BAU HEALTH AND INNOVATION

DOI: 10.14744/bauh.2023.98608
BAU Health Innov 2024;2(1):34–41

Review

A New Method for Sportive Performance and Recovery: Auricular Vagus Nerve Stimulation (Review)

Ali Veysel Özden,[1] Hasan Kerem Alptekin,[2] Berkay Eren Pehlivanoğlu,[2] Mehmet Ünal[3]

[1]Department of Physiotherapy, Bahçeşehir University, Vocational Faculty of Health Services, İstanbul, Türkiye
[2]Department of Physiotherapy and Rehabilitation, Bahçeşehir University Faculty of Health Sciences, İstanbul, Türkiye
[3]Department of Physiotherapy and Rehabilitation, Yeniyuzyıl University Faculty of Health Science, İstanbul, Türkiye

Abstract

During sports and exercise, the cardiovascular system, respiratory system, musculoskeletal system, nervous system, endocrine system, and immune system play an active role. With the start of exercise, sympathetic activity in the body increases and parasympathetic activity is suppressed. With the end of the exercise, sympathetic activity decreases, whereas parasympathetic activity increases and contributes to the recovery process of the individual. The contribution of the parasympathetic system to the restructuring/recovery during the rest period is important in terms of reducing the fatigue of the athletes and enabling them to recover in the early period. Stimulation of the vagus nerve, which is the main branch of the parasympathetic system, can affect many cardiovascular, pulmonary, and metabolic parameters both during rest and exercise. Our article aims to evaluate the potential benefits and effects of using auricular vagus nerve stimulation (VNS) for sports purposes on the recovery and performance of athletes in light of the literature. Recovery after exercise can be accelerated with auricular VNS. The negativities caused by overload and excessive training can be reduced. Thanks to better rest and early recovery, the performance in the following training program can be increased. Injuries that may occur due to insufficient recovery can be prevented or injuries can be reduced. We can expect that the auricular VNS method will be used soon in light of sufficient scientific data due to its effects that cannot be considered doping.

Keywords: Auricular vagus nerve stimulation, autonomic nervous system, exercise, sportive performance, sportive recovery.

Cite This Article: *Özden AV, Alptekin HK, Pehlivanoğlu BE, Ünal M. A New Method for Sportive Performance and Recovery: Auricular Vagus Nerve Stimulation (Review). BAU Health Innov 2024;2(1):34–41.*

Today, sport is one of the most important social activities that are followed with great interest by a wide audience and performed by most of us personally. Even in today's world countries, sports have become the way for countries to show strength to each other. As such, it is not just an athlete who is involved in physical activity. The capability of athletes, who function as modern-day gladiators in the arena, to perform at their best for themselves, their teams, and their countries involves numerous variables. This encompasses the duration, frequency, and intensity of training, along with the athlete's adequate and balanced nutrition, sleep patterns, equipment utilized, training conditions, and the subsequent rest periods. The process of preparing for the next activity requires a multidisciplinary and interdisciplinary approach. It is only possible for athletes to increase their performance, to reach the optimal level, and to maintain this level for a long time, by operating in perfect harmony with so many variables. In addition, the short recovery time is very important for the athlete to be ready for the activity again.

Address for correspondence: Ali Veysel Özden, MD. Bahçeşehir Üniversitesi, Sağlık Hizmetleri Meslek Yüksekokulu, Fizyoterapi Bölümü, İstanbul, Türkiye
Phone: +90 506 599 42 33 **E-mail:** aliveysel.ozden@bau.edu.tr

Submitted: January 04, 2024 **Revised:** January 16, 2024 **Accepted:** January 31, 2024 **Available Online:** December 31, 2024

In recent years, professional athletes in all branches of sports have had a very intense training and match schedule. For example, in the US National Basketball League, it is seen that athletes play every 2 days for some periods. When football clubs are considered, when the league matches, European matches, and cup matches come in the same period, the athletes play for periods of 2–3 days. As a result of this intense calendar, the recovery of the athletes cannot reach the desired level. Inadequate recovery, on the other hand, reduces performance in the long run and can lead to injuries in addition to this. The insufficiency and limited nature of the applications and methods currently used in the market for this problem do not meet the need.

