IMPROVING PHYSICAL PERFORMANCE

The Role of Jaw-Repositioning

By

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A Dissertation submitted to the

Graduate School-New Brunswick

Rutgers, The State University of New Jersey

In partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

Graduate Program in Nutritional Sciences

written under the direction of

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and approved by

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New Brunswick, New Jersey

May 2012

ABSTRACT OF THE DISSERTATION

Improving Physical Performance: The Role of Jaw-Repositioning

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Advances in mouthguard design applied the dental technique of jaw-repositioning to not only prevent negative effects but to enhance athletic performance. Improved posture and proprioception have been observed with use of jaw-repositioning appliances (1-4). In a previous study, a jaw-repositioning mouthguard improved muscular power in athletes (5). We compared a neuromuscular dentistry-designed jaw-repositioning mouthguard to a standard mouthguard in a randomized, crossover study evaluating muscular endurance and anaerobic capacity in male athletes. The advanced jaw-repositioning mouthguard led to improved muscular power performance (6). Although effective, the neuromuscular dentistry-designed mouthguard was highly expensive causing it to be impractical for the typical athlete. The next two studies utilized affordable versions of the above mouthguard to expand the practical application of the findings.

We evaluated the effects of two jaw-repositioning mouthguards on other aspects of physical performance including balance, flexibility, agility, power and strength in male athletes. A battery of exercise tests was completed in a randomized, controlled, crossover study. No significant differences between the jaw-repositioning mouthguards, the placebo mouthguard, and the no-mouthguard control were observed in these aspects of physical performance.

Our final study evaluated the effects of two jaw-repositioning mouthguards on aerobic performance. Jaw-repositioning devices treat sleep apnea by increasing the size of upper respiratory airways (7-11). Jaw-repositioning mouthguards may have similar effects on the airways in athletes lending to improved aerobic performance. The effects of two jaw-repositioning mouthguards on aerobic dynamics at rest and during a graded treadmill test in male athletes were evaluated. No significant differences between the jaw-repositioning mouthguards and the controls were observed in respiratory functional tests, ventilation, gas exchange, or maximal aerobic performance.

These results indicate that the affordable jaw-repositioning mouthguards did not have any effect, positive or negative, on various performance aspects. This information can be used to encourage mouthguard compliance and dissuade the concerns of performance impediments. Incorporation of advanced dental techniques and individualized design may be necessary to obtain an “optimal jaw position” that promotes positive physical responses. Future research on jaw-repositioning mouthguards should use advanced dental techniques and explore effects on other aspects of physical performance.

ACKNOWLEDGEMENTS & DEDICATION

Firstly, I would like to acknowledge those who directly provided guidance regarding this work. My graduate advisor, Dr. Shawn M. Arent, made all this possible. I have grown as a person because of him and I thank him for his guidance, thoughtfulness, and friendship. Dr. Daniel Hoffman, Dr. Sue Shapses, Dr. Gregory Henderson, and Dr. Carey Williams provided advice and feedback that was essential to my progression. I admire and respect these researchers and am honored to have been their student.

I dedicate this dissertation to my loved ones. My mother and father, Paula and Gregg Golem, are my inspiration and have taught me to work hard, live well, and enjoy myself. The most genuine of people, my parents have taught me to be true to myself, follow my mind and heart, and to make the best of all situations. They are my role models, my advisors, and my best friends. My brother and sister, Adam and Kristina Golem, are such unique individuals that have opened my eyes to different ways of life and ways of thinking. Their sharp wit and satirical humor only provides a glimpse into the depth of their intelligence. My older brother remains to be the most intelligent person I know. I thank him for challenging me and setting me up for success. I am grateful to the both of them for supporting me throughout this endeavor.

The friends that I have made on this journey have become my "family away from family". I am honored to be surrounded and loved by so many great people. I thank them for their generosity and support. Finally, I dedicate this body of work and all it represents to my fiancé, Alex Jakubow. I deeply appreciate his support at every step of this endeavor. There is no one for which I have more love and respect.

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Introduction

Mouthguards as Safety Equipment

In the early 18^{th} century, mouthguards were introduced as protective devices in the sport of boxing (12). A few decades later, mouthguard use was adopted by football players as nearly half of all previously incurred injuries were dental-related (12). In 1973, the National Collegiate Athletic Association (NCAA) mandated mouthguard use for football. This was shortly followed with the mouthguard mandate placed by USA Hockey in 1975. As of 2003, the only collegiate sports requiring the use of mouthguards include football, boxing, ice and field hockey, and lacrosse (12).

The risk of orofacial injury in the above listed sports may be more apparent than other sports; however the American Dental Association (ADA) and International Academy of Sports Dentistry (IASD) have identified other sports with an inherently high risk of dental trauma for which mouthguard use is recommended. These sports include: basketball, volleyball, softball/baseball, racquetball, rugby, soccer, wrestling, martial arts, water polo, weight lifting, gymnastics, equestrian sports, track and field, and inline skating (13). The use of mouthguards reduces the incidence and severity of sport-related injuries to the orofacial area (13).

Typically, mouthguards are composed of ethylene vinyl acetate (EVA) copolymer material that fits over the maxillary (upper) teeth. This material provides a protective barrier that mitigates any applied force (13). Evidence suggests that a 4mm EVA thickness provides optimal protection and comfort while 5-10mm thickness may lead to discomfort (14). The protective barrier prevents dental fractures and separates the soft tissues (cheeks and lips) from the teeth minimizing the risk of soft tissue lacerations (13). Evidence exists indicating that mouthguards may even protect against concussions and injuries to the cervical spine (15), however more research is warranted.

There are three main types of mouthguards: stock, self-adapted, and custom-fitted. The stock type is ready-made and no fitting process is required. It is the least expensive and also the least satisfactory among athletes (15). The self-adapted type (a.k.a boil-and-bite) consists of a "thermoplastic" liner that can be manipulated with heat to promote a fit to the maxillary teeth during the at-home fitting process. This type is also inexpensive and widely available. Finally, the custom-fitted type requires dental impressions as the copolymer material is formed around the dental models of an individual's teeth. This type is the most expensive of the three types and often requires expertise of a dentist (15). Custom-fitted mouthguards are often rated as the most comfortable of the three types of mouthguard (14).

Despite the usefulness and variety in mouthguard design, many athletes do not comply with recommendations of use due to concerns of impairment of performance (14, 16). Difficulty breathing, speech interference, feelings of nausea, impingement on soft tissue, and dry mouth are factors that have been identified by athletes as possible distractions that may lead to poor athletic performance (16). The research that has been completed to address these concerns found that the size and fit aspects of mouthguards are strongly associated with comfort (17, 18). Manufacturers are continuing their efforts to encourage mouthguard use through design and architecture. Recently, jaw-repositioning techniques have been incorporated into mouthguard design in efforts not only to reduce discomfort, but to also to promote the mouthguard as an ergogenic aid.

Jaw-Repositioning

Dental occlusion is defined as the relationship between the lower (mandibular) and upper (maxillary) teeth (19). Increases in the dental occlusion and forward protrusion lead to changes in jaw position. Mandibular Orthopedic Repositioning Appliance (MORA) and Mandibular Advancement Device (MAD) are general terms used to describe an oral appliance that repositions the jaw in a forward and/or vertical direction. Discrepancies exist regarding the "optimal jaw position" and observation of physiological effects. Most studies evaluating the effects of jaw-repositioning on athletic performance used a 1-3 mm lateral movement from dental occlusion (17, 20). The literature examining the effects of jaw-repositioning on respiratory airway openings describes a variety of mandible positions resulting in varying degrees of effect (9, 21, 22).

Positioning a rigid material between the upper and lower molars is a jaw-repositioning technique used to promote a standardized increase in centric occlusion. The expertise of a dentist is not required for this technique allowing for decreased costs and increased availability of this type of jaw-repositioning mouthguard. On the other hand, dental expertise is required for the production of a neuromuscular dentistry-designed, jaw-repositioning mouthguard. Transcutaneous electric neural stimulation (TENS) is a low frequency, low voltage pulse administered through electrodes to the surface of facial and masticatory muscles. These electric pulses promote a contraction followed by an immediate relaxation of these facial muscles. Typically this technique is used to treat chronic orofacial pain and temporomandibular joint disorder (TMD) (23, 24). In the first chapter, TENS and electromyography (EMG) were used in the design of the advanced jaw-repositioning mouthguard. These advanced techniques can be costly and therefore may be impractical for many amateur athletes.

