). In addition, large deformation option was enabled to incorporate the deformation of tendon and nano-arms into consideration. In total, 670526 elements and 946618 nodes are incorporated in analysis (Habibi *et al.* 2017, Alipour *et al.* 2020, Al-Furjan *et al.* 2021b, Wu and Habibi 2021b). This mesh size and number of elements was based on our convergence study on the model. All the loadings are in the

form of displacement and 1mm displacement is applied in one end of the tendon in its axial direction. The other end of the ruptured tendon is fixed.

3. Results

In this section, the effects of using nanorobot-based grips are presented in detail. In particular, effects of geometrical parameter and number of nanorobot arms on the force required for 1 mm tensile displacement. A sample of finite element results showing von Mises stress value in all components are depicted in Fig. 4. As seen, the most critical sections in the nanocomposite cage are its columns

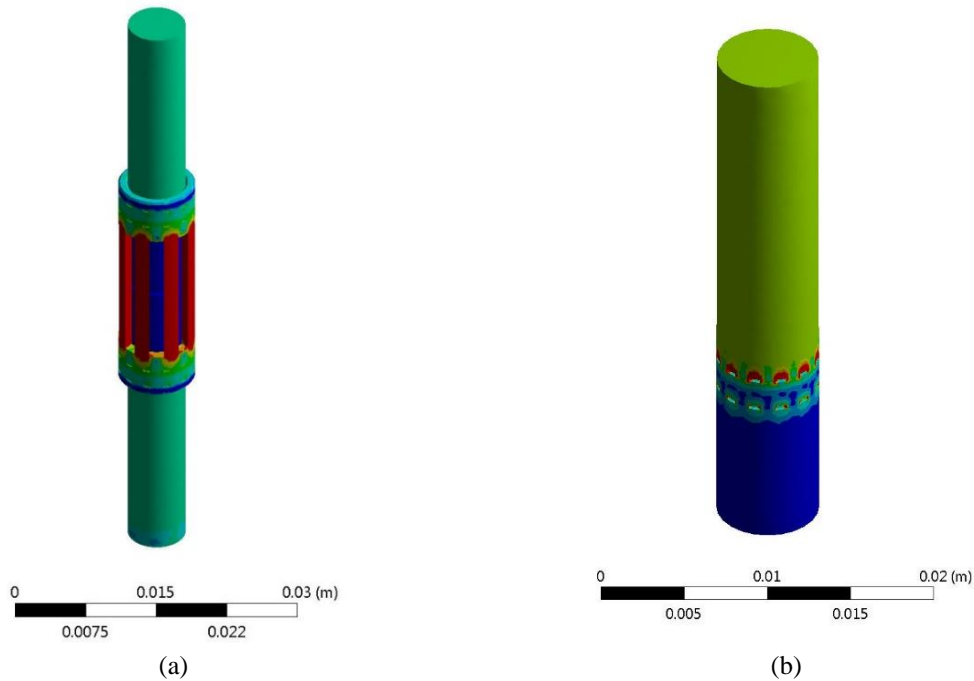


Fig. 4 (a) Von Mises stresses in the tendon and nanorobot repair system in tensile loading (b) Von Mises stresses in the tendon around cavities made by nanorobots

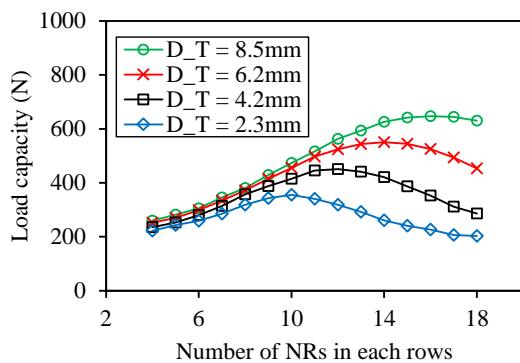


Fig. 5 Load capacity against number of nanorobots (NRs) in each row in the nanorobot tendon repair system

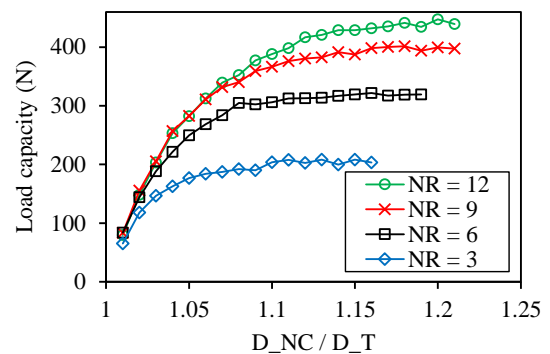


Fig. 6 Load capacity against diameter ratio D_{NC}/D_T for different values of NRs

connecting upper and lower sections. The stress distribution in tendon indicates that stress values concentrates in the region around the cavity generated by nanorobots arms.

