The Application of Exercise Physiology on Flute Pedagogy:

Optimizing Deliberate Embouchure Muscle Training

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Abstract

This thesis examined the activation of perioral muscles during flute playing in order to elucidate embouchure muscle recruitment and, in turn, enable the application of exercise physiology training principles on flute practice, thereby potentially improving muscle development and skill acquisition during flute mastering. Surface electromyographic (sEMG) data of 3 muscles (orbicularis oris superior – OOS, depressor anguli oris – DAO, and zygomaticus major – ZYG) were collected bilaterally from 14 players with an extensive background on the instrument ($\bar{x} = 14 \pm 6.7$ years), both male ($n = 4$) and female ($n = 10$), aged 18-50 ($\bar{x} = 26 \pm 10$). Participants played a) a chromatic scale, b) Marcel Moyse's widespread tone exercise, and c) the first movement of the Bach sonata for flute in C major. Three assessments were derived from these excerpts, identifying: the correlation between pitch and muscle activation, the fatiguing effect of the tone exercise, and the distinction in muscles' behavior while playing the piece versus the exercise. Results showed: a significant change ($p \leq 0.001$) in the activation of all the muscles as pitch moved toward the high register, evidencing a positive linear correlation between both variables (Pearson's $r > 0.85$); a fatigued state induced by the tone exercise ($p \leq 0.01$); and superior intensity and variability in the muscle activation recorded during the repertoire piece, although these last results were not significant according to the post hoc analysis (Bonferroni correction). These results, in conjunction with the physiological characteristics of facial muscles, suggest that flute practice aiming to develop the embouchure should: center on interval training rather than a continuous one; aim for a strength- or endurance-oriented training, depending on the intensity level of the musical excerpt; and prioritize the practice of repertoire pieces over exercises.

Résumé

Cette thèse, sur l'activation des muscles péribuccaux durant le jeu de la flûte, vise à comprendre leur participation dans la formation de l’embouchure du flûtiste en vue d’appliquer certains principes d’entraînement de la physiologie de l'exercice à la pratique de la flûte et, ainsi, potentiellement améliorer le développement musculaire et l’acquisition de compétences menant à la maîtrise de l’instrument. Les données électromyographiques de surface (sEMG) de 3 muscles péribuccaux (orbicularis oris superior - OOS, depressor anguli oris - DAO et zygomaticus major - ZYG) ont été mesurées bilatéralement auprès de 14 flûtistes, des hommes (n = 4) et des femmes (n = 10), possédant une vaste expérience instrumentale ($\bar{x}$ = 14 ± 6,7 ans) et étant âgés de 18 à 50 ans ($\bar{x}$ = 26 ± 10). Les participants ont joué a) une gamme chromatique, b) un exercice de sonorité de Marcel Moyse, et c) le premier mouvement de la sonate de Bach pour flûte en do majeur. Les mesures ont permis d’établir : la corrélation entre les notes jouées et l'activation musculaire, la fatigue engendrée par l'exercice de sonorité, et la distinction entre les patrons musculaires utilisés durant le morceau et l’exercice. Les résultats démontrent: un changement significatif ($p \leq 0{,}001$) d'activation des muscles péribuccaux durant les notes du registre aigu, faisant ressortir une corrélation linéaire positive entre les deux variables (coefficient de Pearson, $r > 0{,}85$); un état de fatigue induit par l'exercice ($p \leq 0{,}01$); et une activation musculaire d’une intensité et variabilité supérieures durant la sonate, bien que ces derniers résultats ne soient pas significatifs selon l'analyse post hoc (correction de Bonferroni). Ces résultats, combinés aux caractéristiques physiologiques des muscles faciaux, suggèrent que les stratégies de pratique visant à développer l'embouchure devraient : prioriser l’entraînement intermittent plutôt que continu; opter pour un entraînement axé sur la force ou l'endurance selon le niveau d'intensité de l'extrait musical; et donner la priorité aux pièces de répertoire plutôt qu’aux exercices.

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To God, who created so many interesting things for us to research; to you, Lord, be all the honor and glory. To my loving wife, who patiently and repeatedly listened to my ideas, complaints, and accomplishments. Thank you, Ketty, for selflessly and sacrificially giving me the support I needed to pursue my dreams. And to you, my son, for whom I am incredibly thankful. You brighten up my days, Benji.

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Introduction

Background and Rationale

Every musician is well aware of the importance of practicing their instrument when it comes to attaining a proficient technique, as this need has been extensively discussed in the literature (Barry, & McArthur, 1994; Lehmann, & Ericsson, 1997). Both quality and quantity of practice have been investigated (Williamon, & Valentine, 2000), yet the factors influencing technique advancement have not been completely unveiled (Williamon, 2004). As a result, many instrumentalists seem to maintain rigorous practice regimes without significantly improving their playing skills. Unaware that their very practice may actually hinder progress and cause injuries (Allsop, & Ackland, 2010), musicians commonly neglect physiological limitations in their training (Martin, Kenny, & Cormack, 2009).

One aspect apparently missing from the research mentioned above is the understanding of how muscular systems respond and adapt to musical exercises during practice, and, more importantly, how one can use these exercises in an optimized manner to increase practice efficiency. What partly explains this lack of information is an existing gap between the areas of exercise physiology and instrument pedagogy (Saxon, & Schneider, 1995). Indeed, studies connecting both fields are scarce, and teachers are reluctant to abandon tradition and incorporate changes in their methods (Wulf & Mornell, 2008). For these reasons, the present study draws on the body of knowledge in athletic training to devise a new approach for flute practice.

Objectives

Applying exercise physiology training principles on instrument practice not only optimizes the learning process, but also confers predictability to it (Özgen, 2006). To do so, however, it is first necessary to measure how the musculature is affected by what is being played. Therefore, the following research question guided this study: how does embouchure muscle activation of flute players vary with (a) pitch, (b) a basic tone exercise, and (c) a piece of the repertoire?

The main objectives were: (1) to determine the relationship between pitch and muscle activation in all registers of the flute, (2) to verify if Moyse's tone exercise has a fatiguing effect on the musculature, and (3) to compare muscle recruitment during repertoire playing and exercise playing. Measuring tone quality was beyond the scope of this study even though the muscle exertion generated during the execution of an exercise to improve tone was assessed.

The examination of the activation of perioral muscles during flute playing is expected to elucidate embouchure muscle recruitment and, in turn, enable the application of exercise physiology training principles on flute practice, thereby potentially improving muscle development and skill acquisition during flute mastering.

This thesis is divided into six chapters. Chapter 1 presents the particularities of the muscle tissue, including classification, composition, and mechanics of different types of muscle, followed by the definition and muscular formation of flute embouchure. Chapter 2 covers the basic concepts and training principles from the area of exercise physiology, and Chapter 3, a review of the literature related to their application in musical contexts. Chapter 4 describes the methods used in this study, and Chapter 5 presents the results obtained. After a discussion on the findings, in Chapter 6, a conclusion is proposed along with some final recommendations.

Chapter 1 – The Muscle Tissue

Muscle histology investigates the functions, composition, and limitations of muscle tissue, an understanding of which is essential to indicate the optimal use of the muscles, thus helping with the prescription of exercises in physical training. This chapter will briefly discuss the classification, structure and mechanics of human muscles, while concomitantly observing the implications specifically related to flute practice.

Classification

The human muscular system can be organized into three categories—skeletal, smooth, and cardiac—depending on the muscle's primary function and location. As a result of their specialization, these muscle types present distinct structural organizations of fibers, as depicted in Figure 1.

Skeletal muscles are mainly used for movement. They are responsible for maintaining posture, contributing to blood circulation, generating heat, acting as energy transducers[1], and protecting internal organs (Plowman & Smith, 2011). Also known as voluntary muscles, they are prompted by our will and controlled by the somatic nervous system (SNS), which transfers nerve impulses from the central nervous system (CNS), namely the primary motor cortex, to the muscles (Porcari, Bryant, & Comana, 2015). More details on how these nerve impulses generate muscle contractions are given in the section Muscle Mechanics.

Cardiac muscles, as the name suggests, control the pumping of the heart with non-stop, rhythmic contractions, which occur from early embryonic stages until death. They feature a fiber

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[1] Skeletal muscles convert biochemical energy to thermal and mechanic energy.

composition similar to that of skeletal muscles, yet are involuntary like smooth muscles because they are activated by the autonomic nervous system (ANS) (Gould, 1973).

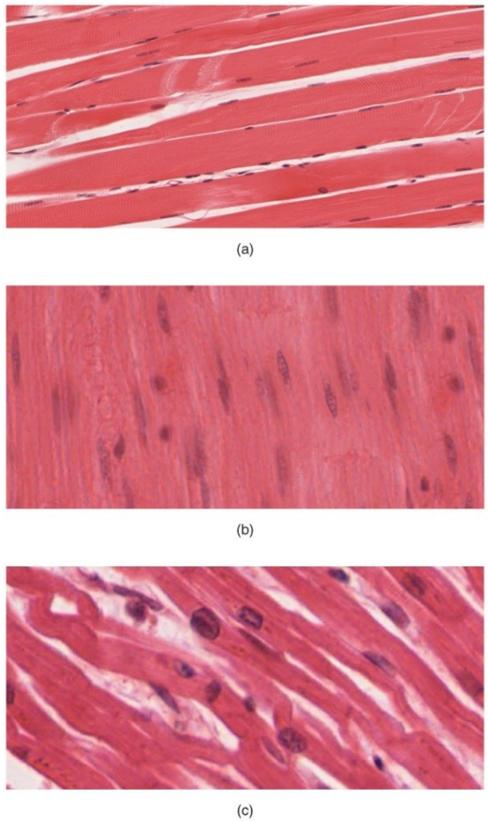

Figure 1. Types of muscle in the human body. Micrographs of the three types of muscle tissue: a) skeletal muscle; b) smooth muscle; c) cardiac muscle. Copyright © 2012 by University of Michigan Medical School.

While skeletal and cardiac muscles contribute to adjust the organism to the environment, smooth muscles are responsible for maintaining the internal balance of the body (Gould, 1973). Also involuntary, smooth muscles are present in most organs, accounting for vital processes such as blood circulation in the cardiovascular system, and food transportation in the digestive system.

The autonomic nervous system, which controls cardiac and smooth muslces, is a collection of nerves and nerve cells (ganglia) that regulate bodily functions (Gabella, 1976), mainly aiming for the maintenance of homeostasis[2] (physiological balance) (Cardinali, 2018). Together with the SNS, the ANS is part of the peripheral nervous system (PNS), which encompasses all nervous structures located outside of the CNS (Porcari et al., 2015). The ANS subdivides into two major categories of opposing functions: the sympathetic and the parasympathetic nervous systems. The sympathetic system tends to stimulate the activation of organs, e.g., heart rate and blood pressure increase, whereas the parasympathetic system does the contrary, inhibiting the activity.

Because this thesis concentrates on the development of muscles in the mouth region, more attention will be given to skeletal muscles for their ability to control movement, particularly of bones and soft tissue, such as the lips and the skin in the face.

Muscle Structure

As it will be shown in this section, many characteristics related to muscle performance largely depend on the structure of the muscle. While the macroscopic elements of skeletal muscles inform on the dynamics of movement, the microscopic components reveal the processes behind muscle contraction.

Skeletal muscles are organized with three layers of connective tissue: the endomysium, the perimysium, and the epimysium, as seen in Figure 2. The endomysium surrounds individual muscle fibers, also called cells. These wrapped muscle fibers are then grouped in bigger structures named fasciculi (plural form of fascicle), which are separated from one another by the perimysium. The epimysium surrounds all the fasciculi and is covered by a thicker connective tissue named fascia. At the extremity of the muscle, all these connective tissues are merged to form the tendons. The tendons link the muscle to solid structures (e.g., calcified and uncalcified fibrocartilages

[2] Various physiological factors that maintain the equilibrium state of the body (Cardinali, 2018), e.g., metabolic rate and body temperature.

(Benjamin, Toumi, Ralphs, Bydder, Best, & Milz, 2006)), which, in turn, attach to the bones (Plowman & Smith, 2011).

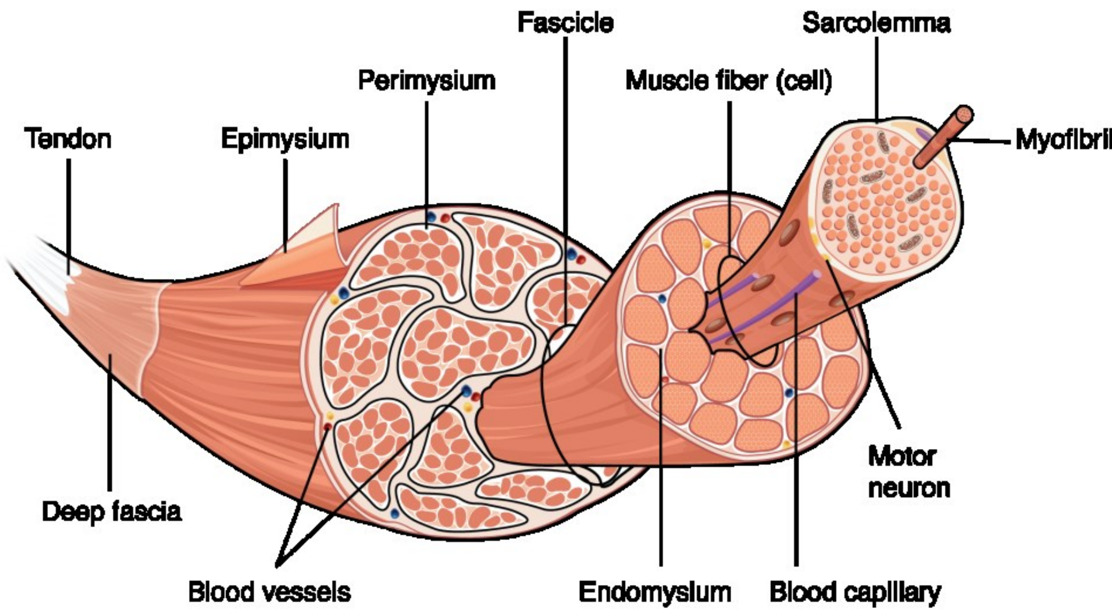

Figure 2. Muscle structure representation. Multiple cells (muscle fibers) are individually separated by the endomysium and grouped in a fascicle. Each fascicle is surrounded by the perimysium. The fasciculi (plural of fascicle) are held together by the epimysium, which is finally covered by a thicker layer called fascia. Adapted from "Muscle Tissue," n.d., In Biga et al. (Ed.), *Anatomy & Physiology*. Copyright © 2018 by Open Oregon State.

Muscle morphology. Much of our capability to control a movement and generate force depends on the structure of the muscle we activate; for this reason it is necessary to examine the architecture of the muscles involved in flute playing, as their structure directly influences performance. Indeed, muscles in the human body present different shapes as a result of how their fasciculi are arranged, and these shapes affect the range of motion, the force, and the power of each muscle. The following are different classifications according to muscle shape: circular, bipennate, unipennate, radiate (convergent), fusiform, longitudinal (parallel) (Plowman & Smith, 2011), and multipennate. These shapes are represented in Figure 3. While fusiform muscles present fibers arranged parallel to the long axis of the muscle, pennate muscles contain fibers at an oblique angle that varies up to 30º. This angle between the fasciculi and the tendon (pennation angle) increases the muscle's sectional area, allowing it to generate more force and power despite its short fibers (McArdle, Katch & Katch, 2010). This is represented in Figure 4. The morphology (study of form) of muscles active during flute playing, specifically, is addressed in Chapter 2.

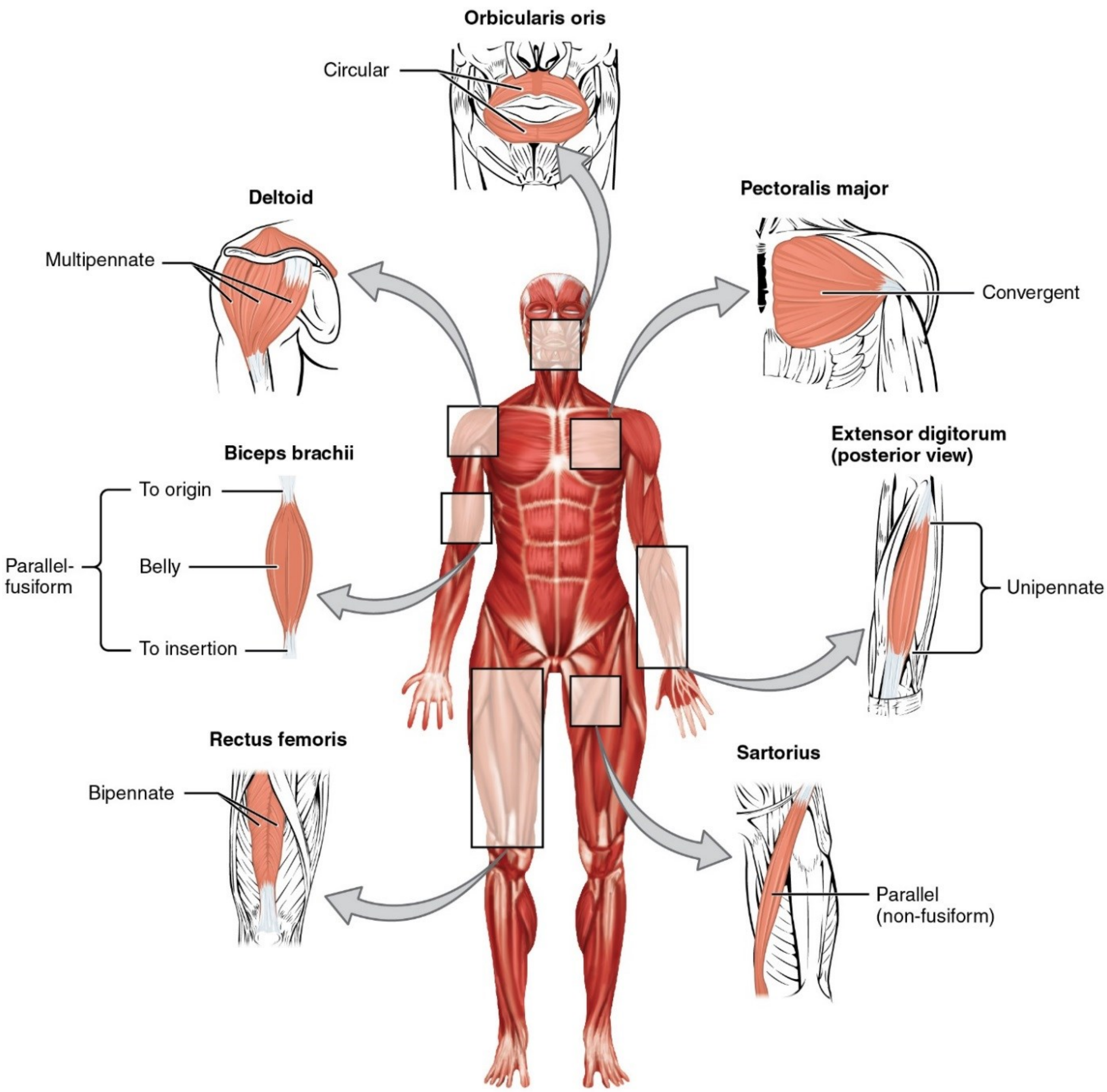

Figure 3. Morphology of skeletal muscles. Seven commonly found structural organizations of skeletal muscle fibers: a) circular, b) convergent, c) unipennate, d) parallel or longitudinal, e) bipennate, f) fusiform, and g) multipennate. Copyright © 1999-2018 by Rice University.

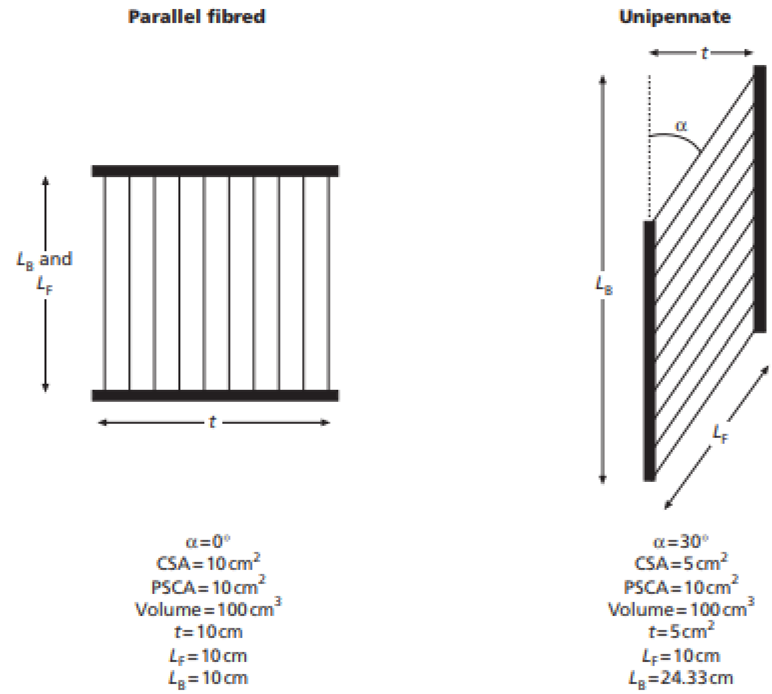

Figure 4. Pennation angle. The angle between muscle fibers and the tendon (α) increases the physiological cross-sectional area (PCSA), measured in a plane perpendicular to the line of action of the fibers. Thus, the muscle is capable of generating more force in spite of its reduced cross-sectional area (CSA). *t* represents the distance from the tendon to the outer portion of the muscle belly; L_F and L_B indicate the length of the limb and the length of the muscle fiber, respectively. Adapted from "Muscle-Tendon Architecture and Athletic Performance," by J. H. Challis, 2008, p. 45 In V. M. Zatsiorsky (Ed.), *Biomechanics in Sport: Performance Enhancement and Injury Prevention,* p. 33-55. Copyright © 2000 International Olypmic Comittee. Used with permission.

Muscle fibers. Unlike the structure described above, the components of the muscle fiber are not visible to the naked eye. This microscopic structure is wrapped by a polarized membrane called sarcolemma and contains specialized organelles that account for the muscle contraction: the sarcoplasmic reticulum (SR), the transverse tubules (T tubules), and the myofibrils, as depicted in Figure 5. Each myofibril is composed of myofilaments (actin, which is thin; and myosin, which is thick) arranged in a repeating pattern (sarcomere) along the length of the muscle. Because of the alternating bands of light and dark striations in the myofibrils, skeletal muscles are often referred to as striated muscles, although striations are also present in cardiac muscles.

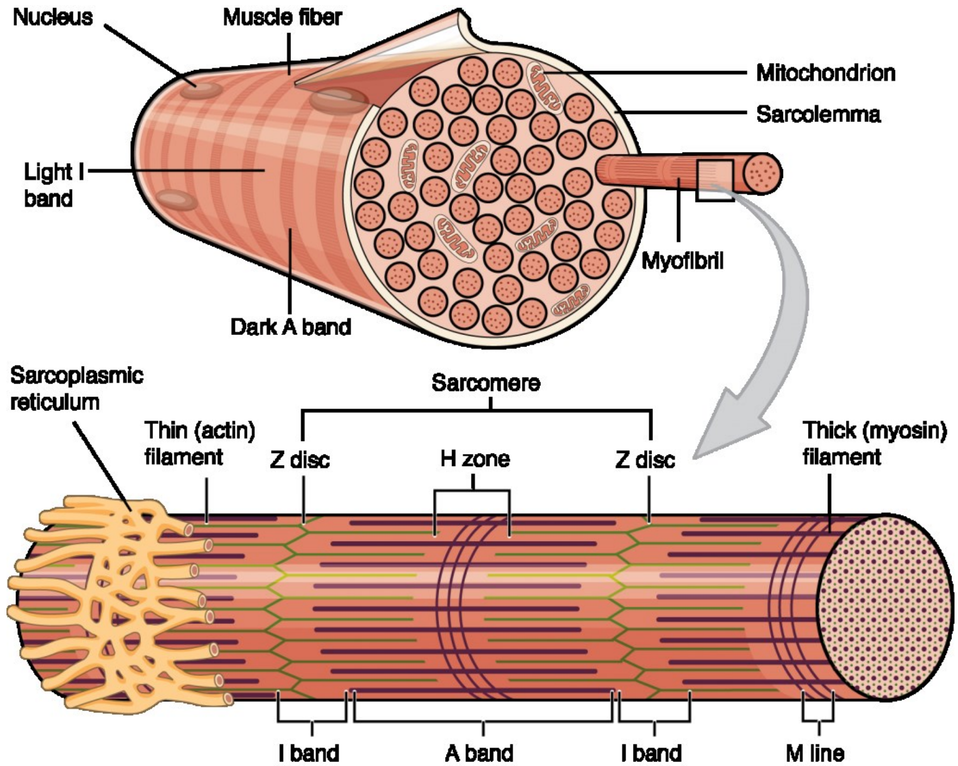

Figure 5. Muscle fiber organelles and myofilaments. Adapted from "Muscle Tissue," n.d., In Biga et al. (Ed.), *Anatomy & Physiology*. Copyright © 2018 by Open Oregon State.

Two types of muscle fiber exist in the human body: type I and type II. They differ mainly in terms of their contractile velocity and, although not as clearly, metabolic properties. Type I fibers are innervated by smaller neurons and feature slower contractile velocities, which is why they are also known as slow-twitch (ST) fibers. They are recruited in tasks requiring low force output and are more resistant to fatigue. To produce energy (adenosine triphosphate – ATP), muscle fibers rely on different metabolic pathways: oxidative, also referred to as aerobic, and phosphagen (also called adenosine triphosphate-phosphocreatine – ATP-PCr) or glycolytic (also called lactic system – LA), both of which are anaerobic. Type I fibers rely more on oxidative processes, even though all muscle fibers can produce energy both aerobically and anaerobically (Plowman & Smith, 2011). Type II, or fast-twitch (FT), fibers are not only faster but stronger as well. They rely either on glycolytic (anaerobic) metabolism or a combination of glycolytic and oxidative metabolism to produce energy. With less access to energy substrate (glycogen), type II fibers show higher fatigability despite their high overload capacity.

While all muscles in the human body present a combination of type I and type II fibers[3] (Powers & Howley, 2015), they are generally comprised of 45% to 55% of type I fibers (Plowman & Smith, 2011). This distribution may vary across individuals. Plowman and Smith (2011) state that "[a]thletes in endurance activities typically have a higher percentage of [slow twitch] ST fibers, while athletes in power activities have a higher percentage of [fast twitch] FT muscle fibers" (p. 531). Even so, as the authors explain, evidence suggests that exercise training may affect the metabolism but not the composition of the muscle. In other words, it is not the activity performed by the athlete that determines the composition of the muscle; rather, it is the genetic configuration of the muscle that more likely determines the tasks which will be better performed by the athlete. In this sense, muscle fiber type composition can be associated with muscle response to training, and this relationship partly explains individual differences in performance (Plowman & Smith, 2011; Mizuno, 1991).

In the context of flute training, as in all sorts of training programs, the influence of muscle composition described above needs to be taken into account. This includes the choice of exercises to be incorporated in a practice session as well as the definition of exercise components such as intensity and number of repetitions (volume of exercise). These components must match the capability of the muscle to respond. Low-intensity activities with numerous repetitions will recruit more type I fibers, whereas high-intensity activities with few repetitions will recruit more type II fibers (Saxon, & Schneider, 1995; Porcari et al., 2015). Thus, one has to make sure that the manner

[3] Note that more advanced methods to type muscle fibers have identified seven types of human muscle fiber (from slowest to fastest): types I, IC, IIC, IIAC, IIA, IIAB, and IIB. (Scott, Stevens, & Binder-Macleod, 2001).

in which a musical excerpt is being played accords with the primary muscle group it activates, otherwise practice is not likely to yield significant results in terms of motor control development. In comparison to embouchure-oriented exercises, for example, breathing exercises may involve more prolonged (or more repetitions) yet less intense tasks, because respiratory muscles show higher proportions of ST fibers (Mizuno, 1991). Conversely, exercises involving muscles in the mouth region can be of high intensity but shorter to conform to the muscles' higher percentage of type II fibers – e.g., orbicularis oris – 71% (Stål, Eriksson, Eriksson, & Thornell 1990); depressor anguli oris – 62-73%; zygomaticus major – 75% (Happak, Burggasser, & Gruber, 1988). Muscle composition then indicates that prolonged exercises focused on the embouchure may lead to fatigue and, consequently, hinder performance. A more in-depth discussion of the definition and the anatomical formation of the embouchure will be provided in the following chapter.