Jaw-Repositioning and Respiratory Airways

Before expanding into the ergogenic aid market, the dental technique of jaw-repositioning has been used to treat sleep disordered breathing (SDB) (7, 8, 10, 11, 25). The underlying rationale behind the use of this type of therapy is that the mandible position affects the soft tissues in adjacent areas.

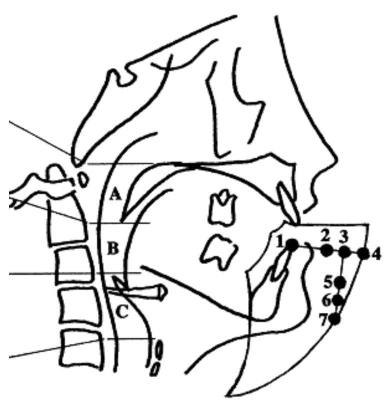
SDB involves repetitive, partial or full closure of the upper airway (hypopnea or apnea, respectively) during sleep. The most common SDB, obstructive sleep apnea (OSA) is typically defined as greater than five apneas or hypopneas per hour of sleep (11). Generally, individuals who suffer from OSA have smaller airways (11), though more research is warranted regarding the causes of this condition. Not only does the fragmented sleep patterns and impairment of daytime functioning in OSA patients lead to decreased quality of life, but these SDB conditions have been linked to hypertension, myocardial infarction, and cerebral vascular accidents (11).

The rationale for using jaw-repositioning devices to treat OSA and other sleep disordered breathing conditions is that the soft tissues of the upper airway interact with the mandible to control the size of the airway (11). Respiratory tract airways transport ambient air to the lungs and allow the projection of expired gases. The ability of the upper airway to function efficiently is directly dependent on its most narrow part (26). Examination of the relationship between the functionality of the upper respiratory tract and the craniofacial skeleton structure revealed that mandibular length and position is positively correlated to upper airway size (26).

Several studies have evaluated the effect of jaw-repositioning on upper airway size through the use of advanced measurement techniques including computer tomography (CT) (8, 10), video endoscopy (7), magnetic resonance imaging (22), radiography (25), and cephalograms

(21). These studies collectively indicate that the improvement in sleep apnea with use of an oral appliance is largely due to the increase in the cross-sectional area (CSA) of the oropharyngeal airways that results from the repositioning of the mandible (7, 8, 10). The increase in pharyngeal airway diameter observed in these studies often surpasses the suggested diameter size of 20 mm^2 for normal breathing (8). Improvement of oxygen saturation in thirty-seven SDB patients wearing mandibular advancement devices has been observed through the use of pulse oximeters (9). Together, evidence from these studies indicates that the use of jaw-repositioning devices promotes an increase in upper airway size leading to improved oxygenation in SDB patients.

Gao, et al. observed a dose-response relationship with mandible position and CSA of the upper airways in fourteen healthy, nonapneic men (21). In this study, the effects of seven different jaw positions with various degrees of forward and vertical movement were evaluated in each subject. Refer to points 1-7 in the figure below.



Gao, et al. 2004

Figure A. Seven points of jaw position.

The greatest increase in upper airway CSA was observed at the maximal protrusion position (position 4 on the illustration above) (21). The indication that jaw position is directly related to airway size in healthy men is consistent with the previous literature in SDB patients.

The principle mechanisms by which jaw-repositioning affects patients treated for SDB may translate to healthy individuals. Increasing the size of upper respiratory airways may potentially induce improvements in aerobic exercise performance through alterations in ventilation and gas exchange.

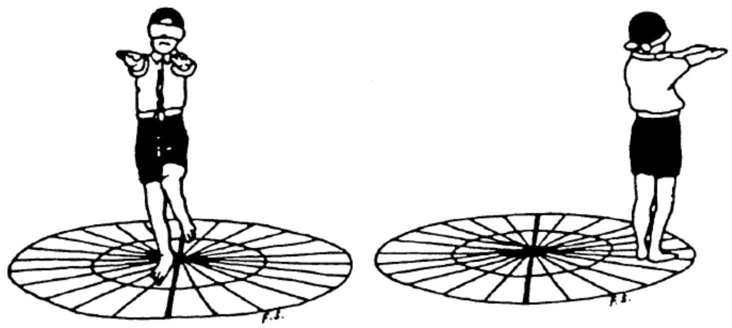
Jaw-Repositioning, Body Posture, and Kinetics

The dental technique of jaw-repositioning has been used to treat TMD (27). TMD is a dental disorder affecting the joint located in front of the ears where the mandible meets the cranio-skeleton. Jaw-repositioning devices are used to treat many of the symptoms associated with TMD including headache, soreness of orofacial musculature, jaw pain, clicking noise with mastication, and dental misalignment (28). The mechanism of action has yet to be elucidated. However, it has been suggested that placing the jaw in a resting position can reduce the tension of the orofacial muscles associated with the signs and symptoms of TMD (28).

In children with TMD, Miralles et al observed improvement in the cervical spine curvature with use of a jaw-repositioning appliance (1). Several studies have observed a strong relationship between jaw position and body posture (1-4) with different dental occlusions promoting changes in postural control (3, 29). In healthy subjects, a synergistic relationship was observed in which jaw position affected body posture and body posture affected jaw position (3).

It has been suggested that jaw-repositioning may influence muscular activity through a change in neurological responses and reflexes, as opposed to solely through changes in curvature or spatial arrangement of the spine (4). Twenty-four subjects, 23-25 years of age, without TMD, participated in an acute muscular activity study. Electromyography (EMG) measurements of postural muscle activity and symmetry, with and without use of a jaw-repositioning appliance, were obtained while subjects stood at rest. The observed postural muscles included right and left pairs of the sternocleidomastoid muscles in the neck, erector spinae at lumbar level of the back, and the soleus muscles in the calves. Reduced EMG voltage was observed across the postural muscles with use of the jaw-repositioning appliance indicating increased relaxation of these muscles with jaw-repositioning. The balance of EMG voltage between right and left muscle pairs was significantly increased with use of the appliance compared to without. This indicates that the distribution of muscle tension was more balanced when the jaw was repositioned (4). This study reveals that, when standing at rest, repositioning the jaw can positively influence general body posture through neuro-mediated effects on postural muscles (4).

This is consistent with a study examining adults without any dental disorders that found that the use of a jaw-repositioning oral device resulted in progressive improvement in proprioceptive function (2). The Fukuda Uterberger proprioception test was administered to 15 subjects who wore the device and 15 control subjects who did not wear any oral appliance. This test evaluates postural attitude and proprioceptive function through the assessment of change in position with blinded, in-place marching. The subjects were asked to take 50 steps at a specified pace, with feet lifting to knee level, and eyes closed. The degree of deviation from the initial testing position was measured. Refer to the figure B below. The scores were significantly better in the jaw-repositioning group compared to the control group. These results indicate that jaw position correlates with proprioception and postural function (2). It is anticipated that other physical performance factors that are governed by proprioceptive function would also be affected by jaw-repositioning.



Milani, et al. 2000

Figure B. Fukuda-Uterberger Proprioception Test.

Proprioception can be described as the responsiveness to body position and movement through neuromuscular communication. Proprioceptors, such as Golgi tendon organs (GTOs) and muscle spindles are receptors located within the muscle that monitor local muscular action and relay information about muscular dynamics and body movement (afferent signals) to the central nervous system (CNS) (30). The flow of communication then reverses back down the neuromuscular chain as the CNS responds to the obtained information by sending efferent signals that elicit specific muscular responses (31).

Muscle spindles are involved in many athletic movements requiring speed and power as they respond to rapid changes in muscle length and tension. During a quick lengthening movement, a sensory neuron from the muscle spindle communicates with a motor neuron in the spine which sends the signal to the brainstem. This communication produces a stretch reflex or shortening in the length of the active muscle (31). An example of the stretch reflex mechanism is the action of muscle spindles during a counter-movement vertical jump. The counter-movement consists of moving from a standing position to a squatted position through rapid flexion of hips, knees, and ankles. The counter-movement is immediately followed by the vertical jump where the lengthened muscles are shortened and muscular force is pushing the body up at a high speed. Muscle spindles are activated during the counter-movement as the large muscle groups in the lower body are quickly lengthened during the eccentric phase. The muscle spindles communicate to the CNS, the CNS communicates contraction of the lower body muscles promoting a forceful, explosive vertical jump. The action of muscle spindles is also observed in other explosive, ballistic movements such as agility and dynamic balance movements.