The autonomic nervous system consists of the sympathetic and parasympathetic nervous system. They usually play opposite roles in the body, when one of them increases activity, the other is suppressed. With the start of exercise or sports activity, sympathetic activity increases in the body and reaches the plateau value in maximal activity after a certain period. With the end of sports activity, the suppressed parasympathetic activity starts to increase, and the sympathetic system returns to the resting state in time.[1] After exercise, parasympathetic system activation continues for up to 48 h. If the exercise is intense and resistant, parasympathetic system activity can extend up to 72 h. Furthermore, due to anaerobic respiration rate increases during exercise, there may be decreased in parasympathetic reactivation.[2] Different parameters depending on the analysis of the variability between heartbeat times can be used in the evaluation of autonomic nervous system activity. One of these, high-frequency power, which indicates parasympathetic system activity, may reflect insufficient recovery from previous training, and this may indicate unfavorable conditions for performance improvements.[3] In a study conducted with swimmers, it was found that the performance was higher in people with high parasympathetic activity at night.[4] Supporting this, in the study conducted by Buchheit et al., those with high pre-exercise sympathetic activity showed low performance. In another trial by Gratze et al.[5,6] involving runners, it was revealed that athletes with low sympathetic activity and low heart rate before the race finished the marathon earlier. Low sympathetic activity and/or high parasympathetic activity and low heart rate before training or exercise can be evaluated as performance indicators. This is also a sign that the recovery after the previous workout or exercise is adequate.

Parasympathetic capacity is the determinant of restructuring and recovery (restoration) after exercise.[7] Endurance training is known to increase running performance and parasympathetic modulation before and after running.[8] Hence, it can be said that there is a reciprocal relationship between exercise and the autonomic nervous system. There are various factors that limit performance during exercise, prevent the individual from doing the activity for a longer period, and thus cause fatigue. Fatigue can be psychological and neurogenic; as well as lactic acid accumulation, ammonia accumulation, increase in blood potassium level, emptying of glycogen stores, increase of adenosine compounds, increase in blood hydrogen level, blood pH shift to acid direction can cause fatigue and decrease in performance.[9] Recovery after exercise is possible by returning all these changes that occur during exercise to baseline values. During the recovery period of the person, the sympathetic system activity is suppressed, and the parasympathetic system activity becomes prominent. Autonomic nervous system regulation, which is not considered doping and can increase physical capacity and recovery in athletes, can be practically done with vagus nerve stimulation (VNS) from the ear.[10] There is no study in the literature examining the effect of VNS on recovery and performance in athletes. In this article, the potential benefits and effects of using this method for sportive purposes are evaluated.

VNS

VNS has long been used invasively in the treatment of depression and epilepsy (since 1997), and vagus nerve modulation continues to be of interest for many physiological/pathological conditions due to the wide distribution of the vagus nerve in the body.[11] VNS can affect cardiovascular parameters both at rest and during exercise.[12] It has been shown in the study of Clancy et al.[13] that auricular VNS can reduce sympathetic activity. Transcutaneous VNS improves cardiac baroreflex sensitivity and autonomic modulation.[14] VNS also has the potential to affect local and systemic circulation. Czura et al.[15] showed in their study that VNS shortened the bleeding time in the incision area and increased local thrombin levels and that thrombin levels did not change in the systemic circulation. It has been reported that non-invasive auricular VNS changes the fluid passage between the extracellular and intracellular compartments by bioimpedance analysis.[16] Both human and animal studies indicate that VNS can reduce or reverse ischemia-related damage.[17–23] VNS also has effects that reduce pain and inflammation.[24–26] These data show that VNS may cause modulation in the autonomic nervous system and thus contribute to recovery after exercise. As aerobic performance increases, parasympathetic system activity is expected to increase in parallel. This situation suggests that people who do regular sports will recover better than normal people. However, after an excessive or intense exercise program, more activity may be needed in the parasympathetic system.

Auricular VNS is used as an effective and safe method in the treatment of many diseases such as epilepsy, depression, and migraine, and it can be claimed to be advantageous compared to the invasive method.[27] Increasing vagus nerve activity causes modulation in the autonomic nervous system and cerebral neuronal networks.[11] Since the method only stimulates afferent fibers, it changes cerebral activity through the nucleus tract solitarius and may cause different effects in different parts of the body through neuronal connections.[28,29] Optimal stimulation parameters in auricular VNS are still unclear and studies have also stated that different stimulation parameters may cause different effects. The vagus nerve provides the brain-gut connection; in addition, its widespread distribution in the body and its relationship with different physiological conditions cause a complicated structure. This situation can be controlled with biofeedback or closed-loop stimulation systems.[30,31] The widespread and local effects of VNS can create an opportunity for its use in different indications. In their study, Staats, Giannakopoulos, Blake, Liebler, and Levy reported clinical improvement in respiratory capacity in two COVID-19 patients treated with non-invasive VNS.[32] Another study by Kaniusas et al.[33] similarly suggests that non-invasive VNS may be potentially beneficial in acute respiratory distress syndrome caused by COVID-19.