The adequacy of exercises, from a physiological perspective, can be influenced by several principles of training. These are more extensively examined in Chapter 3.

Muscle Mechanics

In addition to their structure, four characteristics regulate how skeletal muscles function: irritability, contractility, extensibility, and elasticity. Irritability is the ability to receive chemical stimuli from neurotransmitters and respond with an electrical current (action potential or AP) along the muscle fiber. Once muscles are exposed to this electrical stimulus, contractility causes them to shorten their fibers and produce force. Depending on changes in muscle length, three types of muscle contraction may take place: isometric, concentric, and eccentric (Porcari et al., 2015). During isometric contractions, muscles generate tension yet without altering muscle length, i.e., there is no movement. In concentric and eccentric contractions, however, the length of the muscle is respectively shortened and elongated. If a muscle is stretched by the exertion of an external force, the extensibility determines how it is lengthened and the elasticity, its return to its original length.

Muscle contractions can be roughly seen as part of a domino effect in which the shortening of the muscle successively pulls on the connective tissues, the tendons, and finally the bone to which the muscle is attached, causing movement. This process is explicated by the sliding-filament theory of muscle contraction (Porcari et al., 2015), according to which muscles generate force through the sliding of the actin and myosin over each other. This filament overlap takes place in a series of physiological events (known as excitation-contraction coupling), starting with an electrical signal (AP) in the neuron of a motor unit[4], which is then transferred to the muscle cell through the release of neurotransmitters into the neuromuscular junction. Once the neurotransmitters reach the receptors in the sarcolemma (membrane of muscle cell), the AP travels along the muscle fiber through the T tubules. The electrical impulse causes the sarcoplasmic reticulum (SR) to release calcium (Ca^{2+}), triggering cyclic biochemical reactions in the myofibrils: the cross-bridging cycle. The steps in the excitation-contraction coupling are represented in Figure 6.

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[4] Structure consisting of a group of muscle fibers and the motor neuron by which they are innervated.

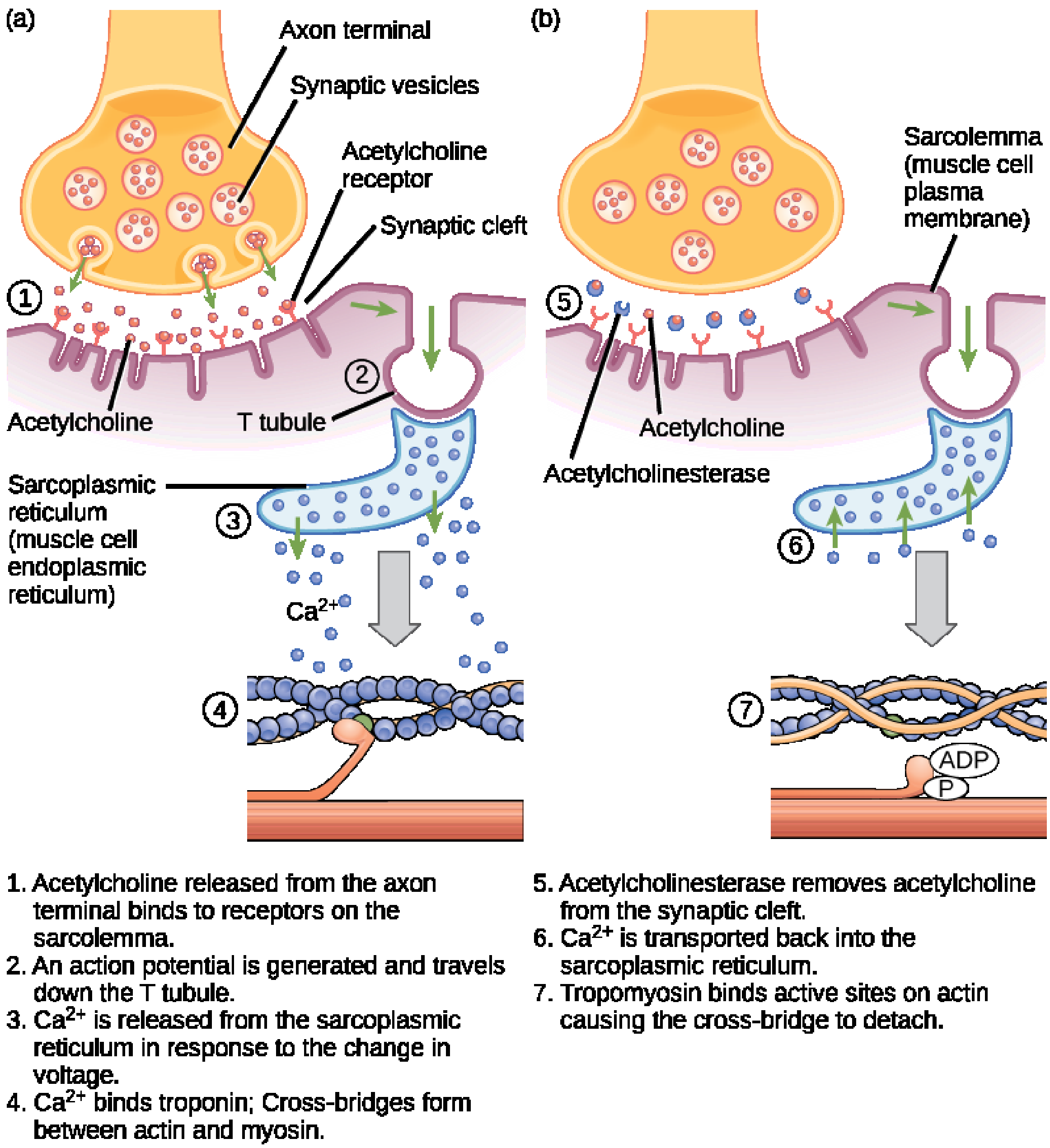

Figure 6. Excitation-contraction coupling phases. Adapted from “19.4 Muscle Contraction and Locomotion,” by C. Molnar, & J. Gair, 2012, Copyright © 2013 by Rice University.

Responsible for the displacement of the myofilaments (actin and myosin), the cross-bridging cycle is fueled by ATP (adenosine triphosphate) molecules and has ADP (adenosine diphosphate) and phosphate as end products. In this cycle, when myosin binds to actin, energy is released causing the connection between both filaments (the cross-bridges) to move. This shortens the fibers leading up to muscle contraction. In order to maintain the contraction, new cross-bridges are constantly formed, which requires another ATP molecule to attach to the myosin, breaking the existing bound to actin. The new ATP is broken down by the ATPase enzyme present in the myosin, thereby generating the necessary energy for reattachment of the myosin to another active site on the actin molecule. These cyclical events, illustrated by Figure 7, continue as long as calcium and ATP are available in the fiber.

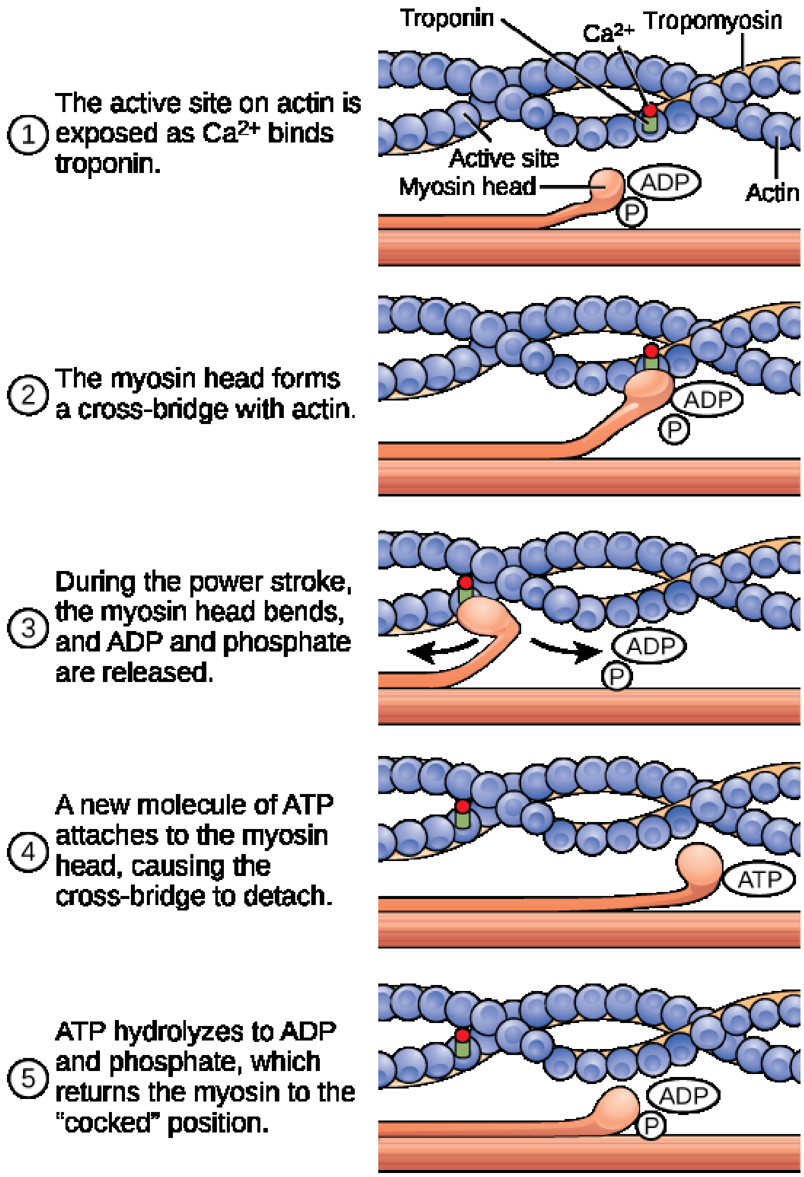

Figure 7. Cross-bridge cycle. The process, triggered by the calcium released by the sarcoplasmic reticulum, is fueled by ATP and has ADP and phosphate as end products. Adapted from "19.4 Muscle Contraction and Locomotion," by C. Molnar, & J. Gair, 2012, Copyright © 2013 by Rice University.

Muscle fatigue. Williams and Ratel (2009) identify three common points among existing definitions of muscle fatigue: 1) fatigue entails a decline in biological systems, often affecting muscle force, velocity and power; 2) fatigue is reversible with rest, which distinguishes it from injury or disease; 3) fatigue may take place before performance decrement or task failure are observed. The third point, as they explain, expands the concept of fatigue to include muscle changes (biological decline) derived from the exposure to prolonged exercise yet before exhaustion is reached: “Fatigue, as defined as a decline in the maximal force of the muscle, differentiates itself from exhaustion in that it is possible for fatigue to be observed during submaximal levels without a noticeable effect on performance” (Williams & Ratel, 2009, p. 6).

The fatiguing process may originate in different parts of the body and for different reasons. The so called central fatigue is a consequence of a disruption in the central nervous system that affects the electrical impulse reaching the muscle. In a study by Kent-Braun (1999), the contributions of central fatigue during sustained maximal effort was assessed through a comparison between the decline in voluntary force, represented by the maximal voluntary contraction (MVC), and the decline in the electrically stimulated titanic force. Results showed that central fatigue accounted for 20% of the total decrease in MVC.

When the fatigue appears at the neuromuscular junction or the motor unit, it is termed peripheral (Williams & Ratel, 2009). Porcari et al. (2015) point energy depletion as the most logical explanation for this type of fatigue. According to the authors, the consumption of the muscle’s PCr reserve would have an impact on the anaerobic system, thus affecting short-duration, high-intensity exercises. Excitation-contraction coupling failure has also been identified as a cause of peripheral fatigue (Kent-Braun, 1999).

The effects of fatigue are similar regardless of fiber type. In the surface EMG signal, they can be perceived through an increase in the amplitude and a decrease in the spectral frequency content (Dimitrov et al., 2006; Phinyomark, Thongpanja, Hu, Phukpattaranont, & Limsakul, 2012). Without sufficient time for recovery, a continued fatiguing process may lead to overuse or overtraining, defined “as an accumulation of training stress that impairs an athlete's ability to perform training sessions and results in long-term decrements of performance" (Powers & Howley, 2015, p. 476). Unlike fatigue, a muscle injury can take days or even weeks to heal.

Normally, the process of fatigue is associated with maximal "all-out" effort, yet the definitions given in this section indicate that prolonged submaximal activities, such as practicing a musical instrument, can too induce fatigue. Not only that, it is possible that unperceived fatigue may still be experienced by musicians before their performance is affected.

When playing the flute, one of the most significant parameters affecting the desired outcome is the control of the player over the lip muscles (Thomas, 1988, cited in McBrearty, 2010, p. 54). Although severe injury on flute players' lips are not reported often, playing may potentially lead to fatigue and light overtraining symptoms, of which players may not be aware. If this is proven accurate, both problems could affect musical aspects related to embouchure (arrangement of the lips on the mouthpiece of the instrument) such as tone quality, intonation, dynamics, etc., with fatigue being responsible for the difficulties within one single practice session and overtraining, for the gradual performance decrement over multiple sessions. A study on embouchure dystonia incidence among wind players suggests that these hypotheses may in fact be true (Termsarasab, & Frucht, 2016). After examining 30 patients with embouchure difficulties, 13.3% were diagnosed with overuse syndrome, which, according to the authors, inconspicuously appears after a sudden increase in practice time. The problem then affects musicians' playing ability over an extended period. Recovery may take months and playing may remain deteriorated in spite of a reduction in practice time.

Possibly because of their small size, lip muscles do not clearly show common signs of overuse such as pain or soreness. This might give instrumentalists the false impression that their body is well recovered to continue undergoing stresses, whether it is a practice session or a performance, when, in fact, their lip muscles might have an impaired responsiveness. This situation then could persist until the next, long rest period.

Therefore, one way to enhance flute performance is by controlling the muscle fatigue generated during playing. Doing so can potentially increase the player's endurance while minimizing muscle impairment. To accomplish this, however, instrument practice sessions must be devised as to allow for muscle recovery. This measure will be discussed more thoroughly in the following chapters.

The Anatomy of the Embouchure

In instrumental music, facial muscles take part in what musicians call embouchure, a term derived from the French word for mouth, bouche, meaning "the way in which a player applies their mouth to the mouthpiece of a brass or wind instrument, especially as it affects the production of the sound" (Oxford Dictionaries, n.d.). Motor control, or coordination, of these muscles is a vital element of sound production in wind instrument performance (Schade, 2007). Thus, in order to understand how the flute embouchure musculature operates during playing, it is important to further examine the physiological and anatomical characteristics of facial muscles whilst looking into various definitions for the concept of embouchure.

Albeit wind players often refer to embouchure as simply "the act of tone production" (Schade, 2007, p. 48), a plurality of definitions have been used in the literature. Basmajian and White (1973), while studying brass players, referred to embouchure as "the control of the firmness and vibration of the lips in relationship to each other and to the mouthpiece" (p. 70). Schade (2007) broadened the concept, defining the ideal embouchure as the element through which it is possible to "control perfectly the complex interaction between the musician's mouth region and the mouthpiece of wind instrument" (p. 48). While there is much variation in the definition of embouchure, scholars seem to agree that it is an important part of the playing technique because it affects various aspects of tone production (Iltis, & Givens, 2005) and many musically relevant sound parameters (Schade, 2007). Moreover, Schade (2007) explains that a deficient embouchure may contaminate sound with involuntary noises. For these reasons, embouchure can be considered a central element in the flute playing technique, and it is often at the core of practice sessions.

Indeed, the concept of embouchure has been addressed in flute methods since the 18th century (Quantz, 1752; Boehm, 1871; Taffanel & Gaubert, 1958; Boland,1998; Debost, 2002; Seed & Seed, 2018). These methods focus on various characteristics of embouchure, such as position, flexibility, aperture size, and control over airstream, yet without stating a clear definition for it. Instead, they gravitate around the implied idea that embouchure is a specific shape formed by the lips, which is necessary to generate sound on the flute. Tolsma (2010) suggests that this idea is inadequate as it does not account for the influence of other anatomical features, such as the teeth, the jaw, the chin, the throat, and several muscles that may also contribute to the embouchure formation in conjunction with the lips. Therefore, for him a more appropriate definition would be the one by Westphal (1978, p. 9): "An embouchure may be defined as the formation of the performer's lips with supporting muscles, teeth and jaw in relation to the embouchure hole which has to do with tone production" (cited in Tolsma, 2010, p. 17). A similar understanding is shared by Termsarasab, and Frucht (2016).

After elucidating the conceptualization of embouchure, it is now possible to clarify its anatomical features. The human head contains a total of 39 muscles (Tolsma, 2010). Approximately 20 of them, depicted in Figure 8, are located on the outer layers of the face (Farnol, 1941). These superficial muscles of the face insert into the skin, except for the risorius (Termsarasab, & Frucht, 2016), and are associated to the control of its movements, which is why they are known as facial muscles, muscles of facial expression, or mimetic muscles. They are thin, flat, and often blend into one another (Larrabee, Makielski, & Henderson, 2004) because they divide into branches as they approach the insertion to the skin (Gould, 1973).

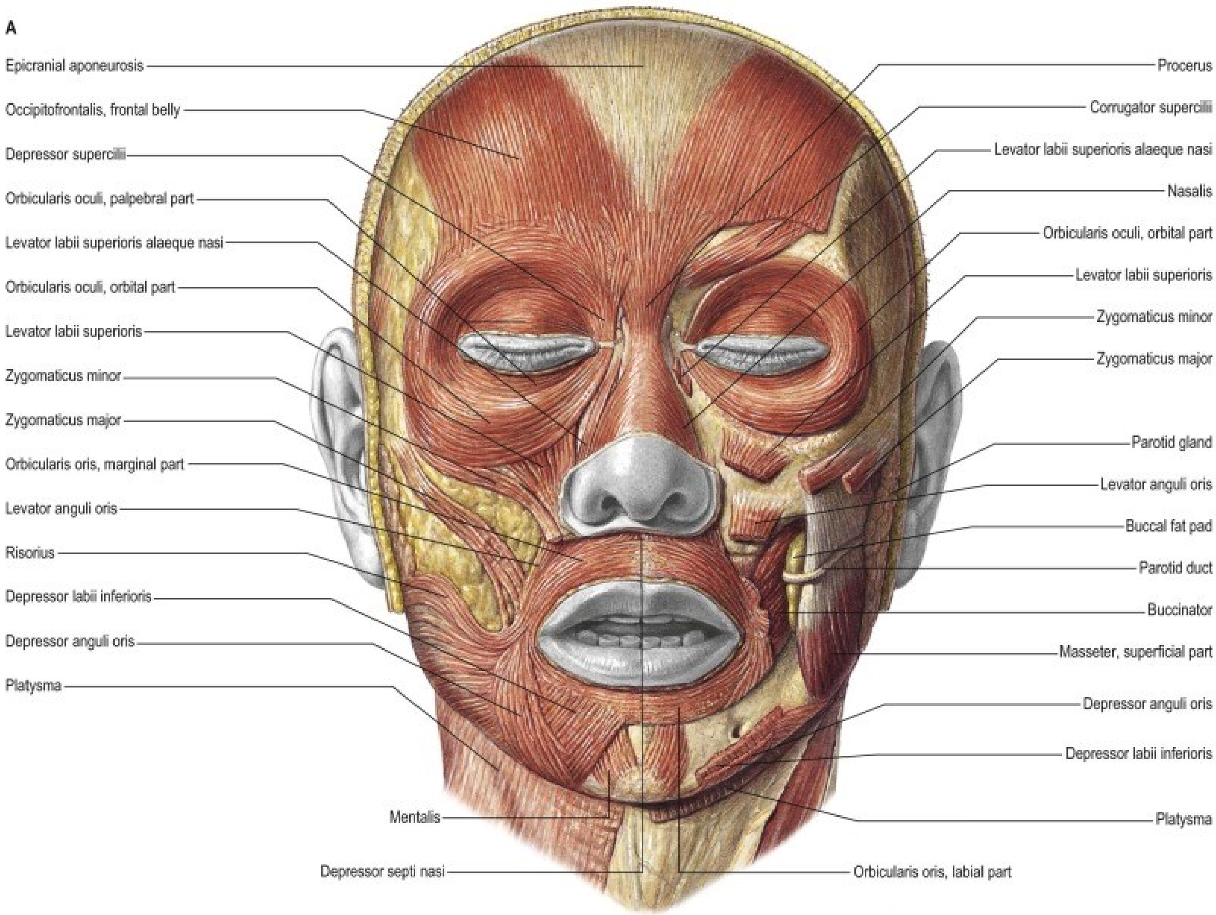

Figure 8. Facial muscles. Note that the masseter is included in the illustration but it is a muscle of mastication, not expression. Adapted from “Grey’s Anatomy,” by S. Standring, 2016, Copyright © 2016 by Elsevier Limited. Used with permission.

Lapatki, Stegeman, & Jonas (2003) explain that facial muscles are “independently controlled muscular slips” (p. 117) subjected to emotional as well as voluntary control. This means they may contract spontaneously, according to the individual’s feelings. In addition to conveying emotions, the primary function of facial muscles is to control the opening of the cavities on the face (Kim, Seo, Lee, & Kim, 2016), i.e., eyes, nose, and mouth. It is worth noting that, although located in the neck, the platysma is also considered a facial muscle because it is supplied by the facial nerve and it is involved in the movement of the mandible (Agur, & Dalley, 2009).

Considering that the player may make use of ancillary body movements as well as facial expressions to better transmit the musical ideas of a piece, it is possible that many or all the muscles of the head, to some extent, may be activated during flute playing, Even so, this thesis will focus on sound-producing gestures of facial muscles near the mouth region, also called perioral muscles.

The 12 perioral muscles, listed in Table 1, are skeletal muscles organized in four layers of different depth, with some present in more than one layer. They control the movements of the lips, thereby affecting activities such as speech and social expression (Larrabee, Makielski, & Henderson, 2004). The orbicularis oris and the buccinators also contribute to mastication (Moses, 2013).

Table 1

Function and Depth-Based Localization of Perioral Muscles

Muscle	Function	Layer*
Orbicularis oris (OO)†	Closes the mouth and puckers the lips	1st and 3rd
Buccinator	Aids mastication and regulates air pressure inside the mouth	4th
Zygomaticus major (ZYG)	Elevates the corners of the mouth	1st and 4th
Zygomaticus minor	Elevates the upper lip	2nd
Levator anguli oris	Elevates the corners of the mouth	4th
Depressor anguli oris (DAO)	Depresses the angle of the mouth	1st
Risorius	Pulls the corners of the mouth when smiling	1st
Levator labii superioris	Elevates the upper lip	2nd and 3rd
Levator labii superioris alaeque nasi	Elevate the upper lip	2nd
Depressor labii inferioris	Depresses the lower lip	3rd
Mentalis	Raises and protrudes the lower lip	4th
Platysma	Depresses the mandible	2nd

* This information was based on the research by Kim et al. (2016). † Abbreviations are provided for the muscles selected for this study.

A study by Termsarasab and Frucht (2016) presents yet another classification of perioral muscles based on their insertion. Three categories are defined: represented in green in Figure 9, the muscles that insert at the upper lip; in brown, the muscles that insert at the modiolos or corner of the mouth; and in purple, the ones that insert at the lower lip (more details on Figure 9 caption).

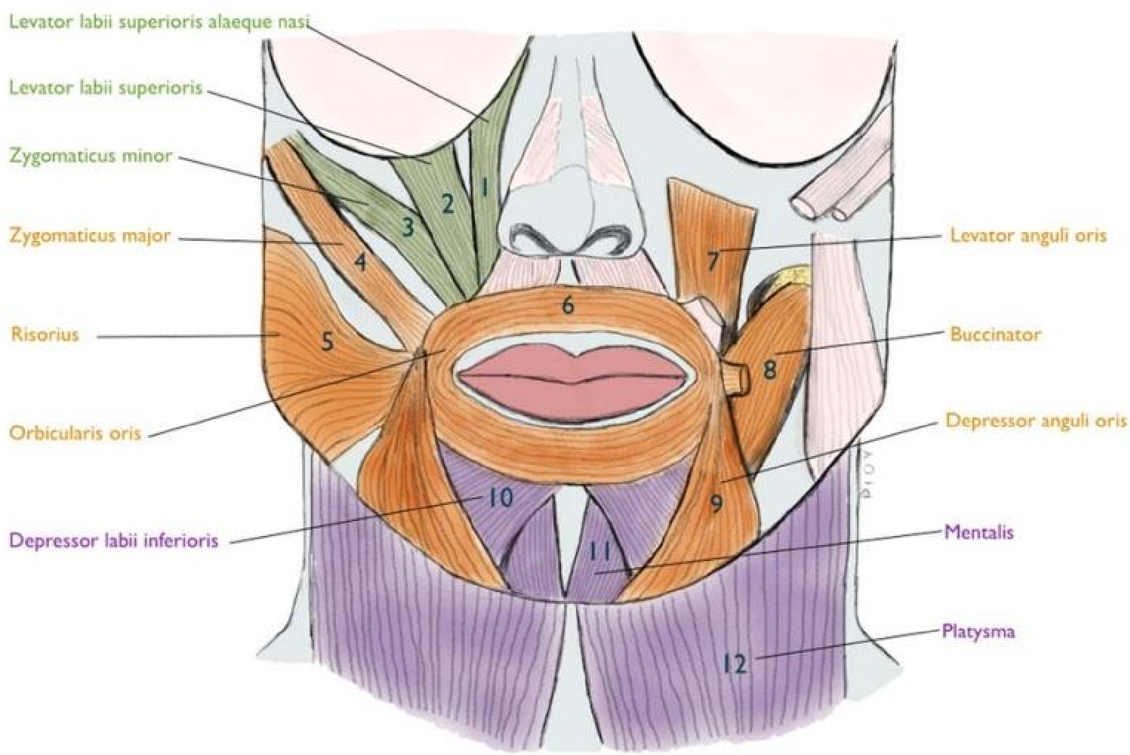

Figure 9. Perioral muscles organized according to their insertion. Represented in green, the levator labii superioris alaeque nasi, the levator labii superioris, and the zygomaticus minor insert at the upper lip; in brown, the levator anguli oris, the buccinator, the depressor anguli oris, the zygomaticus major, the risorius, and the orbicularis oris insert at the modiolos or corner of the mouth; in purple, the mentalis, the platysma, and the depressor labii inferioris insert at the lower lip. Adapted from "Evaluation of Embouchure Dysfunction: Experience of 139 Patients at a Single Center," by Termsarasab, P., & Frucht, S. J., 2016, *The Laryngoscope*, 126, p. 1328. Copyright © 2016 by Wiley and Sons. Used with permission.

There is little information about which muscles of the face are recruited in the embouchure of flute players specifically. Most publications tend to refer to the embouchure of brass players only or, in an even broader approach, wind players. Table 2 contains a compilation of writings on various wind instruments, which reveals that scholars tend to agree on the use of perioral muscles in the formation of the embouchure, although some may include the masseter, a muscle mainly used for mastication (Ferrario & Sforza, 1996), as relevant to the tone production. Some of these papers are based on observations, literature review, or the author's expertise, while others are based on electromyographic analyses involving perioral muscles; both theoretical and pragmatic evidence can be regarded as valuable in the still nebulous field of flute embouchure. The three most frequently mentioned muscles in Table 2 are the orbicularis oris, the depressor anguli oris, and the zygomaticus major. Not only do they all belong to the first layer of perioral muscles, inserting at the corner of the mouth, but they also have shown to be measurable with surface electromyography (sEMG). For these reasons, they have been chosen for the present study.