Improvements in neuromuscular communication pathways with jaw-repositioning have been observed through improvements in muscular activation and proprioceptive function (2, 4). However, it is important to note that there are many neural and mechanical communication pathways involved in the control of body movement (32). Changes in movement and performance cannot solely be attributed to one aspect of locomotive control such as proprioceptive function or muscle activation. Nevertheless, the neuromuscular effects of jaw-repositioning may translate to improved neuromuscular responses in active exercise movements.

Objectives

1. To compare the effects of a neuromuscular dentistry-designed, jaw-repositioning mouthguard versus a standard custom-fitted mouthguard on muscular endurance and anaerobic power performance in male athletes.

2. To determine the effects of two standardized, jaw-repositioning mouthguards on balance, flexibility, muscular power, agility, and muscular strength performance in male athletes.

3. To examine the effects of two standardized, jaw-repositioning mouthguards on aerobic capacity and respiratory functional tests in male athletes.

Effects of a Neuromuscular Dentistry-Designed Mouthguard on Muscular Endurance and Anaerobic Power

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Published in

Comparative Exercise Physiology 7(2): 73-79; August 2010

INTRODUCTION

Athletes are often required to use mouthguards during training and competition for the purpose of providing protection against orofacial and dental injuries. The prevalence of these types of injuries is high, not only in contact sports, but also in non-contact activities and exercises (12, 13, 33, 34). Their use has also been promoted in an effort to reduce concussion frequency and severity, though the evidence for this is fairly inconclusive (13). Mouthguards function by absorbing impact stresses which results in a reduction of force transmitted to the teeth, bone structure, cranium, and surrounding soft tissue (13, 35). Comparing the benefits to risks provides the justification behind requiring the use of mouthguards during training and competition. It is commonly agreed upon that the benefit of providing protection against orofacial injury outweighs the speculative concerns put forth by athletes of possible discomfort, reduced ability to breathe, and decreased performance (18). The latter concern seems to be a major consideration for high-level athletes who are typically looking to gain any competitive advantage. Recently, efforts have been made to address these concerns through redesigning the mouthguards using neuromuscular dentistry techniques that promote specific jaw positioning. Some studies have found that jaw positioning may affect posture and stability (36). Whether jaw positioning positively affects gross motor functioning has yet to be conclusively determined and remains to be a topic of controversy. In an effort to examine the effectiveness of the neuromuscular dentistry-design approach, research on the comparison of performance outcomes associated with the use of standard, custom-fitted mouthguards (CFM) *versus* neuromuscular dentistry-designed mouthguards can be particularly useful.

There are three primary categories of mouthguard: stock, self-adapted, and custom fitted. A stock mouthguard is ready-made and placed over the upper teeth without individualized fit, whereas the self-adapted type (also known as boil and bite) is heated until pliable and then moulded to the upper teeth and arch by the consumer (15, 37). The expertise of a dentist is needed to obtain the CFM type, as it is formed to the mould derived from impressions of the upper teeth and dental arch (15, 37). While limited research exists on the performance impacts of each of these types, the studies that have been done have generally concluded that mouthguards do not produce negative effects on aerobic performance capacity or measures of ventilatory capacity (17, 18, 38, 39). At least two studies (17, 18) have found that both custom-fitted and stock mouthguards actually improved maximal aerobic capacity or improved economy at higher workloads. While these are useful findings, they should not be directly translated to the effects of mouthguards on *anaerobic* exercise performance. This is an important consideration in light of the bio-energetic requirements of most sports that require mouthguard use. While studies have found that modification of mandible position, particularly through changes in vertical dimension, can positively impact isometric strength of the upper extremities and cervical flexors even in asymptomatic subjects (40-42), these findings may not readily translate to the more dynamic movements required in athletic contests and training.

However, a recent study did find that wearing a traditional CFM improved anaerobic power and peak torque in taekwondo athletes, but that strength and vertical jump (VJ) were not impacted (43). Research comparing the muscular endurance and anaerobic power performance outcomes associated with the use of a standard CFM *versus* a neuromuscular dentistry-designed mouthguard may prove applicable to the athletes participating in sports where mouthguard use is required or strongly encouraged.

Neuromuscular dentistry focuses on the alignment of the temporomandibular joint (TMJ), masticatory muscles, bones, teeth, and the neural circuitry associated with the oral cavity (23). Transcutaneous electric neural stimulation (TENS) is often used in this area of dentistry to reduce hyperactivity of musculature, to act as a local anesthetic, to act as a chronic pain reliever and to treat TMJ dysfunction (23, 24). A low-voltage, low frequency TENS is administered to patients to cause the facial and masticatory muscles to contract (24, 36) and to relax into the mandibular resting position. This provides for the identification of more ideal occlusion positions of the jaw (24).

A relatively new mouthguard, the Pure Power Mouthguard™ (PPM; Pure Power Athletics, Inc., Ontario, Canada), uses neuromuscular dentistry techniques in its custom-fitting design. In addition to traditional protective effects of mouthguards, PPM is purported to increase performance in sports by improving such things as strength, speed, endurance, agility, accuracy and balance. PPM developers provide a theory indicating that improved strength and balance will occur when muscles in the face and jaw are properly aligned and relaxed. This theory stems from the evidence that jaw position may affect posture and stability in human subjects (36). However, the relationship between jaw positioning and gross motor performance has not been definitively established and remains to be a controversial topic requiring further research.

Strategies to improve human performance while maintaining safety are crucial in the ever increasingly competitive athletic environment. The application of neuromuscular dentistry principles in the design of athletic mouthguards is a novel technique which warrants scientific evaluation. First and foremost, evaluation must take place to determine whether designing a mouthguard using neuromuscular dentistry techniques leads to change in physical performance compared with a mouthguard designed using traditional techniques. The purpose of the current study was to contrast the effects of the neuromuscular dentistry-designed PPM with a traditional CFM on competitive athletes' muscular endurance, anaerobic power, and anaerobic capacity. It is hypothesized that the PPM will elicit superior performance compared to the CFM on VJ height, number of bench press (BP) repetitions completed, peak power and mean power on a modified Wingate anaerobic test (WAnT) protocol.

METHODS

Experimental Approach

A double-blind, crossover design was used to compare the effects of the neuromuscular dentistry-designed mouthguard (PPM) to a traditional CFM on anaerobic power and muscular endurance. PPM and CFM were matched for material and appearance. A 'no-mouthguard' condition was not used due to the fact that athletes are often required or strongly encouraged to wear mouthguards, not only during competition but also during training and practice.

Because of this, the primary consideration was to compare the effects of different mouthguards on key performance outcomes. All subjects underwent custom fittings for the CFM and PPM. A familiarization session was paired with the fitting session. The subjects underwent two testing sessions 5-7 days apart, where anaerobic power and muscular endurance were assessed using VJ, BP with a load equal to body weight, and a 30s WAnT + eight 10s WAnT intervals. The order of mouthguard use was randomized between subjects. Verbal screening prior to each testing session confirmed that all the subjects followed between-testing instruction and refrained from training/extraneous activity for at least 24 h prior to each testing session.

Subjects

Healthy, male professional and collegiate athletes (N=22; M_{weight} = 86.2 $\pm$ 3.1 kg) ages 18-34 with 2+ years of weight-training experience participated in this blind, crossover study. Each subject was required to have been training anaerobically 4+ days per week for at least the last 2 years. All athletes were familiar with wearing mouthguards due to the sports in which they participated. Sports that were represented included football *(n = 5)*, college lacrosse *(n = 2)*, basketball *(n = 4)*, wrestling *(n = 8)* and mixed martial arts *(n = 3)*. This study was limited to males in order to control for muscular power differences that exist between genders, even if controlling for training history. Risks and benefits were explained to the subjects and each of them gave written informed consent prior to participation in the study. All individuals were free from current injuries, illnesses or metabolic conditions limiting their ability to train and complete physiological testing. A health screening was completed with each subject in accordance with American College of Sports Medicine exercise testing procedures. The study was approved by the Rutgers University Institutional Review Board.