Auricular VNS can increase peripheral perfusion. In addition, studies are also seen in the literature showing increased healing by VNS in brain ischemic damage.[34–39] In rat models with ischemia and reperfusion, it was found that post-ischemic angiogenesis in the brain was increased by auricular VNS; and in ischemic penumbra, expression levels of brain-derived neurotrophic factor, endothelial nitric oxide synthase, and vascular endothelial growth factor were found to be high.[40] VNS can improve functional status after traumatic brain injury.[41] Similar positive results regarding VNS have been reported in peripheral nerve injury.[42] In addition, intraoperative VNS can accelerate wound healing by autonomic mechanisms.[43] Auricular VNS allows a more controlled effect only by stimulation of afferent fibers. Side effects are also very rare compared to cervical, abdominal, or other vagal nerve stimulation methods containing efferent fibers.[44] Common side effects include tingling or pain around the stimulation site; also, some participants reported itching or a rash in the ear.[27,45]

The small number of studies, the application of different stimulation parameters, and different protocols may cause different results in the literature about VNS. In addition, it can be said that invasive, cervical non-invasive, and auricular applications of VNS can lead to different results. Auricular VNS includes only afferent fiber stimulation and acts through cerebral neuromodulation. For this reason, the effects of regulation on homeostasis may be mostly in the form of adaptive or capacity increase. The fact that auricular VNS is non-invasive and easily applicable suggests that it can be used to increase physiological adaptations in athletes. In a situation where physiological data are collected from the body and stimulation is personalized with machine learning, VNS can increase the sportive potential and capacity of the users.

Recovery and Performance

It is stated that parasympathetic effects in normal persons persist during high-intensity exercise and are evident in the early stages of recovery. These parasympathetic effects may play an important role in preventing sudden cardiac death during these periods of increased risk.[46] After exercise, vagus-mediated heart rate recovery accelerates in well-trained athletes but decreases in patients with chronic heart failure.[47] Ebersole, Cornell, Flees, Shemelya, and Noel stated that sympathetic nervous system withdrawal after maximal exercise may be more effective during recovery than previously thought.[48] However, there are also studies indicating that the delayed decrease in heart rate within the 1st min after gradual exercise is a strong data on overall mortality, regardless of exercise workload, the presence or absence of myocardial perfusion defects, and heart rate changes. It has been suggested that this may reflect decreased vagal activity.[49,50] Abnormal heart rate recovery may be caused by delayed sympathetic withdrawal, delayed parasympathetic reactivation, or both.[51] If the exercise intensity increases, acute recovery of the pre-ejection period weakens. This event is an indicator of parasympathetic withdrawal after exercise.[52]

Genetic and environmental factors can affect recovery and autonomic nervous system activity after exercise or sports. In a study conducted in Chinese healthy people, it has been observed that there is a delayed regulation in the autonomic nervous system after exercise compared to Caucasian races. This delayed autonomic recovery may result from elevated sympathetic activity or vagal withdrawal in the Chinese.[53] In people with high body mass index, autonomic recovery worsens after activity and the parasympathetic level remains low.[54] Caffeine intake impairs autonomic recovery after exercise by increasing sympathetic activity. Heart rate and blood pressure were found to be higher during recovery in people who took caffeine.[55–57] Normotensive subjects with higher resting systolic blood pressure (110–120 mmHg) had moderately delayed autonomic recovery after exercise compared to subjects with lower systolic pressure (<110 mmHg).[58]

Fatigue and incomplete recovery after exercise are important as it leads to a decrease in exercise performance and a greater risk of injury. With correct exercise programs, it is possible to increase parasympathetic activity after exercise in the long term.[59] When evaluated acutely, as exercise intensity increases, the decrease in sympathetic activity and parasympathetic reactivation slows down after exercise.[52,60] Prolongation of exercise duration does not affect the withdrawal in sympathetic activity after exercise, but it suppresses the recovery in parasympathetic activity.[61] Sympathetic hyperactivity seen after exercise competes with endothelial (nitric oxide) dependent vasodilator activity by causing vasoconstriction.[62] In addition to changes in the cardiac autonomic nervous system during the recovery period, muscular sympathetic nervous system activity in the periphery is also higher than the resting state.[63] However, there are studies showing a decrease in blood pressure along with a decrease in parasympathetic activity after exercise. This situation has been associated with peripheral vasodilation.[64] Recovery and performance status are closely related to autonomic nervous system activity levels. Insufficient recovery adversely affects the next performance. Different measurement methods, different exercise programs, and individual and environmental differences can affect assessments of recovery and performance. Biofeedback-controlled application of autonomic nervous system modulation can provide more efficient sports recovery and performance.