Table 2

Embouchure Muscle Recruitment of Various Wind Instruments

Muscle	A	B	C	D	E	F	G	H	I
Orbicularis oris	X	X		X	X	X	X		X
Levator labii superioris				X	X	X	X		X
Levator labii superioris alaeque nasi					X*				X
Levator anguli oris		X		X			X		X
Depressor labii inferioris				X	X	X	X		X
Platysma							X		X
Buccinator	X			X			X		X
Depressor anguli oris		X	X	X	X	X	X	X	X
Risorius	X						X		X
Mentalis					X	X	X		X
Zygomaticus major			X	X	X	X	X	X	X
Zygomaticus minor				X	X*	X			X
Masseter**	X						X		

Note. These perioral and mastication muscles have been appointed as part of the embouchure by different authors based on their review of the literature, expertise, or empirical observation. Sources are organized in chronological order. The X in blue indicates the muscles that have been measured by some form of electromyography. * Lapatki et al. measured these muscles along with the levator labii superioris, not separately. ** This is a mastication muscle, not part of the facial muscles group.

Reference Letter	Author	Publication Year	Instrument investigated	Type of Electromyography
A	Farnol	1941	All musicians	
B	Basmajian & White	1973	Trumpet	Fine wire
C	Heuse & McNitt-Gray	1991, 1993, 1994, 1998	Trumpet	sEMG
D	Frucht et al.	2001	Brass players	
E	Lapatki, Stegeman, & Jonas	2003	Trumpet	sEMG
F	Iltis & Givens	2005	Wind instruments/French horn	sEMG
G	Tolsma	2010	Flute	
H	Bianco et al.	2012	Trumpet	sEMG
I	Termsarasab & Frucht	2016	Wind instruments	

Fortunately, the descriptions of the embouchure patterns adopted by trumpeters seemingly resemble that of flutists in that both groups of instrumentalists aim for the combined depression of the corners of the mouth and a quasi-smiling facial expression (Tolsma, 2010; Bianco, Freour, Cossette, Bevilacqua, & Caussé, 2012). Parker (1957) reinforces this idea stating that the same groups of muscles are used in the formation of the embouchure for all brass and woodwinds, i.e., orbicularis oris, caninus, triangularis, quadratus labii superioris, quadratus labii inferioris, zygomaticus, risorius, mentalis, buccinators, masseter, platysma, and supra- and infrahyoids. His claim, however, is not evidence-based. Although more studies are needed, these apparent commonalities allow us to infer that potentially the same muscles are activated in the flute and trumpet embouchures, thus enabling some level of data comparison between studies on these instruments.

Histochemical analyses of the selected muscles aforementioned have demonstrated that they are predominantly composed of type II fibers (Stål et al., 1990; Happak et al., 1988), which are responsible for accelerated movements. The research conducted by Stal et al. (1990) also revealed that the type II fiber found in these perioral muscles has an oxidative capacity that is more elevated than that of the limbs, indicating a larger capacity for aerobic metabolism. The study by Happak et al. (1988) classifies all three muscles as part of the same functional group, named "intermediate," as they are approximately one third type I fiber. This ratio reflects their intermittent behavior in daily activities in contrast with what the authors called "tonic" muscles, which participate in more prolonged activities as a result of their higher percentages of slow-twitch fibers.

Chapter 2 – Exercise Physiology Training Principles

In order to understand how the principles of exercise training apply to different conditioning programs, it is first necessary to clarify the terminology through which the literature refers to different aspects of training. Various classifications are described below.

Types of Training

Scholars agree that every training session should include at least three phases: warm-up, workout, and cool-down (Powers & Howley, 2015; Plowman & Smith, 2011; Saxon & Schneider, 1995; Schneider, Saxon, & Dennehy, 2006; Williamon, 2004). The warm-up phase, often neglected, is responsible for increasing blood flow to the skeletal muscles. Besides elevating muscle tissue temperature, this phase simultaneously reduces injury and increases performance. It should involve 10-15 minutes of low-intensity activity aiming to activate the muscle groups to be developed. In the conditioning or workout phase, muscles are subjected to exercises of known intensity for a specific duration, which may vary depending on the type of training used. Following the workout is the cool-down phase, responsible for redirecting the "pooled" blood from the extremities to the central circulation. It is based on the same activity used during the workout yet in a much lower intensity. It lasts approximately 5-10 minutes. Research indicates that this phase, under appropriate conditions, is beneficial to performance recovery (Poppendieck, Faude, Wegmann, & Meyer, 2013).

Table 3 presents different terms attributed to physical training depending on the energy system it predominantly activates, the way it organizes exercises, the type of system it targets, and the trainable characteristic it seeks. These terms then are used to label distinct types of training that can be applied in the workout phase. Note that a physical training can be associated with more than one of the terms below, e.g., be concomitantly aerobic and anaerobic.

Table 3

Training Classifications

Energy System	Organization of Exercises	Type of System	Trainable Characteristic
Anaerobic (ATP-PCr/LA)*	Interval	Resistance (muscular system)	Endurance Strength Power Weight
Aerobic (oxidative)*	Continuous	Aerobic (cardiorespiratory system)	Fitness Endurance Health status
Aerobic/Anaerobic	Continuous/Interval	Neuromotor (nervous system)	Balance Flexibility Coordination Agility

* These systems have been discussed in Chapter 1, p. 9-10.

Types of training according to energy system. According to Powers and Howley (2015), "Knowledge of the relative anaerobic-aerobic contributions to ATP production during an activity is the cornerstone of planning a conditioning program" (p. 476). These energy systems (aerobic or anaerobic), also called metabolic pathways, are activated to generate the ATP in the muscle, depending on how exercise components are combined. These combinations, in turn, form the basis of aerobic and anaerobic training.

Anaerobic. The anaerobic training can activate both the phosphagen (ATP-PCr) and the glycolytic (LA) systems depending on the duration of the activity. When the exercise lasts between 10 and 30 seconds, the muscles rely on their phosphate pool (ATP-PCr). This energy system can be overloaded by the repetitious activation of the muscles at maximum effort for five to ten seconds followed by a rest period of 30 seconds to 1 minute (Saxon & Schneider, 1995). This would be the most appropriate training for football players, considering the average football play lasts 4-7 seconds (Plowman & Smith, 2011). In slightly longer activities lasting between 30 seconds and 2 minutes, the glycolytic pathway is activated. Recovery time for the LA system is usually between 1.5-3 minutes (Plowman & Smith, 2011).

Aerobic. Any work duration longer than 2-5 minutes will primarily stress the oxidative system. Training that includes an exercise like this will be classified as aerobic for its reliance on oxygen as the main source of energy. This is the type of training associated with most sports such as soccer, basketball, and long-distance running. Recovery time for the aerobic system may vary from a few minutes to several hours. The process is slow and involves the removal of lactate and H^+ from the blood, as well as glycogen resynthesis (Tomlin, & Wenger, 2001).

Types of training according to organization of exercises.

Interval training. Interval training is characterized by the periodic interspersion of rest periods and work (or exercise) periods. The exercise bouts can vary from a few seconds to several minutes. The recovery period too can vary in duration, taking place in the form of a complete rest (passive rest) or a low-intensity activity (active rest). This relief interval is usually prescribed as a ratio of exercise duration to rest duration. The ATP-PCr, glycolytic, and oxidative energy systems generally use the respective ratios of 1:3, 1:2, and 1:1 or 1:1.5. Because of these constant rest periods, interval training makes large quantities of highly intense exercise more attainable. The rest delays lactate buildup in the blood, reducing fatigue and consequently allowing the individual to exercise longer (McArdle, Katch, & Katch, 2010).

Continuous training. Unlike interval training, continuous training involves prolonged, uninterrupted exercises of moderate to high intensity. It applies to aerobic training, usually requiring 60-80% of the peak amount (or volume) of oxygen consumed in the activity (VO_2max). This parameter, in turn, reflects the maximal capacity of the cardiorespiratory system, thus indicating an individual's fitness level. One interesting benefit of continuous training is that it “allows endurance athletes to exercise at nearly the same intensity as actual competition” (McArdle, Katch, & Katch, 2010, p. 483).

Types of training according to targeted system. Training programs can be classified into three categories based upon the bodily systems they tax. Cardiorespiratory training focuses on the cardiovascular system, resistance training focuses on the muscular system, more precisely, the skeletal muscles, and neuromotor training focuses on the interactions between the nervous and the muscular system, i.e., the control over motor skills such as coordination, agility, balance, etc.

Cardiorespiratory (cardiovascular system). Cardiorespiratory training, often referred to as aerobic training, is rooted in the use of oxygen during a physical activity. It involves from 20 to 60 minutes of exercise whose intensity is commonly measured as a percentage of either the peak oxygen consumption (VO_2max) or the heart rate reserve (HRR). It induces physiological adaptations in the heart and lungs. Among other changes, it increases heart size and volume, cardiac output, VO_2max, and lung function. For these reasons, it is frequently sought out as a way to improve health condition. Other commonly pursued goals in cardiorespiratory training include fitness and endurance. Each of these goals entails a different combination of exercise frequency, intensity, duration, and type, although it is unlikely that an individual engaged in cardiorespiratory training will achieve one of these goals without benefiting from the others.

According to a document issued by the American College of Sports Medicine (ACSM, 2011), physical fitness is understood as: ‘‘The ability to carry out daily tasks with vigor and alertness, without undue fatigue and with ample energy to enjoy [leisure] pursuits and to meet unforeseen emergencies’’ (Caspersen, Powell, & Christenson, 1985, cited in Garber et al. 2011). Cardiorespiratory fitness, one of the components of physical fitness, is usually interpreted as the maximum aerobic power (VO_2max) (Wenger & Bell, 1986) and associated with lower risk of all cause and cardiovascular diseases mortality and morbidity (Garber et al., 2011).

The term *endurance* often appears in the literature as a synonym for cardiorespiratory training for its reliance on oxidative metabolic processes. In the context of elite athletic training, however, it can designate activities of extended duration, such as cycling performance in 40 km time-trials, where athletes compete alone, during approximately 1 hour, on a flat sea level course (Coyle et al., 1991). Jones and Carter (2000) define endurance as “the capacity to sustain a given velocity or power output for the longest possible time” (p. 373). According to the authors, endurance training enables athletes to exercise for longer periods at a specific intensity level, or to exercise at a higher intensity level for a certain time. This is possible, they explain, because the training causes acute physiological adaptations on the cardiorespiratory and neuromuscular systems, thereby optimizing muscle metabolism and improving the delivery of oxygen to the mitochondria[5].

Resistance (musculoskeletal system). Resistance training usually consists of concentric and eccentric muscle contractions opposed by a constant or variable load. Through a varied combination of exercise components, it can be designed to improve specific muscular

[5] Organelle “involved in the oxidative conversion of foodstuffs into usable cellular energy” (Powers & Howley, 2015, p. 40)

characteristics: strength, size (hypertrophy), endurance, and power (jump and sprint performance). Traditionally, the resistance exercise for strength development and the resistance exercise for endurance development have contrary prescriptions. While the first involves high-intensity, low-repetition exercises, the latter involves low-intensity, high-repetition exercises (Heyward, 2006).

Neuromotor training (nervous system). Neuromotor training combines motor skills (e.g., agility, balance and coordination) with proprioceptive training[6]. Popular illustrations of it in the literature are the Chinese martial art Tai Chi, and Yoga. Although widely studied, the benefits of neuromotor training have yet to be determined (Garber et al., 2011). Niemeijer, Smits-Engelsman, and Schoemaker (2007) demonstrate that neuromotor task training (NTT)—"a task-oriented approach focusing directly on teaching … skills" (p. 406)—is effective to improve coordination of children suffering from developmental coordination disorder (DCD). NTT, as the authors explain, addresses motor control through cognitive neuroscience. Based on these definitions of neuromotor training, one may argue that music training itself is another example of it. Although no studies connecting both areas have been reported, prolonged instrument training has been shown to improve motor skills (Jabusch, Alpers, Kopiez, Vauth, & Altenmüller, 2009). The American College of Sports Medicine (ACSM) recommends a total of 60 minutes or more of neuromotor training per week distributed in 20-30-minute sessions, 2-3 days per week.

The Principles of Training

Largely applied in sports, the science of exercise physiology centers on bodily responses to physical activity and investigates ways to "maximize human physical potential" (Plowman & Smith, 2011, p. 2). Exercise physiologists identify four basic principles as the foundation for any

[6] Related to the "perception or awareness of the position and movement of the body" (Oxford Dictionaries, n.d.)

successful physical training program: *Overload, Specificity, Individuality*, and *Reversibility*. These principles are described below. Saxon and Schneider (1995) refer to them as the "blueprint for achieving our training goals" (p. 47). They also argue that, in order to develop conditioned muscles, these principles must be incorporated into training programs. Although scholars tend to agree on the primacy of these four principles, additional principles can be found in the literature. Plowman and Smith (2011) add the principles of *Rest*, *Progression*, *Maintenance*, and *Warm-up/Cool-down* to the four mentioned above. Heyward (2006) adds the principles of *Progression*, *Initial Values*, and *Diminishing Returns* principles. Powers and Howley (2015), on the other hand, consider only *Overload*, *Specificity*, and *Reversibility* as the basic training principles.

Overload. Development only takes place when a muscle is submitted to a load that is bigger than usual. This relationship is regulated by the *Overload Principle*, which states, roughly, that improvements in performance are directly proportional to the overload on a particular system. The application of this principle must be gradual (one step at a time), discontinuous (with regular intervals), and progressive (continuously increasing over time).

A common overload technique among athletes is the *Periodization Cycles*. It consists of the administration of different loads according to four cycles throughout the year: load, recovery, peak, and conditioning. The first and third cycles are intended for intense workout building up for competition, whereas the second and fourth aim for muscle recovery based on active rest[7]. The technique promotes maximum muscular conditioning and skill development (Kraemer, Duncan, & Volek, 1998).

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[7] Recovery interval during exercise that involves work with low to moderate intensity as opposed to a complete rest (Signorile, Tremblay, & Ingalls, 1993)

Overload can be generated by the combined manipulation of the following training components: frequency, intensity, time, and type or mode (American College of Sports Medicine, 1978). They determine the dose of any physical activity, thereby forming the basis of exercise prescription. In planned physical activities with the purpose of improving or maintaining fitness, these components are assigned according to the individual's initial physical condition, type of training and goal. It is important to consider, however, that these components are inter-dependent and may affect one another. Intensity and duration, for example, should not be simultaneously increased in order to avoid overuse. Thus, the total amount of work associated with an exercise has to be observed.

To avoid plateaus, the duration and intensity of an exercise have to be systematically increased to continuously overload the cardiorespiratory and the muscular systems. Individuals fatigue less as they become more fit, so increments are necessary every 2 or 3 weeks to make the exercise as challenging (Saxon & Schneider, 1995). A guideline commonly used in training programs to determine the appropriate load increase is the *Ten-percent Rule*. It states that, in order to avoid overuse injuries, the increase in training intensity or duration should not exceed ten percent per week (Powers & Howley, 2015).

Training components. In this section, the training components named above will be discussed in relation to two major types of physical training: cardiorespiratory training and resistance training.

Frequency. Frequency indicates how often the exercise is performed per unit of time (e.g., per week or per day). An appropriate frequency of exercise allows the muscles to recover between training sessions, thus avoiding overtraining. The ideal frequency of an aerobic exercise ranges from three to five days a week. Two or one day of exercise per week will not produce any conditioning effect, whereas more than five will dramatically increase the risk of injury without substantial gains in performance (Saxon & Schneider, 1995). For individuals engaged in resistance training programs, 2 to 3 nonconsecutive days of exercise per week are recommended (Kraemer et al., 2002 cited in Heyward, 2006). See Table 4 for more detailed information.

Intensity. Intensity is commonly conceived in terms of "%VO_2max, % maximal heart rate, rating of perceived exertion, and the lactate threshold[8]" (Powers & Howley, 2015, p. 353). During an activity of increased overload, the cardiac output is heightened to supply muscles with greater amount of oxygen. In this process, the heart may activate two mechanisms: pulse elevation or stroke volume increase (Saxon & Schneider, 1995).

The oxygen consumption expressed by the VO_2max also relates to energy expenditure. It derives from a technique called indirect calorimetry, which estimates the metabolic rate during an activity based on the volume of oxygen consumed. This technique is termed indirect because it indirectly assesses the heat production associated with an activity. The relationship between oxygen and heat is given by the following metabolic reaction: Foodstuffs + O_2 → Heat + O_2 + H_2O, where *foodstuffs* can be different types of nutrient (i.e., carbohydrate, fat, or protein) (Powers & Howley, 2015, p. 21). The direct calorimetry, on the other hand, measures energy expenditure by monitoring changes in body temperature, i.e., the substantial increases resulting from exercise and the small decreases due to the evaporation from the skin and respiratory passages. This is done in a large chamber (called a calorimeter), normally insulated from the external environment by circulating water. Although more precise, direct calorimetry is costly and highly unpractical.

[8] Lactate is a normal subproduct of muscle contraction. However, when the intensity level of an exercise exceeds a certain point, usually between 50-55% of the maximal aerobic capacity, blood lactate equals lactate disappearance and begins to accumulate. This point, known as the blood lactate threshold, is higher in trained athletes due to metabolic adaptations among other factors (McArdle, Katch, & Katch, 2010).

To be effective, the aerobic exercise has to be intense enough as to raise the heart rate above 65% of the individual's total cardiovascular capacity; 90% is the equivalent of the maximal intensity recommended by the ACSM. In terms of oxygen consumption, the range in which an exercise produces a conditioning effect is 50-85% (Pollock et al., 1998). In resistance training, Heyward (2006) recommends an intensity ranging from 60-100% 1-RM[9] to develop strength, and below 60% 1-RM to develop endurance. Table 4 contains more detailed recommendations for resistance training according to specific goals.

Another important intensity index in the aerobic training is the metabolic equivalent of task (MET[10]) (Garber et al., 2011). The MET expresses the amount of oxygen being consumed in an exercise per kilogram of body weight per minute. This index is, by definition, a physiological measurement of an individual’s metabolic rate, thus informing on the energy expenditure of a physical activity. It is, however, often used to determine intensity level (Ainsworth et al., 2000).

Time. Time is simply the duration of the activity; usually in minutes. In an ideal conditioning program, the length of an exercise and its intensity often vary inversely. Thus, the more intense the exercise the shorter its duration should be (Heyward, 2006). The ACSM (2006) recommends between 20 and 60 minutes of continuous or intermittent activity in aerobic training. In resistance training, the duration of a session is expressed in terms of volume of training rather than minutes. This volume, in turn, is the result of the sum of the total number of repetitions performed multiplied by the load used, in kilograms (ACSM, 2009). The recommended volumes

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[9] Repetition maximum or RM refers to the highest possible load applied in a certain number of repetitions of a dynamic task,

[10] The metabolic equivalent of task expresses the energy cost of an activity. 1 MET is “the energy expenditure for sitting quietly, which for the average adult is approximately 3,5ml $O_2.kg^{-1}.min^{-1}$” (Ainsworth et al., 2000, p. 72)

for resistance training according to conditioning level (novice, intermediate, and advanced) and training goals (strength, hypertrophy, endurance, and power) are included in Table 4.

Table 4

Resistance Training Recommendations According to Individual's Initial Conditioning Level and Training Goal

	Novice				Intermediate				Advanced			
Goal	*Intensity*	*Volume*	*Frequency*	*Rest interval*	*Intensity*	*Volume*	*Frequency*	*Rest interval*	*Intensity*	*Volume*	*Frequency*	*Rest interval*
Strength	60-70% 1-RM	1-3 sets of 8-12 reps	2-3 days/wk	1-3 min.	70-80% 1-RM	1-3 sets of 6-12 reps	2-4 days/wk	1-3 min.	80-100% 1-RM	Multiple sets of 1-12 reps, periodized	4-6 days/wk	1-3 min.
Hypertrophy	70-85% 1-RM	1-3 sets of 8-12 reps	2-3 days/wk	1-2 min.	70-85% 1-RM	1-3 sets of 1-12 reps	2-4 days/wk	1-2 min.	70-100% 1-RM	3-6 sets of 1-12 reps, periodized	4-6 days/wk	1-3 min.
Endurance	50-70% 1-RM	1-3 sets of 10-15 reps	2-3 days/wk	1-2 min.	50-70% 1-RM	1-3 sets of 10-15 reps	2-4 days/wk	<1 min.	30-80% 1-RM	Multiple sets of 10-25 reps	4-6 days/wk	<1 min for 10-15 reps; 1-2 min for 15-25 reps
Power	>80% 1-RM for strength 30-60% 1-RM for speed	1-3 sets of 3-6 reps	2-3 days/wk	2-3 min.	>80% 1-RM for strength 30-60% 1-RM for speed	1-3 sets of 3-6 reps	2-4 days/wk	1-3 min.	85-100% 1-RM for strength 30-60% 1-RM for speed	3-6 sets of 1-6 reps, periodized	4-6 days/wk	1-3 min.

Note. Adapted from “Advanced Fitness Assessment and Exercise Prescription,” by V. H. Heyward, 2006, pp. 143-144. Human Kinetics.

Type. Type or mode is the characteristic that most distinctly qualifies the activity, e.g., resistance or cardiovascular endurance (Powers & Howley, 2015). The type or mode of an exercise has to be specific to the activity to be improved as determined by the "specificity principle"; to Saxon and Schneider (1995), it also needs to be rhythmical (periodic).

Specificity. According to the *Specificity Principle*, muscular performance can only be enhanced when the training program closely resembles the activity to be performed. Not only does the exercise have to stress the same muscle used in the performance but it also has to be used in the same manner. This is true even for activities of similar nature. An athlete who trains to improve their oxygen uptake through running, for example, will not benefit from the exact same cardiorespiratory performance in swimming. In addition to reflecting on a particular skill, the specificity principle also reflects on the energy system exerted during the activity, i.e., the duration of an exercise determines which energy system will be predominantly developed. While the skill is associated with the necessary muscle coordination, i.e., a certain movement pattern with precise speed and force, the energy system is associated with the metabolic pathway that is activated during the activity to generate ATP molecules and fuel muscle contraction (Gastin, 2001). As mentioned earlier, on pages 9-10, three different systems may operate in the muscle to produce energy: ATP-PCr, glycolytic, and oxidative. They respectively take place when the activity lasts a few seconds, a couple of minutes, and more than two minutes.

Individuality. People respond differently to exercise. Its effectiveness then depends on the individual who is being subjected to it (Saxon & Schneider, 1995). Numerous factors can influence this relationship, e.g., fitness level, body type, gender, etc., and these factors have to be considered in the design of a conditioning program. Additionally, expected results are not instantaneous; they unfold gradually over time as the body is exposed to a certain physical activity. Responses can be grouped in four categories: acute (appear after initial exercise bouts yet without further improvement), rapid (occur early after training onset and plateau), linear (feature continuous development) and delayed (take place after weeks of training) (Powers & Howley, 2015).

Reversibility. "Detraining occurs rapidly when exercises cease" (Saxon & Schneider, 1995, p. 54). This tenet is the essence of the *Reversibility Principle*. According to MacArdle, Katch, & Katch (2010), the loss of physiologic and performance adaptations, termed *detraining*, may begin as early as 1 or 2 weeks after the activity is interrupted. Some metabolic functions, on the other hand, will only be fully lost within several months. The authors also explain that these detraining effects may be perceived in both untrained and highly trained individuals.

Chapter 3 – Literature Review

Despite lengthy practice periods (Williamon, 2004), aspiring professional flutists, along with other instrumentalists, frequently suffer from inconstant progress (Williamon, 2015) and lack of satisfactory results in their search for a proficient technique. As wind instrumentalists, they rely heavily on the use of perioral muscles to produce sound through a delicate arrangement of the lips on the mouthpiece of the instrument, i.e., *embouchure*. Indeed, achieving and maintaining a good tone quality is identified as a major challenge in flute playing (BastaniNezhad, 2012) and, as it will be shown, the literature suggests that there is a close relation between this musical parameter and muscle training.

The following literature evidences the physical nature of flute practice and the viability of the implementation of a muscular conditioning program aiming to optimize such activity. Schade (2007) investigates ways to improve the embouchure of wind players by systematically building up the motor control of the lips through myofunctional exercises (exercises for the mouth and face regions used in speech and language therapy). Toff (2012) explains that flute practice is essentially a physical rather than intellectual process. This point of view is corroborated in a study by Shin, Kang, Hallet, and Sohn (2012), which found that prolonged instrument training, as in the case of professional musicians, leads to structural changes in the sensorimotor cortex. Paull and Harrison (1997) equate musicians' rigorous routine of musical exercises to athletic training. Schneider, Saxon and Dennehy (2006) broaden this idea, explaining that "[a]ny activity that involves working muscles can be enhanced by regularly and consistently applying the principles of muscle training and conditioning" (p. 301). Belcher (2004) discusses how these established sport-science practices can be applied in clarinet practice. Therefore, this study turns to the area of exercise physiology in search for tools to optimize the deliberate training of flute embouchure muscles. One of these tools is the principles of training.

The literature related to the application of exercise physiology training principles on the advancement of music practice is rather scarce. In one of the earliest attempts to point out physical factors influencing music performance, in 1941, Farnol writes to alert musicians of the importance of physiological aspects during playing. He explains that the muscular activity and muscle fatigue involved in playing a musical instrument may affect the player's technique in addition to their anatomical features. In his discussion of the mouth, he explains how excessive pressure on facial muscles compromises both blood flow and energy supply. This condition, when persistent, results in an accumulation of waste, carbon dioxide, and lactic acid in the muscles. Farnol then observes that, without the proper training and the development of an energy reserve, the prolonged exposure to pressure damages the muscle tissue. Although these remarks encompass the application of physiology in general without specifically addressing training principles, Farnol's writings suggest that there is a close relation between how musicians perform and how they train their muscles, yet this is not evidence based. At the end of his article, he states: "We should realize that the function of any particular muscular part of the body depends upon proper exercise and stimulus." (Farnol, 1941, p. 73)

Fortunately, the number of publications encompassing the use of athletic training in music settings has been gradually increasing, particularly after the 90's. These writings focus on the application of training principles on specific forms of music practice such as voice (Saxon and Schneider, 1995; Atherton, 2001; Sandage, & Hoch, 2018), trumpet (Pursell, 2000), clarinet (Belcher, 2004), and classical guitar (2006).

In a comprehensive review of physiological mechanisms and training principles, Pursell (2000) explores how “sports-related weight training can be adapted to trumpet practice to encourage the development of … embouchure” (p. 55). After discussing muscle function, muscle development, and embouchure muscles, he then lays down recommendations regarding the incorporation of rest during practice sessions, the organization of musical exercises, and the gains of muscle strength and endurance. This knowledge, according to the author, helps the trumpeter to better understand how to train for optimum performance.

Other contributions to the field are reviewed below, organized according to the four basic principles of training (overload, specificity, individuality, and reversibility), the structure (warm-up, workout, and cool-down) and types of training (aerobic, anaerobic, cardiorespiratory, and resistance), and training components (frequency, duration, and time).

Training Principles and Music Practice: An Overview

Overload. At the Institute for Voice Analysis and Rehabilitation, in Dayton, a study by Stemple, Lee, D’Amico, and Pickup (1994) demonstrated a successful application of the overload principle. In the experiment, a group of 12 singers were submitted to vocal function exercises aiming to strengthen the laryngeal musculature. They exercised twice a day, 7 days per week, for a period of 28 days. Each session lasted between 15 and 20 minutes. Results "showed significant changes in phonation volume, flow rate, maximum phonation time, and frequency range" (Stemple, Lee, D'Amico & Pickup, 1994, p. 271).

Specificity. Based on the specificity principle, one may infer that a musical performance will improve minimally with any exercise other than playing itself, unless the exercise mimics the activity of playing. Also, this principle raises the question if traditional practice is generally adequate to develop the energy systems necessary for playing. Most instrumentalists, for example, will normally practice short excerpts, as orchestral soli normally are, for long periods not knowing that they may be in fact developing a different energy system from the one actually used in the performance. In their discussion on the development of specific energy systems, Saxon and Schneider (1995) suggest that, in order to improve the performance of arias, singers should practice stressing the anaerobic energy system as this is the system most likely used in this type of repertoire, markedly short in duration. There is however no evidence demonstrating the superiority of this practice strategy as relates to the training of arias by singers.