Procedures

Each subject completed a fitting session for the mouthguard followed by a familiarization session to control for practice effects on the anaerobic test (44). This was followed by two separate testing sessions (T1 and T2). During T1 and T2, participants warmed up and then completed three different performance tests: VJ, BP with a load equal to bodyweight for maximal repetitions, and a modified WAnT, which included the standard 30s WAnT followed by a 5 min rest, then eight 10s intervals with 2 min rest between each interval. This latter protocol was used to simulate the interval-based nature of work efforts found in many sports and to simulate the intensity needed to elicit reliance on the anaerobic energy system. The participants were instructed to continue with their normal exercise training during the study, yet were required to refrain from training for 24 hours prior to each testing session. Additionally, each subject was tested at the same time of day for T1 and T2.

Following the familiarization session, which included the health screening, the fitting process to take dental moulds to make the mouthguard, and a familiarization WAnT, the subjects were randomly assigned to order of use of the PPM or CFM mouthguards. The mouthguards were matched for appearance and material, which was an ethylene vinyl acetate polymer. The fittings for the mouthguards were performed by dentists, who were also certified in PPM application and first involved in take standard dental impression for the CFM. The fitting for the PPM then involved the attachment of TENS surface electromyography (EMG) electrodes (Myotronics, Inc., Kent, WA). A very low-voltage pulse was delivered using this device in order to facilitate muscular relaxation of the lower jaw. Muscular activation was continuously monitored to ensure a relaxed lower jaw position. Following this, new fast-setting impressions were taken to capture this 'optimal' bite alignment. The total fitting process took about 80-90 min. The dentists were responsible for taking the moulds and for the PPM fitting process, but an independent laboratory was contracted for production of both the mouthguards. Following the dental impressions, subjects underwent familiarization with the tests to be used during the actual testing. This included practice attempts on the VJ and familiarization with the BP weight, as well as completion of the 30s WAnT plus one interval using the load to be used during testing. Once the mouthguards were produced, subjects returned to the laboratory and the dentists ensured proper fit and comfort prior to commencing with testing. Following this, subjects completed T1 and T2, with the two trials separated by 5-7 days.

For each testing day, the subjects reported to the Rutgers University Human Performance Laboratory. The subjects were instructed to arrive for testing normally hydrated, having eaten a meal 2 hours prior, and to refrain from ingesting substances that could affect normal physiological functioning (i.e., tea, coffee, alcohol and nicotine). Verbal questioning revealed 100% compliance with these instructions. At each trial, the subjects completed a 10 min systemic warm-up before being tested on the VJ, followed by the BP with a load equal to body weight for maximal repetitions. VJ was assessed using the "Just Jump Mat" (Probotics, Huntsville, AL). Subjects completed 3 trials with 45-60s rest between the trials. The highest of the three jumps was recorded. VJ tests have demonstrated coefficient of variations (CVs) as low as ~2.0% (45) and the Just Jump Mat is highly correlated with measures obtained with a three-camera motion analysis system ($r = 0.967$) (46). After completing the VJ, the individuals rested for 3 min and then completed a standard upper body muscular endurance test (BP with body weight for repetitions). After two warm-up sets of eight to ten repetitions with 50% of the weight to be used, subjects were given a 4-5 min rest before attempting the test. The score consisted of the total number of repetitions completed in good form before momentary muscular failure. Pilot testing in our laboratory revealed a CV of 10.3% for the BP test. The athletes rested for 5 min rest before beginning the WAnT protocol.

The subjects performed the 30s WAnT plus eight 10s intervals on a Monark 894E Anaerobic Test Ergometer (Monark Exercise AB, Sweden). The load was set according to each subject's weight (19) and was equivalent to 0.10 kp/kg body weight. Following the 30s WAnT, subjects rested for 5 min and then completed eight 10s intervals using the same load with a 2 minute rest between each interval. The WAnT has previously demonstrated reliability between 0.89 and 0.99 (47). The use of high-level athletes as well as a familiarization session further improves the reliability (45).

Performance Measures

Peak power during the WAnT was defined as the highest mechanical power output elicited during each 30s test. Mean power was calculated based on the average mechanical power produced during the test. Average peak power and average mean power were calculated across the WAnT plus intervals. Maximal VJ height was used to establish power and the number of repetitions completed for the BP constituted the scores for muscular endurance.

Statistical Analyses

A repeated measures multivariate analysis of variance was used to assess the effects of the PPM and CFM mouthguards on VJ, BP repetitions, peak power for the 30s WAnT, mean power for the 30s WAnT, average peak power for the WAnT + intervals and average mean power for the 30s WAnT + intervals. Significant multivariate effects were followed by univariate follow-up tests. For each univariate analysis, the Huynh-Feldt epsilon was calculated to test the assumption of sphericity. If this statistic was > 0 .75, the sphericity assumption was considered to have been met and the unadjusted statistic was used. If epsilon was < 0.75, sphericity was considered to have been violated and the Huynh-Feldt adjusted statistic was used to test significance.

Because of the impact that even small effects may have on overall performance of athletes at this level and in accord with recent recommendations for statistical follow-up (48), effect sizes (ES) were calculated to compare magnitude of changes in the PPM and CFM conditions using Hedges' *g* formula for ES computation. This ES computation was used for all variables. Group data are expressed as mean $\pm$ SD and statistical significance was set at $a < 0.05$.

RESULTS

There was a significant multivariate effect for condition ($P = 0.008$). Follow-ups indicated significantly better performance for PPM compared with CFM for VJ (67.6 $\pm$ 9.4 cm *vs*. 65.3 $\pm$ 8.6 cm; $P = 0.003$; ES = 0.27), peak power for the 30s WAnT (11.6 $\pm$ 1.7 $W \cdot kg^{-1}$ *vs*. 11.1 $\pm$ 1.5 $W \cdot kg^{-1}$; $P = 0.038$; ES = 0.33), average peak power for WAnT + intervals (10.6 $\pm$ 1.4 $W \cdot kg^{-1}$ *vs*. 10.1 $\pm$ 1.2 $W \cdot kg^{-1}$; $P = 0.025$; ES = 0.42) and average mean power for WAnT + intervals (9.0 $\pm$ 1.1 $W \cdot kg^{-1}$ *vs*. 8.7 $\pm$ 1.0 $W \cdot kg^{-1}$; $P = 0.034$; ES = 0.3) (See Figures 1-4). There were no significant differences between PPM and CFM for either BP repetitions (16.1 $\pm$ 5.4 reps *vs*. 15.8 $\pm$ 5.5 reps; $P = 0.48$; ES = 0.05) or mean power for the 30s WAnT (8.5 $\pm$ 1.2 $W \cdot kg^{-1}$ *vs*. 8.4 $\pm$ 1.0 $W \cdot kg^{-1}$; $P = 0.54$; ES = 0.1).

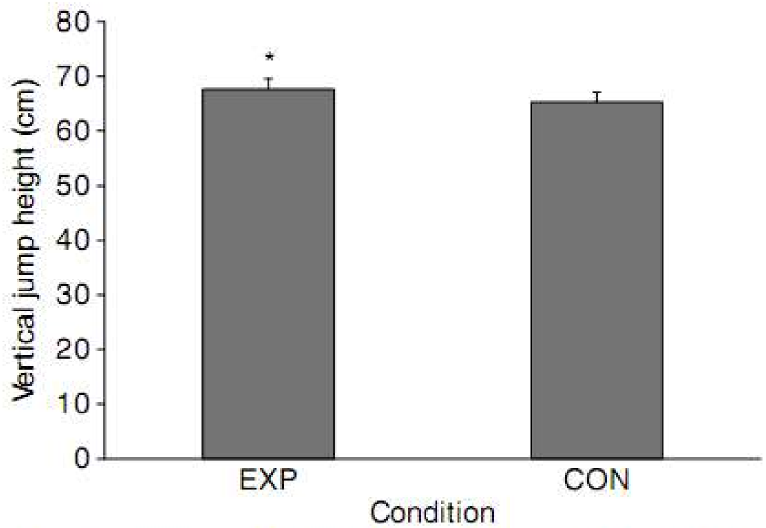


Fig. 1 Vertical jump (VJ) height (cm) with experiment (EXP) and control (CON) conditions. VJ height was significantly higher for EXP compared with CON (* $P = 0.003$)