Sportive use of the VNS

In the recovery period after exercise, parasympathetic nervous system activity occupies a very important place.[65] Metaboreflex stimulation (e.g., muscle and blood acidosis) is probably a key determinant of parasympathetic reactivation in the short term (0–90 min post-exercise). On the other hand, baroreflex stimulation (e.g., exercise-related changes in plasma volume) probably mediates parasympathetic reactivation in the medium term (1–48 h post-exercise). Autonomic recovery occurs faster in people with more aerobic fitness, but if the intensity and duration of the exercise increase, the recovery becomes longer. When writing an exercise prescription, the autonomic nervous system activity of the person must be taken into consideration. The time required for recovery after a training session is important for optimizing physiological adaptations and performance. These adaptations can be achieved in the long term with exercise and training applications customized according to the autonomic nervous system activity. Increasing evidence indicates that the level of parasympathetic activity after exercise is a marker of performance increase.[5,66] The elevation in vagal activity at rest and after exercise occurs when positive adaptation to exercise takes place and allows increases in performance.[67]

Autonomic recovery after exercise can be affected by exercise intensity, exercise duration, maximum exercise modality as well as recovery posture and recovery activity.[60] While intensive training may result in suboptimal performance in subsequent training sessions, chronic imbalance between training stress and rest can lead to overload or overtraining syndrome. Whole-body cold-water application after exercise is used by athletes to increase and accelerate recovery and has been shown to increase parasympathetic reactivation. It is also stated that parasympathetic reactivation is associated with longer-term physiological recovery and daily training performances.[68,69] Modulation of parasympathetic activity after exercise may have beneficial effects in the elimination of dysfunction in the autonomic nervous system due to exercise, in the recovery of microtraumas, and regaining of homeostasis. In this way, recovery after exercise can become faster and more effective. Electrical stimulation of the auricular vagus nerve may be beneficial in increasing parasympathetic activity after exercise. In regular use, permanent effects may occur because VNS increases neuroplasticity and changes in neuronal firing patterns.[70] The autonomic nervous system controls physiological parameters such as increased hydrogen concentration, decreased glycogen stores, and lactic acid accumulation. VNS after exercise can provide regulation of the dysfunctional state in the autonomic nervous system and/or can facilitate recovery.[71–74]

Conclusion

Autonomic nervous system changes and resultant bodily adaptations are critical during exercise and sportive activities. In the treatment of diseases such as epilepsy and depression, neuromodulation of the autonomic nervous system is already performed invasively or non-invasively, but there is no data on its use for sports purposes. Parasympathetic enhancement after exercise or sports is essential for controlling the sympathetic system and normalizing the functions to the resting level. Auricular

VNS seems efficient in increasing parasympathetic activity with the advantages of being non-invasiveness and not having apparent side effects. Hence, it can be said that recovery after exercise can be accelerated with auricular VNS. In this way, the negativities caused by overload and excessive training can be reduced. Thanks to better rest and recovery, the performance in the next training program can be increased. Injuries that may occur due to insufficient recovery can be prevented or reduced.

Disclosures

Authorship Contributions: Concept – A.V.Ö.; Design – A.V.Ö.; Supervision – A.V.Ö.; Funding – A.V.Ö.; Materials – A.V.Ö., H.K.A., B.E.P., M.Ü.; Data collection and/or processing – A.V.Ö., H.K.A., B.E.P., M.Ü.; Data analysis and/or interpretation – A.V.Ö., H.K.A., B.E.P., M.Ü.; Literature search – A.V.Ö., H.K.A., B.E.P., M.Ü.; Writing – A.V.Ö., H.K.A., B.E.P., M.Ü.; Critical review – A.V.Ö., H.K.A., B.E.P., M.Ü.

Conflict of Interest: Ali Veysel Ozden is one of the co-founders of Vagustim® Company which produces VNS devices.

