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Instrumental Assessment of Aero-Resistive Expiratory Muscle Strength Rehabilitation Devices

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Abstract

Purpose: Expiratory muscle strength training (EMST) is increasingly being used to treat voice, cough, and swallowing deficits in a wide range of conditions. However, a multitude of aero-resistive EMST models are commercially available, and the absence of side-by-side comparative data interferes with clinicians' ability to assess which model is best suited to a particular client's needs. The primary aim of this research was to test and compare the pressure and flow parameters of six currently available EMST models to help inform clinical decision making. **Method**: We identified and tested five devices of each of six different EMST models to generate benchmark data for minimum trigger pressures across settings. The reliability was tested within each device and between five devices of the same model across settings using coefficient of variation. **Results**: All six models required higher pressures to initiate flow at the highest setting compared to the lowest setting, as expected. Detailed descriptive statistics for each model/setting combination include average flow-triggering pressure for each model/setting and the variability across trials within a device and across devices of the same model. From these, ranked order of the least to most stable EMST model was derived. **Conclusions**: Systematic testing of several commercially available expiratory resistance training devices yielded clinical benchmarks and reliability data to aid clinicians in selecting an appropriate therapy device and regimen for a client based on their available airflow and air pressure as well as reliability of the device. These findings allow clinicians to directly compare key parameters across EMST devices.

Exercise regimes, such as the expiratory muscle strength training (EMST), that primarily aim to enhance the capacity of respiratory muscles can also stimulate upper airway musculature. Capitalizing on this notion, it is assumed that EMST can improve the functioning of the upper aerodigestive tract during phonation, coughing, and swallowing (Sapienza & Hoffman, 2020; Sapienza et al., 2011; Sapienza & Wheeler, 2006). These assumptions are well supported by several experimental studies and literature syntheses that suggest EMST to be an efficacious modality for the treatment of voice, cough, and swallowing deficits in a wide range of conditions (Brooks et al., 2019; Desjardins & Bonilha, 2020; Eom et al., 2017; Hutcheson et al., 2018; Mancopes et al., 2020; Patchett et al., 2017; Plowman et al., 2019; Reyes et al., 2020; Templeman & Roberts, 2020; Troche et al., 2010; Wang et al., 2019; Wheeler-Hegland et al., 2008). Although most experimental studies have utilized a specific model of EMST device(s), (Mancopes et al., 2020) clinical implementation of EMST regimens is carried out using a wide range of commercially available respiratory training devices.

Commercially available respiratory training devices fall into two main categories: (a) devices that impose a resistance (strength) training stimulus and (b) those that impose an endurance (aerobic) training stimulus (McConnell, 2013; Sapienza, 2008) to either inspiratory and/or expiratory musculature. A strength training stimulus subjects the targeted muscle group to a high-resistance load within a short-duration session. This type of stimulus induces muscle adaptations that enhance the muscle's ability to generate maximum force (expiratory pressure). In contrast, an endurance stimulus involves extended repetitive muscle contractions against a comparatively light resistance load. Notably, most clinical research on the rehabilitation of voice, cough, and swallowing functions has utilized a strength training paradigm that primarily targets expiratory muscles (Brooks et al., 2019) and is delivered through positive expiratory pressure (PEP) devices. Therefore, the focus of the current work is solely on PEP devices; interested readers can refer to the article by Sapienza (2008) for a detailed review of other types of respiratory training devices.

PEP devices generate aero-resistance through one of the following three ways: (a) flow resistor, (b) threshold resistor, and (c) oscillatory PEP. A flow resistor PEP device exhibits a flow-dependent nature, meaning that the degree of resistance it introduces is contingent on the flow rate produced by the patient. This resistance is primarily achieved by varying the size of the orifice, with a smaller orifice diameter resulting in a higher level of imposed resistance. A threshold resistor–type PEP uses a spring or magnet to generate resistance to flow and requires PEP to reach a particular level (threshold) to overcome the resistance load and allow flow. The most common type of threshold resistor is the pressure threshold resistor, which requires individuals to produce an expiratory pressure sufficient to overcome a pressure load and initiate an expiratory flow. The threshold-type PEP

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permits resistive loading at a quantifiable, variable intensity by providing nearflow–independent resistance to expiration. The third type is the oscillatory PEP, which uses an external mechanism to create a series of temporary occlusions of expiratory flow to generate oscillatory airway pressure (Demchuk & Chatburn, 2021; de Menezes et al., 2018; McConnell, 2013; Sapienza, 2008). It is important to note that each PEP device is characteristically different from the other and varies mechanistically regarding two main factors: (a) resistance levels offered and (b) the shape (design). Although most commercial PEPs are designed to be held in the mouth, the range of resistance levels available for each device varies, which can significantly impact their clinical utility. For example, if the minimum trigger pressure is too high, it may be difficult for the patient to generate sufficient expiratory flow. On the other hand, if the minimum trigger pressure is too low, the patient may not be getting enough expiratory airflow resistance to be challenging. Therefore, appropriate resistance (adjustable by the clinician to meet the client's evolving needs) is crucial to achieving optimal clinical outcomes.

