STUDIES ON A PARADOX IN THE WORK OF THE UPPER LIMBS IN ISOMETRIC STRETCHING

Sergey Ranchev¹, Ivan M. Ivanov², Ivan Iotov¹, Stoyan Stoytchev²

¹Institute of Mechanics, Bulgarian Academy of Science, Sofia, Bulgaria

²National Sports Academy "Vassil Levski", Sofia, Bulgaria

ORCID

Sergey Ranchev <https://orcid.org/0000-0001-8319-9892>

Ivan M. Ivanov <https://orcid.org/0000-0001-7519-9657>

Ivan Iotov <https://orcid.org/0000-0003-3167-3980>

Stoyan Stoytchev <https://orcid.org/0000-0002-7389-8232>

ABSTRACT

Stretching is a common activity used by athletes, elderly, rehabilitation patients, people involved in fitness programs and many others. In isometric stretching an elongation in the linear dimensions of the kinematic chain of the upper limbs is observed. The aim of this study is to show the importance of intra-articular processes as response of isometric stretching force, as well as to mark the basic factors which define the joint answer to stretching, describing experimental data, relative to these factors. The present work has a programmatic character in terms of the directions in which the answer to the laid aims should be sought. The main focus is on the biomechanical processes in the joints involved in the obtained kinematic chain extension.

Key words: isometric stretching, joint, intra-articular processes.

INTRODUCTION

Stretching is a common activity used by athletes, elderly, rehabilitation patients, people involved in fitness programs and many others (Page, 2012). Weerapong, Hume, & Kolt (2004), define stretching as "movement applied by an external and/or internal force in order to increase muscle flexibility and / or joint range of motion".

Static stretching is the most widely used technique by athletes due to its simplicity and ease of execution. It has been found that static stretching affects both the mechanical and neurological properties of the muscle-tendon block, leading to increased musculoskeletal flexibility (Weerapong, Hume & Kolt, 2004).

Isometric stretching is a type of static stretching (in the sense that it does not use motion) which involves the resistance of

muscle groups through isometric contractions (tensing) of the stretched muscles (Appelton, 2009). Due to the fact that in this type of stretching the muscles work in an isometric mode, the developed muscle forces will undoubtedly affect the joints around which the respective muscles are located. These muscular forces are applied to the bones at the points of attachment of the tendons to the bone. When we have active isometric stretching of more muscle groups passing over a certain joint, the muscular forces obtained during this stretching will cause processes inside the joint itself.

The effects of stretching on muscle properties are well studied and depend on various factors, such as the stretching techniques used, the stretching time, the length of stay, the rest time and the time difference between the intervention and the measurement, and

many others. Most publications have studied the effects of static stretching on the passive properties of the muscle-tendon block (Magnusson et al., 1996a, 1996b), (McNair et al., 2000), (Magnusson et al., 1995), (Magnusson et al., 2000). In a series of studies by Magnusson et al., (1996a, 1996b, 1996c), static stretching for 90 seconds with five repetitions reduced muscle resistance, measured by passive stiffness, maximum torque, and stress relaxation. Another team of researchers concluded that changes in the viscoelastic properties of the muscle-tendon block depend more on the duration of stretching than on the number of stretches (Kubo, Kanehisa, Fukunaga, 2001).

Prolongation of static stretching (from five to ten minutes) has been shown to reduce tendon stiffness (Kubo, Kanehisa, Fukunaga, 2001), (Kubo, Kanehisa, Fukunaga, 2002). The reduction in stiffness may be due to a change in the arrangement of the collagen fibers in the tendon (Kubo, Kanehisa, Fukunaga, 2001).

The combination of stretching exercises with other therapeutic techniques, such as warm-up (Magnusson et al., 2000) (Stojanović et al., 2017), heat/cold (Henricson, 1984), (Taylor, Waring, Brashear, 1995), (Burke et al., 2001) and massage (Weerapong, Hume & Kolt, 2004), (Rodenburg et al., 1994), have been used to improve practical results of stretching.

Warming up causes an increase in muscle temperature, which helps to improve tissue flexibility. In a study by Magnusson et al., (2000), warming up (jogging) for 10 minutes (performed at 70% increase in oxygen flow), leads to increased muscle temperature by 3%.