Use of AI for Writing Assistance: Not declared.

Financial Disclosure: The authors declared that this study received no financial support.

Peer-review: Externally peer-reviewed.

References

1. Coote JH. Recovery of heart rate following intense dynamic exercise. Exp Physiol 2010;95(3):431–40.
2. Buchheit M, Laursen PB, Ahmaidi S. Parasympathetic reactivation after repeated sprint exercise. Am J Physiol Heart Circ Physiol 2007;293(1):H133–41.
3. Chalencon S, Busso T, Lacour JR, Garet M, Pichot V, Connes P, et al. A model for the training effects in swimming demonstrates a strong relationship between parasympathetic activity, performance and index of fatigue. PLoS One 2012;7(12):e52636.
4. Garet M, Tournaire N, Roche F, Laurent R, Lacour JR, Barthélémy JC, et al. Individual Interdependence between nocturnal ANS activity and performance in swimmers. Med Sci Sports Exerc 2004;36(12):2112–8.
5. Stanley J, Peake JM, Buchheit M. Cardiac parasympathetic reactivation following exercise: Implications for training prescription. Sports Med 2013;43(12):1259–77.
6. Gratze G, Mayer H, Luft FC, Skrabal F. Determinants of fast marathon performance: Low basal sympathetic drive, enhanced postcompetition vasodilatation and preserved cardiac performance after competition. Br J Sports Med 2008;42(11):882–8.
7. Chen JL, Yeh DP, Lee JP, Chen CY, Huang CY, Lee SD, et al. Parasympathetic nervous activity mirrors recovery status in weightlifting performance after training. J Strength Cond Res 2011;25(6):1546–52.
8. Boullosa DA, Tuimil JL, Leicht AS, Crespo-Salgado JJ. Parasympathetic modulation and running performance in distance runners. J Strength Cond Res 2009;23(2):626–31.
9. Unal M. Athlete Health and Performance. İstanbul: İstanbul Tıp Kitabevi; 2019.
10. Pugh J, Pugh C. Neurostimulation, doping, and the spirit of sport. Neuroethics 2021;14(Suppl 2):141–58.
11. Kaniusas E, Kampusch S, Tittgemeyer M, Panetsos F, Gines RF, Papa M, et al. Current directions in the auricular vagus nerve stimulation I - a physiological perspective. Front Neurosci 2019;13:854.
12. Mulders DM, de Vos CC, Vosman I, van Putten MJ. The effect of vagus nerve stimulation on cardiorespiratory parameters during rest and exercise. Seizure 2015;33:24–8.
13. Clancy JA, Mary DA, Witte KK, Greenwood JP, Deuchars SA, Deuchars J. Non-invasive vagus nerve stimulation in healthy humans reduces sympathetic nerve activity. Brain Stimul 2014;7(6):871–7.
14. Antonino D, Teixeira AL, Maia-Lopes PM, Souza MC, Sabino-Carvalho JL, Murray AR, et al. Non-invasive vagus nerve stimulation acutely improves spontaneous cardiac baroreflex sensitivity in healthy young men: A randomized placebo-controlled trial. Brain Stimul 2017;10(5):875–81.
15. Czura CJ, Schultz A, Kaipel M, Khadem A, Huston JM, Pavlov VA, et al. Vagus nerve stimulation regulates hemostasis in swine. Shock 2010;33(6):608–13.
16. Ulgen Y, Buyuksarac B, Tunc B, Solmaz H. Extracellular and intracellular fluid shifts on the onset of transcutaneous auricular vagus nerve stimulation. Annu Int Conf IEEE Eng Med Biol Soc 2019;2019:6888–91.
17. Xia H, Liu Z, Liang W, Zeng X, Yang Y, Chen P, et al. Vagus nerve stimulation alleviates hepatic ischemia and reperfusion injury by regulating glutathione production and transformation. Oxid Med Cell Longev 2020;2020:1079129.
18. Zhang Q, Lai Y, Deng J, Wang M, Wang Z, Wang M, et al. Vagus nerve stimulation attenuates hepatic ischemia/reperfusion injury via the Nrf2/HO-1 pathway. Oxid Med Cell Longev 2019;2019:9549506.
19. Wang M, Deng J, Lai H, Lai Y, Meng G, Wang Z, et al. Vagus nerve stimulation ameliorates renal ischemia-reperfusion injury through inhibiting NF-κB activation and iNOS protein expression. Oxid Med Cell Longev 2020;2020:7106525.
20. Inoue T, Abe C, Sung SS, Moscalu S, Jankowski J, Huang L, et al. Vagus nerve stimulation mediates protection from kidney ischemia-reperfusion injury through α7nAChR+ splenocytes. J Clin Invest 2016;126(5):1939–52.
21. Yagi M, Morishita K, Ueno A, Nakamura H, Akabori H, Senda A, et al. Electrical stimulation of the vagus nerve improves