While research studies have increasingly focused on evaluating the efficacy of EMST in treating voice, cough, and swallowing deficits, clinicians are faced with challenges in selecting an EMST model as more models become commercially available in the market. Device parameters that may be especially relevant to clinical selection include the range of resistance offered and the reliability of that resistance. A device's range is critical in that it should suit the client's current abilities and also accommodate increases in aero-resistance as the client improves. Increasing load is a central tenet of motor rehabilitation (Schoenfeld et al., 2016). The reliability of a device is also relevant to the selection process; the specific device issued to an individual patient needs to provide the expected level of resistance for each repetition of the prescribed exercises. Together, these performance characteristics inform a clinician's ability to match a given device to a particular client's needs.

Some data regarding resistance levels are available for each of the EMST devices currently on the market, but there are several limitations. For some devices, these data are produced by the manufacturers in ideal lab conditions rather than clinical use, and the data are made available only upon request. Published data are available for only a few devices. Furthermore, the variety of testing procedures and reported measures across these sources and devices undermines side-by-side comparisons to enable efficacious selection of EMST models in clinical situations. The current study aimed to address this gap by testing and comparing the pressure and flow outcomes of six currently available EMST models during use by two adults over a range of settings for each model. The specific questions that the current study aimed to address were as follows:

1. What is the minimum pressure required to initiate flow for each EMST model at each tested setting?
2. What is the variability within and between each device of the same model across settings, and what is the overall stability of a particular EMST model?

Method

EMST Devices and Settings

We queried clinical providers to determine which EMST models were being used in various inpatient and outpatient settings at health care institutions across the United States. As a result, we identified five different EMST models that fall into one of the three categories and were commercially available at the time of study. A newer model, the EMST75 Lite (Aspire Products), was also included for testing in the study (see Figure 1). A power analysis (G*Power Version 3.1.9.4) was conducted using data from two devices of five EMST models (n = 10) to determine the sample size. The analysis results showed that 28 devices would be required to have 80% power at an α of .05 for an effect size < 0.3 and moderate correlation between two devices of the same EMST model. Hence, a total of 30 devices, five of each of the six EMST models, were tested in this study.

For devices with discrete settings (such as 1–5 for the Breather 2), all available settings were used. Other devices that allowed continuous adjustment with intermittent labeling were assessed at the lowest setting, the highest setting, and four additional settings that were as evenly spaced as possible between these extremes. For example, Acapella DM allows such continuous adjustments and has 20 tick marks (see Figure 2), so we divided across the available values and tested at 1, 5, 9, 13, 17, and 20 "ticks." Similarly, the EMST150 has markings at 30, 60, 90, 120, and 150, although innumerable incremental adjustments between these markings are also available. These increments were carefully recorded for the first device tested of a given model, and testing adjustments for each subsequent device from the same model were cross-checked against these settings from the first (reference) device to confirm that they were being assessed at the same resistance levels based on the device markings and researcher notes prior to any testing of the device at the selected setting.

Calibration and Testing Setup

A custom testing setup allowed us to track and measure the levels of pressure (in cmH2O using a digital pressure sensor Model 3200 V, AWM3000 Series, Honeywell) and flow (L/min) using a pneumotachometer (R4719 Series, Hans Rudolph) coupled to a Honeywell 163PC01D36 dualport sensor to sample air volume

velocity. Before each testing session, the measurement and digital capture equipment described below was calibrated for pressure and flow measures using a U-tube manometer and rotameter. After calibration, an EMST device was attached to the testing equipment (see Figure 3). The testing setup was identical across all EMST devices, except for minor adjustments to the tubing connectors to accommodate the variously shaped outflow ports of the EMST devices and ensure an airtight seal for each device. Analog signals from the pressure and flow sensors were digitized using PowerLab (Model 16/35, AD Instruments, 16-bit, ± 5 V, 1KHz). These digitized signals were further conditioned using the Octal BridgeAmp (AD Instruments) and recorded on the LabChart software (v8.1.9, AD Instruments) on a laptop computer (WIN10).

Testing Procedure

Two participants, a man (age = 28 years, author R.K.) and a woman (age = 21 years, author K.Y.), with body mass index in the healthy range, no history of pulmonary or other health conditions, and a consistent program of cardiovascular exercise generated the expiratory stream for all device testing. Since we were interested in device parameters across a full range of settings rather than how the devices aligned to the tester's maximum performance, maximum expiratory pressures for these individuals were not obtained. As part of the testing protocol at each tested setting, the tester formed an airtight seal around the device mouthpiece and completed three exhalations, starting with minimum expiratory force and increasing to maximum expiratory force within each exhale, for all devices and models. Nose clips (provided by the EMST device manufacturers) were in place for all testing. Testers performed three exhalations at each tested setting for all six EMST models to evaluate minimum trigger pressure and variability for each EMST model. Five devices of the same EMST model were tested to evaluate the variability between devices. We randomized the order in which the devices were tested, the order in which settings were tested, and the number of devices tested on a given day to minimize the prevalence of patterns in the breathing cycle and fatigue for specific devices. The participants were given five 15-s breaks between repetitions and a 2-min break between sets. A maximum of three devices were tested on a single day.