Individuality. Music instrument learning is definitely an evidence of the *Individuality Principle*. The literature contains examples of skillful players who attained high levels of proficiency without engaging in extensive practice as well as of individuals who practiced for long periods without achieving satisfactory results. Williamon (2004) cites a study by Sloboda et al. from 1996, a study by Sosniak from 1985, and two studies by Williamon and Valentine from 2000 and 2002, which confirm these observations. He also states: "[t]he relationship between the practice time invested and proficiency obtained has not been completely elucidated" (p. 22). Simply engaging in a sufficient amount of practice is not enough to achieve an optimal performance (Ericsson, Krampe & Tesch-Römer, 1993). These remarks indicate that the individuality principle possibly holds true in musical contexts. Thus, from a physiological point of view, the development of the muscles recruited by each individual, during instrument playing, would depend on the muscles' response to training and not just the training itself. Additionally, musicians would gain efficiency in their musical practice if training programs were to be implemented taking into account the current state of an individual and the specific needs in terms of targeted system.

Reversibility. The reversibility principle is the reason why Saxon and Schneider (1995) advise against absolute rest for singers, suggesting active rest instead. The authors theoretically base their recommendation on the premise that exercise cessation is followed by rapid detraining, in which case minimal vocal exercise would be necessary for the maintenance of previously acquired skills. Sandage and Hoch (2018) explain that prolonged periods of complete rest or even insufficient vocal load may lead to the loss of physiological adaptations associated with technique proficiency. Based on the threshold for cardiorespiratory development established in exercise science (70% of total capacity), the authors analogously hypothesize that if the load placed upon laryngeal and respiratory muscles falls below 70% for more than a couple of weeks, gains in strength and endurance may be reversed. They state, however, that, despite ample anecdotal evidence, reversibility of vocal fitness has not been confirmed through physiological parameters.

The Structure and Types of Training in Musical Contexts

Phases of training. In sports training, three phases have been shown to constitute the ideal practice routine: warm-up, workout, and cool-down. In the context of music practice, the same structure seems to be needed. In his *A Training Manual for the Low Voice*, Atherton (2001) alerts students and teachers of the importance of warming up and cooling down during a practice session. The warm-up phase, he argues, has been shown to make muscles less susceptible to injury. Moreover, his recommendation is that practice habits should observe the training components of frequency, intensity, and duration. In order to obtain results, he states, a minimum of 4 days of practice per week are required, with practice sessions lasting 20-30 minutes. Rest periods are to be strictly followed to ensure sufficient recovery. According to Atherton, the application of physiological knowledge and training principles can be used to enhance singers' performance.

Other researchers have also supported the implementation of the warm-up and the cool-down phases in music practice sessions. Using infrared thermography, a study by Bertsch and Maca (2001) observed changes in facial muscles of three groups of brass players (professionals, students, and beginners) during the warm-up phase. Its duration across participants was of 30 minutes. After this period, it was noted that blood had been redistributed to central parts of the face, more so to the muscles orbicularis oris, depressor anguli oris, and levator anguli oris. Additionally, results revealed that professionals warm-up more symmetrically and efficiently than beginners. This was verified based on the infrared images, which showed that, for professionals, the area indicated as active was more homogenous and concentrated around the embouchure region.

Unlike the warm-up phase, the cool-down does not seem to yield results as concrete. Gottliebson (2011) investigated the effects of cool-down on vocal function and determined that the relationship between them remains unclear. The study assessed nine actively performing elite singers, using physiological (phonation threshold pressure), acoustic (accuracy of tone production, duration of notes and duration of intervals between notes), and subjective (perceived phonatory effort and Singing Voice Handicap Index) measures. Data were collected in three conditions following a 50-minute voice lesson: after cool-down, after complete rest, and after conversation period. A second data collection took place 12-24 hours later. It was expected that improvements in physiological and acoustic measures, obtained with cool-down exercises, would surpass those yielded by the other recovery methods, yet this was not confirmed in the results. Furthermore, greater accuracy of tone production and reduced effort (subjective measures) were observed in the second dataset, collected 12-24 hours after the cool-down. The author then concluded that the benefit of cooling down after rigorous use of the voice may not be immediate, becoming apparent only after 12-24 hours later.

Types of training. Despite its paucity, the literature connecting exercise physiology and music practice contains a few writings addressing different types of training, namely the aerobic, cardiorespiratory and resistance trainings.

A study by Penn, Chuang, Chan, and Hsu (1999) investigated the biochemical adaptations derived from long-term piano playing in order to identify if such activity had an aerobic or anaerobic nature. Changes in the electromyographic power spectrum of 13 pianists and a control group were examined during muscle contractions of incremental load. This was done before and after a fatiguing task. The muscle observed was the first dorsal interosseous (FDI). No significant difference in the median frequency was found between both groups, however, the pianists needed a significantly longer time to have their muscle fatigued (14.3 ± 5.8 min vs 5.8 ± 3.3 min, $p < 0.005$). The authors concluded that piano training can be classified as an endurance (aerobic) training.

In a case study involving cardiorespiratory training, Borkowski (2011) showed that exercise training principles can affect flute performance. After 6 months engaged in a conditioning program, the player experienced improvements in their fitness condition, which, in turn, allowed them to offset breathing challenges in a repertoire considered “brute” by the author.

Indeed, in a more physically fit person, the VO_2 max is higher and their cardiorespiratory system is optimized, so they use less energy to perform any activity, including playing. For this reason, Saxon and Schneider (1995) state that singers or voice patients who are more fit can perform longer.

A study by Ackermann, Adams, and Marshall (2002) investigated whether strength or endurance training was more effective in assisting undergraduate music majors in their preparation for the athletic task of playing an instrument for a prolonged period. After a 6-week control period without intervention, participants were randomly allocated to either a strength group or an endurance group. Each group trained during another 6 weeks, maintaining a conditioning program with 11 exercises for the upper body that contrasted in intensity and number of repetitions. The strength group performed exercises of 6-8 RM to fatigue, whereas the endurance group adopted exercises of 25-30 RM to fatigue. Changes resulting from training were monitored through laboratory tests and field measurements. Even though both groups experienced an increase in strength, results showed that participants who engaged in endurance training had a significantly greater reduction in their rating of perceived exertion (RPE) for playing, suggesting that musicians may benefit more from endurance than strength training. This association between instrument practice and endurance training has also been appointed by other researchers (Belcher, 2001).

Of all the concepts covered in the field of exercise physiology, the training components (i.e., frequency, intensity, time, and type) are perhaps the most favorite topic of musicians. Numerous accomplished performers have attempted to prescribe their correct way of practicing music through a series of recommendations regarding the duration and the content of practice sessions. It was not until recently, though, that the basis underlying these instructions for the ideal practice shifted from traditional to scientific. The following studies exemplify the discussion of training components in musical contexts with a scientific perspective.

Training Components Applied to Music Practice

Frequency. According to the principle of adaptation cited by Plowman and Smith (2011), it is during the rest period that physiological changes take place in response to the stress caused by the training. This confirms the importance of recovery periods between training sessions, hence the critical role of frequency in muscle conditioning. Williamon (2014) cites a study of student violinists by Ericsson et al. from 1993 that showed that the more accomplished players took more naps than the less accomplished players.

Scholars from the sports-science area still have controversial opinions regarding the frequency of an exercise within the same day. Studies indicate that exercising for 30 minutes once or in three bouts of 10 minutes delivers similar results (DeBusk, Stenestrand, Sheehan, & Haskell, 1990). While this fragmentation of the exercise may involve practical changes and affect the adherence to the training program, using shorter bouts of exercise multiple times, in terms of musical training, may have a positive effect on the development of the embouchure muscles considering their high level of fatigability. Additionally, bouts of shorter duration are more likely to effectively stimulate the perioral muscles recruited in the embouchure because of their metabolic properties.

Intensity. Flute playing, in sitting position, has been established in the literature as an activity that demands 2 METs (Ainsworth et al., 2000). This qualifies it as a low-intensity activity in a scale ranging from 0.9 (sleeping) to 18 METs (running at 10.9 mph), where moderate-intensity activities are within 3.0-5.9 METs and vigorous-intensity activities are associated with 6.0 METs or more (Powers & Howley, 2015).

Indeed, research has shown that playing the flute does not overly stress the cardiorespiratory system, which confirms the previously established measurement of 2 METs. In a study by Harmat and Theorell (2010), the heart rate variability of flutists ($n = 4$) and singers ($n = 5$) was measured during the performance of two pieces of different levels of difficulty (i.e., easy and strenuous) in two conditions (i.e., with and without an audience). Results showed an average heart rate increase of 5.08% (i.e., 94.5 ± 4.6–99.3 ±4.8) in rehearsal condition without an audience, and of 7.42% (i.e., 117.3 ± 5.1–126.0 ± 4.7) in concert condition, but the statistical analysis revealed the difference was non-significant ($p = 0.5$).

The aerobic indexes, nonetheless, do not take in consideration the stress undergone by the skeletal muscles. Research shows that pain affects 85% of professional musicians (Silva, Lã, & Afreixo, 2015) and over 66% of college music students (Spence, 2001). Lonsdale, Laakso, and Tomlinsom (2014), after a survey involving 421 flute players, reported that 49.7% had experienced performance-related discomfort or pain. This high incidence of performance-related musculoskeletal disorders (PRMD) among flute players suggests that the intensity level demanded by the instrument is considerable. Spence (2001) explains that medical problems do affect flute players and need our attention. It is true, though, that most of these problems are in areas other than the embouchure. In a study by Termsarasab and Frucht (2016) on 109 musicians with embouchure dystonia (disfunction that takes place during the performance of a specific task) only 17 were flutists.

The monitoring of the intensity associated with flute playing, at the level of skeletal muscles, is best done in the context of resistance training. In this type of training, the parameters used as the basis to determine the intensity of an exercise are: RM (repetition maximum), MVC (maximum voluntary contraction) (ACSM, 2009), and sub-MVC (submaximal voluntary contraction) (Dankaerts, O'Sullivan, Burnett, Straker & Danneels, 2004). These parameters usually rely on the weight (in kilograms) of the load applied in a certain task. An electromyographical signal, nonetheless, can also be used to estimate the load on individual muscles (Hagberg, 1979), which, in turn, corresponds to a certain intensity level. While other studies have investigated the role (Levee, Cohen, & Rickles, 1976; Lapatki, Stegeman, & Jones, 2003; Iltis & Givens, 2005; Tolsma, 2010) and the disorders (Frucht et al., 2001; Lonsdale, 2011;

Termsarasab & Frucht, 2016; Storms, Elkins, & Strohecker, 2016) of facial muscles in wind instrument playing, to the knowledge of the researcher, as relates to the training of flute embouchure muscles and the exertion derived from the performance of basic exercises and standard pieces, specifically, such information is currently inexistent.

In his study on the use of exercise physiology principles to design a technical training program for classical guitarists, Özgen (2006) includes *velocity of* (hand) *movement* and the musical element of *tempo* (speed with which the musical excerpt is executed) in his definition of intensity. These variables, according to the author, could then be used to generate overload and improve the MCT (maximum comfortable tempo), which refers to the "fastest tempo that can be performed fluently with proper technique at a given dynamic level, articulation, and tone color" (p. 120-121).

Time. The matter of exercise duration, here referred to as time, is of particular importance for musicians. While literature shows that injury can also derive from the prolonged exposure to low-intensity exercises (Saxon & Schneider, 1995; Williams & Ratel, 2009), most instrument pedagogy disregard muscular limitations and often impose long practice sessions as well as long exercises. This is partly due to the fact that traditional methods for instrument learning are largely limited by conventions and reluctant to change (Visentin & Shan, 2011; Wulf & Mornell, 2008; Albrecht, Janssen, Quarz, Newell, & Schöllhorn, 2014). Galway, one of the most prominent flute players in the second half of the 20th century, compels students to practice for as long as they can stand it, in his book titled Flute (1982). This idea that skill acquisition is directly proportional to the volume of practice seems to be a consensus among music instrument teachers. Consequently, students have long been haunted by the idea that to experience great results they should undergo lengthy practice sessions for as many days as possible, if not every day of the week. What most likely allows such custom to persist is both the success of a minority group of players and the apparently harmless effects of flute playing. On this matter Williamon writes:

> Insistence on many hours of practice a day by some music schools and conservatories has led to a culture of work intensity (a recent brochure of one academy has stated that violin pupils are expected to practice 6 hours per day). An excessive workload on tired muscles—compounded by lack of instruction in correct posture, practice regime, and care of the body in general—is the most common cause of injuries with students. (2014, p. 12)

One example of a traditional yet long exercise practiced by flutists is the tone-development exercise proposed by Marcel Moyse in the first part of his method *De la Sonorité* (1934). It "is one of the most famous tone exercises written for the flute, consisting of melodic motion between subsequent half-steps throughout the range of the flute" (Fair, 2008, p. 38). Through Moyse's writing and teaching, his exercise gained international recognition. Its popularity then made it commonplace in players' daily practice routines. Even so, there are no studies verifying its effectiveness. The exercise requires the player to work on tone quality for a prolonged period of time (approximately 12 minutes) without breaks, focusing on the control over the embouchure muscles. These long periods of activation, nevertheless, may induce fatigue in the small perioral muscles of the embouchure, which as it has been shown, are predominantly composed of easily fatigued, fast-twitch fibers.

Contrarily to traditional exercises such as Moyse's, the literature suggests that a reduced training volume may actually enhance performance. A study by Costill et al. (1991) compared two groups of collegiate male swimmers during 25 weeks of training. For a period of 6 weeks (weeks 5-11), one of the groups trained three hours per day and the other trained 1,5 hours per day. Results showed that the group who trained longer experienced a decrease in sprinting velocity whereas the group who trained less experienced an increase in training velocity. This effect of the training volume has also been demonstrated in activities involving fine motor skills, such as typing. In a study by Baddeley and Longman (1978), four groups of postmen learned to type. Four different conditions were employed: sessions of one or two hours taking place once or twice per day. The results revealed that the group training one hour once per day had the most efficient learning, whereas the group with the greatest training volume (two sessions of two hours per day) showed the least efficient learning.

In spite of the applications demonstrated above, a great gap remains between the areas of instrument pedagogy and exercise physiology (Saxon & Schneider, 1995). As a result, little information is available regarding the relationship between specific music exercises and their respective muscle development. This leads to an inaccurate understanding of bodily functions, which could explain why some flute students often encounter plateaus, inconsistencies, performance-related injuries, and other problems in their learning process. This reflects the pressing need for a more profound understanding of the human muscular system and its interactions with music practice.

Chapter 4 – Methodology

Rationale, Research Questions and Hypotheses

Drawing on techniques engineered to enhance athletic training, a more stable and predictable technique-development process could be made available to students and teachers in order to optimize flute training, facilitate skill acquisition, and potentially minimize the aforementioned problems in students' learning process.

In order to be applied in flute training, exercise physiology knowledge, clearly established in sports, has to be defined in the context of musical exercises. This includes the training components of frequency, intensity, duration, and type. As the level of exertion generated by flute practice on embouchure muscles have not yet been systematically assessed, the training component of intensity remains without a musical equivalent.

The present study then addresses this issue by answering the question: how does embouchure muscle activation vary with (a) pitch, (b) a basic tone exercise, and (c) a standard piece of the repertoire? The main objectives in answering this question are: (1) to determine the relationship between pitch and muscle activation in all registers of the flute, (2) to verify if Moyse's tone exercise has a fatiguing effect on the musculature, and (3) to compare muscle recruitment during repertoire playing and exercise playing.

The main hypothesis of this study is that the level of activation in the embouchure muscles is a dependent variable of what is being played. Consequently, register should affect the intensity with which muscles are recruited. We hypothesize that this relationship between register and muscle activation is not linear, in which case different amplitude levels will be seen for different registers. The middle register will most likely elicit the lowest activation levels (close to rest condition) in all three muscles, as its execution probably requires a very relaxed and neutral embouchure. As pitch moves away from the middle register, more control and angulation are needed of the embouchure. Accordingly, in the low register, the depressor anguli oris (DAO) will likely be more active to help direct the airstream downward whereas the orbicularis oris superior (OOS) and zygomaticus major (ZYG) will show low activation levels. Inversely, in the high register, the OOS will probably be the most active muscle, followed by the DAO, and finally the ZYG. Overall, the activation levels in the high register should be higher due to the elevated air pressures.

Even though flute playing is not considered an intense cardiorespiratory activity because of its low oxygen consumption (McArdle, Katch & Katch, 2010), some exercises can highly tax specific muscles, and thus, be classified as strenuous. We hypothesize that Moyse's tone exercise may fatigue the embouchure musculature as a result from the lengthy exposure to stress with minimal variation and no breaks.

Finally, when comparing muscle recruitment during the execution of a piece of music and a technique-specific exercise, we hypothesize a distinct pattern will take place in terms of amplitude level and consistency of activation. Signals recorded during the exercise should reveal more constant and intense activation than during the piece. This discrepancy will possibly appear because musical exercises involve long, repetitive gestures that approximate static contractions whereas pieces of the repertoire generally include varying elements such as different pitches, articulation, rhythm, and rests, resembling dynamic tasks. The Bach sonata for flute in C major is a good example of a musical excerpt with great variability of musical parameters. Not only is it a standard piece of the repertoire, familiar to most students majoring in performance, but it also contains two contrasting tempi (andante and presto) as well as various articulations, dynamics markings (musical symbols to designate variations in loudness), and notes.

Musical Tasks and Protocol

The first part of the experiment involved a questionnaire concerning demographics, injury history, musical background, and practice habits. This informed the researcher of the current training condition of each player and how acquainted they were with Moyse's tone exercise. Then, after sensor placement and warm up, each participant performed the following sequential tasks (Figure 10): (a) hold still for 5 seconds; (b) play a 4-second long B3 four times; (c) play and sustain the notes C3, C4, C5, and C6 for four seconds, with a 4-second interval between them; (d) play the tone exercise number 1 and 1bis from the flute method *De la Sonorité* by Moyse, following the tempo instructions of the author (60 bpm); (e) repeat task described in (c); (f) take a 5-minute break; (g) play a chromatic scale from C3 to C6, sustaining each note for four seconds; (h) play the first movement of Bach's flute sonata in C major. The scores of these musical tasks may be found in Appendices D–G.

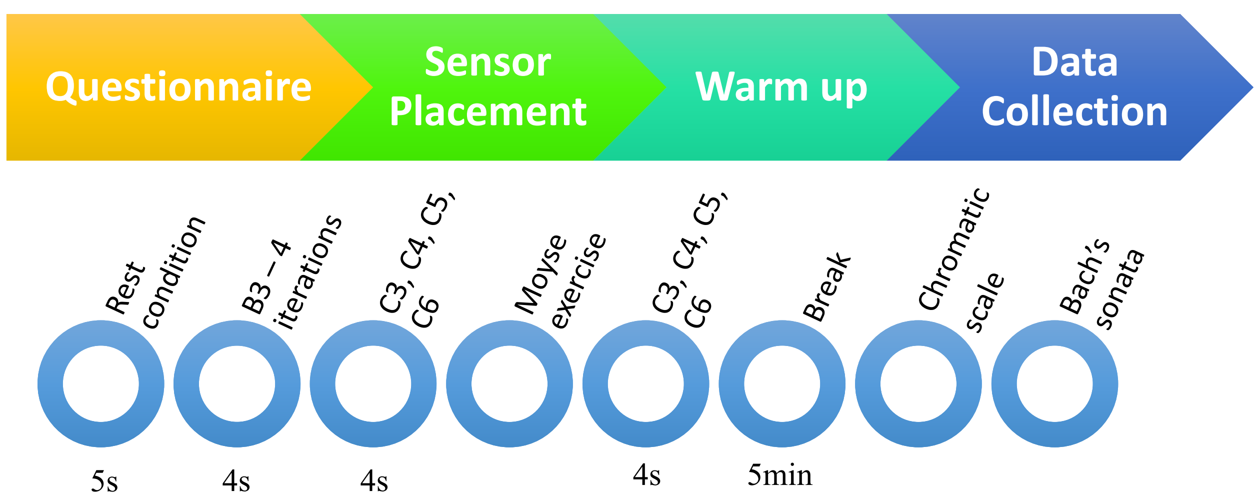

Figure 10. Steps of the study and sequential tasks performed by participants during data collection.

In tasks (b) through (g), participants were instructed to perform at a mezzo-forte[11] dynamic level and with a metronome. This was done to reduce variability, respectively, in their sound intensity and tempo (speed with which musical excerpts are played). In (g), the chromatic scale contained three octaves with a total of 37 pitches. These pitches were divided per octave (C3–B3, C4–B4, C5–C6), representing all three registers of the instrument, and their order of execution was randomized. Participants were asked to warm up for 5 minutes before the experiment began to familiarize themselves with the setup. The content of this warm up was limited to easy repertoire and simple exercises, none of them involving notes in the high register in order to avoid fatigue. No specific exercise was assigned at this point as each musician has their individual warm up routine. Forcing a different one might have increased tension levels and compromised the results.

Participants

Fourteen flute players, both male (n = 4) and female (n = 10), aged 18–50 ($\bar{x} = 26$), were recruited from McGill University and surrounding area. All of them had at least six years of experience on the flute ($\bar{x} = 14 \pm 6.7$ years) and were either pursuing or had completed a performance degree. The participants practice an average of 2.8 ± 1.1 hours per day and are all familiar with Moyse's tone exercise. Thirteen practice the exercise on a weekly basis from 1–7 days per week. Fifty percent of the participants experienced problems with performance-related musculoskeletal disorders (PRMDs) at the time of the experiment or at some point in their career. Three reported difficulties with their jaw, a phenotype that has been understood as indicator of

[11] Musical term that designates the dynamic (sound loudness) level with which a particular note or excerpt must be executed. It implies moderation. "Thus mezzo-forte is less loud than forte ; and mezzo-piano is less soft, therefore louder, than piano (Grove Music Online, 2001).

embouchure dystonia (Termsarasab, & Frucht 2016), although none of the participants presented themselves as suffering from such dysfunction, nor had they been officially diagnosed with it by a physician. When specifically asked about embouchure muscles, participants also denied suffering from the following symptoms, which have been previously associated with embouchure dystonia (Termsarasab, & Frucht 2016): discomfort, pain, numbness, and tingling. Participant 8 was pregnant at the time of the experiment. More detailed information is included in Table 5. The present study was approved by the McGill Research Ethics Board. Written informed consent was obtained from all participants prior to experimentation.

Table 5

Demographics, Musical Background, Practice Routine, and Injury History of Participants.

Participant	Age	Sex	Other instrument played on a weekly basis	Years of training on the flute	Hours per day spent practicing the flute	Type of instruction received prior to post-secondary music education	Practices Moyse's tone exercise how many times per week	Performs more frequently in which style	On average, exercises	Currently presents possible signs of embouchure dystonia	Has experienced symptoms of embouchure dystonia in the past	Has experienced PRMDs
1	23	F	N/A	12	2	lessons (private, conservatory, and at school)	4	Classical	occasionally	No	No	No
2	41	F	piano	31	2	lessons (private and conservatory)	6	Classical, rock	every day	No	No	No
3	50	M	clarinet	15	6	lessons (private, conservatory, and at school); autodidactic studies;	0	Classical, pop	every week	No	No	No
4	19	F	piano	9	3	lessons (private and at school)	7	Classical	every day	No	No	No
5	29	F	N/A	17	4	lessons (private, conservatory, and at school)	2	Classical	every few days	No	No	Yes
6	18	F	N/A	10	3	private lessons;	6	Classical	every day	No	No	No
7	24	M	piano	15	0.5	lessons (private and at school)	1	Classical, improvisation	every day	No	No	Yes

Participant	**Age**	**Sex**	**Other instrument played on a weekly basis**	**Years of training on the flute**	**Hours per day spent practicing the flute**	**Type of instruction received prior to post-secondary music education**	**Practices Moyse's tone exercise how many times per week**	**Performs more frequently in which style**	**On average, exercises**	**Currently presents possible signs of embouchure dystonia**	**Has experienced symptoms of embouchure dystonia in the past**	**Has experienced PRMDs**
8	34	F	piano	25	3-5	lessons (private, conservatory, and at school)	7	Classical	every few days	No	No	No
9	23	M	piano	16	**3**	conservatory lessons	5	Classical, jazz	rarely	No	No	Yes
10	19	F	keyboard	7	3-4	lessons (private, conservatory, and at school)	6	Classical	rarely	Yes	No	Yes
11	23	F	N/A	13	3	lessons (private and at school)	5	Classical	every day	Yes	No	Yes
12	19	F	piano	12	2.5	lessons (private and at school)	5	Classical	occasionally	No	No	No
13	22	M	piccolo	10	4	lessons (private and at school)	7	Classical	rarely	No	No	Yes
14	18	M	piano	7	3.5	private lessons	6	Classical	every few days	Yes	No	Yes

Measurements

After skin preparation (shaving of hair and cleansing of skin with alcohol), surface electromyography (sEMG) sensors were placed parallel to muscle fibers, in agreement with Lapatki, Stegeman and Jonas (2003), as indicated in Table 6. Attachment to the skin was done using specialized, double-sided adhesive tape (Delsys Trigno^{TM} adhesive, Boston, MA, USA). Figure 11 depicts sensor location over muscles. Three muscles were assessed bilaterally on the face: orbicularis oris (OO), zygomaticus major (ZYG) and depressor anguli oris (DAO). The orbicularis oris muscle has two parts, one of which, the lower portion (orbicularis oris inferior), cannot be measured because it is located at the same place where the flute is placed, therefore only the orbicularis oris superior (OOS) was monitored. Before the playing tasks, a 5-second recording was made without the instrument (task (a)) to measure the level of activation of the embouchure muscles in rest condition. sEMG signals (2KHz sampling rate, 16-bit resolution) were recorded using a Delsys Trigno^{TM} Wireless System (Delsys Inc., Boston, MA, USA), which included small reusable sensors (37 mm × 26 mm × 15 mm), with bipolar Ag (silver), bar-shaped electrodes distant 10 mm from one another. The system had an integrated amplifier, and common mode rejection ratio[12] (CMRR) was of 80 dB. Input impedance was less than 0.75 uV (value calculated as a root mean square over a 3-second window sampled at 1926 Hz). No gain was applied on the measurements. Sound and video data were recorded with a Sony camera (PMW-EX3) and a Neumann condenser microphone (km100) for future consultation. During the execution of the four iterations of the note B3, sound intensity was measured with a Kleton sound level meter (K7010).

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[12] "The common mode rejection ratio provides an index on the extent to which common signal components [e.g., signals from power sources and electromagnetic devices] are attenuated from the signal" (Day, 2002, p. 12).

Table 6

sEMG Sensor Placement and Behavioral Test

Channel	Muscle	Abbreviation	Location	Behavioral test
1	Right orbicularis oris superior	ROOS	Immediately above vermilion border, at midpoint between corner of mouth and midline of face.	Protrude lips as in whistling
2	Left orbicularis oris superior	LOOS		Protrude lips as in whistling
3	Rigth depressor anguli oris	RDAO	2 mm lateral to the corner of mouth, inferior one-half the distance from lower lip to the inferior border of chin.	Draw angles of the mouth downwards
4	Left depressor anguli oris	LDAO		Draw angles of the mouth downwards
5	Right zygomaticus major	RZYG	Midpoint between cheek bone and corner of the mouth.	Smile
6	Left zygomaticus major	LZYG		Smile

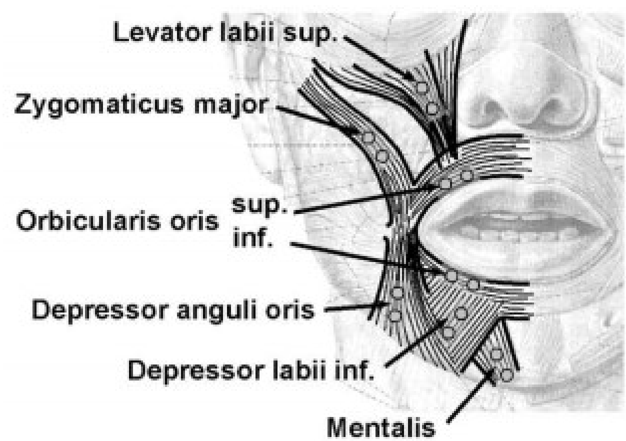

Figure 11. Representation of sEMG sensor location over the muscles orbicularis oris superior, depressor anguli oris, and zygomaticus major. Adapted from "A surface EMG electrode for the simultaneous observation of multiple facial muscles," by Lapatki, Stegeman & Jonas, 2003, *Journal of Neuroscience Methods*, 123*(2)*, 117-128. Copyright ©2018 by Elsevier. Used with permission.

