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A Brief Review of the Use of Near Infrared Spectroscopy with Particular Interest in Resistance Exercise

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Contents

Abstract

There is growing interest in resistance training, but many aspects related to this type of exercise are still not fully understood. Performance varies substantially depending on how resistance training variables are manipulated. Fatigue is a complex phenomenon usually attributed to central (neuronal) and/or peripheral (muscular) origin. Cerebral oxygenation may be associated with the decision to stop exercise, and muscle oxygenation may be related to resistance training responses. Near infrared spectroscopy (NIRS) is a non-invasive optical technique used to monitor cerebral and muscle oxygenation levels. The purpose of this review is to briefly describe the NIRS technique, validation and reliability, and its application in resistance exercise. NIRS-measured oxygenation in cerebral tissue has been validated against magnetic resonance imaging during motor tasks. In muscle tissue, NIRS-measured oxygenation was shown to be highly related to venous oxygen saturation and muscle oxidative rate was closely related to phosphocreatine resynthesis, measured by ^{31}P-magnetic resonance spectroscopy after exercise. The test-retest reliability of cerebral and muscle NIRS measurements have been established under a variety of experimental conditions, including

static and dynamic exercise. Although NIRS has been used extensively to evaluate muscle oxygenation levels during aerobic exercise, only four studies have used this technique to examine these changes during typical resistance training exercises. Muscle oxygenation was influenced by different resistance exercise protocols depending on the load or duration of exercise, the number of sets and the muscle being monitored. NIRS is a promising, non-invasive technique that can be used to evaluate cerebral and muscle oxygenation levels simultaneously during exercise, thereby improving our understanding of the mechanisms influencing performance and fatigue.

Although there is increasing interest in studying the outcomes and mechanisms of resistance training, many aspects related to this type of exercise in humans are unclear. The interaction of multiple combinations of variables involved in resistance training makes it difficult to distinguish their individual contributions and to establish definite training recommendations. Manipulation of the training variables influences performance and this may be partly related to fatigue mechanisms. Examples of differences in performance include: (i) a slower movement velocity elicits a significantly smaller number of repetitions for the same load on leg extension exercise than a faster velocity;[1] and (ii) a shorter intra-set rest interval results in greater decreases in the total number of repetitions in multiple sets with a given load because of a reduced time for replenishment of intramuscular substrates.[2]

Fatigue is a complex phenomenon that is not fully understood and is generally attributed to either central (neuronal) or peripheral (muscular) origin, or both.[3] It is postulated that central fatigue is caused by failure of the CNS to adequately stimulate the motoneurons from both supraspinal and spinal factors.[3] Peripheral fatigue is related to disturbances in the surface membrane, excitation-contraction coupling and metabolic factors,[4] such as reduction in phosphocreatine (PCr) concentrations and increase in H^+ concentrations.[5] It has also been suggested that localised ischaemia may cause muscle fatigue[6] and that in the early phase this may be related to oxygen availability.[7] It should be noted that Noakes and St Clair Gibson[8] have challenged the traditional 'catastrophe' models and proposed that fatigue may be a regulating response of the brain in order to maintain homeostasis of all body systems during exercise. Recently, it has been suggested that interruption of exercise may be a protective decision for vital organs, such as the brain, when low glycogen or oxygenation levels may threaten their integrity.[9]

Sustained isometric[10] and isokinetic[11] muscle contractions are linearly and inversely related to intramuscular pressure and, in part, to reductions in muscle blood flow.[12] However, this seems to depend on muscle fibre type, since at 100% maximal voluntary contraction (MVC), blood flow occlusion may occur in the gastrocnemius muscle (thicker muscle, mainly fast-twitch fibres) but not in the soleus muscle (thinner muscle, mainly slow-twitch fibres). It has been speculated that this may be related to the anatomical arrangement of the fibres or arteries, as tension per unit weight in these muscles would probably be similar.[13] On the other hand, during intermittent isometric or isotonic contractions, mean muscle blood flow is not decreased and even increases above resting levels,[12,14,15] probably because of compensatory flow during the relaxation phases.[10] However, it has been suggested[16] that resistance exercise (10 repetition maximums [RMs] of one-arm curl exercise, 3 seconds per repetition) results in a state of restricted circula-

tion caused by reduced venous outflow with no restriction to arterial inflow. This could be the likely stimulus for the high proportion of slow-twitch fibres seen in bodybuilders.