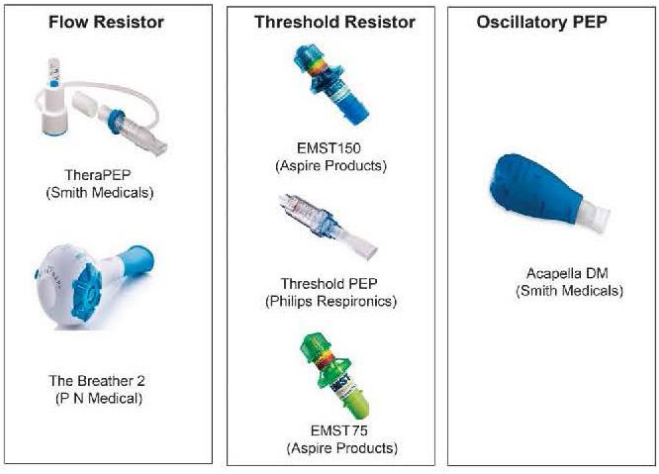

Figure 1. Six different aero-resistive expiratory muscle strength rehabilitation devices tested in the study. PEP = positive expiratory pressure; EMST = expiratory muscle strength training.

Figure 2. Annotated reference device for cross-checking intermittent levels.

Data Extraction

The measure of interest was minimum trigger pressure, operationally defined as the lowest pressure (in cmH_2O) required to initiate flow at a particular setting. It represented the pressure required at the device's chosen setting to overcome the resistance at that setting and thus trigger airflow. One of the investigators extracted minimum trigger pressure at the initiation point of flow for each device across its settings, as shown in Figure 4. To assess intrarater reliability, 10% of the data were reextracted by the same investigator after 2 weeks to ensure the reliability of the extracted data. An additional individual not affiliated with the study

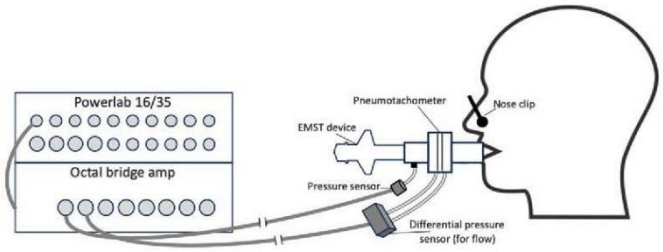

Figure 3. Schematic of flow and pressure testing equipment. EMST = expiratory muscle strength training.

was recruited and briefly trained to extract a randomly selected 10% subset of the data to assess interrater reliability. This individual was blinded to the study's research objectives.

Analyses

Descriptive statistics, including means and standard deviations, were tabulated for minimum trigger pressure for each device across settings. Mixed groups factorial analysis of variance (ANOVA) with follow-up analyses using the least significant difference (LSD) procedure was performed to examine the effects of the model and settings on minimum trigger pressure. We hypothesized that there would be an interaction between model and setting, as it related to minimum trigger pressure. The expected pattern of interaction was that the trigger pressure for each model would be distinct (different) across settings. We also hypothesized that there would be main effects for model, that is, each model would have different trigger pressure, and for setting, that is, lower settings would have lower trigger pressure than higher settings. To further investigate the interaction patterns and the main effect patterns, cell means and marginal means of each model across its settings were compared to the LSD minimum mean difference (LSD_{mmd}) of the interaction effect and the main effects.

Coefficient of variation (CV; standard deviation/mean) was used to evaluate the variability within and between devices and settings. The lower the CV, the lesser the variability and, thus, the greater the stability. We obtained CV between three exhalations at each setting for five devices of a particular EMST model, which were further merged to obtain within-device stability. To evaluate the stability of a particular EMST model, CVs obtained for each of the five devices across settings were merged to obtain a single representative value. A two-way mixed model intraclass coefficient correlation (ICC) was used to measure the intra- and interrater reliability between two sessions of data extraction.

Results

Reliability of Data Extraction

A two-way mixed-model ICC revealed a high level of intrarater (.95) and interrater (.87) reliability between two sessions of data extractions.