Data Processing and Analysis

During acquisition, the sEMG sensors automatically filtered the raw signals with a built-in Butterworth bandpass filter (20-450 Hz). After demeaning the raw data and applying the necessary filters, as in the case of the comparative analysis described below, normalization was done based on the root mean square (RMS) value of the average of the activation levels measured during the four iterations of the note B3. This value was calculated for each muscle, separately. The reference for normalization was then a submaximal voluntary contraction (sub-MVC). This practice of using an alternate performance task to substitute the MVC for embouchure muscles has been advised in the literature as an acceptable solution (Iltis & Givens, 2005).

The signal-to-noise ratio (SNR) in the measurements was estimated based on the signals recorded during rest condition (representing noise) and during the first iteration of the note B3 (representing signal). Computations were done in Matlab R2016b (Mathworks^{TM}, USA), resulting in an average of 15.9 ± 1.7 dB across six muscles and across participants. Studies have established that, in order to be considered adequate (i.e., indicative of good signal quality), the SNR has to be ≥ 15 dB, when combined with other parameters (Sinderby, Lindström, & Grassino, 1995), or ≥ 18 dB (Fraser, Chan, Green, & MacIsaac, 2014). It is important to note, however, that participants showed minimum muscle activation during the execution of the note B3, thus the difference between noise and actual signal is likely clearer for all the other tasks.

To account for variations in sound intensity, the average of the sound intensity associated with (b) was recorded and will be reported. According to a study by Miśkiewicz and Rakowski (1994), the pressure level of a sound emitted by the flute ranges from approximately 70–90 dB. For the set of notes closest to B3, the results showed values roughly from 72.5–82.5 dB, when players were requested to execute in the extreme dynamic levels of pianissimo (very soft) and fortissimo (very loud), respectively.

For all the notes in (b), (c), (e) and (g), only the middle part (seconds 2 and 3) were considered in the analysis. An average of the activation in those 2-second periods was calculated and the results were understood as representative of the notes played.

Defective signals, depicted in Figure 12, were excluded from the analysis. The task during which they were identified and respective participant are indicated in Table 7.

Table 7

Muscle, Participant, and Task of Defective Signals Identified During Data Analysis.

Muscle	Participant	Task	Representation
LOOS	8	Sub-MVC	Figure 12A
LDAO	11	Chromatic scale	Figure 12B
LDAO, LZYG	14	Chromatic scale	Figure 12C
All	5	Tone exercise	Figure 12D

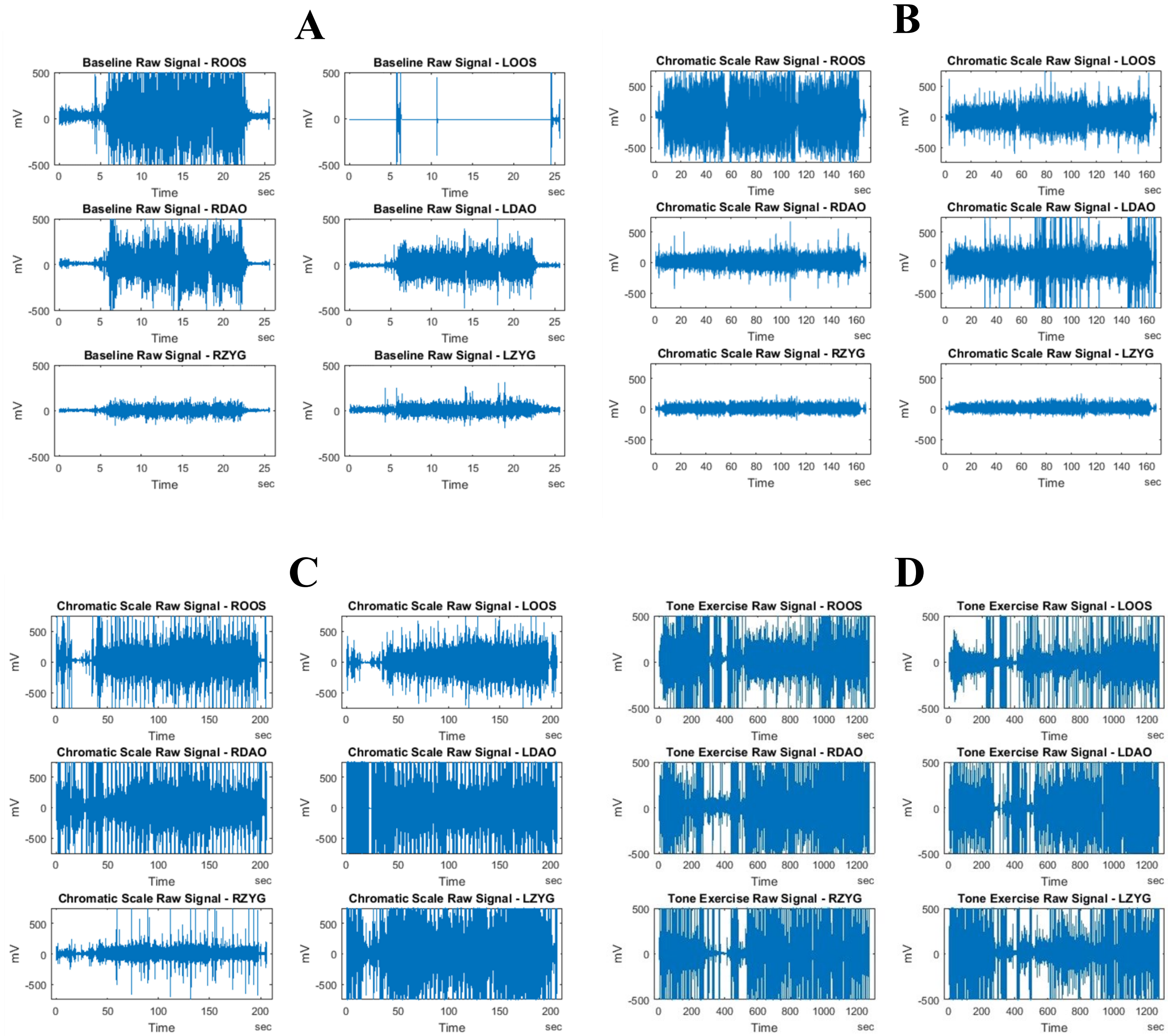

Figure 12. Defective signals identified during data analysis due to signal interruption (A) or heavy contamination with noise (B-D). A) LOOS of participant 8 during the baseline. B) LDAO of participant 11 during the chromatic scale. C) LDAO and LZYG of participant 14 during the chromatic scale. D) All the muscles of participant 5 during the tone exercise.

Data analysis was organized according to the three objectives in the study. Matlab R2016b (Mathworks^{TM}, USA) was used in all the computations. The main processes, summarized in Table 8, are explained below.

Table 8

Objectives of the Study, Protocol Tasks, and Associated Data Analysis Procedure.

Objective	Musical Tasks	Analysis Procedure
1- To determine the relationship between pitch and muscle activation	Task (g): Play the chromatic scale	i) Assessment of muscle activation variation in relation to pitch • Percent root mean square (%RMS) value for the activation of each muscle according to pitch; • Percent increase in the activation level for each muscle, measured from the lowest to the highest notes in the chromatic scale. • Graph of correlation between pitch and muscle activation across participants;
2- To verify if Moyse's tone exercise has a fatiguing effect	Task (c): Play the notes C3, C4, C5, and C6. Task (e): same as (c) after the tone exercise	ii) Comparison of the muscle activation during notes played immediately before and after the tone exercise: • %RMS values (González-Izal, Malanda, Gorostiaga & Izquierdo, 2012); ○ Correlation between fatigue level and participants' practice habits • Median power frequency (MPF); • Dimitrov's index (Dimitrov, Arabadzhiev, Mileva, Bowtell, Crichton & Dimitrova, 2006);
3- To compare muscle recruitment during the execution of an exercise and a piece of the repertoire	Task (d): Play Moyse's tone exercise. Task (h): Play Bach's sonata	iii) Comparison of muscle activation during the execution of the Bach's sonata and the Moyse's tone exercise: • Amplitude probability distribution function[13] (APDF) (Hagberg, 1979); • Histogram of mean muscle activation; • Smoothed curves of muscle activation;

[13] The APDF (amplitude probability distribution function) indicates, at different contraction levels, the probability of the myoelectric activity being lower than or equal to those contraction levels.

(i) Relationship between muscle activation and pitch along the three registers of the flute was carried out by analyzing the muscle activation variation among four specific notes (C3, C4, C5, and C6) which delimit each register. This was done to give a better sense of the relationship between muscle activation and pitch along the three registers of the flute.

(ii) In order to investigate the existence of a fatiguing effect associated with the Moyse's tone exercise, three parameters were used: a) percent root mean square (%RMS), b) median power frequency (MPF), c) and Dimitrov's fatigue index (FI_{nsmk}). All three assessments involved a comparison between the same set of notes (C3, C4, C5, and C6), which were executed immediately before and after the exercise.

a) The percent RMS value for the sEMG signal amplitude, which represents the level of activation of the muscles, was measured in relation to the sub-MVC task. According to the literature, muscle fatigue can be associated with an increase in the sEMG amplitude during isometric contractions (Dimitrov et al., 2006), thereby increasing the %RMS value. To assess the correlation between the practice habits of the participants and their fatigue level after the execution of the tone exercise, we examined the mean difference in the muscle activation (in %RMS) across all muscles for each participant and related this value to the total amount of hours each participant practices per week on average. The latter was calculated based on the participants' answers to the questionnaire, more specifically, the average time they spend practicing per day and the number of days they practice Moyse's tone exercise.

b) The MPF has also been shown to be effective in EMG analyses investigating fatigue. Indeed, in a fatigued condition, the frequency spectrum of the EMG signal shifts toward lower frequencies thus causing a decrease in the MPF (Phinyomark et al., 2012). In the present study, this parameter was obtained through the Matlab (Mathworks™, USA) function *medfreq*, which estimates the median normalized frequency of the power spectrum of a time domain signal. Before applying the function, sEMG signals were demeaned and fully rectified.

c) The Dimitrov's Fatigue Index was designed to surpass the low sensitivity of the MPF and adequately reflect the changes in the muscle during peripheral fatigue (Dimitrov et al., 2006). It is expressed in terms of the relative change between repetitions of an exercise. The first iteration is taken as 100% and the subsequent repetitions are expressed as a percentage of that 100% reference. An increase in this relative change, i.e., values above 100%, suggests the presence of muscle fatigue. The index was calculated in agreement with the study by Miranda et al. (2018) using the spectral moment of order 5, which has been indicated to yield the best results (González-Izal, Malanda, Gorostiaga, & Izquierdo, 2012). The computations included a code developed by Niklas Brown (Stuttgart University, 2015).

(iii) Finally, the comparative analysis of the muscle activation during the tone exercise and the repertoire piece was done using three techniques: a) the amplitude probability distribution function (APDF), b) the muscle activation histogram and c) the muscle activation smoothed curves. In all the techniques' calculations the average amplitude signals were fully rectified, linear enveloped with a low-pass Butterworth filter of fourth order (cut off frequency of 5Hz), and normalized to the sub-MVC task once this normalizing value had undergone the same processes.

Moyse's exercise was considerably longer than the piece (average duration of 14min 36s across participants), which lasted, on average, 109 seconds across participants. Thus, to ensure that the analysis was carried out on musical tasks of approximately equal duration, the comparison between both excerpts was conducted using the piece in its entirety and the initial and final 109 seconds of the exercise.

a) The amplitude probability distribution function (APDF) was applied in agreement with Hagberg (1979) and Jonsson (1982), expressing probability over a percentage of the sub-MVC. Its main purpose was to determine two important aspects of muscle recruitment: overall intensity level and intensity variability during each task. The overall intensity was associated with the location of the curve along the X-axis, whereas the intensity variability was associated with the inclination of the most linear portion of the curve. To enable the comparison between the curves for each task, threshold values were used for each parameter: the X-axis location was compared based on the intensity level associated with 50% of probability, which Hagberg (1979) terms *median force of contraction*, and the inclination (α) was compared based on the angle of the most linear portion of the curves, here considered as the section of the graph where $0.2 \leq y \leq 0.8$. To estimate the median force of contraction and the inclination of the lines in the APDF, the data points within the specified range were inputted to Matlab R2016b (Mathworks^{TM}, USA) so that the linear function that best fitted the section could be identified.

b) The histogram of the mean activation in each muscle across participants was produced with a fixed number of bins (200).

c) The smoothed curves were generated with an additional moving average filter with a 1-second window (2001 data points). In the curve representing the piece of repertoire, we indicated the average (± SD) point at which participants transitioned from the slow to the fast section. This point was identified aurally, after a review of the audio recordings, and reported as a percentage of the duration of the piece.

Statistical Analysis

To verify the significance in the relationship between pitch and muscle activation (Objective 1), we conducted a) a Pearson correlation coefficient (*r*) statistical analysis between both variables. Taylor (1990) cites a convention according to which a strong correlation is identified when the absolute value of *r* is between 0.68 and 1. The analysis also included b) the mean and standard deviation of the activation level in each muscle across participants, c) a one-way repeated measures ANOVA ($p \leq 0.05$) on the amplitude of muscle activation measured at each pitch, and d) an ANOVA with post hoc analysis (Bonferroni correction) on the notes C3, C4, C5, and C6. The scrutiny of these specific notes revealed how muscles behaved along the registers and where the statistically significant change was located.

To verify if the Moyse's tone exercise had a fatiguing effect (Objective 2), a one-tailed *t*-test (significance level of $p = 0.01$) was applied on the group of notes played before and after the exercise. Three independent tests were conducted, one for each of the calculations applied, i.e., Dimitrov's fatigue index, MPF, and RMS. The correlation between participants' practice habits and fatigue level was assessed through Pearson's correlation coefficient (*r*).

The comparative analysis between the exercise and the piece (Objective 3) involved a two-way repeated measures ANOVA ($p = 0.05$) with a post hoc test (Bonferroni) on the values of median force and inclination for the initial and final portions of the exercise and for the piece of repertoire.

Finally, the statistical analysis also included a power analysis based on the %RMS results for the reference notes C3, C4, C5, and C6 played before and after the tone exercise. An online power calculator was used for this computation.

Chapter 5 – Results

Rest Condition

The activation level in rest condition without the instrument was measured for each participant before the playing tasks. The average values are reported in Table 9. All muscles showed an activation close to 20% of the sub-MVC task. Data from participant 8 were not included in this analysis due to a defective signal.

Table 9

Average Muscle Activation in Rest Condition.

Muscle group	**Activation level (%RMS)**	**σ**
ROOS	18.53	±13.48
LOOS	23.29	±13.35
RDAO	21.43	±17.29
LDAO	24.75	±21.75
RZYG	23.38	±13.52
LZYG	27.76	±18.98

Sound Intensity

Sound intensity measurements demonstrated in Table 10 reveal that participants had a similar notion of the mezzo-forte dynamic level. The average value across participants was 71.6 ± 4.1 dB. Participants 14 and 3 respectively featured the highest (78.1 dB) and the lowest (65.3 dB) sound intensity during the four iterations of the note B3 used for normalization.

Table 10

Mean Sound Intensity During sub-MVC Task.

Participant	**Sound level (dB)**	**σ**
1	68.9	±1.8
2	73.7	±2.3
3	65.3	±3.0
4	66.6	±1.4
5	72.8	±0.9
6	78.7	±2.0
7	67.5	±2.3
8	72.4	±2.2
9	69.5	±1.8
10	75.7	±2.5
11	70.1	±2.1
12	69.1	±1.9
13	73.3	±1.9
14	78.1	±3.8
	$\bar{x} = 71.6$	**±4.1**

Correlation Between Pitch and Muscle Activation

The analysis of muscle activation as a function of pitch during the chromatic scale consisted of two main assessments: the observation of each separate muscle (Figure 13) across participants and the examination of all six embouchure muscles in relation to one another. Data from the LOOS of participant 8, the LDAO of participant 11, and the LDAO and LZYG of participant 14 were removed from this analysis due to a defective signal.

The single-muscle observation revealed a quasi-linear relationship with an increase in the activation level as pitch moved toward the high register. This correlation was verified through the Pearson correlation coefficient showed in Table 11. The positive values close to 1.0 indicate a very strong, direct correlation.

Table 11

Pearson's Correlation Coefficient Between the Mean Activation of Each Muscle and Pitch, During the Chromatic Scale.

	ROOS	*LOOS*	*RDAO*	*LDAO*	*RZYG*	*LZYG*	*Pitch*
ROOS	1						
LOOS	0.99	1					
RDAO	0.96	0.93	1				
LDAO	0.92	0.92	0.95	1			
RZYG	0.90	0.88	0.95	0.95	1		
LZYG	0.87	0.87	0.90	0.93	0.93	1	
Pitch	0.99	0.98	0.96	0.91	0.89	0.85	1

Figure 13A exemplifies the changes in activation level for each muscle in relation to pitch, as seen with participant 1. The values are a percentage RMS of the sub-MVC task. The increase tendency seen in Figure 13A is however present in the results of all participants. Figure 13B confirms this observation with the mean activation and standard deviations for the ROOS muscle across participants. More results regarding the activation levels recorded during the chromatic scale can be found in Appendices A and B.

Table 12 shows the total increase in activation from the lowest pitch (C3) to the highest (C6), measured for each muscle during the chromatic scale. This was calculated based on the mean activation for each muscle across participants. The largest increase (111.8%) was seen on the right side of the depressor anguli oris (RDAO) whereas the smallest increase (30.1%) was seen on the left side of the zygomaticus major (LZYG). A one-way repeated measures analysis of variation (ANOVA) was used to evaluate the change in the level of activation of each muscle. Pitch was used as the within-subject factor. Results, presented in Table 12, show that all muscles had a significant change with $p \leq 0.001$.

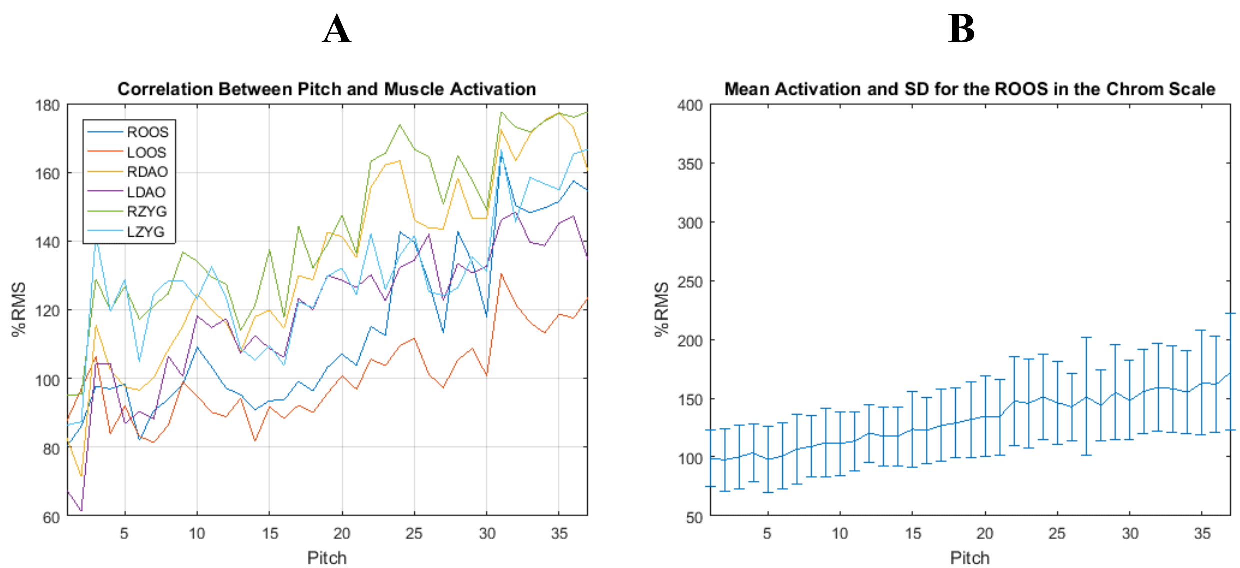

Figure 13. Correlation between pitch and muscle activation. All the pitches in a chromatic scale from C3–C6 are numerically represented from 1–37. A) %RMS of sub-MVC for participant 1, measured for each muscle during the execution of the chromatic scale. B) Mean activation and standard deviation of the %RMS of sub-MVC for the ROOS across participants, measured during the execution of the chromatic scale.

Table 12

Total Percent Increase of Activation (from C3 to C6) and *p*-value for the Repeated-Measures ANOVA during the Chromatic Scale.

Muscle group	**Total increase (%)**	***p* value**
ROOS	74.3	<0.001
LOOS	95.2	<0.001
RDAO	111.8	<0.001
LDAO	69.2	<0.001
RZYG	48.5	<0.001
LZYG	30.1	<0.001

Figure 14 contains the mean activation level and standard deviations measured during the chromatic scale, more precisely at the notes C3, C4, C5, and C6, which delimit the three registers of the flute. Results demonstrate that each register is associated with successively higher muscle activations in a relatively linear fashion. This seems true in the orbicularis oris and depressor anguli oris muscles. In the zygomaticus major, the level of activation is similar in the low and middle registers. A significant increase appears only in the high register.

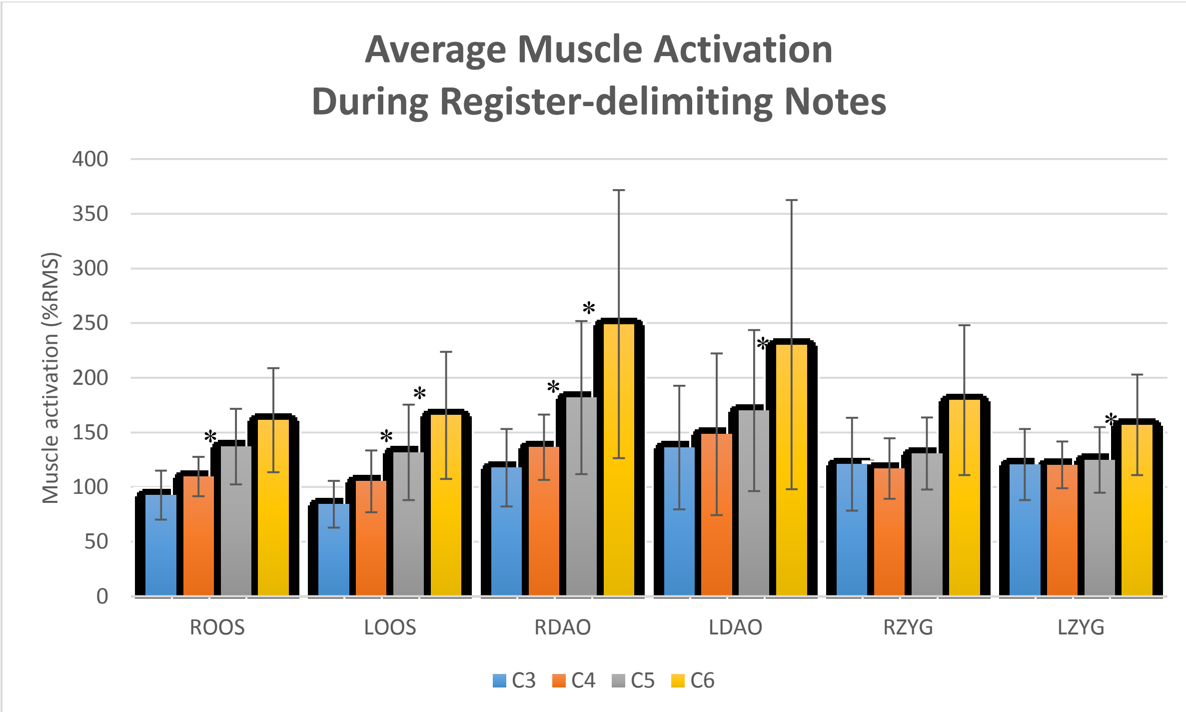

Figure 14. Mean and SD of muscle activation during the chromatic scale. %RMS values of sub-MVC during the notes C3, C4, C5, and C6 (register-delimiting notes) are presented. A one-way ANOVA revealed that all the changes observed in the transitions between registers are significant. A more conservative post hoc test, however, indicated that not all muscles presented a statistically significant variation in all the registers. * indicates the register transition where the change in activation is statistically significant according to the post hoc test.

A one-way repeated ANOVA was applied to the changes between these four landmark notes in each muscle. A statistically significant difference was found in all of them. The more conservative post hoc test (Bonferroni correction for multiple comparisons), nevertheless, using a two-tailed *t*-test, revealed which register transitions (C3-C4, C4-C5, C5-C6) actually involved a significant variation in the level of activation of the muscles. The corrected *p* value was $p \leq 0.0125$. The register transitions with significant change are indicated in Figure 14. No significant changes were observed in the low register (C3-C4). The middle register (C4-C5) showed significant changes in the ROOS, LOOS, and RDAO. The high register (C5-C6) showed significant changes in the LOOS, RDAO, LDAO, and LZYG. These results suggest that the muscles of the flute embouchure feature asymmetric changes in their level of activation with each side functioning independently from one another.

The collective examination of the six embouchure muscle groups through all the notes in the chromatic scale, albeit less obvious, also yielded some interesting findings. The muscles interacted quite differently for each player yet at least three groups of patterns were observed. Figure 15A-C exemplifies them:

a) Gradual: All six muscles showed a gradual, somewhat uniform, increase in their activation level as pitch moved up. This was seen with participants 1, 2, 11, and 12—Figure 15A.
b) Constant: In this pattern, muscles seemed less sensitive to pitch thus showing less variation. An increase was perceived only near the end of the high register. This behavior was noticed with participants 3, 5, and 13—Figure 15B.
c) Selective: With participants 6, 7, 8, and 10, the embouchure muscles were selectively recruited showing independent activation variations—Figure 15C. Part showed an increase and part remained constant or even showed a decrease in their activation level. In some cases (participants 6 and 10), there were sudden changes in the activation as register changed.