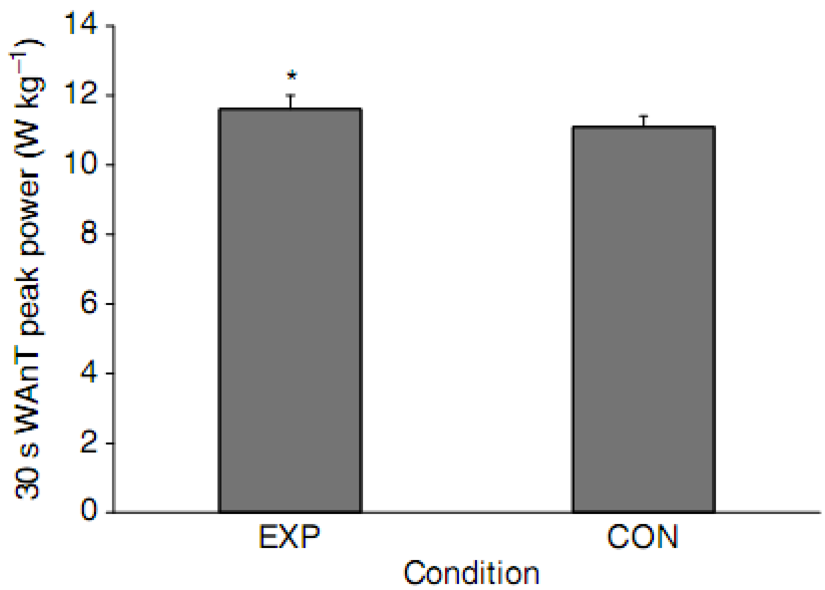


Fig. 2 30 s WAnT peak power (W kg^{-1}) for experiment (EXP) and control (CON) conditions. Peak power was significantly higher for EXP compared with CON (* $P = 0.038$)

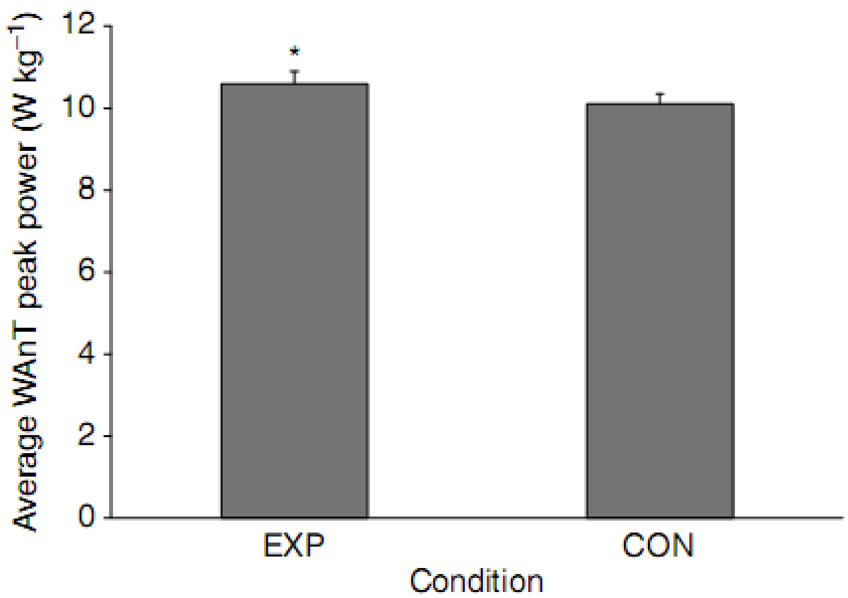


Fig. 3 Average peak power for WAnT + intervals (W kg^{-1}) for experiment (EXP) and control (CON) conditions. Average peak power was significantly higher for EXP compared with CON (*$P = 0.025$)

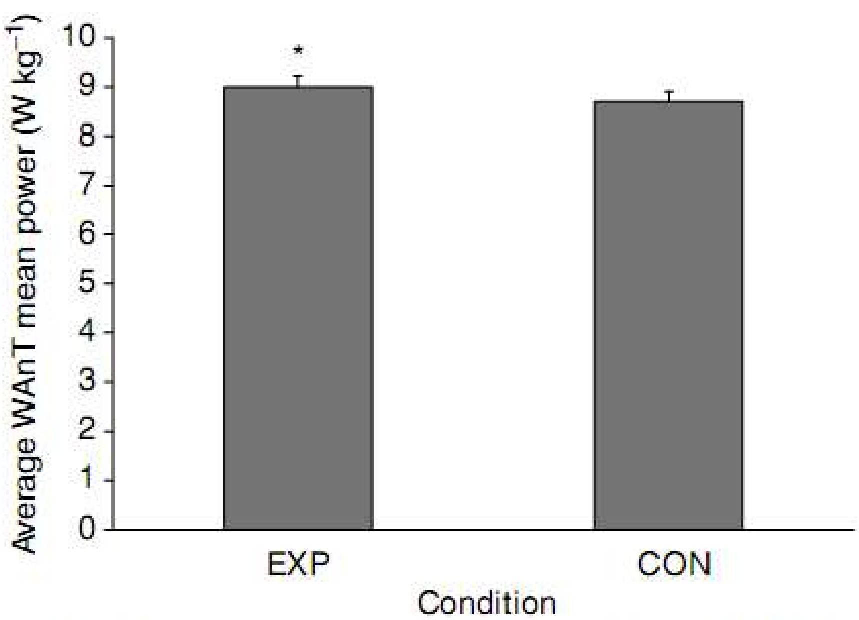


Fig. 4 Average mean power for WAnT + intervals (W kg^{-1}) for experiment (EXP) and control (CON) conditions. Average mean power was significantly higher for EXP compared with CON (*$P = 0.034$)

DISCUSSION

The results of the current study indicate that, in comparison to a traditional CFM, a neuromuscular dentistry-designed mouthguard resulted in greater VJ, peak power on a 30s WAnT and greater average peak power and average mean power across nine WAnT intervals. There was no apparent effect on measures of muscular endurance or anaerobic endurance, expressed as repetitions completed on a BP with body weight test and a 30s WAnT, respectively. Overall, these findings may hold practical relevance for all athletes required to use mouthguards, as these athletes are typically involved in sports that entail explosive ability and high levels of anaerobic capacity. It is possible that these positive effects on power and anaerobic capacity can translate beyond immediate use in a single performance bout and hold promise for improving overall progressive gains acquired during multiple performance bouts. Compared with the CFMs that have traditionally been used to prevent facial and dental trauma, neuromuscular dentistry-designed mouthguards that promote superior performance in outcome measures such as those assessed in the current study have the potential to facilitate the use of an overall greater workload in high-intensity activities. This may be particularly useful during interval-based training, given the improvements in average peak power and average mean power seen over the WAnT intervals.

The use of a mouthguard to reposition the jaw in an attempt to improve performance is not a new concept. Early work in this area focused on a mandibular orthopedic repositioning appliance. While some positive effects on isometric strength about the head and neck were reported (49), the findings were mostly mixed and the studies were plagued with methodological problems, such as lack of placebo-control conditions and non-individualized mouthguard fittings, as well as a lack of applicability to sport-specific tasks (49). Since that time, however, neuromuscular dentistry techniques have become more advanced. Based on the current study, it appears that a mouthguard designed using neuromuscular dentistry techniques has the potential to impact athletic performance in areas related to maximal power and repeatable power outputs. This may hold significance for the athlete who is required to wear a mouthguard while looking for a competitive advantage and improvement in performance.

This study represents one of the first to apply neuromuscular dentistry-designed mouthguards to sport performance, and adds to the small amount of existing literature evaluating the effects of dentistry on physical performance. Bracco et al. (36) found that optimal jaw alignment achieved using neuromuscular dentistry techniques resulted in improved posture and stability. Future studies should evaluate the mechanism(s) responsible for the positive physical effects elicited by the use of the PPM. In addition, future research should consider evaluating the use of neuromuscular dentistry-designed mouthguards on range of motion, agility, speed, accuracy and balance in athletes. Based on the theories driving the application of neuromuscular dentistry, it is conceivable that the position of the mandibular joint may impact neural conduction and proprioception (36). Given the peak power production, the use of these next-generation neuromuscular dentistry techniques appears to hold some promise for the strength and power athlete. Further research is warranted to evaluate the effects of long-term PPM use.