Massage, stretching and warming up are often used in sports practice to prevent muscle injuries. Rodenburg et al., (1994) reported that combining these techniques may reduce

some of the negative effects of eccentric exercise-induced soreness. Applying warm-up procedure aims to reduce the viscosity of muscle tissue and stretching aims to reduce passive tension. The results show that the combination of these techniques does not affect the treated areas more than any individually performed technique per se. Other studies have reported that warm up effectively reduces muscle sensitivity and loss of functionality (Weerapong, Hume & Kolt, 2004), (Nosaka, Clarkson, 1997), massage is effective in reducing the sensation of pain (Weerapong, Hume & Kolt, 2004), (Bale, 1991), (Tiidus, Shoemaker, 1995), while stretching has no effect. (Johansson et al., 1999). However, the influence of a combination of stretching exercises with other therapeutic techniques (warm-up, heat/cold, massage) on joint response and joint biomechanical properties is not studied in detail yet.

The results of Maeda et al. show that static stretching for 2 minutes a day significantly increases the range of motion of the joint. There has also been a significant reduction in muscle stiffness (Maeda et al., 2017). Several teams noted an individual response of the body during stretching exercises (Curry et al., 2009), (Dalrymple, 2010). Therefore, stretching programs can and should be individualized in view of different factors, goals and individual characteristics of the patient or athlete (Weerapong, Hume & Kolt, 2004).

A review by Harvey et al. shows an assessment of the impact of different types of stretching for the prevention and treatment of contractures (contracture is a permanent shortening or stiffening of muscles, tendons, ligaments, skin or connective tissue, which leads to reduced range of motion). The same team reported challenging results on the lack of clinical effect of stretching on joint mobility. These results contradict the fundamental

acceptance in physiotherapy that stretching is effective in treating and preventing contractures (Harvey et al., 2017).

The preceding analysis shows the effects of stretching on the muscle-tendon block. However, the influence of stretching on the function and processes inside the joints is insufficiently studied. In other words, what happens inside the joint in isometric stretching, as far as we know, has not been studied and clarified.

Over 70% of the problems that occur in the human musculoskeletal system are of joint origin, and in some specific categories of work, including sports, it is higher. In this regard, the study of intra-articular processes and the effects of the reaction to the load on the joints could be the basis of approaches to:

- finding optimal motor tasks related to joint training;
- joint rehabilitation;
- synthesis of rehabilitation and sports simulators;
- synthesis of artificial joints, applicable both in medical practice and in technical devices supporting human movements (exoskeletons, active orthoses, etc.)

The creation of an appropriate motor program for studying the intra-articular processes and movements depending on the purpose of the work with the respective joint is a complex interdisciplinary problem.

The aim of this study is to show the importance of intra-articular processes as response of isometric stretching force loading, as well to mark the basic factors which define the joint answer to stretching, describing experimental data, relative to these factors. The

present work has a programmatic character in terms of the directions in which the answer to the laid aims should be sought. The main focus is on the study of the reasons for elongated kinematic chain of stretched upper limbs, involved in presented experimental model.

MATERIALS AND METHODS

In musculoskeletal biomechanics, the model considering the interaction of skeletal and muscular elements is based on analogies with the interaction of units and forces in lever mechanisms (Hall, 2007). According to this model, bones are the units and muscles are the engines that drive them. The magnitudes of the forces of interaction between the units of the mechanism (i.e., load in the joints) and the magnitudes of the muscular forces of the overall interaction with the internal and external environment are a consequence of the geometric proportions of the connections between skeletal and muscular elements. The idea for this is shown in Figure 1 (Hall, 2007). In general, this model presents the joints of the limbs, as mechanisms with alternative bilateral muscle drive (Figure 2), and the limbs themselves as open lever mechanisms. With its help the force-speed characteristics of the limbs are well described and explained (Miladinov, Velin, 2018; Peev, Gadev, 2018), but some effects of the musculoskeletal interaction cannot be explained, such as the lengthening of the kinematic chain of the upper limbs when their muscles are tensed. This effect will be described below and is a “paradox”.