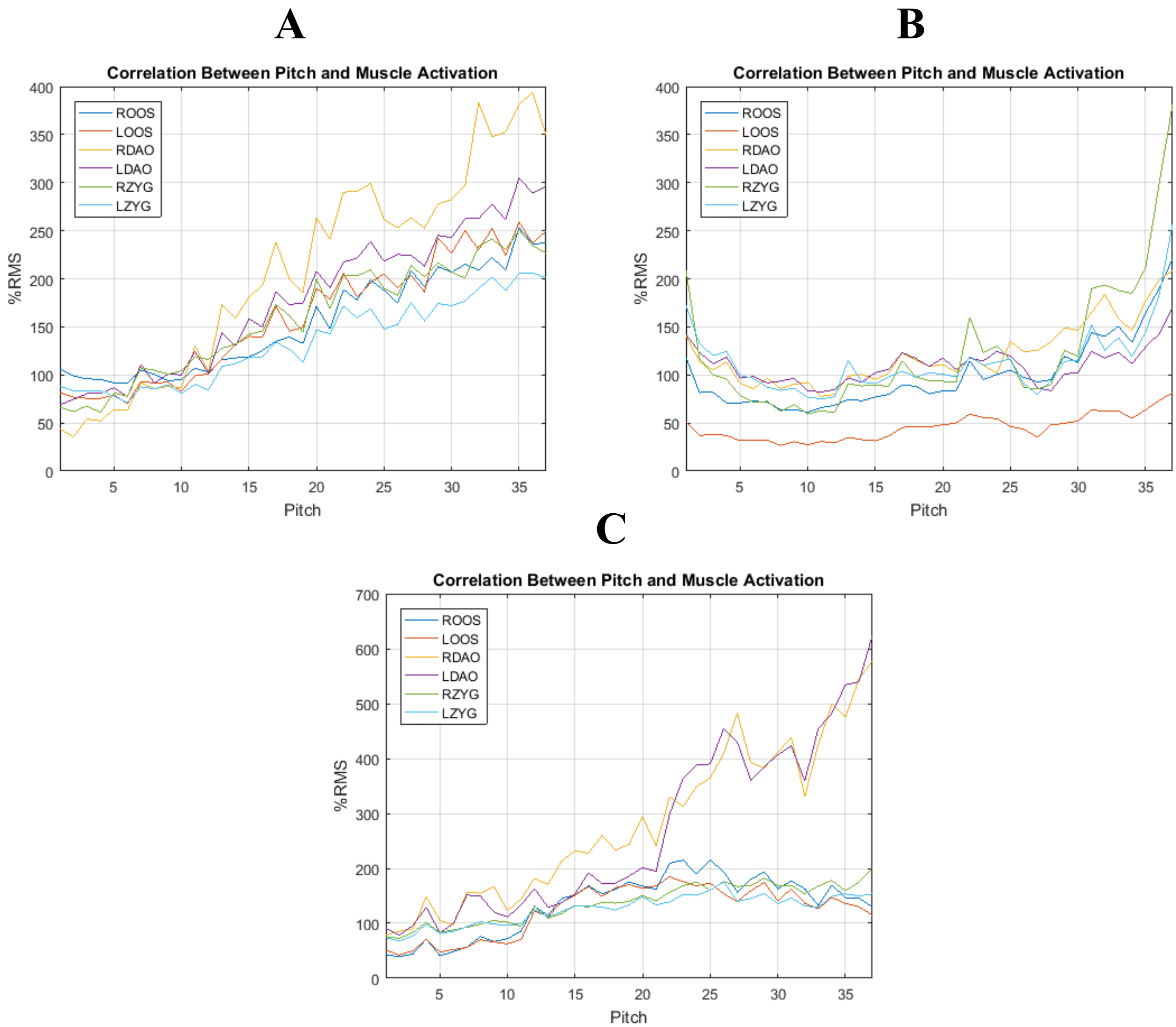

Figure 15. Patterns of interaction of embouchure muscles during the chromatic scale. A) Gradual pattern, observed in the results of participants 1, 2, 11, and 12, here illustrated with the results of participant 2. B) Constant pattern, observed in the results of participants 3, 5, and 13, here illustrated with the results of participant 3. C) Selective pattern, observed in the results of participants 6, 7, 8, and 10, here illustrated with the results of participant 7.

Another relevant phenomenon identified was the consecutive increase and decrease in the activation level of multiple muscles. This was largely present throughout the chromatic scale, producing a serrated graph as opposed to a smoother curve. In some cases, three or more muscles featuring this behavior synchronized for brief periods. This synchronization, illustrated in Figure 16, was noticed with six participants (2, 4, 6, 7, 10, 11).

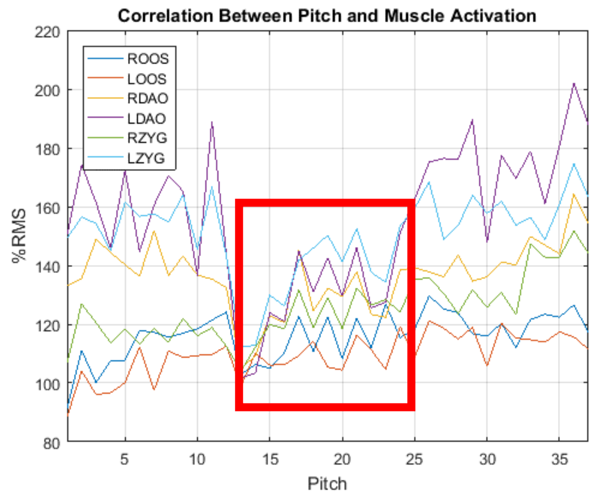

Figure 16. Consecutive increases and decreases in muscle activation during the chromatic scale. For brief periods, this phenomenon happened in a synchronized manner among multiple muscles, as seen in the results of participant 10.

Tone Exercise Fatiguing Effect

Data referring to the LOOS of participant 8 were excluded from these analyses due to a defective signal.

1st Parameter – %RMS. Results, seen in Table 13, are based on the average activation at each reference note, i.e., C3, C4, C5, and C6, prior and posterior to the tone exercise. The increase in the average activation suggests the existence of fatigue in all the muscles. While a large standard deviation suggested that this observation was not significant, a one-tailed *t*-test demonstrated otherwise for $p \leq 0.01$. The post hoc power for these results returned a value of 75.2%[14]. Table 14 includes the differences in activation for each reference note in each muscle. Its positive values show that there was indeed an increase in the percent activation in all the muscles and that this

[14] The power of a study determines the probability that a false null hypothesis will be rejected. The literature does not establish standards regarding minimum statistical power values. However, it has been recommended that studies should be designed aiming for a power of .80 (Cohen, 1988).

increase was observed in all the registers. The DAO was the muscle with the highest average increase in activation (48.04).

Table 13

Average Activation Before and After Tone Exercise, at Each Reference Note, Across Participants

	Activation level at C3 (%RMS)		**Activation level at C4 (%RMS)**		**Activation level at C5 (%RMS)**		**Activation level at C6 (%RMS)**	
Muscle Group	***before***	***after***	***before***	***after***	***before***	***after***	***before***	***after***
ROOS	85.24 ±28.24	99.73 ±23.81	96.80 ±11.78	123.96 ±37.14	130.58 ±26.64	144.05 ±42.95	156.39 ±54.69	160.97 ±57.44
LOOS	83.73 ±28.76	83.99 ±17.03	98.71 ±14.78	111.83 ±35.05	137.88 ±26.19	159.69 ±65.68	159.31 ±41.71	171.51 ±77.72
RDAO	97.30 ±31.55	129.32 ±41.08	110.04 ±22.02	154.32 ±32.17	147.91 ±31.91	204.30 ±72.75	196.09 ±68.03	255.56 ±139.96
LDAO	110.91 ±43.44	143.15 ±68.64	106.72 ±19.67	153.24 ±35.66	132.25 ±20.13	180.80 ±46.54	174.17 ±49.70	217.69 ±72.00
RZYG	113.32 ±52.68	144.14 ±54.61	107.41 ±29.70	152.97 ±38.69	127.08 ±39.43	169.87 ±50.79	163.06 ±71.16	191.73 ±75.75
LZYG	120.80 ±53.33	139.47 ±77.64	113.97 ±29.98	160.37 ±89.92	119.46 ±20.21	161.13 ±54.45	139.86 ±28.26	161.86 ±45.69

Table 14

Activation Increase After Tone Exercise

Muscle Group	**Activation difference at C3 (Δ%RMS)**	**Activation difference at C4 (Δ%RMS)**	**Activation difference at C5 (Δ%RMS)**	**Activation difference at C6 (Δ%RMS)**	**$\bar{x}$ (%RMS)**
ROOS	+14.50	+27.16	+13.48	+4.58	**+14.93**
LOOS	+0.26	+13.13	+21.81	+12.20	**+11.85**
RDAO	+32.02	+44.28	+56.39	+59.47	**+48.04**
LDAO	+32.24	+46.52	+48.55	+43.52	**+42.71**
RZYG	+30.82	+45.56	+42.79	+28.67	**+36.96**
LZYG	+18.67	+46.40	+41.67	+22.00	**+32.18**

Correlation between practice habits and fatigue level observed after tone exercise. The correlation between participants' practice habits and level of fatigue, illustrated in Figure 17, seems fairly weak, r = 0.513541. Results, shown in Table 15, are inconclusive although the higher increases in activation tend to be associated with participants practicing over 20 hours per week. The participant with the highest fatigue level, represented in red, practices 20 hours a week on average, whereas the participant with the lowest fatigue level practices 8 hours a week. Participant 3 had a decrease in the myoelectric signal amplitudes after the exercise.

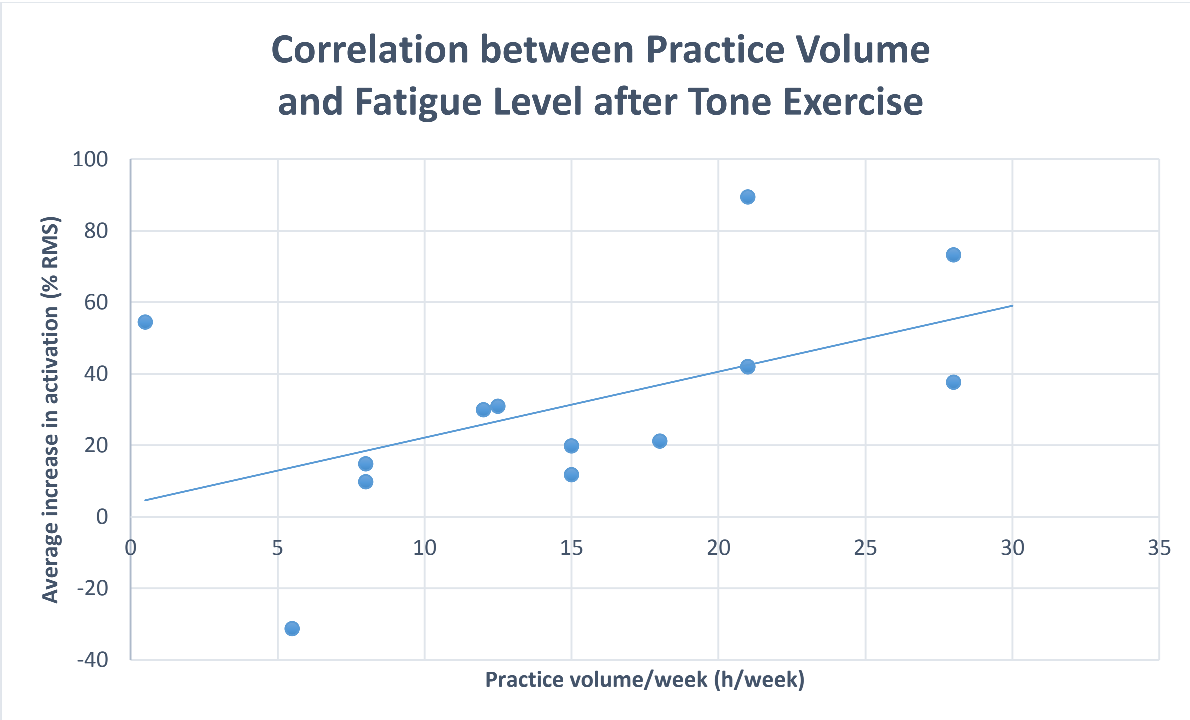

Figure 17. Correlation between practice volume and level of fatigue recorded after the tone exercise. Fatigue is indicated through the increase of the signal amplitude, measured in % RMS.

Table 15

Correlation Between Participants' Practice Habits and Fatigue Level

Participant	**Age**	**Sex**	**Hours of practice per day**	**Days of practice per week**	**Hours of practice/week**	**Average increase in activation (%RMS)**
3	50	M	1	5-6	5.5	-31.26
5	29	F	4	2	8	9.83
11	23	F	3	5	15	11.8
1	23	F	2	4	8	14.87
9	23	M	3	5	15	19.88
6	18	F	3	6	18	21.14
2	41	F	2	6	12	29.91
12	19	F	2.5	5	12.5	30.93
13	22	M	4	7	28	37.62
4	19	F	3	7	21	41.91
10	19	F	3-4	6	21	42
7	24	M	0.5	1	0.5	54.43
8	34	F	3-5	7	28	73.24
14	18	M	3.5	6	21	89.49

Note. Results are in order of increasing average activation.

2nd Parameter – MPF. The comparison between the MPF values before and after the tone exercise (Table 16) revealed a decrease in the median frequency in all the muscles and at all reference notes, suggesting a fatigued state of the muscle. The one-tailed *t*-test ($p \leq 0.01$) showed that this decrease was statistically significant. Table 17 summarizes the MPF decrease found in each muscle at each reference note. The left side of the OOS was the muscle with the highest average decrease in MPF (20.60).

Table 16

MPF Values Before and After the Tone Exercise, at Each Reference Note, Across Participants.

	Activation level at C3 (Hz ± SD)		**Activation level at C4 (Hz ± SD)**		**Activation level at C5 (Hz ± SD)**		**Activation level at C6 (Hz ± SD)**	
Muscle	***before***	***after***	***before***	***after***	***before***	***after***	***before***	***after***
ROOS	104.11 ±13.41	81.78 ±21.56	100.16 ±9.36	78.68 ±16.68	100.95 ±11.69	84.45 ±15.34	97.03 ±18.69	87.09 ±14.96
LOOS	95.10 ±18.25	75.24 ±21.85	95.29 ±18.15	71.69 ±14.32	99.06 ±19.95	76.28 ±22.01	99.19 ±19.18	83.02 ±24.56
RDAO	76.72 ±11.87	57.03 ±11.50	76.44 ±10.77	56.53 ±11.03	81.49 ±12.06	61.79 ±10.73	78.91 ±10.54	61.82 ±11.27
LDAO	76.15 ±28.36	59.22 ±14.78	78.88 ±26.19	64.09 ±22.12	78.32 ±15.72	58.69 ±16.05	79.34 ±13.38	64.80 ±13.11
RZYG	70.97 ±10.51	57.88 ±9.71	73.81 ±12.81	59.62 ±11.35	76.30 ±13.05	62.17 ±12.51	74.94 ±11.25	65.23 ±12.71
LZYG	66.86 ±16.79	57.58 ±21.77	68.09 ±17.92	61.10 ±20.59	70.39 ±20.44	60.28 ±15.09	66.35 ±16.77	63.70 ±18.12

Table 17

MPF Decrease After Tone Exercise, at Each Reference Note, Across Participants.

Muscle Group	**Activation difference at C3 (ΔHz)**	**Activation difference at C4 (ΔHz)**	**Activation difference at C5 (ΔHz)**	**Activation difference at C6 (ΔHz)**	**$\bar{x}$ (ΔHz)**
ROOS	-22.34	-21.48	-16.50	-9.95	**-17.57**
LOOS	-19.87	-23.60	-22.78	-16.17	**-20.60**
RDAO	-19.69	-19.91	-19.70	-17.09	**-19.10**
LDAO	-16.92	-14.79	-19.64	-14.54	**-16.47**
RZYG	-13.09	-14.19	-14.13	-9.71	**-12.78**
LZYG	-9.29	-6.99	-10.11	-2.65	**-7.26**

3rd Parameter – Dimitrov's fatigue index. Results, depicted in Figure 18, demonstrate the relative change in the Dimitrov's index after the tone exercise. Even though all the muscles showed an increase in the fatigue index indicating the presence of fatigue, the difference between the values before and after the tone exercise was not significant according to a two-tailed *t*-test using $p = 0.05$ as the significance level. Table 18 contains the mean relative change of fatigue index for each muscle. LOOS, RDAO, and LDAO had equally high increases indicating more fatigue.

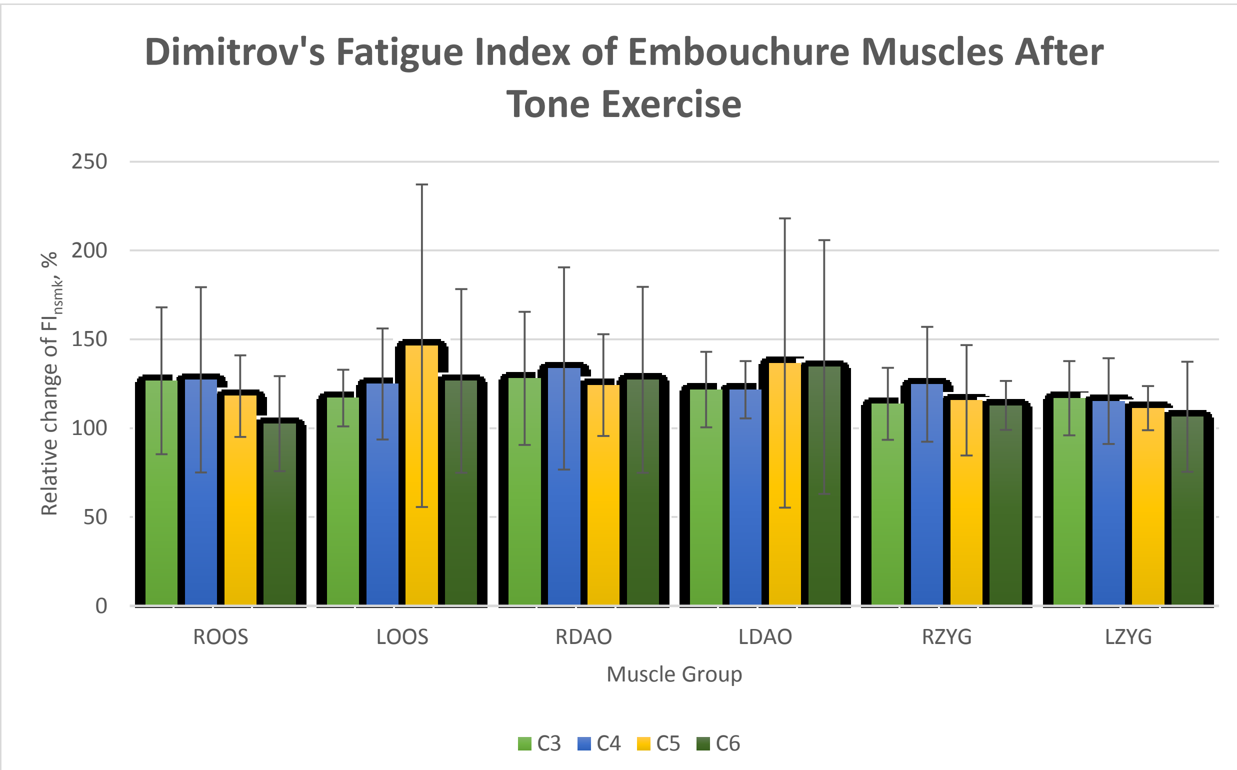

Figure 18. Dimitrov's fatigue index (FI_{nsmk}) per muscle group. The index, calculated with order k = 5 of the normalizing spectral moment. Results were measured at each reference note and are presented with the respective standard deviation error bars. Data are represented as relative change against the corresponding index value for the measurement before the tone exercise.

Table 18

Mean Relative Change of Dimitrov's Fatigue Index

Muscle Group	$\bar{x}$ (%)	σ (%)
ROOS	18.60	±35.79
LOOS	28.73	±47.40
RDAO	28.30	±43.83
LDAO	28.61	±47.54
RZYG	16.70	±24.37
LZYG	12.48	±22.14

Comparison Between Tone Exercise and Piece of Repertoire

The differences in muscle recruitment during the execution of a basic tone exercise (Moyse's exercise) and a standard piece of repertoire (Bach sonata in C major) was first assessed through the amplitude probability distribution function (APDF). Results for the average activation across participants for the initial and final portions of the exercise, and for the piece are represented in Figure 19. As it can be seen, the curve representing the initial portion of the tone exercise is located to the left of the curves representing the final portion and the piece of repertoire for all the muscles. This indicates an overall inferior level of muscle activation during the initial portions of the exercise. Moreover, the inclination (α) of the most linear portion of the curves ($\text{here adopted as } 0.2 \leq y \leq 0.8$) for the piece of repertoire seems to be inferior to the one for the initial portion of the exercise for all the muscles, more so for the RDAO, LDAO, and LZYG suggesting more variability of intensity level in these muscles' activation during the piece.

The curves representing the final portion of the exercise, however, are dislocated to the right on the X-axis in relation to the curves representing the initial portion of the exercise, suggesting greater levels of activation. This discrepancy between the initial and the final portions of the exercise is in agreement with the previous analyses in this study, as both the high register and the accumulated fatigue present in the final portion have been shown to elevate muscle activation.

A comparison between the curves for the final section of the exercise and the piece shows what appears to be an overlap in the ROOS, LOOS, and RZYG muscles. In the remaining muscles (RDAO, LDAO and LZYG), nonetheless, the piece surpasses the exercise, both in activation and variability.

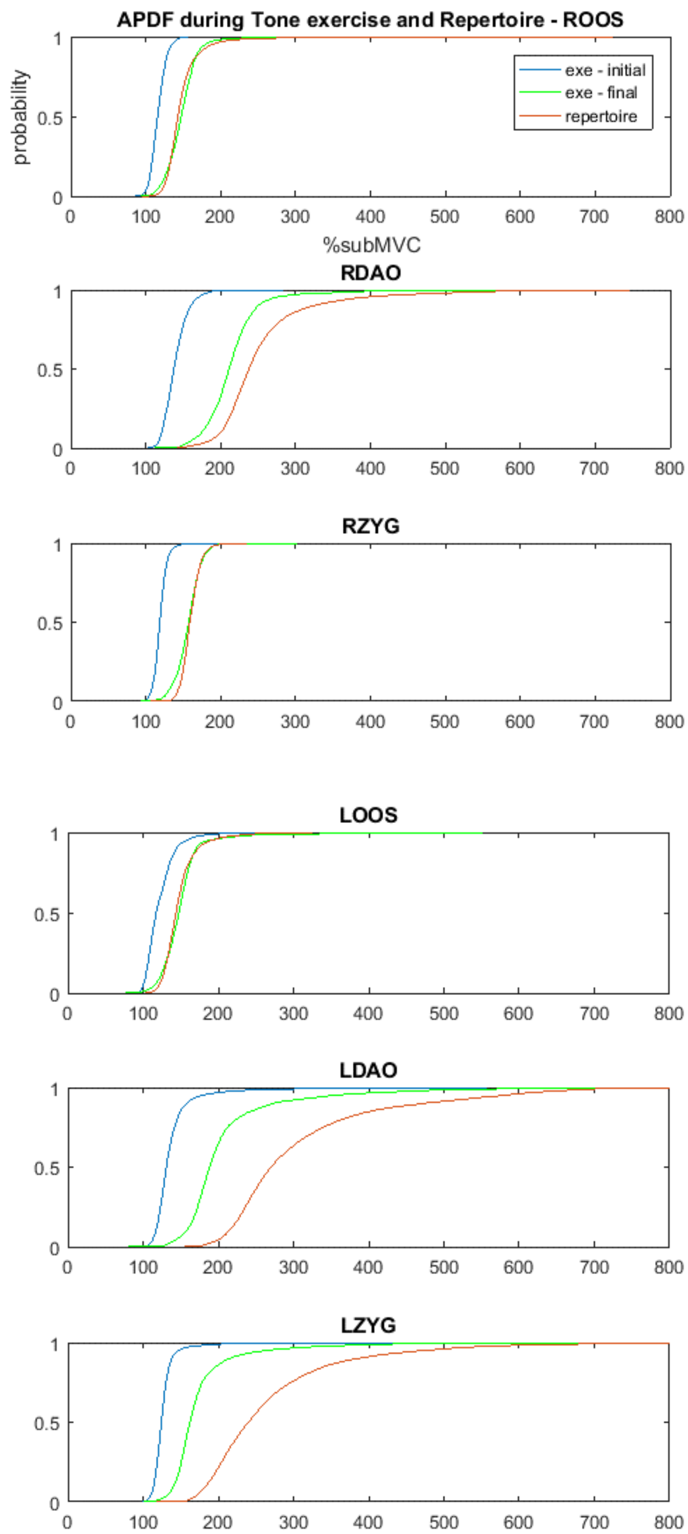

Figure 19. Amplitude probability distribution function (APDF) for the average activation during the tone exercise and piece of repertoire. The blue line represents the initial portion of the exercise, the green line, the final one, and the red line, the piece of repertoire.

Table 19 contains the median force of contraction and the inclination of the curves, in degrees, representing both the tone exercise—initial and final portions—and the piece of repertoire. These results show that the initial portion of the Moyse's tone exercise may elicit less muscle activation but also with variability. Except for the LOOS, the approximate inclination of the exercise curves (initial section) is greater than the inclination of the repertoire curves. In other words, there is a higher probability that lower intensity levels will be used during the exercise, and these lower levels will be more constant throughout the initial portion of the exercise than during the Bach sonata. The verticality quality of the exercise curves also implies more resemblance with static contractions.

Table 19

Estimated Median Force of Contraction and Inclination for the Tone Exercise and Piece of Repertoire.

	Tone Exercise				**Piece of Repertoire**	
	Initial portion		**Final portion**			
Muscles	*Median force of contraction (% of subMVC)*	*α (°)*	*Median force of contraction (% of subMVC)*	*α (°)*	*Median force of contraction (% of subMVC)*	*α (°)*
ROOS	113.28	80.02	142.20	76.69	139.51	78.19
LOOS	113.99	74.08	141.64	76.67	139.88	77.46
RDAO	133.88	77.99	204.15	76.22	229.01	73.44
LDAO	127.89	78.19	181.78	73.05	254.06	62.94
RZYG	116.79	82.91	152.82	79.15	155.97	81.71
LZYG	122.09	82.01	157.12	75.11	224.49	63.37

Note. A significant difference ($p < 0.05$) in the median force of contraction and inclination angles was observed between the three conditions assessed (initial and final portions of the exercise, and repertoire piece).

A two-way repeated-measures ANOVA with $p = 0.05$ on the values in Table 19 pointed that there was a significant difference between the conditions (i.e., initial portion of exercise, final portion of exercise, and piece). The post hoc analysis (Bonferroni correction), on the other hand, did not confirm that the variation was significant.

The histogram of the average of the normalized signals for each task is represented in Figure 20. The differences within the exercise are somewhat consistent in all the muscles, as the levels of activation are higher in the final portion than in the initial. However, the final portion of the exercise seems to feature higher counts than the initial portion in the ROOS, LOOS, and RDAO muscles, indicating less variability. The differences between the exercise and the piece are not as clear. Even so, it is possible to observe in the RDAO, LDAO, and LZYG, that the repertoire elicits higher activation levels yet with inferior counts than the exercise.

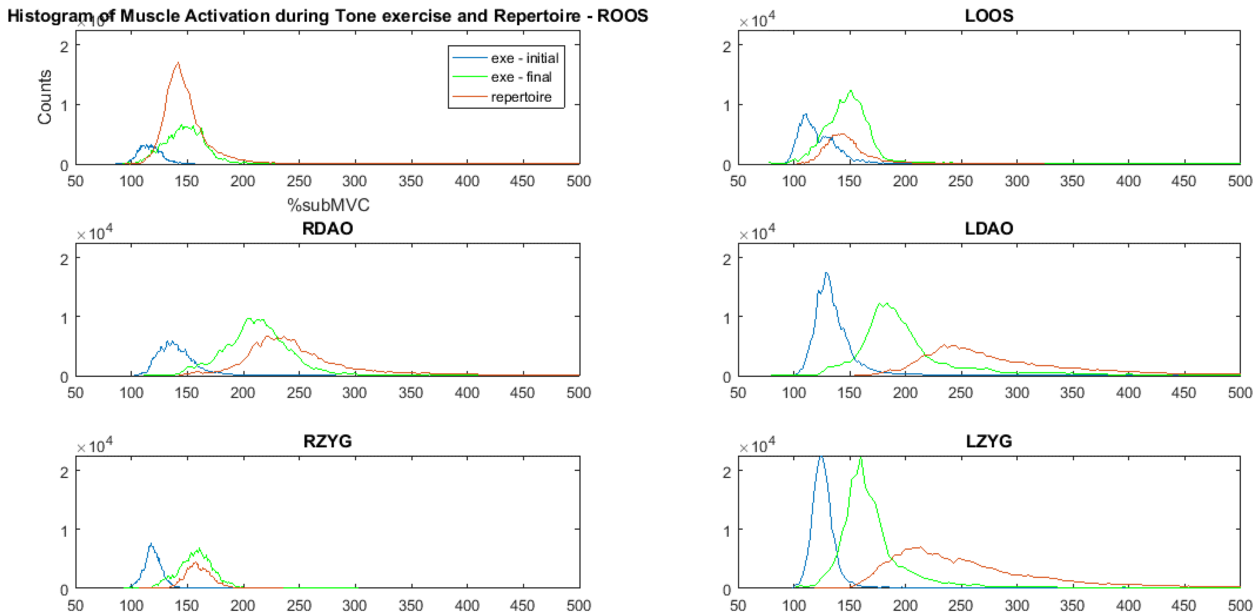

Figure 20. Histogram of the muscle activation during the tone exercise and the piece of repertoire. The blue line represents the initial portion of the exercise, the green line, the final one, and the red line, the piece of repertoire.