There is evidence that vascular occlusion itself[17,18] may account for increases in muscle strength, cross-sectional area and indices of neuromuscular function. Identical resistance training programmes with light loads, with and without occlusion, resulted in greater adaptations in the groups training with occlusion; these results were similar to those obtained by a group training with heavier loads.[17] These chronic adaptations are speculated to be due to the observed acute responses to resistance exercise with occlusion (i.e. increased motor unit activity[19] and increased growth hormone, norepinephrine and lactate concentrations).[20] However, conclusions from acute studies to chronic adaptations should be viewed with caution, since acute responses often subside after chronic exposure to the stimuli or do not produce the expected changes.

Near infrared spectroscopy (NIRS) is a relatively new, non-invasive optical technique that has been used successfully to monitor tissue oxygenation and blood volume levels *in situ* in humans. During the last decade, there has been an exponential growth in the application of NIRS to evaluate human exercise performance. While the majority of the studies have focused on muscle performance during static and dynamic exercise, recently, there has been some research that has applied this technique to evaluate the cerebral responses during whole-body exercise. Currently, there is limited research that has applied this technique to examine the cerebral and muscle NIRS responses simultaneously during exercise. Research along these lines would increase our understanding of the central (neuronal) and peripheral (muscular) factors limiting exercise performance. The purpose of this brief review is to: (i) describe the principles of NIRS; (ii) examine NIRS validity and reliability during human performance; (iii) summarise the cerebral and muscle oxygenation, and blood volume responses during resistance exercise; and (iv) provide some examples of the simultaneous measurements recorded from the cerebral and muscle tissue during resistance exercise. Detailed reviews of the research pertaining to the principles of the different NIRS techniques,[21] and the muscle oxygenation and blood volume responses during dynamic exercise[22] have been published elsewhere and, therefore, will not be included in this review.

1. Principles of Near Infrared Spectroscopy (NIRS)

NIRS is a non-invasive, optical technique that has been widely used to monitor tissue oxygenation through the absorption of light photons in the 700–1000nm spectrum by haemoglobin (Hb), myoglobin (Mb) [only in muscle tissue] and cytochrome oxidase. Although the Hb and Mb absorption spectra overlap, Mb is thought to represent only a small portion of the NIRS signal.[23] Since large blood vessels contain a relatively large molar quantity of blood, absorption of near infrared light photons is virtually complete and, therefore, the NIRS signal is derived mainly from the small blood vessels (i.e. arterioles, capillaries and venules).[23]

There are several types of NIRS devices, the most widely used being the continuous-wave spectrometer. Time- and frequency-resolved spectroscopy measure the distribution of path lengths travelled in tissue by monitoring the impulse response of light emitted at a known distance away and the phase-shift of the detected light with respect to the incident light, respectively.[24] With continuous-wave spectroscopy in a scattering medium, the path length is not known and the attenuation of light in tissue represents relative oxy- and deoxy-Hb concentration changes and not absolute values.[21] The peak absorbency for deoxy-Hb occurs at 760nm, whereas the peak for oxy-Hb is observed at 850nm. The isobestic (cross over) point for oxy- and deoxy-Hb is at

798nm. The difference in the tissue absorbency between the 850nm and 760nm wavelengths indicates the balance between the delivery and removal of oxygen at the level of the small blood vessels. The sum of these absorbencies provides an index of the relative change in total Hb, which is considered to reflect the localised blood volume.

2. NIRS of Cerebral Tissue

Cerebral oxygenation changes measured by NIRS have been validated against a variety of techniques in humans. Strong correlations[25,26] have been reported between the blood oxygen level dependent measurements during functional magnetic resonance imaging and the changes in deoxy-Hb measured by NIRS from the left motor cortex during finger-tapping tasks. Alteration of cerebral oxygenation by inhaling hypoxic gas mixtures showed a close correlation between the NIRS-measured oxygenation and jugular oxygen saturation at rest in anaesthetised humans.[27] The test-retest reproducibility of NIRS in evaluating the alterations in cerebral oxygenation and blood volume has been demonstrated under a variety of experimental conditions including head-up and head-down tilt,[28] carbon dioxide rebreathing,[29] cycling[30] and handgrip[31] exercises. The reproducibility of oxy-Hb concentrations during an incremental cycle ergometer test in cardiac patients was high ($r = 0.88$).[30] In additon, intraclass correlation coefficients of 0.83 and 0.80[31] have been reported for the changes in cerebral oxygenation and blood volume in healthy subjects performing rhythmic handgrip contractions on alternate days.