Figure 1. Interaction of skeletal and muscular elements is based on analogies with the interaction of units and forces in lever mechanisms.

Figure 2. The limbs as lever mechanisms.

The “paradox” extension, experiments.

Figure 3 shows a diagram of an experimental setup using which the following experiment was performed:

- The participant lies on his back on a hard surface so that full contact of the shoulder girdle with it need to be obtained.

- Stretches his arms out to the side (Figure 3). The endpoints (A - lateralis dexter digitus medius and B-lateralis sinister digitus medius) are in contact with the sensing axes of micrometers (linear displacement reading accuracy 0.01 mm).

Figure 3. Measurement scheme.

- In this position, the measuring instruments are reset by fixing the distance between their contact points A and B.

- In the next stage, the participant performs an isometric contraction of the muscles (which he can control voluntarily) included in the formed kinematic circuit between the two

measuring devices (points A and B). It should be noted here that for different individuals, although isometric, the contraction of these muscles is not the same, both in the characteristics of the contractile act of each of the participating muscles and in their nomenclature, as the total effect of this multiple muscle contractions

depends on the individual characteristics of the individual participants in the experiment.

- Despite these differences, as a result of the performed motor task, the following common effect is observed for all participants in the experiment: the formed kinematic chain between points A and B increases its length. According to the existing in the literature kinematic models of the bone and joint apparatus of the shoulder girdle and the forelimbs, it is built only of rotational connections. With this structure and the maximum extension of the arms before stretching, which is carried out in the study, there should be no increase in its linear dimensions. While in fact such an increase is registered, which is the paradox in its behavior.

RESULTS

The effect described above was observed in an experiment with 30 participants, athletes,

in the age group 13-17 years, 18 boys and 12 girls. In Table 1 and Table 2 (Table 1 - girls and Table 2 - boys) in the first column is given the number of the participant, and in the next two columns (respectively Right and Left) are given the measured readings of the micrometers in millimeters. The increase in the length of the kinematic circuit is the sum of the two readings (Right + Left). It should be noted here that this effect is also observed in other stretching exercises performed both by individual joints and by connected bone chains. Naturally, the question arises as to the reasons for the elongation of the kinematic chain (in the case of the upper limbs), which we have described as a paradox.

The answers to this question are related to the experimental study of intra-articular movements, processes and effects of force loading of the joints.

Table 1. *Kinematic chain elongation in mm, left and right micrometric devices, girls.*

<i>Girls</i>	<i>Left, mm</i>	<i>Right, mm</i>
1.	18.00	18.00
2.	13.00	13.00
3.	14.00	14.00
4.	1.00	2.55
5.	5.00	6.30
6.	20.00	20.00
7.	10.00	10.00
8.	16.00	16.00
9.	10.00	10.00
10.	12.00	12.00
11.	10.00	10.00
12.	11.10	11.10

Table 2. *Kinematic chain elongation in mm, left and right micrometric devices, boys.*

<i>Boys</i>	<i>Left, mm</i>	<i>Right, mm</i>
1.	7.57	8.10
2.	5.00	4.80
3.	3.90	8.14
4.	3.80	3.30
5.	7.70	8.10

6.	3.50	3.25
7.	7.70	8.13
8.	7.30	8.10
9.	10.00	10.00
10.	6.00	7.00
11.	10.00	10.00
12.	15.00	15.00
13.	0.20	0.00
14.	10.00	10.00
15.	8.00	6.00
16.	10.00	10.00
17.	15.00	15.00
18.	10.00	10.00

A recent study by Stoytchev et al. (2020), analyzed the experimental mechanical properties of synovial fluid and cartilage and their constitutive models, as well as their dynamic interaction under load. Due to the greater strength of the bones, their deformability during joint loading is not taken into account. The results can be summarized as follows:

- Synovial fluid is a dialysis of blood plasma and hyaluronic macromolecules, which lead to non-Newtonian rheological properties such as viscoelasticity and pseudoplasticity;