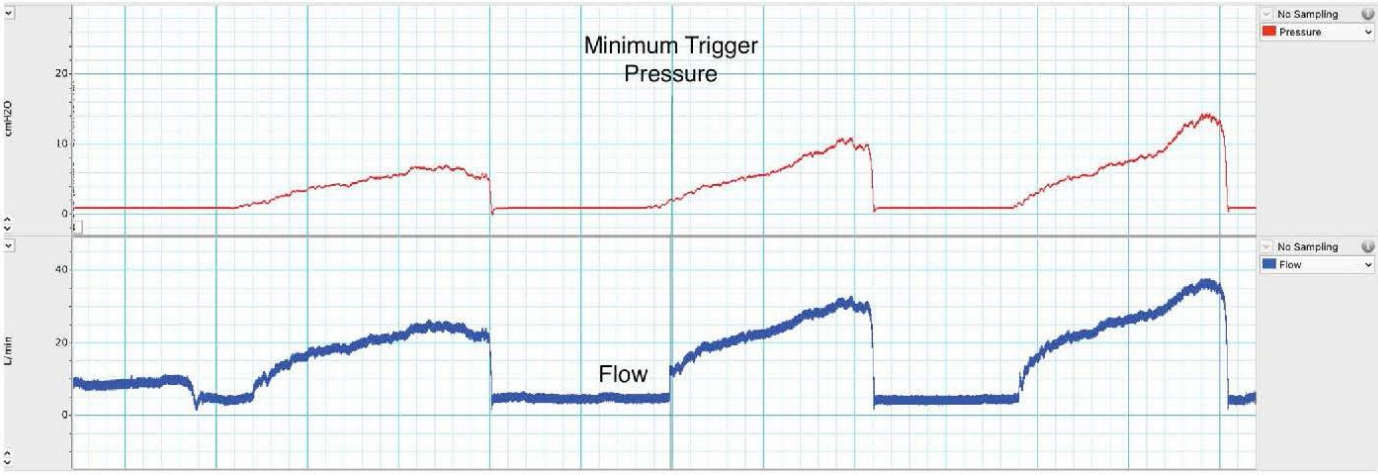

Figure 4. Procedure for extracting minimum trigger pressure.

Minimum Trigger Pressure Across Models and Settings

A mixed group factorial ANOVA with follow-up analyses using the LSD procedure was performed to examine the effects of the model and setting on minimum trigger pressure. Table 1 shows the means and standard deviations for minimum trigger pressure across each model and setting. As hypothesized, a significant interaction was observed for model and setting, $F(6, 552) = 13.765$, $p < .01$, MSe = 1.874, as they relate to minimum trigger pressure. Further analysis of LSD follow-ups using cell mean ($LSD_{mmd} = 0.89$) revealed that each model and setting yielded distinct trigger pressures compared to other model/setting combinations.

This ANOVA also yielded a significant main effect for model, $F(4, 552) = 104.648$, $p < .01$. However, contrary to the main effect hypothesis, only EMST150, EMST75, ThresholdPEP, and Acapella DM models had trigger pressures that were distinct from each other, whereas TheraPEP and Breather 2 ($LSD_{mmd} = 1.2$) had similar trigger pressures to each other. The EMST150 model offered the highest resistance (129.42 cmH_2O), whereas ThresholdPEP, Acapella DM, TheraPEP, and Breather 2 models had the lowest trigger pressure in the range of 0.85–0.98 cmH_2O.

There was also a main effect of setting, $F(21, 552) = 3976.6$, $p < .01$. As hypothesized, the pattern of this effect was that the minimum trigger pressures increased from the lowest tested setting through the highest setting across all EMST models ($LSD_{mmd} = 1.2$), that is, lower settings had lower minimum trigger pressure and higher settings had higher minimum trigger pressures.

Variability Within Device Across Settings

Figures 5–10 show the merged CVs of five devices across three exhalations at each available setting. A common trend across all six EMST models was that the trigger pressures were less variable and, thus, more stable at lower settings. In contrast, greater variability was observed in higher settings.

Variability Across Devices of the Same Model

We tested five devices of each of the six EMST models, and CVs of the devices at various settings were merged to evaluate across-device variability. Table 2 shows the ranked order of least to most stable EMST model, created based on merged CVs of five devices across setting of the same model.

Discussion

The theoretical rationale that supports the use of EMST for remediating voice, cough, and swallowing deficits is based on two foundational facts. First, the abdominal and internal intercostal muscles, which are the primary target of EMST regime,

Table 1. Minimum trigger pressure (cmH_2O) represented as mean and standard deviation across model and settings.

Model	**Lowest setting**	**Minimum trigger pressure across setting**			**Highest setting**	
TheraPEP (Smith Medicals)	1	2	3	4	5	6
	0.96 (0.29)	2.1 (0.53)	3.36 (0.55)	4.12 (0.45)	5.31 (0.61)	6.47 (0.58)
The Breather 2 (P N Medical)	1	2	3	4	5	
	1.19 (0.63)	1.42 (0.59)	3.43 (0.57)	4.34 (0.44)	5.56 (0.41)	
Threshold PEP (Philips Respironics)	5	8	11	14	17	20
	1.96 (0.34)	3.27 (0.31)	4.04 (0.49)	6.11 (0.51)	7.23 (0.67)	9.25 (0.63)
EMST150 (Aspire products)	30	60	90	120	150	
	28.03 (1.38)	50.58 (2.81)	90.97 (2.43)	113.6 (3.15)	129.42 (4.91)	
Acapella DM (Smith Medicals)	1	5	9	13	17	21
	1.61 (0.66)	4.76 (0.76)	7.13 (0.88)	12.15 (0.94)	15.47 (1.12)	15.8 (1.14)
EMST75 (Aspire Products)	5	15	35	55	75	
	4.79 (0.48)	15.01 (0.6)	24.16 (1.43)	52.77 (4.01)	69.62 (1.34)	