intestinal blood flow after trauma and hemorrhagic shock. Surgery 2020;167(3):638–45.
22. Zhang Y, Li H, Wang M, Meng G, Wang Z, Deng J, et al. Vagus nerve stimulation attenuates acute skeletal muscle injury induced by ischemia-reperfusion in rats. Oxid Med Cell Longev 2019;2019:9208949.
23. Ortiz-Pomales YT, Krzyzaniak M, Coimbra R, Baird A, Eliceiri BP. Vagus nerve stimulation blocks vascular permeability following burn in both local and distal sites. Burns 2013;39(1):68–75.
24. Chakravarthy K, Chaudhry H, Williams K, Christo PJ. Review of the uses of vagal nerve stimulation in chronic pain management. Curr Pain Headache Rep 2015;19(12):54.
25. Busch V, Zeman F, Heckel A, Menne F, Ellrich J, Eichhammer P. The effect of transcutaneous vagus nerve stimulation on pain perception--an experimental study. Brain Stimul 2013;6(2):202–9.
26. Lerman I, Davis B, Huang M, Huang C, Sorkin L, Proudfoot J, et al. Noninvasive vagus nerve stimulation alters neural response and physiological autonomic tone to noxious thermal challenge. PLoS One 2019;13(14):e0201212.
27. Yap JY, Keatch C, Lambert E, Woods W, Stoddart PR, Kameneva T. Critical review of transcutaneous vagus nerve stimulation: challenges for translation to clinical practice. Front Neurosci 2020;14:284.
28. Frangos E, Richards EA, Bushnell MC. Do the psychological effects of vagus nerve stimulation partially mediate vagal pain modulation? Neurobiol Pain 2017;1:37–45.
29. De Couck M, Nijs J, Gidron Y. You may need a nerve to treat pain: The neurobiological rationale for vagal nerve activation in pain management. Clin J Pain 2014;30(12):1099–105.
30. Kaniusas E, Kampusch S, Tittgemeyer M, Panetsos F, Gines RF, Papa M, et al. Current directions in the auricular vagus nerve stimulation II - an engineering perspective. Front Neurosci 2019;13:772.
31. Wang Y, Li SY, Wang D, Wu MZ, He JK, Zhang JL, et al. Transcutaneous auricular vagus nerve stimulation: from concept to application. Neurosci Bull 2021;37(6):853–62.
32. Staats P, Giannakopoulos G, Blake J, Liebler E, Levy RM. The use of non-invasive vagus nerve stimulation to treat respiratory symptoms associated with COVID-19: A theoretical hypothesis and early clinical experience. Neuromodulation 2020;23(6):784–8.
33. Kaniusas E, Szeles JC, Kampusch S, Alfageme-Lopez N, Yucuma-Conde D, Li X, et al. Non-invasive auricular vagus nerve stimulation as a potential treatment for Covid19-originated acute respiratory distress syndrome. Front Physiol 2020;11:890.
34. Khodaparast N, Hays SA, Sloan AM, Fayyaz T, Hulsey DR, Rennaker RL 2nd, et al. Vagus nerve stimulation delivered during motor rehabilitation improves recovery in a rat model of stroke. Neurorehabil Neural Repair 2014;28(7):698–706.
35. Khodaparast N, Kilgard MP, Casavant R, Ruiz A, Qureshi I, Ganzer PD, et al. Vagus nerve stimulation during rehabilitative training improves forelimb recovery after chronic ischemic stroke in rats. Neurorehabil Neural Repair 2016;30(7):676–84.
36. Hays SA, Ruiz A, Bethea T, Khodaparast N, Carmel JB, Rennaker RL 2nd, et al. Vagus nerve stimulation during rehabilitative training enhances recovery of forelimb function after ischemic stroke in aged rats. Neurobiol Aging 2016;43:111–8.
37. Baig SS, Falidas K, Laud PJ, Snowdon N, Farooq MU, Ali A, et al. Transcutaneous auricular vagus nerve stimulation with upper limb repetitive task practice may improve sensory recovery in chronic stroke. J Stroke Cerebrovasc Dis 2019;28(12):104348.
38. Kimberley TJ, Pierce D, Prudente CN, Francisco GE, Yozbatiran N, Smith P, et al. Vagus nerve stimulation paired with upper limb rehabilitation after chronic stroke. Stroke 2018;49(11):2789–92.
39. Wu D, Ma J, Zhang L, Wang S, Tan B, Jia G. Effect and safety of transcutaneous auricular vagus nerve stimulation on recovery of upper limb motor function in subacute ischemic stroke patients: A randomized pilot study. Neural Plast 2020;2020:8841752.
40. Jiang Y, Li L, Ma J, Zhang L, Niu F, Feng T, et al. Auricular vagus nerve stimulation promotes functional recovery and enhances the post-ischemic angiogenic response in an ischemia/reperfusion rat model. Neurochem Int 2016;97:73–82.
41. Pruitt DT, Schmid AN, Kim LJ, Abe CM, Trieu JL, Choua C, et al. Vagus nerve stimulation delivered with motor training enhances recovery of function after traumatic brain injury. J Neurotrauma 2016;33(9):871–9.
42. Darrow MJ, Mian TM, Torres M, Haider Z, Danaphongse T, Seyedahmadi A, et al. The tactile experience paired with vagus nerve stimulation determines the degree of sensory recovery after chronic nerve damage. Behav Brain Res 2021;396:112910.
43. Murakami H, Li S, Foreman R, Yin J, Hirai T, Chen JD. Intraoperative vagus nerve stimulation accelerates postoperative recovery in rats. J Gastrointest Surg 2019;23(2):320–30.
44. Ben-Menachem E, Revesz D, Simon BJ, Silberstein S. Surgically implanted and non-invasive vagus nerve stimulation: A review of efficacy, safety and tolerability. Eur J Neurol 2015;22(9):1260–8.
45. Redgrave J, Day D, Leung H, Laud PJ, Ali A, Lindert R, et al. Safety and tolerability of transcutaneous vagus nerve stimulation in humans; a systematic review. Brain Stimul 2018;11(6):1225–38.