- From a mechanical point of view, cartilage is a porous, viscoelastic material consisting of three phases: solid phase, about 20% by volume, from folded collagen with a pore size of about 60 angstroms; interstitial fluid, normally 80% of the volume; a combination of different ions;

- Intensive experimental hydro-mechanical studies and modeling of processes in synovial joints have been performed since the early 1980s, mainly by Mow and his coworkers (Mow, Lai, 1979), Mow et al., 1980). It was found that:

- a) the rheological properties of cartilage are best described by the quasi-linear viscoelastic model of Fung (Fung, 1981);

- b) the interstitial fluid is transported through

the porous cartilage according to Darcy's law, the interaction between the deformable porous matrix and the fluid determines the so-called viscous friction;

- c) the biomechanical processes in the joint capsule are determined by the rheological properties of the cartilage and synovial fluid, on the one hand, and by the applied load, on the other hand;

- d) constitutive models (Mak, 1986), (Setton, Zhu, Mow, 1993) agree best with experimental results.

The widespread use of nuclear magnetic resonance (NMR) in research has made it possible to elucidate in vivo some processes in the joint capsule at certain loads. For example, Cotofana et al., (2011) found that cartilage thickness decreased to 5.2% with a knee load of 50% of body weight. Herberthold et al., (1999) received a 44% deformation of the cartilage of the kneecap under a load of 150% of body weight. For the first time, they also determine the amount of fluid flow from the cartilage into the capsule cavity. In these studies, however, the load is on the feet and does not involve muscle groups. Also, the load is selected to be proportional to the body weight of the studied participant. While in the experimental design of the present study each participant applies

an isometric load according to their individual capabilities.

An in-depth review Eckstein, Hudelmaier, Putz (2006), found that physical activity (going downstairs, running and cycling) led to a slight deformation of the articular cartilage, which recovered after 90 minutes. Studies by the Kubo group (Kubo, Kanehisa, Fukunaga (2001) and (2002)), show that isometric exercises increase the volume of muscle groups up to 7% as well as their strength and Young's

modulus.

Recently, Ranchev et al., (2019) reported a study concerning the volume change of the knee joint capsule during isometric stretching. These data experimentally showed that in active isometric stretching there is a change in the distance between the cartilaginous surfaces of the femur and tibia (femur, tibia), which is associated with changes in the size of the muscle-tendon block of adjacent muscle groups due to their contraction (Figure 5).

Figure 5. *Reduction of the distance between the cartilaginous surfaces of the femur and tibia in isometric stretching. A). At rest; B). At isometric stretching.*

DISCUSSION

The main purpose of the stretching exercises is to achieve better performance of the muscles in sports, rehabilitation, and everyday activities. The synovial joints serve as a critical unit in realizing movements due to mechanical and biochemical processes inside the joint cavity. Eckstein, Hudelmaier, Putz (2006) suggested that human cartilage deforms very little *in vivo* during physiological activities like deep knee bends, static loading, running, cycling training bike and recovers from deformation within 90 min after loading.

For the present, the quantitative measurement of the forces developed by the muscles

during stretching is practically impossible due to the different individual anatomical structure, the many connections with tendons and bones, as well as the individual biomechanical muscle properties. Therefore, for the indirect determination of these forces, structural mechano-mathematical models are used, for the input data of which EMG signals are used. It is reported that developed models from different author teams are successfully used for such calculation (Raikova, (2020)). A future task for the presented experimental model (Figure 3) is to quantify the muscular forces causing the observed elongation of the kinematic chain of the upper limbs and to examine the relation be-

tween the magnitude of these muscular forces and obtained kinematic chain extension.

The evaluation of the muscular forces acting on the joints of the kinematic chain of the upper extremities in the presented experimental model in Figure 3 would allow clarifying the processes inside the joint capsule. The most important of these is a change in the distances between the cartilaginous surfaces of the bones that make up the joint. These muscle forces cannot be calculated directly because the number of unknown muscle forces and reactions in the joints is much larger than the equilibrium equations that can be written. Therefore, in most cases, modeling and optimization methods are used, choosing an optimization function according to physiological considerations (Raikova, Prilutsky, 2001).