Note. Bolded numbers represent the setting at which those measures were obtained for the respective device. PEP = positive expiratory pressure; EMST = expiratory muscle strength training.

are histologically skeletal muscles and share several structural and metabolic properties of limb musculature (Sapienza & Wheeler, 2006) and, thus, their response to strength training would be similar to that of limb muscles. Second, evidence indicates that, during EMST regimens, there is synergistic activation of upper aerodigestive tract in addition to respiratory musculature. Several experimental studies have exploited these facts and report beneficial functional changes in voice, cough, and swallowing functions associated with EMST (Eom et al., 2017; Hutcheson et al., 2018; Patchett et al., 2017; Plowman et al., 2019; Reyes et al., 2020; Templeman & Roberts, 2020; Troche et al., 2010; Wheeler-Hegland et al., 2008). For example, therapeutic changes to the phonatory function following EMST regime are attributed to improvements in airflow, and increased subglottic pressure, which purports to have a direct effect on overall sound pressure level (perceived vocal loudness; Reyes et al., 2020). Functional improvements in cough function are attributed to improvements in the ability to generate and maintain expiratory force (pressure) following an EMST regime, and improvements in swallowing function are attributed to increased movement of the hyolaryngeal complex and increased opening of the upper esophageal sphincter (Troche et al., 2010; Wheeler-Hegland et al., 2008).

Although most research studies on EMST have utilized a specific protocol and EMST model (Mancopes et al., 2020), several different commercially available PEP devices are being used in clinical practice to deliver EMST for treating voice, cough, and swallowing deficits. It is important to note that these commercially available PEP devices differ in the way they generate resistance (Demchuk & Chatburn, 2021; de Menezes et al., 2018; McConnell, 2013; Sapienza, 2008), which is a crucial factor to consider when selecting an appropriate EMST device for clinical use. However, there are limitations to the data that are available for each EMST device on the market. Manufacturers may only provide data in ideal lab conditions, rather than in actual clinical use. For instance, in a laboratory setting, researchers have more control over the environment and can manipulate variables ranging from temperature and humidity to the stability and duration of airflow to create controlled conditions for testing. In contrast, clinical conditions are often less controlled and can vary widely depending on the health care facility, patient population, and real-world factors. Thus, it is important to consider these tangible differences when interpreting results and translating them into real-world clinical practice. Additionally, published data are

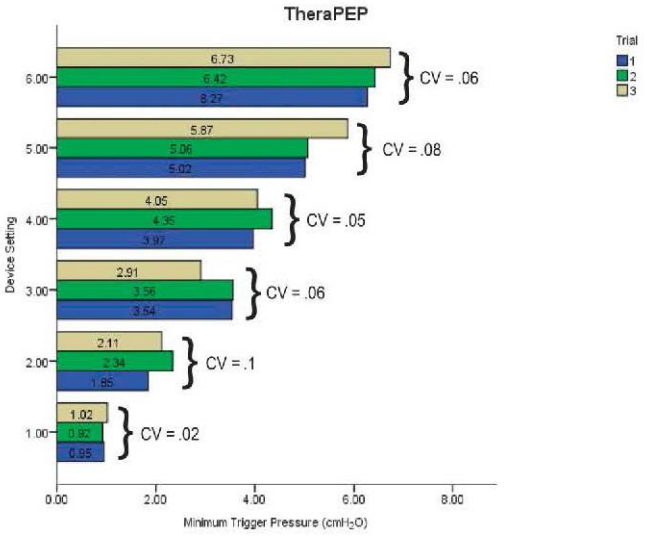

Figure 5. Variability of TheraPEP across settings. CV = coefficient of variation.

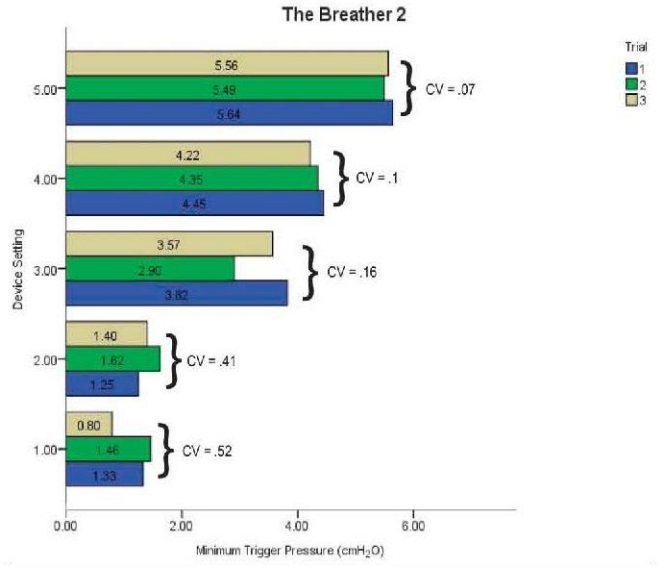

Figure 6. Variability of Breather 2 across settings. CV = coefficient of variation.