The findings of this study indicate that athletes perform better when using the PPM than when using the CFM. Either the PPM was less of a hindrance on performance compared with the CFM or it was effective in improving the performance. Comparison to a 'no-mouthguard' condition was not implemented in this study and therefore it is not possible to conclude in absolute terms whether the PPM improved or hindered performance. However, the working assumption driving the design of this study was that athletes are often required to wear mouthguards during practice/training and competition particularly for the sports represented in this study. In this case, the important consideration was to contrast the effects of these two different mouthguards on key performance outcomes. In previous studies that have compared CFMs with a no-mouthguard condition, it has been concluded that CFMs do not project any negative effects on aerobic performance or ventilatory capacity, nor do they interfere with maximal exercise performance (17, 18, 39). The results have been mixed for non-CFMs, with Francis and Basher (38) noting improvements in economy at higher intensities while Delaney and Montgomery (50) found no differences at submaximal intensities, but a decrease in V_E and VO_2 at maximal intensities. Based on these previous results, as well as a general agreement among researchers that the CFM provides more protection and is more accepted by athletes (51, 52), we opted to compare the effects of PPM versus a CFM on anaerobic performance in order to provide the most stringent comparison.

These previous studies may provide insight into why significant effects were not found with the PPM for BP and for average power during the 30s WAnT. These tests may have led to open-mouth breathing which would negate the positioning effects of the PPM, or any other mouthguard for that matter, on occlusion. In these particular tests, either mouthguard may have influenced performance outcomes, even in a negative manner. The inability to bite down into the PPM during prolonged anaerobic activities renders it similar to standard CFMs, which do not require forced biting. Future studies focusing on athletes that do not traditionally use mouthguards and who may be looking for a performance edge should include a 'no-mouthguard' control when evaluating the effects of multiple mouthguards on physical capacity. It appears that there is an optimal bite conundrum for muscular endurance activities, which may limit or negate the ergogenic effects of the PPM. Specific training and practice on PPM use may be needed to ensure that athletes benefit from the occlusional positioning.

PRACTICAL APPLICATION

Overall, the present study indicated that use of the novel mouthguard, PPM, resulted in significantly improved performance in a VJ, peak power of a 30s WAnT, average peak power and average mean power across nine WAnT intervals compared to a standard CFM. Each of these tests requires quick bursts of anaerobic energy at very high-intensity levels, much like activities encountered in many sports. These findings can be applied to athletes and non-athletes engaged in activities that require power-based movements and explosive strength (e.g., MMA, football, baseball). Additionally, these findings may potentially translate to long-term training effects since, compared with the CFM, the PPM may improve peak power gains and workload during training, especially interval-based training. Using neuromuscular dentistry techniques to design a mouthguard proved effective in improving anaerobic peak performance compared to the use of a standard CFM. Use of the PPM is another strategy that may help improve performance in individuals required to use a mouthguard while engaging in sports.

The above manuscript has been published in the peer-reviewed journal Comparative Exercise Physiology.

Arent S, McKenna J, Golem D. Effects of a neuromuscular-dentistry designed mouthguard on muscular endurance and anaerobic power. *Comparative Exercise Physiology* 7(2): 73-79, August 2010.

Effects of Standardized Jaw-Repositioning Mouthguards on Physical Performance

Devon L. Golem and Shawn M. Arent

INTRODUCTION

Mouthguards are typical safety devices recommended for use by athletes in various sports to decrease the risk of orofacial injuries. Reduced compliance with these recommendations is reported to be due to concerns of decreased performance with mouthguard use (16). Mouthguard manufacturers have responded to this concern with smaller designs that are well-fitted to the teeth of the athletes. The majority of research examining the effects of mouthguards on athletic performance focuses specifically on aerobic aspects and reveals that these design modifications generally prevent any impedance on aerobic capacity and respiratory functional tests (17, 37, 38). The effects of mouthguards on other aspects of physical performance have not been examined in detail.

The dental technique of jaw-repositioning has been incorporated in efforts to advance the design of mouthguards to not only reduced possible negative effects, but promote positive effects on physical performance. The premise to include this technique into mouthguard design stems from the positive effects observed in patients with and without TMD. Jaw position is correlated with postural control and spinal alignment (2-4, 29) and has been shown to improve spinal alignment in children with TMD (53). Jaw-repositioning has also been observed to improve posture and functional proprioception in adults without TMD (2). Changes in spinal alignment and proprioception induced by jaw-repositioning may promote changes in physical movement and performance.

With regards to athletic performance, most of the literature on jaw position and physical performance has focused on muscular strength. It has been consistently found that jaw-repositioning, through use of an oral appliance, does not affect strength (5, 54-60). Many types of strength tests were used in these studies, including shoulder adduction and abduction, knee extension and flexion, bench press, and hip sled exercises. Different measures were used including: 1) isokinetic strength: maximum amount of force produced against a resistance in one isolated movement, and 2) maximal strength: maximal load for one repetition of a specific exercise. Only one study reported an increase in peak torque of shoulder extension and external rotation with the use of a jaw-repositioning appliance (27). However, the improvement in these movements could be associated with changes in flexibility and ROM as opposed to the claim of increased strength.

Although muscular strength and muscular endurance were not observed to be affected by jaw-repositioning, muscular power was improved (5, 6). Muscular power is an essential component of athletic performance. Most sports require high power outputs in order to rapidly accelerate or decelerate (61). The observation of increased muscular power without concurrent increases in muscular strength or endurance leads to questions regarding these correlates of physical performance and mechanism of action of the jaw-repositioning technique. Muscular power differs from strength and endurance in that it requires rapid neuromuscular responses and is time dependent. Commonly known as “speed strength”, muscular power relies on *rapid* communication between peripheral proprioceptors and central command (31, 62). The examination of the effects of jaw-repositioning on other aspects of physical performance that require rapid neuromuscular communication may provide more insight regarding mechanism of action.

It is unknown whether jaw-repositioning can also influence other modes of physical activity, despite anecdotal evidence that it may. Agility, balance, and flexibility are all important in physical performance. Athletic movements require skillful application of force under variable conditions. Part of this skill is demonstrated as agility, or the change in movement velocity (61). Any movement requiring rapid change in speed or direction is considered an agility movement. Retaining balance throughout the execution of these movements is also essential to athletic performance (63). Along with agility and balance, physical movements require flexibility. Flexibility is a measure of range-of-motion (ROM) that occurs at a joint. Different optimal levels of flexibility exist for a variety of athletic activities (31). Dynamic balance and agility relate to muscular power as they all require *rapid* neuromuscular communication (64-67) and, along with flexibility, are regulated by proprioceptors within the muscle (31). The same neuromuscular factors that governed changes in proprioception (2) may also influence agility, balance, and flexibility.

The current literature lacks any evidence regarding the effects of jaw-repositioning on agility, balance, and flexibility. The purpose of this study is to determine the effects of standardized jaw-repositioning mouthguards on these aspects of physical performance. The secondary purpose of this study is to examine the effects of standardized jaw-repositioning mouthguards on muscular strength and power to determine if the jaw-repositioning method of standardized occlusion will promote similar effects as more expensive, neuromuscular dentistry-design techniques. It is hypothesized that the standardized jaw repositioning-mouthguards will improve agility, balance and muscular power performance. It is anticipated that the spinal alignment effects of jaw-repositioning will promote improvements in active flexibility with use of these mouthguards.

METHODS

Experimental Approach

A randomized, blind, controlled, crossover design was used to examine the effects of two jaw-repositioning mouthguards on various aspects of physical performance. All subjects completed performance testing in each of four conditions in a randomized order: self-adapted jaw-repositioning mouthguard (SA); custom-fitted jaw-repositioning mouthguard (CF); placebo mouthguard (PLA); and a no-mouthguard control (CON). The conditions differed in appearance and feel, yet the subjects were blinded to the placebo condition and to the jaw-repositioning concept that was being evaluated. All mouthguard fittings were completed in the Human Performance Laboratory at Rutgers University. The researchers were initially guided by a dentist on proper fitting procedures and TMD assessment. The subjects completed a familiarization session, which was paired with the fitting session, to control for learning effects on the performance tests, which included dynamic balance, flexibility, power, agility, and strength. Following the fitting/familiarization session, subjects completed each of the four conditions, which were separated by at least 48 hours in order to allow for sufficient recovery.