Table 20 contains the highest counts found in each task and their respective levels of activation for comparison. The values observed in the initial portion of the exercise (represented in blue) are inferior to those in the piece (in red), suggesting lower muscle activation in the exercise. This is no longer true for the final portion of the exercise, except for the RDAO, LDAO, and LZYG (represented in green). Additionally, the counts values found in the exercise (indicated in with *) are generally higher than those found in the piece, characterizing less variability. This is most evident in the LZYG during the performance of the tone exercise. During the initial 109 seconds of the task, the LZYG presented an activation level (125.25% of sub-MVC) that fell within the same range for 22545 data points. This is the equivalent to 11.27 seconds or 10.3% of the total time of the task.

Table 20

Activation Level with Highest Counts in the Histogram of the Average Normalized Signal for the Tone Exercise and Piece of Repertoire

	Tone Exercise				Piece of Repertoire	
	Initial portion		Final portion			
Muscles	*Activation level (% subMVC)*	*Counts*	*Activation level (% subMVC)*	*Counts*	*Activation level (% subMVC)*	*Counts*
ROOS	113.26	3356	144.95	6583	141.98	17038
LOOS	111.01	8464*	150.97	12475*	143.85	5099
RDAO	132.01	5882	203.8	9712*	221.30	6781
LDAO	128.63	17554*	183.23	12342*	234.08	5266
RZYG	117.36	7641*	160.73	6970*	157.35	4477
LZYG	125.25	22545*	160.03	22329*	214.19	7015

Note. The activation levels during the initial portion of the exercise (represented in blue) are inferior than the ones recorded during the piece (represented in red). Represented in green are the levels of activation observed during the final portion of the exercise that are inferior to those in the piece. * These counts values are greater than those in the repertoire piece.

Figure 21 contains the smoothed curves of the percent activation level per muscle for the tone exercise—initial and final portions—and the piece of repertoire. The graphs are in agreement with the results above: amplitude levels are consistently higher and more variable during the piece. Moreover, there is no clear change in the activation pattern of the repertoire signal, even though the piece (1st movement of Bach sonata in C major) contains two highly contrasting sections, the second of which includes faster tempo, more articulated notes, and more variation of pitch; this transition of sections occurred, on average, at 58.3% ± 4.1% of the piece's entire duration. This may indicate that there may be factors influencing muscle activation other than the content of the piece.

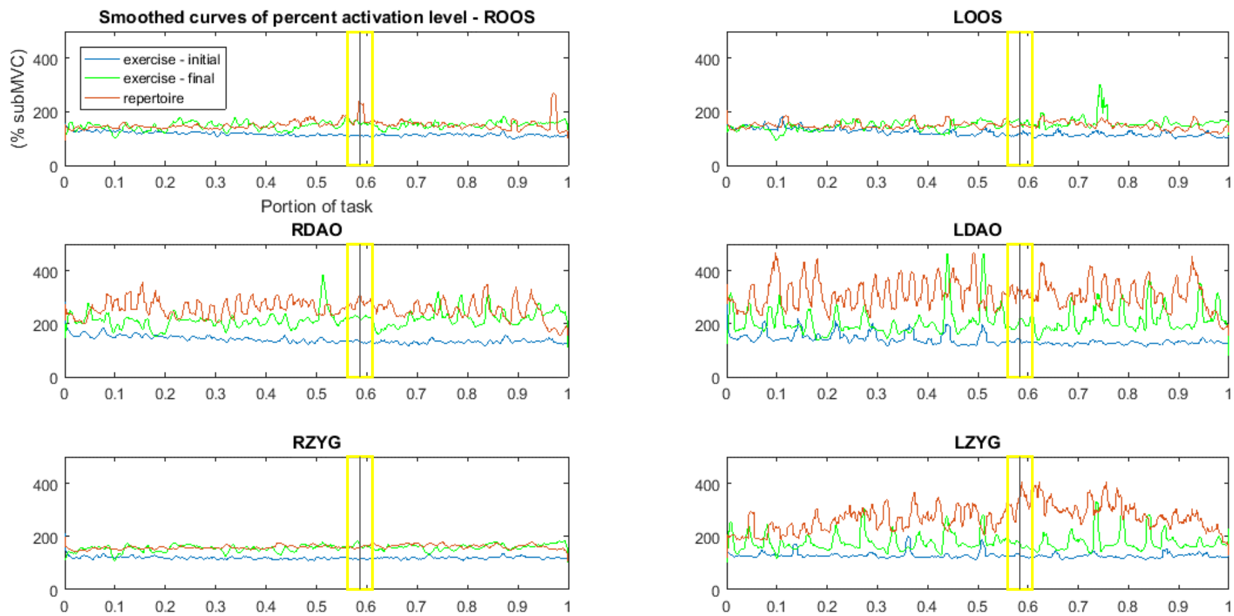

Figure 21. Smoothed curves of percent activation level per muscle for the tone exercise and the piece of the repertoire. The blue line represents the initial portion of the exercise, the green line, the final one, and the red line, the piece of repertoire. The gray vertical line and yellow column represent, respectively, the average (58.3%) and standard deviation (4.1%) of the transition from the slow to the fast section in the piece of repertoire.

Data from the LOOS of participant 8 and from all the muscles of participant 5 during the tone exercise were excluded from all comparative analyses above.

Chapter 6 – Discussion

This study was designed to explain how the embouchure muscle recruitment of flute players is affected by the performance of multiple excerpts. Using surface EMG, three muscles were observed bilaterally: orbicularis oris superior, depressor anguli oris, and zygomaticus major. Participants were monitored in rest condition and during the execution of three musical tasks: a chromatic scale, Moyse's tone exercise, and the first movement of Bach sonata in C major. The main goal was to explore how basic exercise components (frequency, intensity, time, and type) and training principles from the area of exercise physiology may impact or be applied to the deliberate training of embouchure muscles through musical exercises.

Rest Condition

In rest condition, embouchure muscles showed an activation equivalent to 20% of the sub-MVC task, approximately. This indicates that performing a note like B3 entails five times the activation measured before the playing starts. At the end of the chromatic scale, during the execution of the note C6, the mean activations measured at the RDAO and LDAO were respectively 249.0 and 230.3% RMS of the sub-MVC. These values are over ten times the activation in rest condition, which could support the idea that playing the flute, in general, greatly taxes embouchure muscles.

Another interesting observation is that the sEMG signal amplitude of the muscles were very similar to one another during rest condition yet not so much during the note B3, used as normalization reference. This allows us to infer that the differences in the activation levels seen in the note B3, as well as in the other tasks, are likely a result of the way muscles are recruited, more than mere differences derived from what Shan and Visentin, (2012) call "individual biological make-up (e.g. skin thickness, subcutaneous layers of fat or other soft tissues, etc.) and technical factors (e.g. placement of the sensors)" (p. 202). If this premise is in fact true, it is possible to identify the extent to which each embouchure muscle is involved in a certain task. Appendix C, for example, gives an idea on the involvement of the muscles during the note B3. Different strategies may be seen across participants and no particular order of muscle recruitment predominates. Nonetheless, further studies would be necessary to confirm this observation as this matter was beyond the scope of this study.

Muscle Activation and Pitch Correlation

During the execution of the chromatic scale, embouchure muscle activation increased as pitch moved toward the high register. This result is in agreement with studies involving other wind instruments (Basmajian & White, 1973). The positive, linear relationship between muscle activation and pitch then suggests that the higher the pitch of a note, the greater the intensity of the task of playing that note. Understanding this aspect of embouchure muscle recruitment is an important step in the application of exercise physiology principles. Knowing which musical parameters to vary (and how to vary them) to control the intensity of a musical exercise enables the adequate overload of the muscles under development and, ultimately, the devise of a successful conditioning program. Aware that pitch directly affects the intensity of a musical task, the student flutist may arrange their practice in a way that exercises and pieces entirely based on the third register, for example, are played for a short amount of time. Conversely, practice sessions exclusively involving the low register may not sufficiently overload the embouchure muscles so that physiological adaptations (i.e., strength or endurance gains) can take place.

The analysis of muscle activation variation according to register showed that the ROOS's activation varied more in the middle register and that the LOOS, RDAO, and LDAO's activation varied more in the high register. Change in the ZYGs was only significant in the high register and only for the left side. In the low register, although nonsignificant, the OOSs presented the most change in activation. These results help us understand how the muscles are potentially distinctly activated as we practice our instrument. In the case of the ROOS, for example, even though the higher register elicited more activation, we now know that more variation occurs in the middle register. This suggests that more neuromotor control is required in the middle register so that the activation of the muscle matches exactly that of the desired note. Other EMG studies on the effects of practice over a given task have shown that, with training, muscle activation tend to display lower levels, a more delineated contour (Lay, Sparrow, Hughes, & O'Dwyer, 2002), and increased repeatability (Abernethy, Neal, Moran, & Parker, 1990).

Different strategies of muscle recruitment were identified in the scrutiny of intra-subject muscle activation during the chromatic scale. Three patterns were identified, informing the researcher on how each muscle behaves, and possibly evidencing different playing techniques adopted by groups of players. The analysis of these patterns showed that, generally, during the chromatic scale, the DAO tends to change more as a function of pitch while the ZYG is more or less constant, and the OOS varies in its response. Even though it is possible that the strategies aforementioned may differ in their efficiency in terms of level of muscle exertion during practice, one cannot be recommended over the other as it is very unlikely that flutists can consciously isolate their muscles when forming their embouchure. The lowering of the activation levels of the muscles, on the other hand, may take place as the result of practice (expertise), as explained above.

One last observation regarding the muscle activation-pitch correlation is the fact that, for most participants, the curves representing the sEMG signal amplitude produced serrated graphs due to constant increases and decreases. In fact, in some cases, these successive increments and decrements in activation were synchronized among all muscles, perhaps indicating a more refined motor control.

Fatiguing Effect

This study confirmed the existence of a fatiguing process associated with the execution of Moyse's tone-development exercise. This was verified through an increase in the signal amplitude, expressed in % RMS, a decrease in the MPF, and an increase in the Dimitrov's index (FI_{nsmk}). The statistical analysis, however, did not validate the changes measured through this last, more sensitive parameter. This could likely be the result from the index's greater sensitivity for peripheral muscle fatigue, the reduced statistical effect size, the small number of participants in the study, or the size of the muscles being assessed. Indeed Dimitrov's index is fairly recent and has been applied in experiments involving much bigger muscles: rectus femoris (Dimitrov et al., 2006), vastus lateralis (Gozalez-Izal et al., 2010; Gonzalez-Izal, Cadore, & Izquierdo, 2014), vastus medialis, and biceps femoris (Gozalez-Izal et al., 2010), and biceps brachii (Lee, Lee, Choi, Choi, & Mun, 2011; Rogers, & MacIsaac, 2013). Moreover, while these studies reported an increase in FI_{nsmk} ranging from 45% to 700%, the present paper showed values which, on average, did not exceed 30%, as shown in Table 18. Lee, Lee, Choi, Choi, & Mun (2011) measured the FI_{nsmk} variation of the biceps brachii of 10 participants performing isotonic contractions[15] at 10% MVC and 20% MVC. Results showed that at exhaustion, interpreted by the authors as the point after which participants could no longer maintain speed for two repetitions, FI_{nsmk} had reached 371 ± 108% and 239 ± 48% for the sets performed at 10% MVC and 20% MVC, respectively. These

[15] Isotonic contractions consist of changes in the muscle length with a fixed resistance or tension.

values suggest that even though Moyse's exercise leads to muscle fatigue, the condition of the embouchure muscles after its execution is probably far from exhaustion.

Another interesting finding in the analysis of the fatiguing effect caused by the tone exercise was the discrepancy in the levels of fatigue measured in each muscle. The fatigue level presented in the DAO is greater than that presented in the ZYG according to all the parameters, yet this is not so clear when it comes to the OOS. In the time domain analysis (using RMS as the parameter), the OOS was indicated as the least fatigued. In the frequency domain analysis (using MPF and the Dimitrov's index), on the other hand, the OOS is presented as having more fatigue than the ZYG.

Other electromyographical studies have investigated muscle fatigue using MPF-based analyses. An experiment by Moritani, Muro, and Nagata (1986) tested the fatiguing rate of the right elbow flexor during a MVC. Changes in the MPF were in the order of 77 Hz. In an experiment involving a much smaller muscle, now on the hand (first interosseous dorsal), by Penn et al. (1999), the fatigued condition was identified by a drop of approximately 10 Hz in the median frequency. With Moyse's exercise, in our study, the MPF showed decreases as big as 20.6 Hz, which implies that the fatigue level experienced by the embouchure muscles are substantial. This puts the exercise at hand as a highly fatiguing exercise to the embouchure muscles, not just in the context of music but as a physical activity in general. This, in turn, has pedagogical implications that should be taken in consideration in flute training. Since Moyse's exercise successfully overloads the embouchure musculature, rest is advised after its completion in order to allow for muscle recovery, thus avoiding overuse and performance decrement within the practice session. Moreover, it is possible that interval breaks during the performance of the exercise, particularly in the high-register section, should be necessary to optimize muscle development, as the uninterrupted practice of the exercise (i.e., playing all 14 minutes of exercise without breaks) conflicts with the resistance training recommended for skeletal muscles.

Although inconclusive, the result of the correlation between fatigue level and volume of training implied that flutists with greater practice volumes over the week had higher fatigue levels. It is intriguing, though, that trained musicians would suffer from fatigue in spite of a strong practice regime. One possible explanation is that the participants who maintain a greater practice volume over the week experience the effects of accumulated fatigue in their embouchure muscles, thus having a more rapid increase in the activation (in % RMS) during the fatiguing task. Alternatively, participants who practice more every week likely developed other muscles in the perioral region—it has been shown in the literature that a prolonged period of isometric strength training can cause an increase in the muscle's maximum activation (Komi, Viitasalo, Rauramaa, & Vihko, 1978)—and the co-activation of these other muscles accentuates the phenomenon of cross-talk in the sEMG (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). Finally, Cifrek, Medved, Tonković, and Ostojić, (2009) cite three factors as the potential cause for the changes in the sEMG signal during fatigue: 1) decrease of muscle fiber conduction velocity, 2) remaining activity of slow motor units, and 3) time synchronization of motor units' activity. The influence of slow motor units is particularly interesting as the type-I muscle fibers in the embouchure muscles could have been developed by the larger volume of training pursued by some of the participants. The prolonged practice routines, resembling an endurance type of training, could have stimulated these slow-twitch fibers (Plowman, & Smith, 2011), which would, in turn, be responsible for increasing the levels of activation while fast motor units "fatigue quickly and are switched off" (Cifrek, et al., 2009, p. 329). In order to clarify this topic, it would be interesting to compare the correlation results with those yielded by novice players.

Comparative Analysis of an Exercise and a Repertoire Piece

Comparing an exercise to a piece of the repertoire may seem, at first, a pointless endeavor. The number of variables between the two is so abundant that any difference may be regarded as meaningless and obvious. This study, nevertheless, assumed that there was a fundamental difference between these two types of musical excerpts that was tied to their nature and, inevitably, their content. In other words, we hypothesized that exercises and pieces of the repertoire, in general, generate different patterns of muscle recruitment and different levels of exertion in embouchure muscles because of the way each of these types of musical excerpts organizes musical elements. Results tend to confirm this belief yet it is still early to generalize findings to all exercises and pieces. We acknowledge that not all exercises are similar, but in the case of Moyse's exercise and the Bach sonata, the latter appeared to impose higher intensities and greater variability in the muscle activation. These observations could support the idea that playing a piece is better for the muscles. Fjellman-Wiklund, Grip, Karlsson, and Sundelin (2004) state that "Playing a string instrument with more relaxed muscles and a greater variation in the muscle activity pattern might prevent pain, avoid stress, and improve performance" (Levy et al., 1992, cited in Fjellman-Wiklund et al., 2004, p. 348). Additionally, the APDF results revealed that playing the exercise approximates to a static contraction, which has been shown to induce fatigue more rapidly than dynamic contractions (Masuda, Masuda, Sadoyama, Inaki, & Katsuta, 1999; Visentin & Shan, 2011). This was expected considering that exercises normally involve repetitive gestures aimed to improve one specific skill. Moreover, higher levels of activation were registered during the piece of repertoire in spite of the fatigued condition and the high-pitched notes at the end of the exercise.

Another interesting observation based on this comparative analysis was the fact that, according to the APDF results, the probability of the muscle activation being below 100% (the activation of the sub-MVC task) was virtually zero for both the exercise and piece of repertoire. This indicates that the note B3 likely elicits less activation than the low and high registers in the initial and final portions of the exercise, respectively. This, in turn, reinforces the idea that the note B3 is the easiest note on the flute, as stated by other flute pedagogues (Wye, 1999).

Embouchure Symmetry

In several instances, participants demonstrated an asymmetric use of their embouchure muscles, evidencing a certain level of independence between left and right sides. This was clearer with the depressor anguli oris (DAO), during the chromatic scale (see Table 12); the zygomaticus major (ZYG), during the tone exercise (see Table 17); and again with the ZYG, during the comparative analysis between the exercise and the repertoire piece (see Figure 19). Additionally, the section titled “Muscle Activation and Pitch Correlation” of this chapter discusses the statistical significance of the changes in the activation of the muscles in the transitions between registers, revealing that the left and right sides of the embouchure do not behave in the same way during these transitions (see Figure 14). While there is a remote chance that these cases of asymmetry were detected due to systematic errors in sensor placement, it is very likely that they were in fact the result of a plurality of strategies adopted by the players to compensate for their anatomical features and the positioning of the flute. It was not possible, nevertheless, to reliably determine the incidence of asymmetry across participants as this was beyond the scope of the present study.

Study Limitations

Before drawing conclusions based on the data from this study, it is important to consider its limitations, which mainly relate to the chosen data acquisition method (i.e., surface electromyography as a noninvasive technique) and the characteristics of the muscles measured (i.e., physiological particularities of perioral muscles). Together, these factors increase measurements' susceptibility to errors (e.g., cross-talk and inconsistency of sensor placement between participants) and may misinform on the correct muscle recruitment. Other researchers have questioned the reliability of recordings made from single muscles or from homogeneous populations of muscle fibers in the perioral region, primarily because muscles in this region attach to soft tissue without a defined fascia, and their fibers interdigitate (Stål et al., 1990).

In the assessment of the muscle activation during the chromatic scale, there were three instances where sudden changes in the activation level were noticed at the transitions between registers. This effect might have been a result from the randomized register order in the chromatic scale, which, for some participants, broke the natural ascending sequence of low, middle and high registers. While this limitation was necessary to help us dissociate the activation levels from the sequence in which the pitches were played, it also may have interfered with the very activations we wanted to measure. Perhaps a better approach would have been to record all possible combinations of the chromatic scale with each participant.

Another observation in the analysis of the correlation between muscle activation and pitch was the presence of distinct patterns of muscle recruitment, identified across participants. Unfortunately, nonetheless, the collected data are insufficient to determine if these patterns are commonplace among flute players or if they are exclusive to the participants in this study.

An important limitation of this study, concerning the fatigue produced by Moyse's tone exercise, is the fact that most participants, when practicing the exercise, will not follow the exact instructions laid down by Moyse in his method *De la Sonorité*. Instead, they play their own modified version of the exercise, which makes it difficult to correlate their practice habits with the level of fatigue they experienced during the execution of the exercise. As with the assessment of the fatigue itself, one inherent factor affected the solidity of the results: only one trial of the exercise was allowed in the experiment since that successive trials within the same day could have been contaminated with fatigue. Therefore, the protocol adopted in this study could be improved to include more trials of Moyse's exercise in more than one day of experimentation.

With regards to the comparative analysis between the exercise and the piece of repertoire, one limitation to be considered was the opposing nature of the excerpts chosen for the study. While Moyse's exercise presented a slow tempo and slurred semitone steps, the first movement of Bach sonata in C major presented contrasting tempi, varied articulations, and disjunct intervals. As a result, it was not possible to evaluate if the participant's embouchure muscle recruitment was affected by an interpretative component, that is, if playing a piece of the repertoire, which supposedly requires more musicality and expressiveness, would elicit different levels of muscle activation and variability in relation to the exercise, which is normally executed in a more mechanic manner.

Application of the Findings to Flute Training Programming

After reviewing the mechanics of muscle contraction, the physiological and anatomical characteristics of embouchure muscles, and the fundaments of exercise physiology training principles, I believe some basic changes should be incorporated in the ordinary practice routine of flute players. These changes are here organized as a set of three scientific-based recommendations.

The first recommendation is to carry out music practice in the form of interval training, typically associated with resistance training programs, instead of continuous training, usually found in cardiorespiratory conditioning programs. Most musicians, nevertheless will only rest once they have completed at least 1 hour of uninterrupted practice (Martin, R., Kenny, D. T., & Cormack, J. 2009; Krampe, & Ericsson, 2009). In the case of flutists, this combination of long work interspersed with few breaks will likely stress the embouchure muscles in a way that diverges from their fiber-type composition. The predominant fast-twitch fibers present in these muscles can be highly taxed yet not for long. This suggests a training program where rests are more frequent would develop the embouchure muscles more appropriately and effectively.

Additionally, it has been shown that type-II fibers rely more on anaerobic energy systems because of their limited blood supply. This reinforces the need for a discontinued activity in which each work period lasts no more than 2-5 minutes. The widespread Moyse's tone exercise contrasts with this ideal duration since it lasts 14.5 minutes on average according to this study. As consequence of this exceedingly long duration, results show that 93% of the participants presented signs of embouchure muscle fatigue.

The second recommendation concerns the specific goal adopted in the resistance training. Previous research mentioned above supports the idea that the resistance training applied to music practice should aim to improve muscular endurance. This implies, generally, in lower to moderate intensity levels and higher number of repetitions; a configuration that will presumably develop the type-I fibers present in the muscle thereby delaying fatigue onset. Nonetheless, as this study has shown, the intensity measured during flute playing is influenced by pitch and can reach high levels near the end of the high register. With this in mind then a strength training would be more advisable for the practice of musical excerpts centered on the high register, which would affect both the practice volume and the duration of the rest intervals—i.e, sets with fewer repetitions (1–12) and slightly longer intervals (1–3 min.). The practice of musical excerpts based on the low and middle registers, however, may benefit from the endurance training, thus featuring sets with higher number of repetitions (10–25) and shorter intervals (1–2 min.). More details on how to combine the exercise components in agreement with the different types of resistance training are described in Table 4.

The third and final recommendation derives from the comparative analysis between a traditional exercise and a standard piece of the repertoire, although the findings supporting this recommendation may exclusively pertain to the specific piece and exercise examined in this study, thus requiring more investigation to enable a reliable generalization. It has been seen that, in spite of more elevated intensity levels, the piece features more variability of muscle activation. From a health perspective, these characteristics are preferable to those found in the exercise. The high intensity, with the proper intervals, will prompt muscle development whereas the variability will minimize the risks of muscle injury. Although flute is the wind instrument that requires the lowest blowing pressures (Flecther, 2000), it does still activate very small muscles to control airflow with absolute precision. This demand, in conjunction with the recurrent fatigued stated produced by long exercises as well as long practice sessions, increases the likelihood of overuse as "cumulative effects of repetitive light stresses may give rise to the same kind of injuries as a sudden severe stress" (Ackermann et al., 2002. p. 34). Therefore, it is recommended that the largest portion of the practice session be dedicated to the practice of musical tasks fostering variability in muscle recruitment, e.g., pieces and etudes with varied pitches and intensities, instead of repetitious exercises requiring extended isometric muscle contractions.

Through these recommendations, I believe it is possible to achieve a more efficient practice technique; one that takes into account the limitations of the human body, envisioning ways to perform all sorts of music excerpts so that the results are obtained more rapidly, continuously, and, in turn, withholding the occurrence of injury and overtraining. Therefore, the application of exercise physiology training principles on flute pedagogy may enable the player to plan practice sessions not only in terms of the expected musical results but also in terms of the muscular results to be achieved. This means that instead of practicing with only the cognitive/artistic side in mind, the player would also be mindful of the muscular side, and practice seeking to develop playing-related muscles so that performance could be improved. In other words, this new practice technique would transform a regular practice session in a workout for the muscles yet using musical rather than physical exercises.

While evidence presented in this thesis indicates that the application of training principles on flute pedagogy is possible and beneficial, future research is needed to verify if this will, in fact, produce better results.

Summary and Conclusion

This thesis examined the activation of perioral muscles during flute playing in order to elucidate embouchure muscle recruitment. The ultimate goal was to enable the application of exercise physiology training principles on flute practice, thus possibly optimizing deliberate training and the associated muscle development. The main objectives were: 1) to determine the relationship between pitch and muscle activation in all registers of the flute, 2) to verify if Moyse's tone exercise has a fatiguing effect on the musculature, and 3) to compare muscle recruitment during repertoire playing and exercise playing. Results showed: a linear correlation between muscle activation and pitch (Pearson's $r > 0.85$); a fatigued state induced by the tone exercise ($p \leq 0.01$); and superior intensity and variability in the muscle activation recorded during the repertoire piece, although these last results were not significant according to the post hoc analysis (Bonferroni correction). Drawing on these findings as well as on the body of knowledge from the science of exercise physiology, it is possible to outline three recommendations for flute practice: 1) interval training should be favored over continuous training in order to better target the skeletal muscles activated during flute playing; 2) training goal may focus on endurance or strength gains according to the intensity of the musical excerpts being practiced; and 3) the largest portion of the practice session should be dedicated to musical tasks fostering more variability to minimize overuse and potentially optimize embouchure development.