The muscle post isometric relaxation (PIR), which is a result of muscle energy technique, is an important contribution to reported “paradox”. The post-isometric relaxation technique begins by placing the muscle in a stretched position. Then an isometric contraction is exerted against minimal resistance. Relaxation and then gentle stretch follow as the muscle releases (Lewit, Simons, 1984) (Shenouda, 2012). It was found that this technique leads to excellent relaxation and an improved resting length of the hyperactive muscles (Lewit, Simons, 1984; Shenouda, 2012; Liebensson, 2007).

CONCLUSION

In isometric stretching an elongation in the linear dimensions of the kinematic chain of the upper limbs is observed.

This study reviews the results of surveys related to the elucidation of the mechanism of the joint response in isometric stretching. They can be summarized in several groups of factors: a) deformation of articular cartilage; b) hydro-mechanical effects and rheological

behavior of synovial fluid; c) deformation of the joint capsule; d) changes in the mechanical properties of muscle tissue during the generation of force loads; e) viscoelastic behavior of the muscle-tendon block; f) muscle post-isometric relaxation (PIR) phenomenon (Lewit, Simons, 1984); g) intra articular processes and movements, respondent to joint loading.

The main question is how to estimate the separate contributions of the listed seven (probably and more) factors, related to the elucidation of the mechanism of the extension of the stretched kinematic chain of the upper limbs. The difficulty is related to the interaction between these factors, which makes the analysis of the observed phenomenon complicated.

This work focuses on the intra articular processes and its biomechanical explanation. The described results contribute to the elucidation of the mechanism of the joint response in isometric stretching. This response depends on many factors, which interact with one another, and can be applied not only to stretching but to all human movements.

These basic biomechanical processes inside the synovial joints are governed by mainly three factors - mechanical properties of articular cartilage and synovial fluid, from one side, and on the loading imposed on the joint, from the other side (Stoytchev et al., 2020).

1) Synovial fluid (dialysate of blood plasma and hyaluronic acid protein (HAP) complex) behaves as non-Newtonian fluid with pseudo-plasticity and visco-elasticity.

2) Articular cartilage - porous, viscoelastic material consisting of three principal phases: a) a solid phase, which is composed predominantly of a densely woven, strong, collagen enmeshed with proteoglycan macromolecules. The collagen and proteoglycan network form a porous, fiber-reinforced, composite solid matrix; b) a fluid phase, which is water (normally 80% by wet weight); and c) an ion phase.

3) Mechanical load applied on the joint, mainly depends on the muscular forces, load conditions and body pose.

The estimation of the mechanical load applied on the joints is the next step to clarification of the “paradox” presented in this study. Finally, the loads imposed on the joint, and especially their magnitude and velocity of application, predispose the intensity of the hydraulic processes inside the joint cavity like permeability of collagen matrix, drain of interstitial fluid etc. To our knowledge, those effects are not sufficiently examined for the moment.

Acknowledgements

This paper is partly supported by The National Scientific Program „Information and Communication Technologies for a Single Digital Market in Science, Education and Security (ICTinSES)“, contract No DO1–205/23.11.2018, by the Ministry of Education, Bulgaria.