NIRS has been used extensively to monitor cerebral oxygenation in healthy subjects and in a variety of patient populations during various functional activities.[32] In one of the initial reports[33] pertaining to the cerebral oxygenation and blood volume responses during right-hand finger tapping in healthy subjects, a significant increase was observed in the cerebral oxygenation and blood volume using continuous-wave NIRS recorded from the left frontal lobe. The increase in these variables was attributed to enhanced neuronal activation during the functional task by means of a neurovascular coupling mechanism. These investigators[33] also demonstrated that the changes in these variables were proportional to the task intensity and that differences were evident when the NIRS measurements were taken from the contra- and ipsi-lateral sides.

Pott et al.[34] examined the cerebral oxygenation, cerebral blood flow and cardiovascular responses during intense, two-legged static leg extension exercise in healthy males under two conditions: with and without the Valsalva manoeuvre (forced expiration against a closed epiglottis). At the onset of exercise with the Valsalva manoeuvre, there was a rapid increase in the mean cerebral blood velocity measured by the transcranial Doppler technique, which declined as the exercise progressed to the point of termination. However, there was a slight delay in the cerebral oxygenation measured simultaneously by NIRS, with the peak value being less pronounced. The correlation between the changes in cerebral oxygenation and mean cerebral blood velocity was 0.87 ($r^2 = 0.77$). During static exercise with continued ventilation (i.e. avoidance of the Valsalva manoeuvre), the cardiac output measured by Finapres instrumentation increased by approximately 10% with a concomitant decrease in the mean cerebral blood velocity. In contrast, there was a 50% decline in the cardiac output during exercise performed with a Valsalva manoeuvre, which was attributed to the large increase in the transmural pressure. The authors suggested that intense, static exercise performed with a Valsalva manoeuvre significantly taxes the cerebral perfusion pressure and, in conjunction with the subsequent hyperventilation, reduces cerebral oxygenation, which may explain the blackouts that are sometimes experienced by weightlifters. Thus, it is evident that NIRS can re-

veal important information pertaining to the cerebral haemodynamics during resistance exercise. Further research along these lines needs to be conducted in order to improve our understanding of this exercise modality.

3. NIRS of Muscle Tissue

The validation of NIRS in exercising human muscle was established by Mancini et al.,[23] who reported that NIRS deoxygenation measurements were closely correlated to venous oxygen saturation. These changes were primarily derived from deoxy-Hb and not Mb (measured by ^{1}H-magnetic resonance spectroscopy [MRS]). The overall trends were altered by limb perfusion changes and minimally influenced by skin blood flow. Furthermore, the NIRS-measured muscle oxidative rate was significantly correlated to PCr resynthesis measured by ^{31}P-MRS after exercise.[35,36] Indeed, van Beekvelt et al.[37] suggested that muscle oxygen consumption measured by NIRS revealed local differences that are not detectable by the traditional Fick method. Muscle blood flow measured by NIRS was well correlated to values obtained by plethysmography,[38,39] although these results were reported to be higher than those obtained with NIRS.[37] This is likely to be due to the more localised nature of the NIRS signal compared with the whole-limb measurement by plethysmography.

The reliability of evaluating muscle oxygenation and blood volume changes using NIRS has been well established. Significant test-retest correlations (r = 0.69–0.84) have been reported for the maximal amplitude variables (difference from minimum oxygenation to baseline and to maximum) in erector spinae muscles during a static muscle endurance test[40] in healthy males. The reproducibility of the oxygenation measurements in the vastus lateralis during the maximum number of knee extensions performed at slow (r = 0.73–0.76) and fast (r = 0.85–0.97) movement velocities has been documented.[41] In addition, a reproducibility coefficient of 0.85 has been reported for the changes in muscle oxygenation level during isotonic knee extensions.[42] A consistent coefficient of variation (CV; 16–25%) has been observed during a broad range of intensities of rhythmic, isometric handgrip exercise performed on different days.[43] The CV of the exponential time constant of recovery in muscle oxygenation after plantar flexion exercise has also been reported (15% intra-day and 5.7% inter-day).[44]