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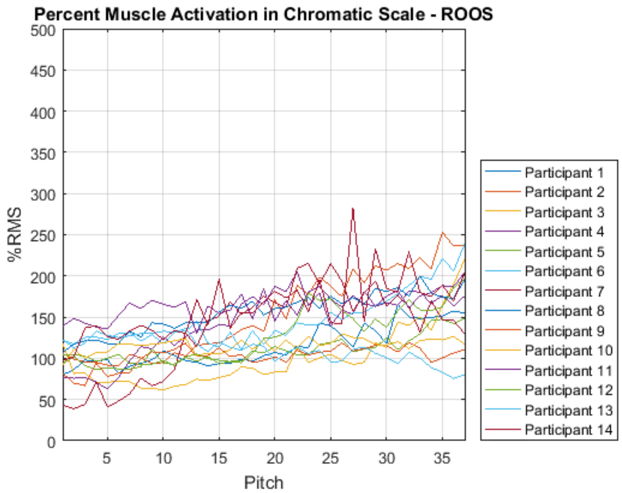
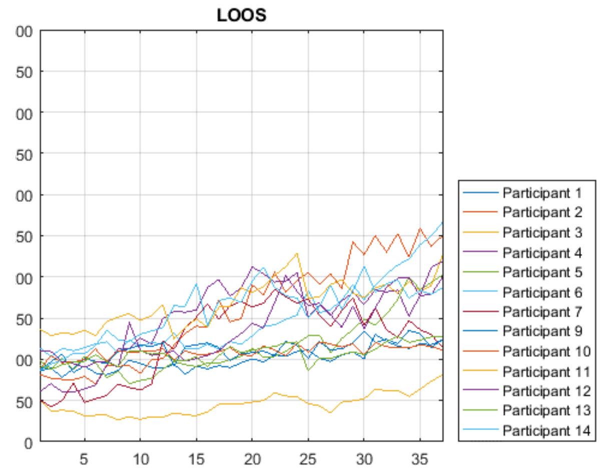
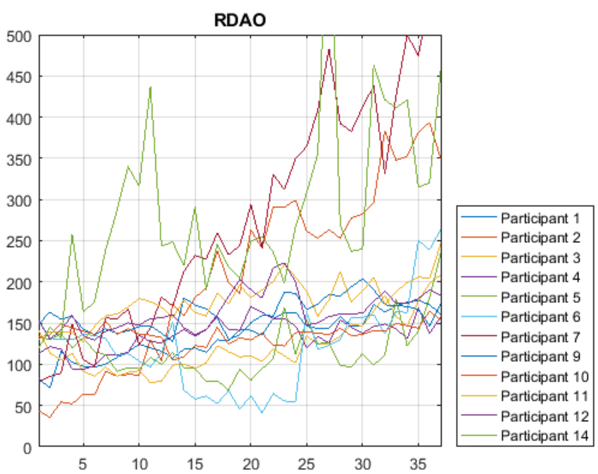
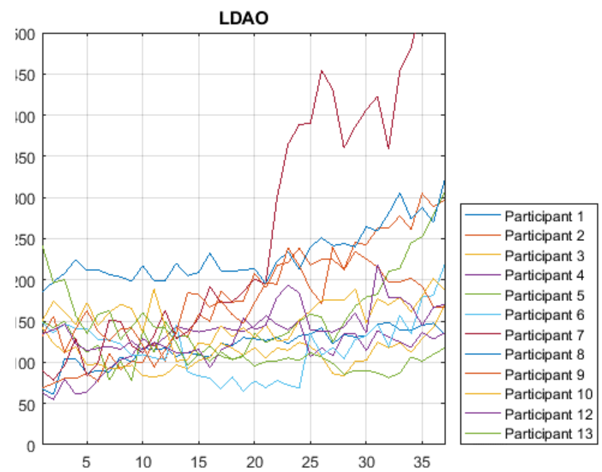
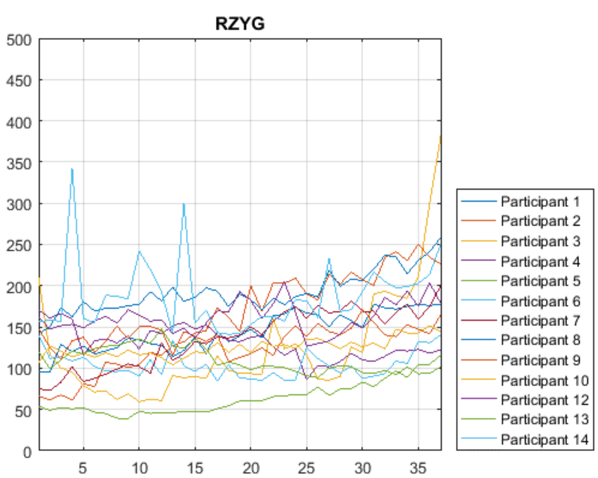
Appendix A – Muscle Activation during Chromatic Scale per Embouchure Muscle

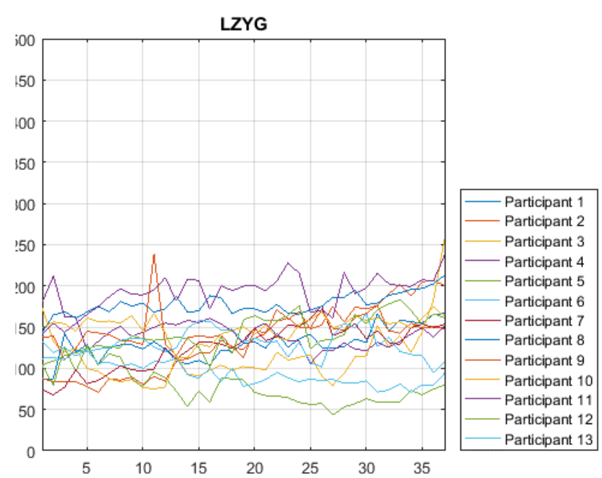




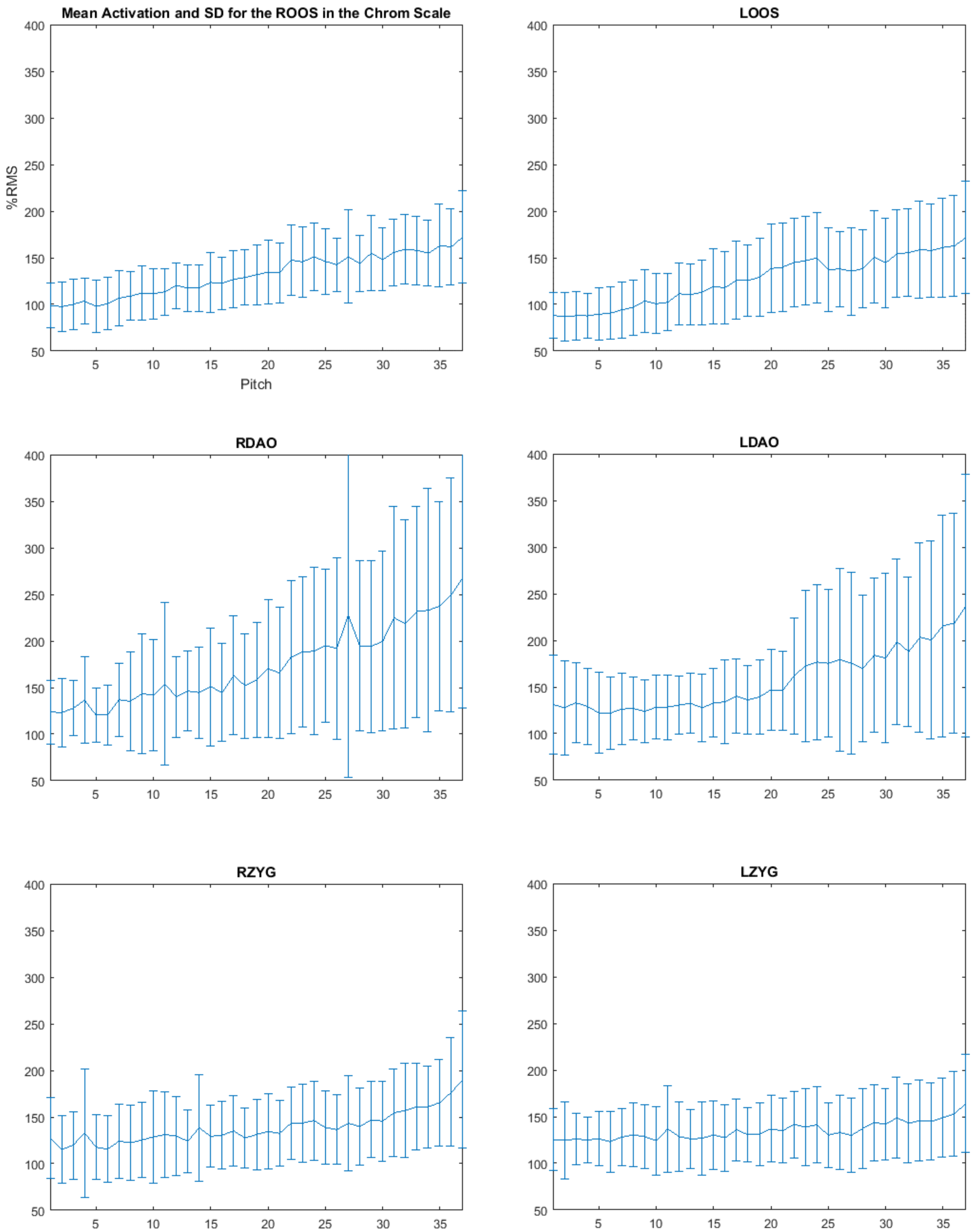






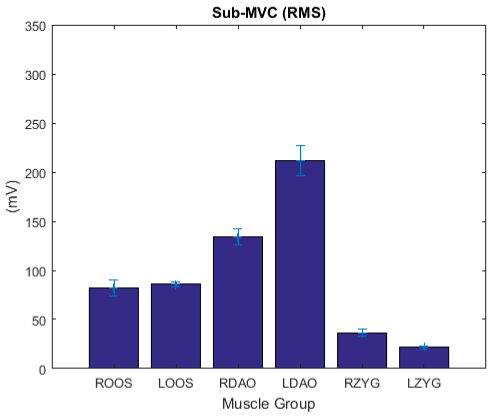


Appendix B – Mean Activation and Standard Deviation Across Participants per Embouchure Muscle



Appendix C – RMS values for sub-MVC Task per Embouchure Muscle

Participant 1



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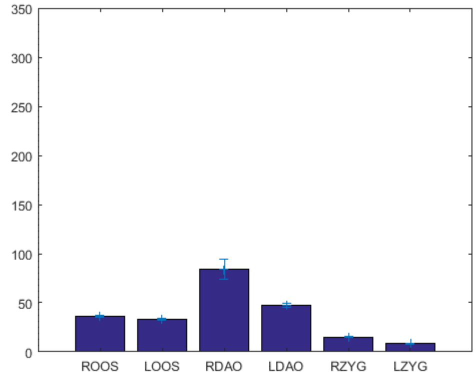

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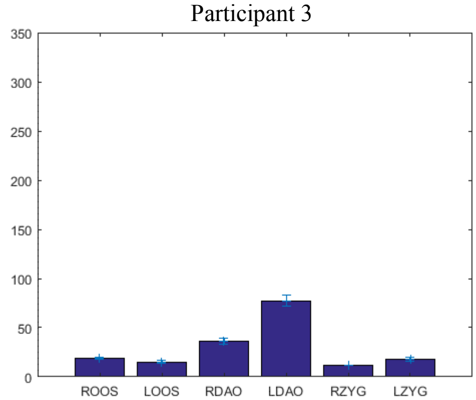

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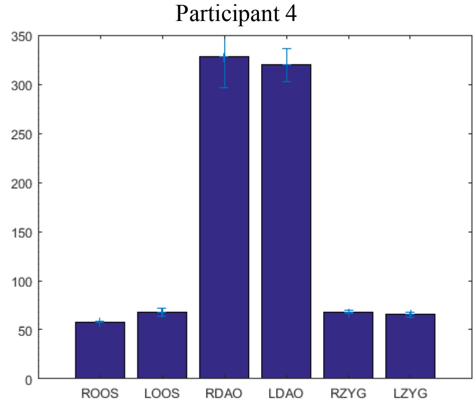

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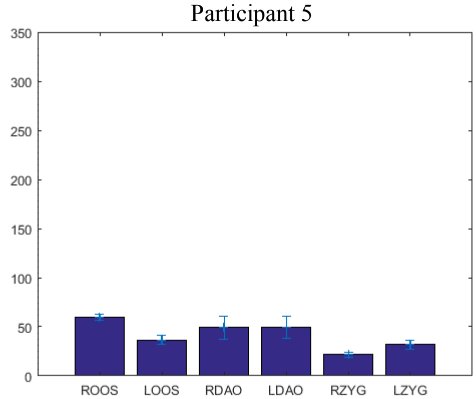

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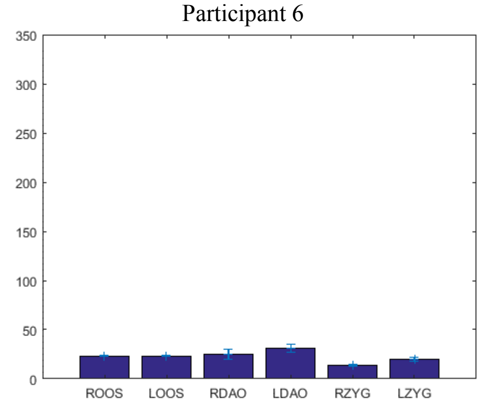

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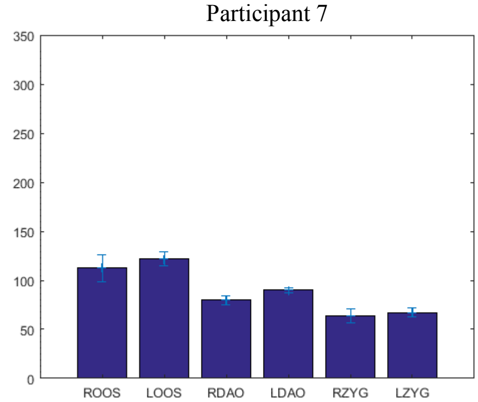

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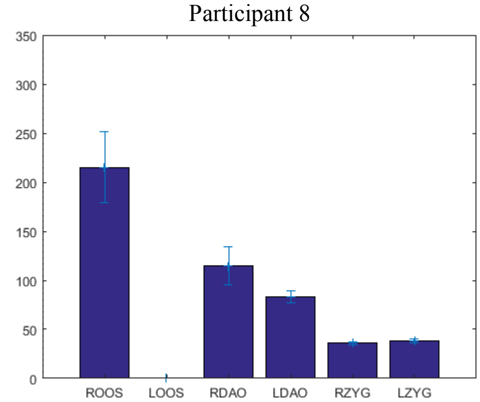
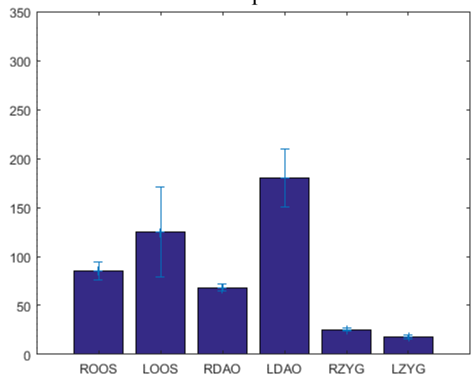


Participant 9



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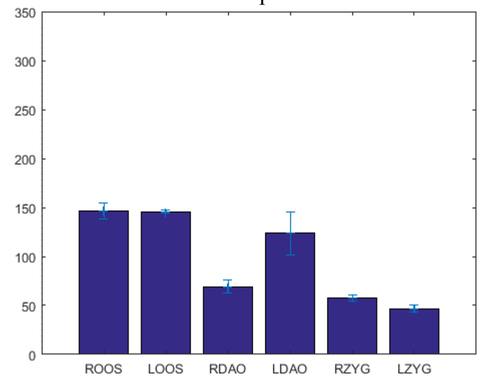

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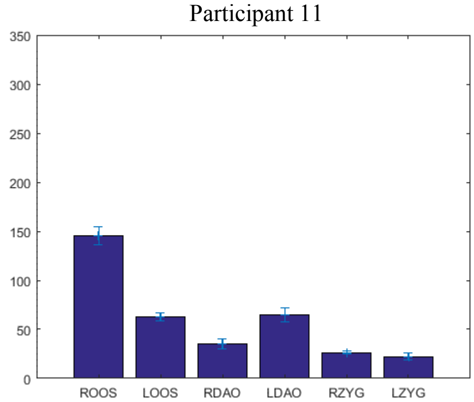

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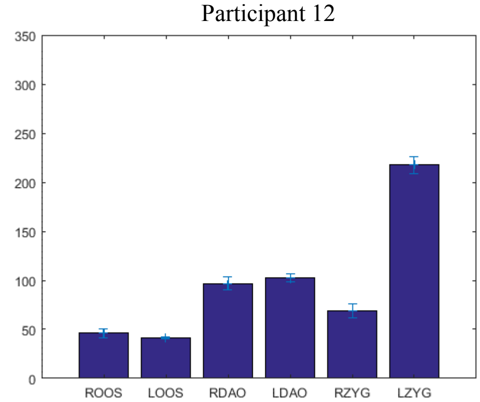

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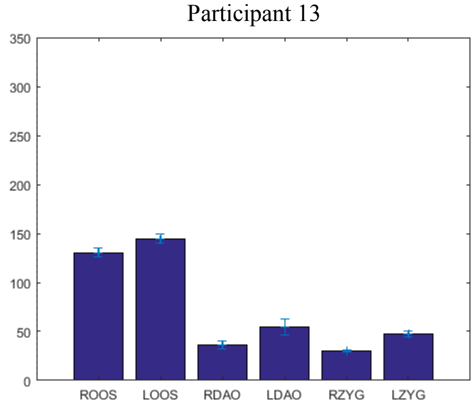
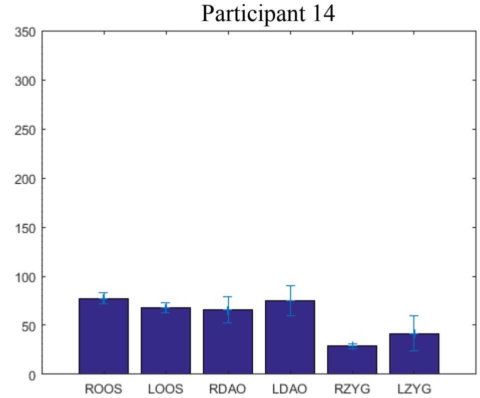
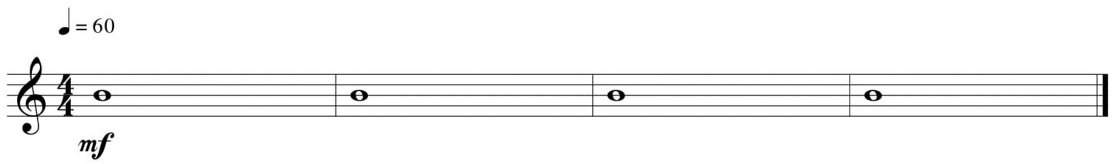


Participant 14

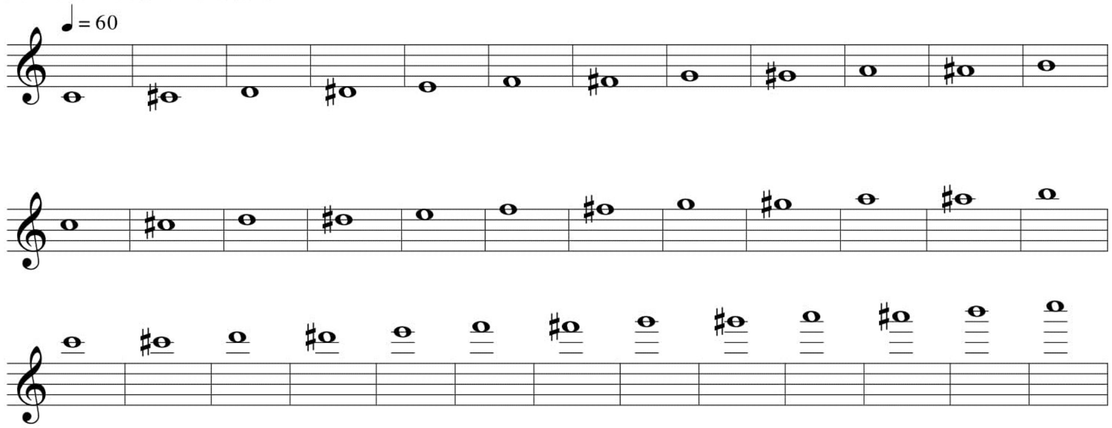


Appendix D – Four Iterations of Note B3

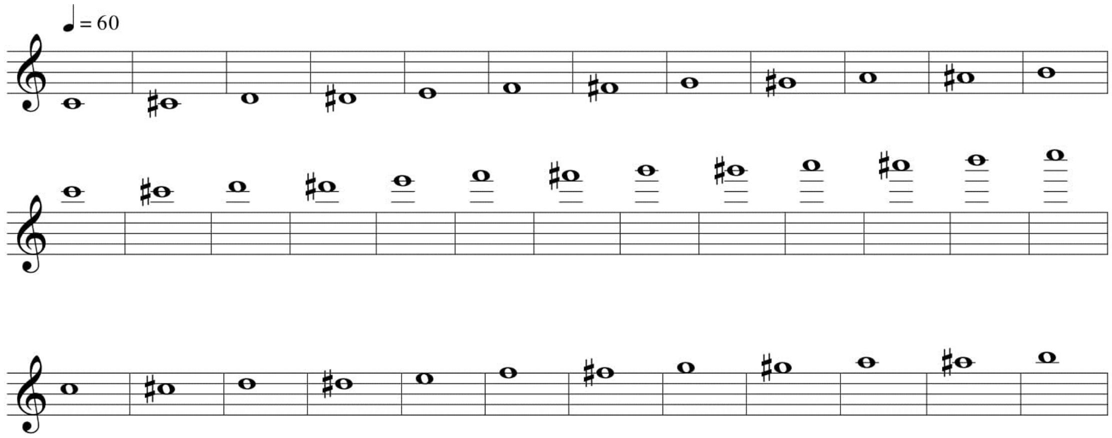


Appendix E – Versions of Chromatic Scale with Varied Register Order

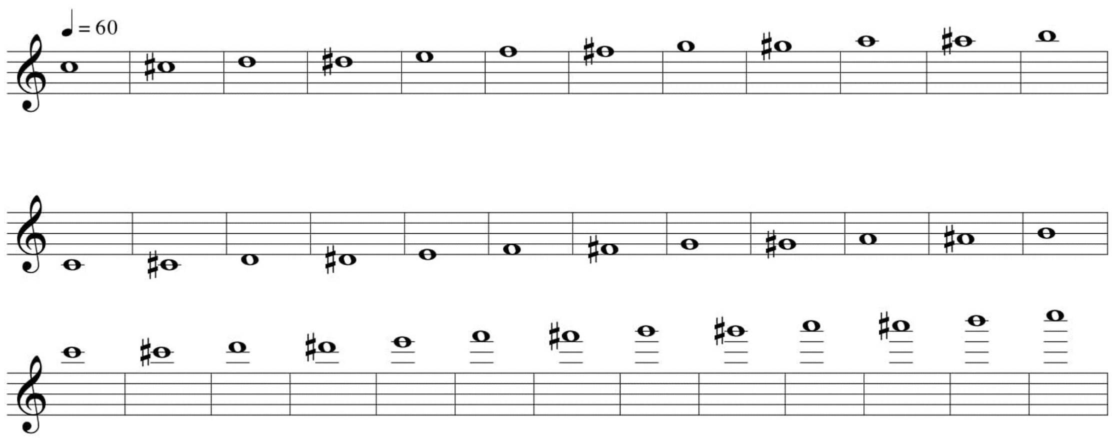
Chromatic Scale A



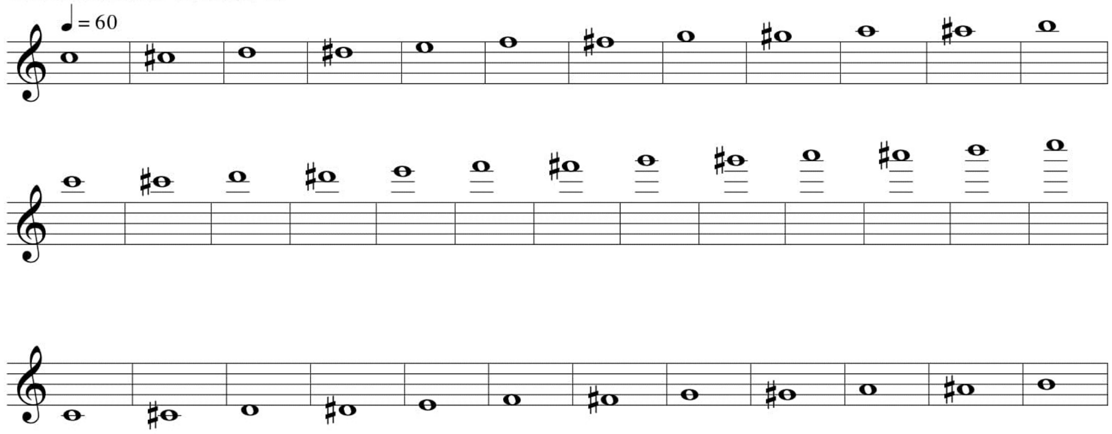
Chromatic Scale B



Chromatic Scale C



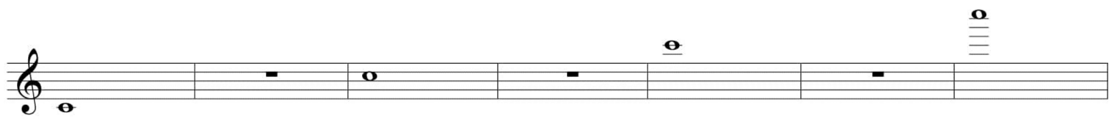
Chromatic Scale D



Chromatic Scale E

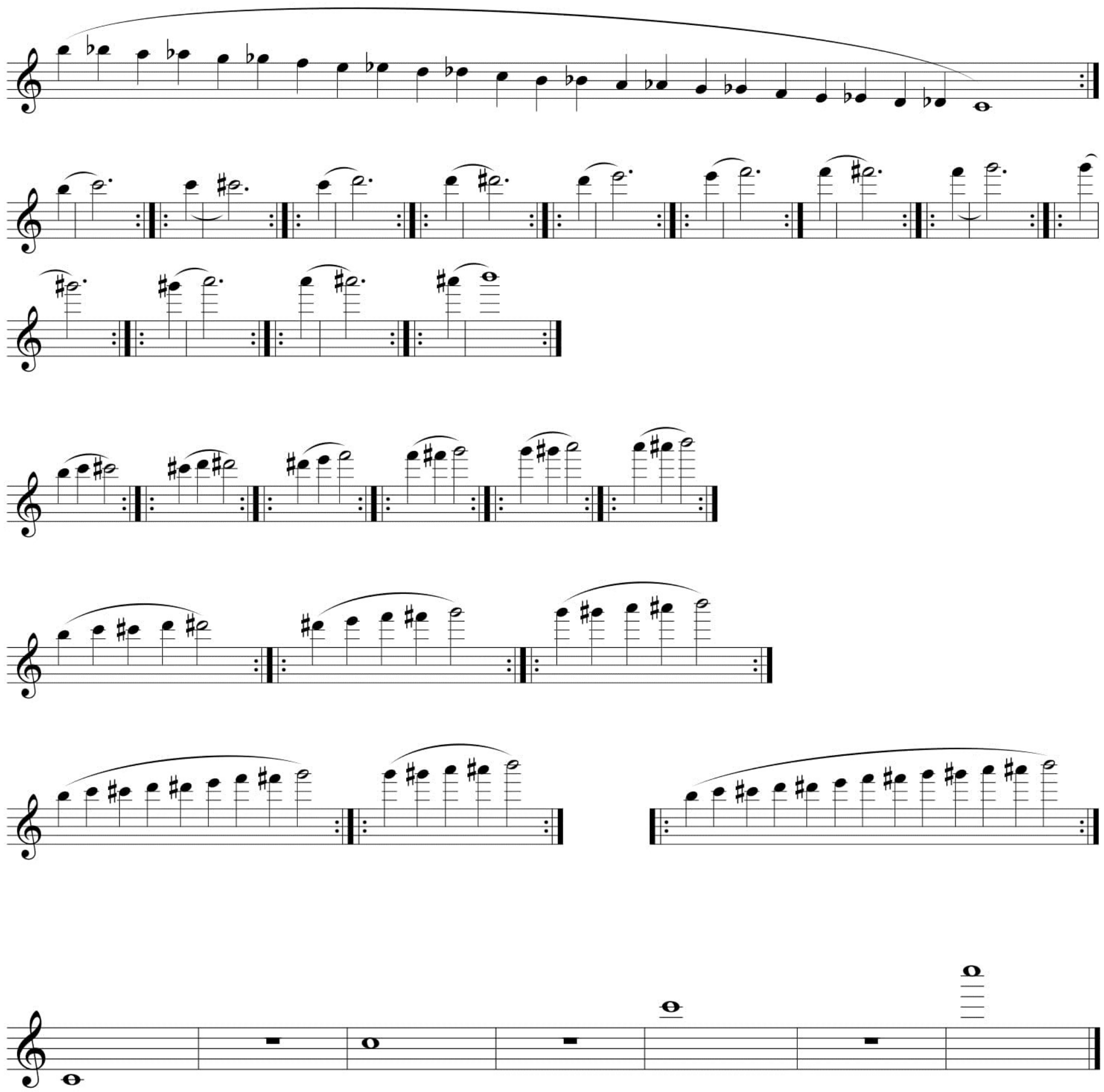
Chromatic Scale F

Appendix F – Moyse's Tone Development Exercise and Reference Notes



Moyse's Tone Exercise

2 Moyse's Tone Exercise



Appendix G – Bach Sonata for Flute in C Major – 1st Movement

Sonata in C Major
for Flute and Piano
BWV 1033
J.S. Bach