REFERENCES

- Appelton, B. (2009). *Stretching and Flexibility*. Retrieved November 04, 2020, from http://web.mit.edu/tkd/stretch/stretching_4.html#SEC34
- Bale, P. (1991). Massage, warm down and rest as recuperative measures after short term intense exercise. *Physiotherapy in Sport*; 13:4-7
- Burke, D, Holt, L, Rasmussen, R, MacKinnon, N, Vossen, J, Pelham, T. (2001). Effects of hot or cold-water immersion and modified proprioceptive neuromuscular facilitation flexibility exercise on hamstring length. *J Athl Train*; 36:16-19
- Cotofana, S., Eckstein, F., Wirth, W., Souza, R. B., Li, X., Wyman, B., Majumdar, S. (2011). In vivo measures of cartilage deformation: patterns in healthy and osteoarthritic female knees using 3T MR imaging. *European radiology*, 21(6), pp. 1127-1135.
- Curry, BS, Chengkalath, D, Crouch, GJ, Romance, M, Manns, PJ. (2009). Acute effects of dynamic stretching, static stretching, and light aerobic activity on muscular performance in women. *J Strength Cond Res*, Sep. 23(6):1811-1819.
- Dalrymple, KJ, Davis, SE, Dwyer, GB, Moir, GL. (2010). Effect of static and dynamic stretching on vertical jump performance in collegiate women volleyball players. *J Strength Cond Res.*, Jan, 24(1):149-155.
- Eckstein, F, Hudelmaier, M, Putz, R. (2006). The effects of exercise on human articular cartilage. *J. Anat.* 208, pp. 491–512
- Fung, Y. C. (1981). *Biomechanics, Mechanical Properties of Living Tissues*, Springer-Verlag, New York.
- Hall, S. J. (2007). Basic Biomechanics, 5th edition
- Harvey, L.A., Katalinic, O.M., Herbert, R.D., Moseley, A.M., Lannin, N.A. and Schurr, K. (2017). Stretch for the treatment and prevention of contracture: an abridged republication of a Cochrane Systematic Review. *Journal of physiotherapy*, 63(2), pp.67-75.
- Henricson, A, Fredriksson, K, Persson, I, Pereira, R, Westlin, N. (1984). The effects of heat and stretching on the range of hip motion. *J Orthop Sports Phys Ther*; 6:110-115
- Herberhold, C., Faber, S., Stammberger, T., Steinlechner, M., Putz, R., Englmeier, K. H., Eckstein, F. (1999). In situ measurement of articular cartilage deformation in intact femoropatellar joints under static loading. *Journal of biomechanics*, 32(12), 1287-1295.
- Johansson, P, Lindstrom, L, Sundelin, G, Lindstrom, B. (1999). The effects of pre-exercise stretching on muscular soreness, tenderness and force loss following heavy eccentric exercise. *ScandJMed Sci Sports*; 9:219-225
- Kubo, K, Kanehisa, H, Fukunaga, T. (2001). Is passive stiffness in human muscles related to the elasticity of tendon structures?

Eur J Appl Physiol; 85:226-232

Kubo, K., Kanehisa, H., Fukunaga, T. (2002). Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Physiol*; 538:219-226.

Lewit, K., Simons, D. G. (1984). Myofascial pain: relief by post-isometric relaxation. *Archives of Physical medicine and rehabilitation*, 65(8), 452-456.

Liebenson, C. (2007). Rehabilitation of the spine, 2nd Ed. A practitioners Manual, 408 – 410.

Maeda, N., Urabe, Y., Tsutsumi, S., Sakai, S., Fujishita, H., Kobayashi, T., Asaeda, M., Hirata, K., Mikami, Y. and Kimura, H., (2017). The Acute Effects of Static and Cyclic Stretching on Muscle Stiffness and Hardness of Medial Gastrocnemius Muscle. *Journal of sports science & medicine*, 16(4), p.514.

Magnusson, S, Aagaard, P, Larsson, B, Kjaer, M. (2000). Passive energy absorption by human muscle-tendon unit is unaffected by increase in intramuscular temperature. *J Appl Physiol*; 88:1215-1220

Magnusson, S, Simonsen, E, Aagaard, P, Gleim, G, McHugh, M, Kjaer, M. (1995). Viscoelastic response to repeated static stretching in the human hamstring muscle. *Scand J Med Sci Sports*; 5:342-347

Magnusson, S, Simonsen, E, Aagaard, P, Kjaer, M. (1996c). Biomechanical responses to repeated stretches in human hamstring muscle in vivo. *Am J Sports Med*; 24:622-8

Magnusson, S, Simonsen, E, Aagaard, P, Sorensen, H, Kjaer, M. (1996a). A mechanism for altered flexibility in human skeletal muscle. *J Physiol*; 497:291-298.

Magnusson, S, Simonson, E, Dyhre-Poulsen, P, Aagaard, P, Mohr, T, Kjaer, M. (1996b). Viscoelastic stress relaxation during static stretch in human skeletal muscle in the

absence of EMG activity. *Med Sci Sports Exerc*; 6:323-328

Mak, A. F. (1986). The apparent viscoelastic behavior of articular cartilage. The contributions from the intrinsic matrix viscoelasticity and interstitial fluid flows. *J. biomech. Engng*, 108, pp. 123-130.