Conditions

The mouthguards in this study promoted jaw-repositioning through a standardized increase in dental occlusion, the space between upper and lower molars. The placement of hard material between the molars promotes a downward movement of the jaw. Unlike typical mouthguards, the material within the jaw-repositioning mouthguards is impervious to dental compression ensuring a permanent increase in dental occlusion. To reduce cost and increase availability, the jaw-repositioning mouthguards evaluated in this study were designed to be constructed without the expertise of a dentist. For the purpose of this study, initial supervision and guidance was provided by a licensed dentist to ensure that the researchers provided proper instructions and assistance to the subjects during the fitting process.

Both SA (a.k.a. boil-and-bite) and CF jaw-repositioning mouthguards were evaluated. The design of both mouthguards allowed the material surrounding the teeth to be molded, while the material between the dental occlusion was stationary, thus promoting a standardized change in jaw position. PLA had a similar fit around the upper teeth, but lacked material between upper and lower molars preventing change in jaw position. Dental occlusion under each condition was measured and recorded. A significant difference between conditions was observed ($P < .001$) with CON and PLA having a significantly lower occlusion than the SA and CF conditions (CON: 72.8 +/- 4.9 mm; PLA: 73.1 +/- 4.7 mm; SA: 75.5 +/- 5.0 mm; CF: 75.9 +/- 4.8 mm; $P < .001$). The mouthguards effectively increased dental occlusion 2-3mm.

Figure 5. **Mouthguard Conditions**. From right to left, the custom-fitted jaw-repositioning mouthguard (CF), the self-adapted jaw-repositioning mouthguard (SA), and the placebo mouthguard control (PLA).

Subjects

Healthy, male collegiate athletes ($N = 20$; M_{weight} = 79.8 +/- 11.7 kg; M_{height} = 176.5 +/- 6.5 cm; M_{age} = 21.5 +/- 2.7 yr) with 12.4 +/- 4.5 years of athletic training experience participated in this crossover study. All subjects participated in sports with which mouthguard use was recommended and were required to have worn mouthguards during their athletic career to ensure familiarity with mouthguard use ($MG_{experience}$ = 7.9 +/- 5.4 years). Thirty participants were initially recruited, but three were excluded due to lack of mouthguard experience, three subjects were injured within the study time period rendering them unable to complete testing, and four subjects voluntarily withdrew from participation due to scheduling conflicts. The sports represented by the subject population include mixed martial arts, wrestling, football, soccer, and lacrosse. This study was limited to males in order to control for muscular power and strength differences that exist between genders (68).

Risks and benefits were explained to the subjects and each of them gave written informed consent prior to participation in the study. All individuals were free from current injuries, dental conditions, and health conditions limiting their ability to complete physiological testing. A health screening was completed with each subject in accordance with American College of Sports Medicine exercise testing procedures. A temporomandibular joint disorder screening was completed to ensure adequate dental health (3, 69). The study was approved by the Rutgers University Institutional Review Board.

Procedures

After screening, each subject was fitted for mouthguards and completed a familiarization session to control for learning effects (44). The SA jaw-repositioning mouthguards were fitted immediately using a boil-and-bite process. Trained research staff assisted the subjects with the fittings to ensure proper fit. The fitting of the CF jaw-repositioning mouthguard consisted of two steps: 1) dental impressions were made in the Human Performance Laboratory by research staff, and 2) these impressions were shipped to the manufacturer for mouthguard construction.

The manufacturer used the impressions to construct the CF and the PLA mouthguards for each subject. These were then shipped to the Human Performance Laboratory. The first session also consisted of a familiarization practice of every performance test. Each test was demonstrated for the subject while also providing verbal instructions. Each subject completed the physical tests a minimum of one time.

The familiarization and fitting session was followed by four separate testing sessions. During each testing session, subjects completed five different performance tests in the following order: dynamic balance, systemic warm-up on a treadmill, flexibility measurements, counter-movement vertical jump (VJ), hexagon agility test, and a bench press strength test. The order of this battery of physical tests is consistent with the National Strength and Conditioning Association testing order guidelines (70). Participants were instructed to continue with their normal exercise training during the course of the study, but were required to refrain from training for 24 hours prior to each testing session. Additionally, each subject was tested at the same time of day (+/- 1 hour) to control for diurnal variation that may impact physical performance (71, 72).

Once the CF and PLA mouthguards were received, subjects returned to the lab to complete the four testing sessions which were separated by a minimum of 48 hours to allow for recovery. Subjects were instructed to arrive for testing normally hydrated, to have eaten and slept per their usual regimen, to maintain consistency in footwear, and to refrain from moderate-vigorous exercise training at least 24 hours prior to the testing session. Written records of previous meal dietary intake, hours slept the previous night, exercise completed in past 48 hours, and shoes worn were obtained at the beginning of each testing session and were used to assess compliance. No significant differences in energy or macronutrient intake were observed between conditions (P = .743). No significant differences between conditions were observed for number of hours of sleep (P = .86) the previous night, as well no significant changes in body weight were observed (P = .19) between conditions.

Performance Measures

Mouthguard Use: To promote proper use of the mouthguards and ensure the jaw position of varying conditions was met, subjects were instructed to bite down into the mouthguard during each performance test.

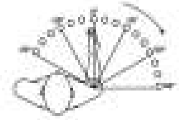
Dynamic Balance: Dynamic balance was assessed using the model 16030 Stability Platform (Lafayette Instrument Company; Lafayette, IN). The platform pivots on a center axis from left to right sides. A 5 degree range of error to either side was designated as “out of center balance”. The subjects used their body to balance the board from leaning laterally during each of four 30s trials. A 30 second rest was taken between each of the trials. The amount of time to the nearest hundredth of a second to the left, center, and right were recorded for each trial. The highest value for time in center balance was used as the score for each condition.

Dynamic Flexibility: After a 5 minute systemic warm-up on the treadmill at a self-selected pace, the subjects performed the dynamic flexibility tests. The initial self-selected pace for warm-up was repeated for each condition. Flexibility can be measured in static or dynamic terms (without or with voluntary muscle action, respectively). Dynamic flexibility is more closely related to sports performance than static flexibility (73, 74) and therefore was evaluated in this study. Dynamic flexibility of the hamstrings was assessed using the sit-and-reach method (70).

Each subject took off his shoes, sat on a floor mat, and pressed his feet flat against the front of the sit-and-reach box. The subjects leaned forward, with their palms facing the floor and their legs fully extended, and stretched as far as possible holding the position for a minimum of 2 seconds. The sit-and-reach test was completed twice and the highest score was recorded to the nearest 1 cm (70).

Dynamic flexibility and ROM was measured at 6 points of the body: shoulder extension, shoulder lateral rotation, hip flexion and extension, lumbar spine lateral flexion, and lumbar spine rotation. These 6 movements were selected to represent ROM in the upper, middle, and lower areas of the body's core. The subjects were not assisted through the ROM and used their own muscular force designating these measures of flexibility as dynamic. These measurements were taken with a goniometer, a protractor-like tool used to measure the ROM in degrees. The measurements were taken on the dominant side of each subject.

1. **Shoulder Lateral Rotation**: The subjects laid supine on the floor mat, with their legs extended, and with their head facing the ceiling. Their dominant arm was abducted 90^{o}, so their forearm was perpendicular to the floor. The researchers ensured the alignment of the subject's humerus with their acromion process (bony projection of the shoulder) before using the subject's olecranon process (bony projection of the inner elbow) as the axis of rotation. The goniometer was placed along the side of the subject's ulna with the stationary arm perpendicular to the floor and the moving arm along the styloid process (sharp edge of the forearm) of the ulna. The researcher stabilized the distal end of the subject's humerus and scapula. The subjects moved their forearm to the floor away from their body. The angle between the arm and the perpendicular position was recorded.