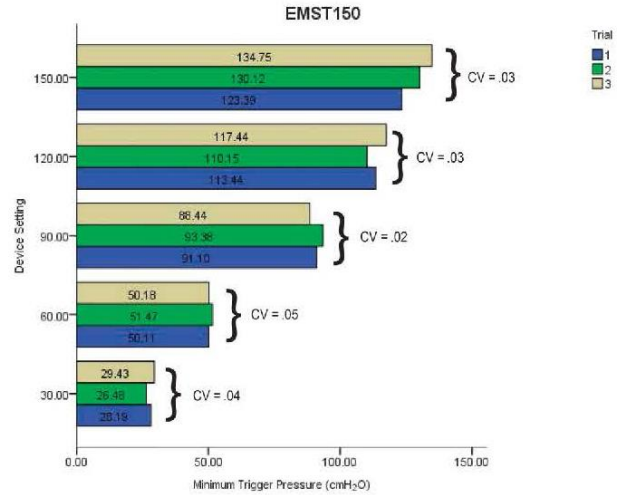

Figure 7. Variability of EMST150 across settings. EMST = expiratory muscle strength training; CV = coefficient of variation.

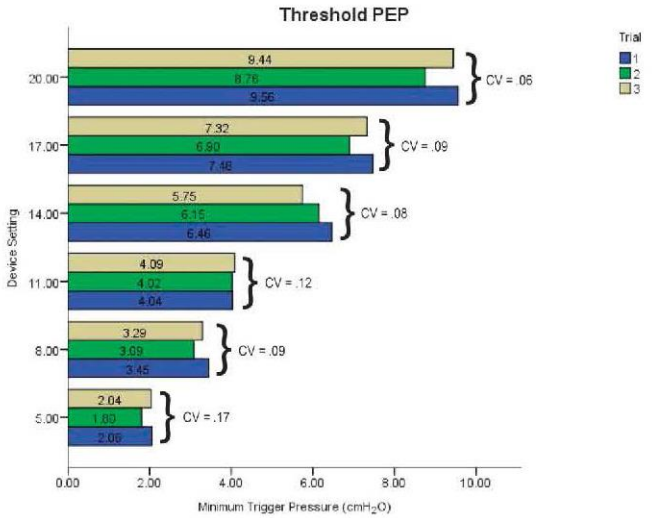

Figure 8. Variability of Threshold PEP across settings. PEP = positive expiratory pressure; CV = coefficient of variation.

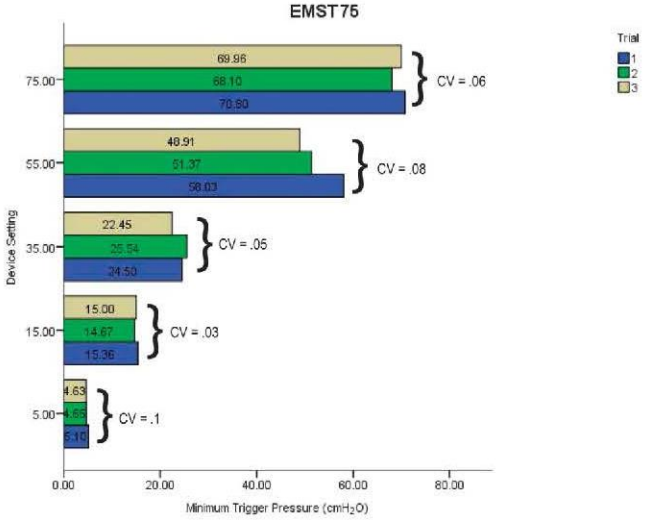

Figure 10. Variability of EMST75 Lite across settings. EMST = expiratory muscle strength training; CV = coefficient of variation.

only available for a few devices, and the variety of testing procedures and reported measures across different sources and devices can make it difficult to make side-by-side comparisons between devices. The current study aimed to address this research-to-practice gap by testing and comparing the outcomes of six currently available EMST models based on pressure and flow at a multitude of settings.

The first objective of the study was to measure the minimum trigger pressure for six commercially available EMST models using a custom testing setup consisting of pressure and flow meters. We operationally defined minimum trigger pressure as the lowest pressure (in cmH_2O) required to initiate flow at a particular setting of the EMST device. This measure is clinically important, because it reflects the level of resistance that an individual must overcome to initiate airflow. Clinicians may use the benchmark data presented in Table 1 as a reference guide for the selection of EMST models based on trigger pressures. When we tested six EMST models for their minimum trigger pressure across settings, we observed a significant interaction effect between model and setting on minimum trigger pressure. As hypothesized, the trigger pressure for each model was distinct across settings. This interaction suggests that the relative performance of different models in terms of minimum trigger pressure varies depending on the setting in which they are used.

