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Muscle Fatigue Physiology Applied to Management of Voice Fatigue

Mary J. Sandage

Auburn University
Auburn, Alabama

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Voice fatigue is a common concern for individuals seeking voice care with and without laryngeal pathology. In exercise science, muscle fatigue is attributed to central fatigue, peripheral fatigue, or a combination of the two. From the perspective of speech-language pathologists who care for voice disorders, voice fatigue is generally considered something to be avoided and little attention has been given to fatigue-resistance training programs. Exercise science training paradigms consider muscle fatigue as something to be managed. Strength and conditioning programs include fatigue-resistance as a critical training component to help avoid injury. Work hardening and return-to-work models for rehabilitation as described in the occupational medicine literature are designed to help bridge the gap between limited work provided in the therapy setting and the functional expectation of the employment setting. After reviewing central and peripheral mechanisms of muscle fatigue, the voice fatigue literature will be discussed from this framework. Employment of a return-to-work approach to voice habilitation and rehabilitation will be discussed as a means to train the voice for fatigue resistance.

The interest in the use of exercise training principles in voice, swallowing, and respiratory function has grown substantially in recent years. This interest is well-placed given that respiratory, laryngeal, articulatory, and swallowing functions are executed primarily with skeletal muscles. Skeletal muscle is characterized by its plasticity and adaptability to exercise as well as lack of use. Neurologic, metabolic, and morphologic mechanisms are upregulated with muscle use that exceeds typical muscle demand (Sandage & Pascoe, 2010). These same mechanisms are downregulated with muscle disuse or use that falls below typical demand. Muscle tissue is constantly adapting to the demands imposed (or not imposed) to maintain tissue efficiency, and fatigue resistance is one of those adaptations. Fatigue-resistance training is an area of laryngeal muscle function that has not received due empirical diligence in the area of voice function, particularly for voice habilitation and rehabilitation practices where there is often a one-size fits all approach. Research on voice fatigue has largely focused on voice function differences that are attributed to laryngeal cover fatigue (Chang & Karnell, 2004; Sivasankar, Erickson, Schneider, & Hawes, 2008) or measures of perceived voice fatigue (Ilomäki, Kankare, Tyrmi, Kleemola, & Geneid, 2017; Nanjundeswaran, Jacobson, Gartner-Schmidt, & Abbott, 2015). Little attention has been paid to intrinsic and extrinsic laryngeal muscle fatigue and aspects of laryngeal muscle fatigue that may be mediated via a fatigue-resistance muscle training program. This discussion will review known mechanisms for muscle fatigue in general and the implications for voice and laryngeal muscle function that is yet to be studied empirically in manner that is consistent with known muscle physiology and training parameters.

In the basic and applied exercise science literature, muscle fatigue is described as any reduction in physical performance, whether perceived or real (MacIntosh, Gardiner, & McComas, 2006). Muscle fatigue generally has been attributed to two different mechanisms, central and peripheral fatigue. Central fatigue is generally attributed to emotions and thought processes related to performance, as well as efferent motor pathways and the interneurons and motoneurons of the central nervous system. Central fatigue has not been as well characterized as peripheral fatigue, the latter of which is believed to have a substantial contribution to the muscle fatigue process. Peripheral fatigue is characterized as a decline in or failure to maintain muscle force for physiological reasons that can be explained by slower action potential conduction and inefficient neuromuscular transmission at the neuromuscular junction and along the muscle fiber. Within the muscle fiber itself, depletion of locally available stores of ATP (the primary muscle fuel) and substrate for manufacturing ATP are believed to contribute to muscle fatigue. Increased levels of lactic acid with exertion (acidosis) has also been attributed to muscle fatigue; however, an excellent review of the fates of lactate refutes this long standing belief, summarizing the fates of lactic acid as muscle fuel substrate used during exercise or conversion to stored glycogen in the liver when exercise stops (Gladden, 2004).

Limited attention has been directed toward muscle physiology mechanisms for voice fatigue (Welham & Maclagan, 2003) and investigations of voice fatigue have not delineated the distinct contributions of central versus peripheral mechanisms for fatigue. This lack of distinction between the two mechanisms makes it difficult to discern if the fatigue perceived is due to laryngeal muscle fatigue (peripheral fatigue), the participants' belief that the voice is tired (central fatigue), or a combination of the two. Because fatigue mechanisms are likely interdependent, Enoka and Duchateau (2016) proposed a more cohesive taxonomy to consider fatigue measurement as a holistic concept that encompasses the interdependent relationship between components of central and peripheral fatigue that these authors describe as *perceived fatigability* and *performance fatigability*. Use of these muscle physiology paradigms in the development of research models of voice fatigue will aide in task selection, perceptual and objective measures selected, and the interpretation of findings.