McNair, P, Dombroski, E, Hewson, D, Stanley, S. (2000). Stretching at the ankle joint: viscoelastic responses to holds and continuous passive motion. *Med Sci Sports Exerc*; 33:354-358.

Miladinov, O., Velin, V. (2018). Kinematic-dynamic interrelations between the drop jump on inclined platform and the take-off in the horizontal athletics jumps. *Journal of Applied Sports Sciences*, 1, 3-13.

Mow, V. C., Kuei, S. C., Lai, W. M., Armstrong, C. G. (1980). Biphasic creep and stress relaxation of articular cartilage: theory and experiments. *J. Biomech. Eng.*, 102, 73-84.

Mow, V. C., Lai, W. M. (1979). Mechanics of animal joints. *Ann. Rev. Fluid Mech.*, 11, 247-288.

Nosaka, K, Clarkson, P. (1997). Influence of previous concentric exercise on eccentric exercise induced muscle damage. *J Sports Sci*; pp. 477-483

Page, P. (2012). Current concepts in muscle stretching for exercise and rehabilitation. *International journal of sports physical therapy*, 7(1), pp.109.

Peev, P., Gadev, M. (2018). Correlation between motor abilities of elite female football players. *Journal of Applied Sports Sciences*, 1, 37-44.

Raikova, R. (2020). *Models of musculo-skeletal systems and methods for their study*. http://biomed.bas.bg/bg/2020/06/raikova_monograph/

Raikova, R., Prilutsky, B. (2001). Sensitivity of predicted muscle forces to parameters of

- optimization-based human leg model revealed by analytical and numerical analyses, November, *Journal of Biomechanics*, 34(10):1243-55
- Ranchev, S., Ivanov I., Iotov I., Stoytchev S. (2019). On the biomechanical processes in human knee joint during active isometric stretching. *Series on Biomechanics*, Vol. 33, No. 3, pp. 56-61.
- Rodenburg, J, Steenbeek, D, Schiereck, P, Bar, P. (1994). Warm-up, stretching and massage diminish harmful effects of eccentric exercise. *Int J Sports Med*; 15:414-419
- Setton, L. A., Zhu, W. E., Mow V. C. (1993). The biphasic poroviscoelastic behavior of the articular cartilage: Role of the surface zone in governing the compressive behavior. *J. Biomechanics*, Vol 26. No. 4/5. pp 581-592.
- Shenouda, M. M. S. (2012). Efficacy of Stretching Exercises Versus Postisometric Relaxation Technique on Pain, Functional Disability and Range of Motion in Patients with Cervical Spondylosis. A Randomized controlled trial. *Bulletin of Faculty of Physical Therapy*, 17(2).
- Stojanović, N. T., Savić, Z., Paunović, M., & Dumbelović, D. (2017). Relations between maximal isometric strength and competition performance among young kayakers. *Journal of Applied Sports Sciences*, 2, 10-18.
- Stoytchev, S., Ivanov, I., Ranchev, S., Iotov, I. (2020). A review of the biomechanics of synovial joints with emphasize to static stretching exercise. *Series on Biomechanics*, 24, 4.
- Taylor, B, Waring, C, Brashear, T. (1995). The effects of therapeutic application of heat or cold followed by static stretch on hamstring muscle length. *J Orthop Sports Phys Ther*; 21:283-286
- Tiidus, P, Shoemaker, J. (1995). Effleurage massage, muscle blood flow and long term postexercise recovery. *Int J Sports Med*; 16:478-483
- Weerapong, P., Hume, P. A., & Kolt, G. S. (2004). Stretching: mechanisms and benefits for sport performance and injury prevention. *Physical Therapy Reviews*, 9(4), 189-206.

Corresponding author:

Ivan M. Ivanov

Anatomy and Biomechanics Department
National Sports Academy "Vassil Levski"
21, Acad. Stefan Mladenov. Str.
Studentski grad, 1700
Sofia, Bulgaria
E-mail: ivanmirchev@abv.bg