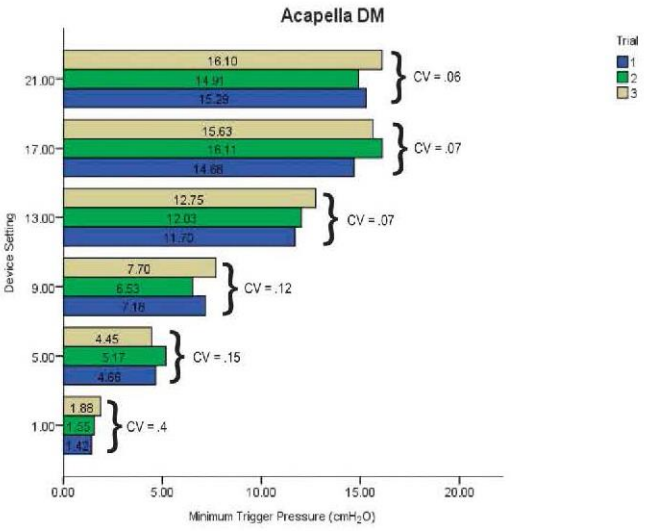

Figure 9. Variability of Acapella across settings. CV = coefficient of variation.

We also observed a significant main effect of model, which suggests that different models do not overlap in the minimum trigger pressures required to initiate airflow. However, this pattern was true only for EMST150, EMST75, ThresholdPEP, and Acapella DM models, which had significantly different ranges of minimum trigger pressures from each other. In contrast, TheraPEP and Breather 2 models had similar trigger pressures to each other, and these pressures were different from the other four models. Similar performances of TheraPEP and the Breather 2 models may be attributed to the functioning principle of these devices. Both TheraPEP and the Breather 2 are essentially flow resistor–type PEP devices and may have similar mechanistic performance (Demchuk & Chatburn, 2021). Furthermore, since these two models accommodate a similar range of trigger pressures across settings, it may be possible that they can be interchanged during testing and training. In the current study, we did not account for the effects of type of PEP device (flow resistor, threshold resistor, or oscillatory) on

Table 2. Stability of aero-resistive expiratory muscle strength rehabilitation devices.

Least stable		◄——►		Most stable	
The Breather 2 (CV = 0.31)	Acapella DM (CV = 0.2)	Threshold PEP (CV = 0.18)	EMST150 (CV = 0.09)	EMST75 (CV = 0.07)	TheraPEP (CV = 0.07)

Note. CV = coefficient of variation; PEP = positive expiratory pressure; EMST = expiratory muscle strength training.

performance; prospective studies should take this factor into account. Clinicians should be cautious while using flow resistor–type EMST models, as they vary the level of resistance depending on the flow rates produced by the patient. These models often require calibrations to account for variations in expiratory flow rates, which involve setting a baseline or reference resistance level at a specific flow rate. For instance, the generated pressure is "controlled" by the patient's expiratory flow and may be monitored by a simple pressure gauge (Demchuk & Chatburn, 2021). In the current study, we did not control for expiratory flow rates, which is representative of clinical practice, and we acknowledge this limitation. Data related to flow rates were collected during the device testing and are being analyzed for future dissemination. This information could potentially inform us about impact of each of these device types.

Of the models tested here, the EMST150 offered the highest resistance; its trigger pressure at the lowest setting was more than 24 cmH_2O—approximately two to four times greater than the highest tested pressure of any other model. From a practical perspective, this means that some patients may be unable to utilize even the lowest setting of the EMST150. For example, individuals whose dysarthria includes compromise of the respiratory subsystem may be unable to generate even 5 cmH2O of water for 5 s, leaving a 20-cmH2O gap before the EMST150 is a viable tool for them. Many persons with dysarthria affecting the respiratory or other speech subsystems will never be able to utilize this model's higher settings. The five other models, including a "lite" version of the EMST150 (EMST75), accommodated relatively low expiratory pressure levels and may be a more suitable option for targeting expiratory muscle strengthening in clients with significant deconditioning or respiratory compromise.

Statistically, we also observed a significant main effect of setting for all EMST models, which suggested that different trigger pressures were required at the different resistance settings of each EMST model. As expected, trigger pressures increased from the lowest tested setting through the highest setting across all EMST models, so clinicians can feel confident that no matter which device is selected for their client, a higher setting does indeed require the user to generate a higher level of expiratory pressure.