In Fig. 5, effect of number of nanorobot arms on the load capacity of the structure is shown for $D_{NC} = 8.2mm$ and $L = 30mm$. It is seen that with increase in number of the nanorobot arms penetrating tendon the load capacity increases in all tendon diameters until a specific number which affects integrity of the tendon cross section area. Therefore, for each tendon diameter there exists an optimum number of NRs in which the highest load capacity of the system achieved. Increase in the diameter of the tendon obviously rises the load capacity of the system which is a direct result of increase in the number of NRs without deteriorate the integrity of the cross section area of the tendon. Indeed, the failure of the system before the optimum number of NRs are mainly due to exceeding load capacity of the NRs while after this number the failure

occurs in the tendon itself. In any case, the maximum load capacity is important to consider here.

The effect of the diameters ratio D_{NC}/D_T on the load capacity for different number of NRs is demonstrated in Fig. 6 for $D_T = 6.2mm$. Increasing the diameter ratio increase the load capacity of the system in low values of D_{NC}/D_T for all number of NRs. It is seen that in all number of NRs there is a limit in which load capacity become constant afterwards. Therefore, considering the minimum material usage the optimum value of the of each condition could be determined using the beginning value of D_{NC}/D_T at which load capacity become constant.

One another parameter to be considered is the ratio of length to diameter of nanocomposite cage L_{NC}/D_{NC} on the load capacity of the tendon repair system. The effect of variation in this ratio is presented in Fig. 7 as calculated by finite element analysis for different numbers of NRs. As seen, change in the ration of length to diameter of the

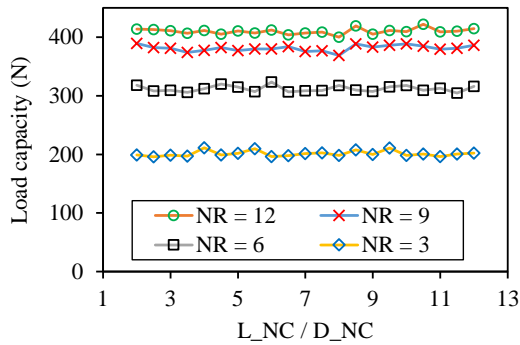


Fig. 7 Load capacity against length to diameter ratio of the nanocomposite cage for different values of nanorobots.

nanocomposite cage has diminishing influence on the load capacity for all values of the NRs. The fluctuations in the results are mostly due to numerical errors in the finite element analysis. Therefore, it could be concluded that change in the length of the cage has no effect on the load capacity so the proper length could be selected in the repair procedure.

4. Discussion

Load capacities of the conventional bonding methods in tendon repair for taekwondo athletes very low according to experimental analysis (Mazurek *et al.* 2011). The load capacity barely exceed 200N which is very low value compared to the tension exerted on the tendons during daily life movements (Kongsgaard *et al.* 2011). Therefore, these repair methods enforce the patient to withstand high care of movement for a long time normally required for tendon repair. The method and mechanisms presented in this study have some merits in comparison to conventional methods.

First, the contact between fixing system, i.e. nanorobots arms, are distributed around the tendon circumferential so the load does not concentrate in few points. The concentration of force results in tearing of tendon near damaged area and in some cases makes the damage worse. On the other hand, for assured securing of the tendons part many stitches are required which significantly twist and compress tendon. This compression results in the permanent change in the shape and length of the repaired tendon. Using the method proposed in the recent work, the tendon parts are precisely connected and perfectly aligned with each other without extreme compression and distortion in their shapes. Second, biodegradable materials used in the proposed methodology excludes the secondary operation in the repair tendons. Moreover, the daily life of the patient is not affected by this system since the load capacity increases to 600N as shown in Fig. 5 (Benthien *et al.* 2006). Finally, the system is controllable by changing in temperature. This is vitally important in increasing or reducing the amount of force, penetration to the tendon and mounting the NRs system on the tendons. Despite other method all the required material and components are prepared before operation using scanned tendons so that the duration of the surgery will be minimized.

5. Conclusions

In the present study, capability of nanobiotics in repairing tendon injuries commonly occur in Taekwondo sport is investigated and some approaches are proposed. In this regard, a brief review on the types and application of nanobiotics is presented. Their capabilities and limitation are discussed. Next, different type of tendon injuries in Taekwondo athletes are discussed along with their treatment approaches. Based on the presented data, a nano-scale feasible robot model carrying nanobiotics is proposed for repairing tendons. Finite element simulations is also conducted to show the effectiveness of the repairing process using nanorobots equipped with nanobiotics. This repairing procedure is a combination of mechanical and chemical treatments. The proposed method of the present study could be utilized by other scientists and technological industry in developing final nanorobots. The main conclusions of this research study are:

- Equipped nanorobots by nanobiotics have double advantages of mechanically fixing the ruptured tendon in taekwondo athletes and also chemically treating the ruptured area by nanodrugs.
- The contact between fixing system, i.e., nanorobots arms, are distributed around the tendon circumferential so the load does not concentrate in few points.
- Biodegradable materials used in the proposed methodology excludes the secondary operation in the repair tendons.
- The daily life of the patient is less affected by this system since the load capacity increases to 600N in comparison to 200N in conventional suture methods.
- The system is controllable by changing in temperature.

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