4. NIRS and Resistance Exercise

Research using NIRS during resistance exercise is limited. Only four studies have used this technique to investigate muscle oxygenation and/or blood volume during commonly used weightlifting exercises. None of these studies investigated cerebral responses during their protocols. Tamaki et al.[16] monitored muscle oxygenation of the biceps brachii during one-arm curl exercises performed under the following conditions: one set of ten repetitions with no load; one set of 10 RMs; and three sets of five repetitions with a 1-minute rest between sets (load not specified). Unloaded repetitions resulted in no change in muscle oxygenation, but the trend in oxygenation parameters during the 10 RMs set was similar to that observed during arm blood-flow restriction; deoxy-Hb increased, oxy-Hb decreased and total-Hb (an indicator of blood volume) showed a small initial decrease, with a subsequent increase during exercise. During the recovery period, all of these parameters gradually returned to near baseline levels. Similar trends were seen during the three-set protocol, although total-Hb did not return to baseline levels until at least 90 seconds after exercise ended. The authors suggested that this type of resistance exercise induces blood-flow restriction, with a relative lack of oxygen supply and that three sets 'accelerate' this effect.

Azuma et al.[45] monitored the NIRS responses in the vastus lateralis and rectus femoris muscles dur-

ing knee extensions. They used 20%, 30% and 40% MVC loads at a rate of 60 extensions per minute to the point of fatigue (362 ± 68 seconds, 110 ± 18 seconds and 51 ± 7 seconds, respectively). Oxygen saturation (calculated from the ratio of oxy-Hb to total-Hb) was lower for the vastus lateralis (significant only at 30% MVC) than for the rectus femoris, and was significantly lower at 30% and 40% MVC for both muscles when compared with 20% MVC. At the point of fatigue, oxy-, deoxy- and total-Hb were no different among intensities for the rectus femoris. For the vastus lateralis, oxy- and total-Hb were significantly lower for 30% and 40% MVC compared with 20% MVC, but deoxy-Hb was similar among intensities. It was suggested that differences between the two muscles may be related to fibre-type composition, since the vastus lateralis is reported to be more abundant in type 1 fibres and would therefore be capable of being more active with lower tissue oxygenation levels.

Hoffman et al.[46] investigated the vastus lateralis muscle during four sets of squats with 3-minute intervals between sets. Two different intensity protocols were compared: (i) low, using 15 repetitions at 60% of 1 RM (41.6 ± 6.6 seconds); and (ii) high, using 4 repetitions at 90% of 1 RM (21.4 ± 3.6 seconds). Although the level of deoxygenation and half-time for reoxygenation were similar between the two protocols, there was a significantly longer delay before reoxygenation started in the low-intensity protocol. The authors suggested that this longer delay may have been caused by the greater lactate concentrations found in the low-intensity protocol compared with the high-intensity protocol, as a result of the Bohr effect. Additionally, this higher lactate concentration may have stimulated the growth hormone response, which was significantly higher for the low-intensity protocol.

Tanimoto and Ishii[42] evaluated the changes in oxygenation of the vastus lateralis muscle during knee extension protocols commonly used in resistance training. Subjects were assigned to the following different groups: (i) low intensity and slow speed (LS), 8 RM (≈50% 1 RM) and 3 seconds for each phase; (ii) high intensity and normal speed (HN), 8 RM (≈80% 1 RM) and 1 second for each phase; and (iii) low intensity and normal speed (LN), 8 repetitions (≈50% 1 RM) and 1 second for each phase. The LS elicited significantly lower muscle oxygenation than the other two protocols, and both LS and HN resulted in significantly higher recovery reoxygenation values than LN. It is evident from these studies that the kinetics of intramuscular oxygenation and blood volume measured by NIRS are dependent upon the resistance training protocols (i.e. different intensities, number of sets and exercise duration) and can vary for different muscles. Tanimoto and Ishii[42] also documented changes subsequent to a 12-week training programme. They reported that the significant increases in muscle size and strength in LS were similar to HN, whereas in LN they were not significant. Therefore, the authors suggested that the larger deoxygenation and blood lactate concentration seen in LS may have induced a greater restriction of blood flow, which may be related to muscle hypertrophy. To the best of our knowledge, no studies have reported the alterations in muscle oxygenation following a resistance training programme. Such studies need to be conducted to evaluate the effects of different intensities and velocities of resistance training to improve our understanding of this area.