The second objective of the study was to investigate the variability within each EMST model and between two devices of the same model across settings using CV. EMST devices must provide consistent and reliable levels of pressure (resistance) to ensure consistent and effective clinical use. From a motor learning perspective, the reliability of a device is an important factor in determining the effectiveness of therapy, as it involves the process of acquiring and refining new motor skills through repeated practice and feedback. In the context of EMST regimes, patients must learn to maintain a consistent breathing pattern and generate sufficient expiratory flow to achieve the intended target performance. Similar to studies on general motor skill learning, and speech motor learning, if the EMST device's performance is unreliable, it can create inconsistencies in the feedback that patients receive during therapy, which can impede their motor learning and hinder their ability to develop and refine the necessary motor skills (Parrell & Houde, 2019; Wolpert et al., 1995, 2001). For example, if the device's pressure output is inconsistent, it can make it difficult for patients to maintain a consistent breathing pattern and generate the appropriate expiratory flow during therapy, making it harder for them to learn (or relearn) the target motor skill.

In the current study, we observed that the trigger pressures were more reliable and stable at lower settings. However, greater variability was observed at higher settings. This trend was common across all devices. Of the models assessed, the Breather 2 was least stable and TheraPEP was most stable. Choosing a device with a more stable performance profile may help ensure more consistent therapy for patients and improve their ability to achieve optimal clinical outcomes. Furthermore, reliable and consistent performance of the EMST model can provide patients with a more stable and predictable learning environment, which can help them focus on developing and refining their motor skills without worrying about unexpected changes in the target performance (behavior). This can help improve patient confidence and motivation, which are essential factors in promoting successful motor learning and achieving optimal clinical outcomes (Magill & Anderson, 2016; Schmidt et al., 2019; Wolpert et al., 2001).

In addition to the results of these analyses, the testers reported qualitative observations associated with device trials. For all six

EMST models, there was some degree of perceived percussion that began once expiratory pressure was adequate to trigger airflow through the device during minimum to maximum breathing. This was anticipated only for the Acapella model that contains a flutter valve. Furthermore, certain models exhibited occasional inconsistencies that may not be obvious in the reported summary statistics. For example, the Breather 2 had limited resistance at the lower settings, which led our healthy testers to rapidly exhaust their available expiratory volume, so the duration of sustained airflow was quite short and thus would have little exercise benefit. Clinically, this effect could be avoided by selecting a device and setting that better matched the client's maximum expiratory force, such that each trial would have an appropriate therapeutic "load." Supervision and feedback from an experienced clinician during initial practice with the prescribed EMST model, plus thorough client education and regular adjustments to settings as the client's strength and endurance change, would further ameliorate these issues.

Conclusion and Future Directions

Systematic testing of six commercially available EMST models yielded technical benchmarks and reliability data to aid clinicians in selecting an appropriate therapy device for a client based on their available airflow and air pressure and the device's reliability. In addition, these findings allow clinicians to compare key parameters across EMST models. Overall, EMST models performed differently in regard to the different resistance settings. For all models, higher pressure was required for flow initiation at the highest setting as compared to the lowest setting. However, reliability within a model and between devices of the same model across settings varied and produced unexpected trends for all six EMST models tested in the current study.

Future studies should consider expanding the current study's findings by testing additional EMST models as they become available. The instrumentation used in the current study utilized precise measurement tools (sensors); however, we believe that a servo-controlled, aero-resistive device could be developed to more accurately regulate and set individualized EMST training parameters based on a patient's chest wall capacity. A servo-mechanism is a feedback control system that continuously monitors and adjusts the output characteristics of a device to maintain a desired state or achieve a specific outcome. Costs associated with servo-controlled pressure regulators have dropped dramatically in recent years with miniaturization of semiconductor technology and embedded controllers (Greenwood & Barlow, 2020). By employing servo-controlled instrumentation that automatically adjusts and regulates certain variables (e.g., air pressure, derived airway resistance), it becomes possible in real time to precisely control, manipulate, and evaluate the parameters of an EMST device that can be sterilized and used repeatedly. Moreover, a servo-controlled EMST device (sc-EMST) could allow for precise biofeedback of chest wall performance during assessment and capture therapeutic change over repeated sc-EMST sessions. This level of control would allow clinical researchers to utilize physiological data to tailor an individualized sc-EMST experience to meet the specific needs and abilities of patients. Another advantage of a programmable sc-EMST device is adaptability across patients, thereby eliminating the need for clinics to purchase/stock several different types of plastic, variable, and disposable EMST devices.

The cost of EMST devices is an additional factor that influences clinical implementation. Prices for the disposable EMST devices tested in this study ranged from approximately $24 to $240 USD and typically are not covered by insurance in the United States. Performance of additional cost-effective models should be evaluated in future studies. Such efforts will capitalize on clinician–researcher partnerships by developing research questions and outcomes that directly relate to clinical practice. Here, our findings are reported in measures that align with readily available clinical assessment tools such as water manometry and can immediately inform the selection of EMST devices for individual clients who may benefit from them as part of a comprehensive program of voice, respiratory, and/or swallowing rehabilitation.

International Review Board/Ethics Statement

This work does not involve human nor animal participants and, therefore, does not require review by an institutional review board.

Data Availability Statement

The data sets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Disclosure

The authors have declared that no competing financial or nonfinancial interests existed at the time of publication.

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