When evaluating research that targets voice fatiguing tasks, it is worth considering which physiological structures are being fatigued. Many studies use reading tasks of varying length and sound level. Reading aloud requires use of all three subsystems of speech (respiration, phonation, and articulation), thus making conclusions about laryngeal fatigue more challenging. It is acknowledged that reading aloud is likely an optimal task choice in a research design that accounts for inter-participant variability; however, isolating laryngeal structure fatigue is difficult with this model. There is evidence to support fatigue resistance of the tongue following extensive speech-like activities in neurotypical individuals (Solomon, 2006). Solomon's body of work that described speech-like task fatigue resistance provided evidence, for reading aloud tasks, that the fatigue perceived was not likely due to the articulation subsystem. Empirical pursuits to isolate the respiratory subsystem from phonation will help delineate sources of fatigue, which then can be included in updated models of voice habilitation and rehabilitation. Preliminary evidence suggests that speech breathing patterns are produced during quiet mental rehearsal of a monologue; however, not at the pulmonary volumes expected for speaking out loud (Hague & Sandage, 2017). This suggests a potential methodological direction by which to study respiratory fatigue without concurrent use of the larynx and articulators. This research is complex given the established age and sex differences in respiratory coordination and the differences in respiratory entrainment for those with and without voice disorders (Lowell, Barkmeier-Kraemer, Hoit, & Story, 2008).

An additional factor for this choice of task in empirical studies of vocal fatigue is the degree to which each participant uses the voice occupationally, avocationally, and socially prior to participation in a research protocol. Some individuals may be trained up and have more fatigue resistance given prior voice use. This inter-participant variable is rarely accounted for in the current body of work that describes voice function with fatiguing voice tasks. Finally, the ecological validity of the task selected when mapped to occupation-specific vocal dose distance and average sound levels should be evaluated. Fatigue resistance may be determined if the task is relatively short compared to the routine large vocal doses produced by a participant, for example, a telemarketer.

With regard to the perceptual and objective measures used in voice fatigue research, the following should be considered: Do the perceptual measures of voice fatigue used in these studies have specificity and isolate voice fatigue or could the perceptual measure of fatigue include respiratory and articulatory muscles? Do the measures of perceived fatigue delineate differences between central and peripheral fatigue? Are the objective measures chosen sensitive enough to detect peripheral intrinsic laryngeal muscle fatigue?

Perceptual measures of fatigue do not always correlate with objective measures of voice function. This may be explained by the perceived fatigability and performance fatigability aspects of fatigue in general. Perceptual measures of voice fatigue may target perceived (central) fatigue components of voice function, whereas objective voice measures may target performance (peripheral) fatigue mechanisms. The merger of central fatigue mechanisms to perceptual constructs of fatigue were well described by Solomon (2006) as a rationale for use of sense-of-effort scales, for example, the Vocal Fatigue Index (Nanjundeswaran et al., 2015). Thus, perceptual scales may be sufficient measures of fatigue generally, as suggested by Enoka and Duchateau (2016). One caution for use of general measures of perceived fatigue made by Enoka and Duchateau (2016) is whether or not the perceptual measure taken can delineate trait fatigue from state fatigue. In other words, would an individual's appraisal of fatigue following a voice loading task be higher because of a general trait of perceived fatigue versus fatigue specifically related to the voice loading task—state fatigue.

Due to the myriad of peripheral or performance mechanisms that are upregulated with training to offset fatigue, at the neuromuscular junction (NMJ) and in the muscle cell, a more refined understanding of voice fatigue will emerge once these mechanisms can be identified and described in intrinsic and extrinsic laryngeal muscles. The morphological, biochemical, and neurologic mechanisms that are developed with muscle training are vital components of the fatigue story. Direct translation from limb skeletal muscle work is not sufficient given the specialized nature of the larynx. Improved efficiency of the rat thyroarytenoid NMJ with exercise, particularly in an aging model, has been empirically supported (Johnson, Ciucci, & Connor, 2013), providing evidence for plasticity of the structure and identifying a potential fatigue-resistant mechanism in the larynx. Additional basic research to describe muscle cell physiology of the intrinsic laryngeal muscles will further our understanding of peripheral fatigue mechanisms for voice.