5. Simultaneous Measurement of Cerebral and Muscle Oxygenation/ Blood Volume During Resistance Exercise

The feasibility of monitoring cerebral and muscle tissue simultaneously using NIRS during cycling[47] and rowing[48] has been documented. To the best of our knowledge, research to evaluate these responses simultaneously during dynamic resistance exercise

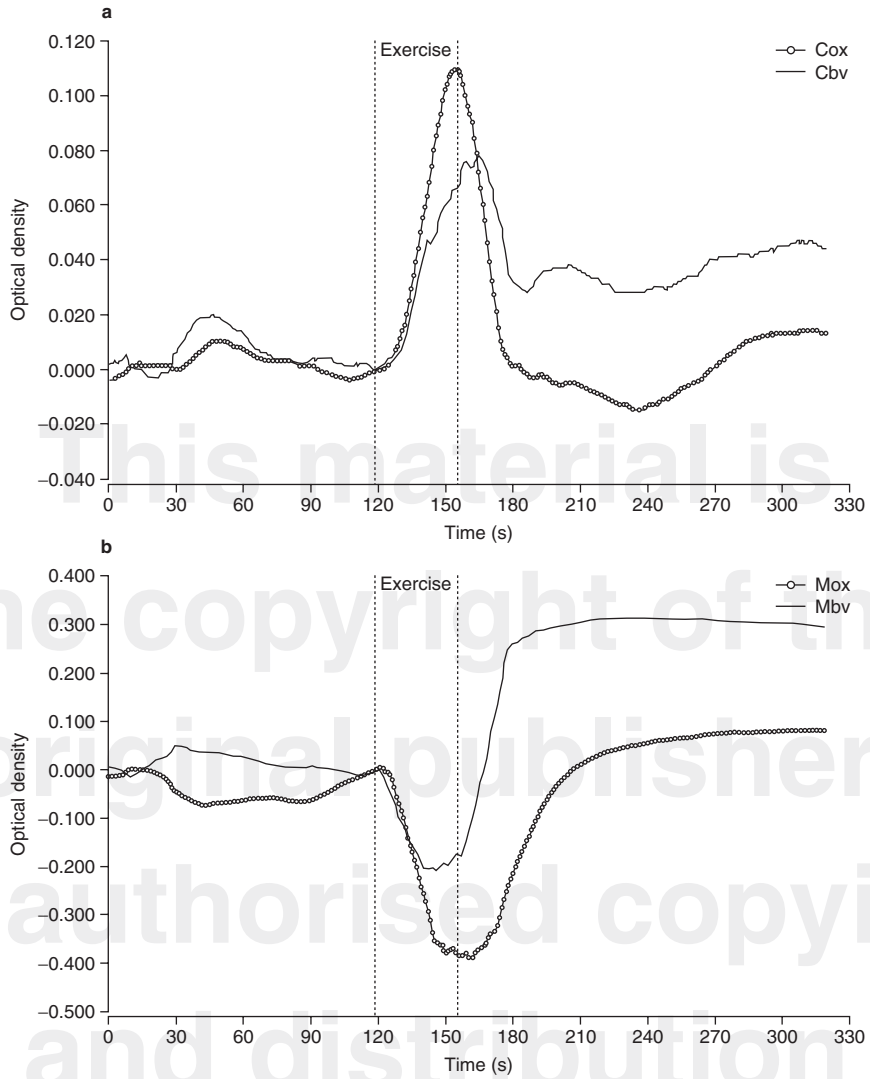

Fig. 1. Typical measurements by continuous-wave near infrared spectroscopy (MicroRunman, Philadelphia, PA, USA) during unilateral knee extension maximum repetitions with 80% 1 repetition maximum load for: (**a**) cerebral blood volume (Cbv) and oxygenation (Cox); and (**b**) muscle blood volume (Mbv) and oxygenation (Mox). The exercise period is indicated.

has not yet been conducted. In our laboratory, we have recently examined these changes simultaneously during unilateral knee extension exercises in healthy subjects at different velocities using the following protocol: 2 minutes rest, exercise to voluntary fatigue and 4 minutes of recovery. The cerebral oxygenation was recorded from the left frontal lobe while the muscle oxygenation was recorded from the right vastus lateralis. The trends observed in the cerebral and muscle tissue in a representative subject exercising at 80% of 1 RM are illustrated in figures 1a and 1b, respectively.