46. Kannankeril PJ, Le FK, Kadish AH, Goldberger JJ. Parasympathetic effects on heart rate recovery after exercise. J Investig Med 2004;52(6):394–401.
47. Imai K, Sato H, Hori M, Kusuoka H, Ozaki H, Yokoyama H, et al. Vagally mediated heart rate recovery after exercise is accelerated in athletes but blunted in patients with chronic heart failure. J Am Coll Cardiol 1994;24(6):1529–35.
48. Ebersole KT, Cornell DJ, Flees RJ, Shemelya CM, Noel SE. Contribution of the autonomic nervous system to recovery in firefighters. J Athl Train 2020;55(9):1001–8.
49. Cole CR, Blackstone EH, Pashkow FJ, Snader CE, Lauer MS. Heart-rate recovery immediately after exercise as a predictor of mortality. N Engl J Med 1999;341(18):1351–7.
50. Shetler K, Marcus R, Froelicher VF, Vora S, Kalisetti D, Prakash M, et al. Heart rate recovery: Validation and methodologic issues. J Am Coll Cardiol 2001;38(7):1980–7.
51. Borresen J, Lambert MI. Autonomic control of heart rate during and after exercise: Measurements and implications for monitoring training status. Sports Med 2008;38(8):633–46.
52. Michael S, Jay O, Graham KS, Davis GM. Higher exercise intensity delays postexercise recovery of impedance-derived cardiac sympathetic activity. Appl Physiol Nutr Metab 2017;42(8):834–40.
53. Sun P, Yan H, Ranadive SM, Lane AD, Kappus RM, Bunsawat K, et al. Autonomic recovery is delayed in Chinese compared with Caucasian following treadmill exercise. PLoS One 2016;11(1):e0147104.
54. Gerardo GM, Williams DP, Kessler M, Spangler DP, Hillecke TK, Thayer JF, et al. Body mass index and parasympathetic nervous system reactivity and recovery following graded exercise. Am J Hum Biol 2019;31(1):e23208.
55. Bunsawat K, White DW, Kappus RM, Baynard T. Caffeine delays autonomic recovery following acute exercise. Eur J Prev Cardiol 2015;22(11):1473–9.
56. Gonzaga LA, Vanderlei LC, Gomes RL, Valenti VE. Caffeine affects autonomic control of heart rate and blood pressure recovery after aerobic exercise in young adults: A crossover study. Sci Rep 2017;7(1):14091.
57. Gonzaga LA, Vanderlei LC, Gomes RL, Garner DM, Valenti VE. Involvement of cardiorespiratory capacity on the acute effects of caffeine on autonomic recovery. Medicina (Kaunas) 2019;55(5):196.
58. de Oliveira LS, Fontes AM, Vitor AL, Vanderlei FM, Garner DM, Valenti VE. Lower systolic blood pressure in normotensive subjects is related to better autonomic recovery following exercise. Sci Rep 2020;10(1):1006.
59. Gifford RM, Boos CJ, Reynolds RM, Woods DR. Recovery time and heart rate variability following extreme endurance exercise in healthy women. Physiol Rep 2018;6(21):e13905.
60. Michael S, Jay O, Graham KS, Davis GM. Influence of exercise modality on cardiac parasympathetic and sympathetic indices during post-exercise recovery. J Sci Med Sport 2018;21(10):1079–84.