A commonly used objective measure of vocal fatigue that may delineate peripheral (performance) fatigue is aerodynamic assessment of phonation threshold pressure (PTP; Chang & Karnell, 2004; Sivasankar et al., 2008). PTP requires production of the quietest voice possible at a target frequency, and it is reported as the minimum amount of subglottic pressure required to initiate phonation (Plexico, Sandage, & Faver, 2011). The PTP task requires coordinated voice onsets during production of /pipipipipi/, which requires fine motor coordination of the intrinsic laryngeal muscles to abduct and adduct the vocal folds in succession at the quietest sound level possible. This measure is often described as an indicator of biomechanical fatigue of the cover following extensive voice use (Solomon, 2008). Solomon (2008) also postulates that fatigue may trigger recruitment of agonistic muscles that lead to higher adductory forces. Therefore, for reasons relating to both cover and body fatigue, PTP remains a compelling objective measure to monitor vocal fatigue and, perhaps, training up for fatigue resistance. Evidence for PTP as a measure of skill acquisition in male singers was discussed by Tanner et al. (2016).

The study of voice fatigue is important work given the prevalence of individuals who present in voice clinics with voice fatigue as the primary complaint. Voice fatigue is generally considered in a negative light, with little consideration for training the voice to be more fatigue-resistant. Fatigue resistance training is an important pillar in exercise training and, along with skill acquisition, is believed to be a vital aspect of injury prevention (Powers, 2014). Measures of fatigue in human performance are also an important gauge for avoidance of overtraining. Investigations of voice function should consider aspects of voice training in a manner that encompasses fatigue resistance mechanisms. Fatigue resistance training is important for a few primary reasons; (1) maintaining optimal performance throughout the entire target behavior (i.e., a recital or vocally demanding work day); (2) faster recovery following the vocal load and improved ability to perform again within a short time while; (3) reducing the tendency to develop negative compensatory strategies to keep voice going when fatigue sets in. Application of training paradigms from exercise science may be a useful strategy to develop a systematic way to “train up” to meet the physiological and psychological demands of voice professionals.

In voice habilitation and rehabilitation constructs, it is compelling to consider use of the central and peripheral measures of voice fatigue described above as evidence for fatigue resistance training. The concept of fatigue-resistance training is in part based on the theoretical constructs of work hardening or work conditioning that are found in occupational and physical therapy domains. Work hardening or return-to-work models are designed to bridge the gap between the limited time a client has in therapy or formal training and the actual voice load requirements of the workplace. The bridge between what we do in the therapy room and what is demanded of the voice in the work place requires an understanding of the occupation-specific voice load and ergonomics. Vocal dosimetry data by occupation is emerging (Manfredi & Dejonckere, 2016; Morrow & Connor, 2011; Van Stan et al., 2015), allowing us to quantify the average sound level and total voicing time required for work-related voice use. Understanding work place voice demands can lead to more prudent design of voice habilitation and rehabilitation programs that include training up to the voicing load required, which can then offset voice fatigue and, perhaps, protect the larynx from injury.

Application of a work hardening/conditioning structure in the context of work-related voice use requirements can be applied habilitatively for teachers in training who would benefit from a strength and conditioning program prior to starting student teaching. Production of the voice in an ergonomically similar environment at the target sound level and increasingly longer voicing durations may trigger upregulation of central and peripheral muscle mechanisms that offset fatigue. This model could also be applied to teachers and performers who take several weeks off on a regular basis and may detrain or downregulate those fatigue-resistant mechanisms, only to have to retrain when they return to the demands of the classroom or performance space. Identification of the minimum vocal dose needed to “stay in shape” during extended breaks could alleviate the voice fatigue experienced with return to work. A systematic approach to voice training that incorporates fatigue-resistance considerations is yet to be formalized for empirical study.

Conclusion

Vocal habilitation and rehabilitation programs require knowledge of perceived (central) and performance (peripheral) fatigue aspects of performance function and acknowledge the interdependence of the two mechanisms. The inclusion of muscle physiology training principles into fatigue-resistant training programs for occupational voice users is an emerging area of interest and research. As the merger between voice science and exercise science develops further, the manner in which voice fatigue and voice habilitation are studied can become more refined.

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