It is evident that during the exercise period, there is a significant increase in the cerebral oxygenation and blood volume, implying increased neuronal activation. Following the contraction, there is usually a

rapid recovery towards the resting baseline values. This is consistent with previous observations during static and dynamic exercise that was reviewed in section 2. Some interesting observations from our preliminary work during resistance exercise are: (i) in some cases, there is a slight delay in these responses recorded from the left frontal lobe; (ii) the changes can reach a peak and begin to decline even before the contraction is terminated; (iii) the trends during the recovery period are variable (in some cases, there is an increase before the values return to the baseline, while in others there is an immediate decline); and (iv) there may be an undershoot in the recovery levels (i.e. the values may decrease to levels below the initial baseline value). It should be noted that all of these trends have been previously documented in NIRS studies. Interestingly, a recent study[49] that examined the NIRS and MRI responses simultaneously during visual stimulation also demonstrated the undershoot in the cerebral oxygenation measurements during both the techniques. The authors suggested that this could be due to the high rate of cerebral oxidative metabolism that was occurring during the recovery period, even though blood flow had recovered to its resting values.

In contrast with the trends observed in cerebral tissue during resistance exercise, the muscle oxygenation and blood volume demonstrated a systematic decrease during our protocol. As soon as exercise was initiated, there was a rapid decline in muscle oxygenation, which tended to level off at the point of fatigue. This plateau suggests that the muscle had reached its maximum capacity for extracting oxygen from the perfusing blood. The blood volume also demonstrated a rapid decline during the muscle contractions, which is opposite to the response observed during dynamic exercise such as cycling, walking or running.[22] The most likely reason for this trend during dynamic resistance exercise is that the intramuscular pressure exceeded the intravascular pressure during the contraction, which resulted in a reduction in localised blood volume. During recovery, both the muscle oxygenation and blood volume demonstrated a rapid hyperaemia in the first 60 seconds, followed by a slower recovery, which usually exceeded the resting baseline value. Previous research[50] has demonstrated that the half recovery time of the muscle oxygenation from cycling exercise is correlated with the aerobic enzyme activity and, therefore, can be used as a marker for aerobic metabolism. Whether this relationship holds good for resistance exercise is unknown and needs to be investigated.

It should be noted that the values of muscle oxygenation and blood volume measured by continuous-wave NIRS are not the absolute values, but merely reflect the changes from the baseline values. In order to obtain additional information pertaining to the relative intensity of the muscle contraction, the magnitude of change in oxygenation can be expressed as a percentage of the change that is observed under maximal hypoxic conditions induced by cuff ischaemia. The maximum degree of deoxygenation is calculated as the difference obtained from the baseline, just before the occlusion is induced, to the lowest value recorded during the cuff ischaemia period. During recovery from cuff ischaemia, there is a very rapid hyperaemia in the muscle oxygenation and blood volume within the first minute, followed by a steady decline towards the resting values during the next 2–3 minutes. It is likely that manipulating the resistance training variables, such as the number of repetitions, training load (RMs) and rest intervals between sets, will alter the blood volume and degree of deoxygenation in the muscle during contractions, and influence the performance and training adaptations.

6. Conclusion

NIRS is a valid and reliable technique for monitoring both cerebral and muscular oxygenation during exercise. Although this technique has been used

extensively during dynamic exercise to increase our understanding of the kinetics of muscle oxygenation *in situ*, its application during resistance exercise has been limited. There is evidence to suggest that this technique can evaluate the trends in cerebral and muscle oxygenation and blood volume responses under different conditions (e.g. intensities, rest intervals) and, therefore, provide some insight into the causes of muscle fatigue. Research into resistance training is a growing field and there is still much to be explained. The advantages of a non-invasive technique cannot be over-emphasised and, therefore, further research is warranted to demonstrate the usefulness of NIRS to increase our understanding of the resistance training variables on performance.

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