61. Michael S, Jay O, Graham KS, Davis GM. Longer exercise duration delays post-exercise recovery of cardiac parasympathetic but not sympathetic indices. Eur J Appl Physiol 2017;117(9):1897–906.
62. Atkinson CL, Lewis NC, Carter HH, Thijssen DH, Ainslie PN, Green DJ. Impact of sympathetic nervous system activity on post-exercise flow-mediated dilatation in humans. J Physiol 2015;593(23):5145–56.
63. Tulppo MP, Kiviniemi AM, Hautala AJ, Kallio M, Seppänen T, Tiinanen S, et al. Sympatho-vagal interaction in the recovery phase of exercise. Clin Physiol Funct Imaging 2011;31(4):272–81.
64. Weberruss H, Maucher J, Oberhoffer R, Müller J. Recovery of the cardiac autonomic nervous and vascular system after maximal cardiopulmonary exercise testing in recreational athletes. Eur J Appl Physiol 2018;118(1):205–11.
65. Javorka M, Zila I, Balhárek T, Javorka K. Heart rate recovery after exercise: Relations to heart rate variability and complexity. Braz J Med Biol Res 2002;35(8):991–1000.
66. Düking P, Zinner C, Reed JL, Holmberg HC, Sperlich B. Predefined vs data-guided training prescription based on autonomic nervous system variation: A systematic review. Scand J Med Sci Sports 2020;30(12):2291–304.
67. Bellenger CR, Fuller JT, Thomson RL, Davison K, Robertson EY, Buckley JD. Monitoring athletic training status through autonomic heart rate regulation: A systematic review and meta-analysis. Sports Med 2016;46(10):1461–86.
68. Ihsan M, Watson G, Abbiss CR. What are the physiological mechanisms for post-exercise cold water immersion in the recovery from prolonged endurance and intermittent exercise? Sports Med 2016;46(8):1095–109.
69. Genç H, Tahmaz T, Akgül O. Effectiveness of mobility and stability exercises in resistance-trained males with shoulder immobility in different age groups. Phys Educ Theor Methodol 2022;22(4):544–550.
70. Conway CR, Xiong W. The mechanism of action of vagus nerve stimulation in treatment-resistant depression: Current conceptualizations. Psychiatr Clin North Am 2018;41(3):395–407.
71. Staley R, Garcia RG, Stowell J, Sclocco R, Fisher H, Napadow V, et al. Modulatory effects of respiratory-gated auricular vagal nerve stimulation on cardiovagal activity in hypertension. Annu Int Conf IEEE Eng Med Biol Soc 2020;2020:2581–4.
72. Samniang B, Shinlapawittayatorn K, Chunchai T, Pongkan W, Kumfu S, Chattipakorn SC, et al. Vagus nerve stimulation improves cardiac function by preventing mitochondrial dysfunction in obese-insulin resistant rats. Sci Rep

2016;6:19749.

73. Nearing BD, Anand IS, Libbus I, Dicarlo LA, Kenknight BH, Verrier RL. Vagus nerve stimulation provides multiyear improvements in autonomic function and cardiac electrical stability in the ANTHEM-HF study. J Card Fail 2021;27(2):208–16.
74. Annoni EM, Van Helden D, Guo Y, Levac B, Libbus I, KenKnight BH, et al. Chronic low-level vagus nerve stimulation improves long-term survival in salt-sensitive hypertensive rats. Front Physiol 2019;10:25.