 Figure 6. **Shoulder Lateral Rotation**

2. **Shoulder Extension:** The subjects laid prone on a floor mat, with their head turned away from their dominant shoulder, their hands down at their sides, and with slight flexion in their elbows. The goniometer was placed with the axis at the subjects' acromion process. With their palm facing toward their body, the subjects lifted their arm backward/upward to the full ability while a researcher stabilized their scapula. The stationary arm of the goniometer remained along the midaxillary line of the subject while the moving arm was aligned with the subject's arm. The angle from the midaxillary line to the lifted arm was recorded.

 Figure 7. **Shoulder Extension**

3. **Hip Flexion:** The subjects laid supine on a floor mat with legs and arms extended downward. The subjects bent their testing leg to their chest without assistance. The goniometer axis was placed on the outside of the subjects' hip over the greater trochanter. The stationary arm was aligned with the midline of the subject's pelvis and the moveable arm was aligned with the midline of the subject's femur using the lateral epicondyle as a reference point. The angle of flexion was recorded.

 Figure 8. **Hip Flexion**

4. **Hip Extension:** The subjects laid prone on a floor mat with their knees extended. The subjects raised their dominant leg while keeping their knees extended**.** The researcher stabilized the subject's hip from rotating off the floor mat. The goniometer axis was placed on the outside of the hip over the greater trochanter. The stationary arm was aligned with the midline of the subject's pelvis and the moveable arm was aligned with the midline of the subject's femur using the lateral epicondyle as a reference point. The angle of extension was recorded.

Figure 9. **Hip Extension**

5. **Lumbar Spine Lateral Flexion:** The subjects stood straight with their feet shoulder-width apart and their hands at their sides. The axis of the goniometer was placed over the sacral spine S1 with the arms of the goniometer pointed toward the ceiling along the spine. The subjects performed lateral flexion (leaned with their spine) toward their dominant side. The moveable arm of the goniometer followed the spine directed towards the cervical spine C7. The angle of lateral flexion was recorded.

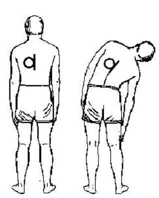


Figure 10. **Lumbar Spine Lateral Flexion**

6. **Lumbar Spine Rotation:** The subjects sat on a foot stool, facing forward, with their spine erect, their feet on the floor, and their pelvis stabilized. The axis of the goniometer was placed

over the center of the cranial aspect of the subjects' heads. The stationary arm of the goniometer was parallel to an imaginary line between the acromion processes. The subjects rotated their spine toward their dominant side to their full ability. The moveable arm of the goniometer followed the imaginary line between the acromion processes while the stationary arm remained in the same position before movement. The angle of rotation was recorded.

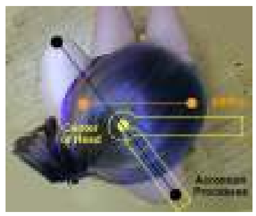


Figure 11. **Lumbar Spine Rotation**

<u>Power:</u> Lower-body muscular power was assessed with the counter-movement vertical jump test (70) using the JustJump™ Mat (Probotics, Inc.; Huntsville, AL). The subject stood on the mat with his feet shoulder width apart. The subjects performed two quick movements:

a. Countermovement: quickly bending knees and hips while moving torso forward and downward, and swinging arms backward

b. Jump: explode upward extending hips, knees, and ankles while reaching upward with one or both arms

The remote to the mat indicated height of each jump in inches. A 30-second rest was given between each of 3 trials. The highest height of the 3 trials was recorded to the nearest 0.1 inches (70). Inches were converted to centimeters to maintain consistency in metric measurement. Power output was calculated with VJ height and body weight using the Sayers formula (75).

Agility: The Hexagon test was used to evaluate agility (70). A hexagon was marked on the floor, each of the six sides measured at twenty-four inches each and every angle was 120 degrees. The subject began the test standing in the middle, facing toward one side of the hexagon. The subjects would double-leg hopped from the center over each side and back to the center in a clockwise fashion starting with the side directly in front of them. A total of 3 revolutions around the hexagon while facing forward was completed (70). The test was restarted if the subject landed on the hexagon markings, lost balance, took extra steps, failed to return back to center, or changed direction. The timer was started the moment the subject's feet lifted from the center ground on the first jump. The timer was stopped the moment the feet had returned to the center upon completion of the third revolution (70). The subjects performed 3 trials for each condition. Two minutes of rest were provided between each trial. The fastest time (to the nearest 0.1 s) of the 3 trials was recorded (70).

Strength: Upper body strength was assessed using the 3-repetition maximum (3-RM) testing method for the bench press exercise (70). Researchers provided spotting as needed and ensured proper form and technique. The subjects completed 2 warm-up sets. The first warm-up set consisted of 8 reps with 65% of estimated 3RM load followed by a 2 min rest. The second warm-up set consisted of 5 reps with 75% estimated 3RM load followed by a 3 min rest. After the warm-up sets, the subjects attempted 100% of estimated 3-RM load. The 3-RM load was determined within 3-5 attempts with 3 minutes rest between each attempt. If the estimated load was too heavy, the load was decreased by subtracting 2.5-5%. If the estimated load was too light, the load was increased by adding 5-10% (70). The highest 3-RM load was recorded for each condition. Strength was compared on an absolute basis (total amount of weight lifted for 3 reps) and on a relative basis (total weight lifted divided by body weight). A direct relationship exists between strength and muscle size therefore athletes with heavier body weights tend to have more total muscle mass compared to those with lower body weights. Taking this into consideration, in this subject population, body weight is positively related to bench press strength. The relative strength (kg load/kg body weight) provides a better comparison measure between subjects.

Statistical Analyses

All statistical analyses were completed using SPSS® statistical software (IBM® SPSS® version 20). Separate repeated measures multivariate analysis of variance (RM MANOVA) were used to assess the effects of the four different conditions (CON, PLA, SA, and CF) on flexibility measures (SR, SE, SLR, HF, HE, LSLF, LSR) as well as related performance variables (VJ, HEX, BP). Significant multivariate effects were followed by univariate tests. Separate RM ANOVA were used to assess the effect of the four conditions on time in center balance, adjusted BP (load/kg BW), and adjusted VJ (jump height/kg BW). For each univariate analysis, the Huynh-Feldt test of sphericity was calculated to test the assumption of sphericity. If this statistic was not significant, sphericity was assumed and the unadjusted statistic was used. If this statistic was significant, then sphericity was considered to have been violated and the Huynh-Feldt adjusted statistic was used to test significance.

To evaluate the magnitude of change in each mouthguard condition, effect sizes (ES) for all variables were calculated using Hedges' *g* formula. The effect sizes were used to compare magnitude of change as small effects may have a large impact in high-level athletes (48). Data are expressed as mean $\pm$ SD and statistical significance was set at $\alpha < 0.05$ level.

RESULTS

Dynamic Balance

No significant difference in balance was observed between conditions (CON: 19.91 +/- 5.6 s; PLA: 19.98 +/- 5.5 s: SA: 20.1 +/- 6.3 s; CF: 20.1 +/- 5.6 s; P = 0.99).

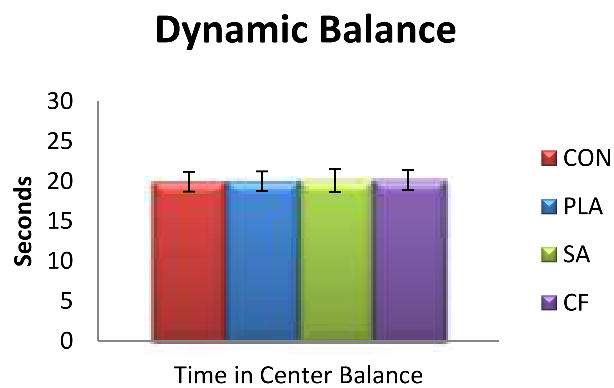


Figure 12. **Dynamic Balance.** Time in center balance on the stability platform did not differ between conditions.

Flexibility and ROM

No multivariate effect was observed (P = .144). No significant differences between conditions were observed for the flexibility measures obtained for the sit-and-reach, shoulder lateral rotation, hip extension, or lumbar spine rotation. Pairwise comparison revealed that the CON condition had significantly higher hip flexion flexibility than the CF condition (CON: 118.85 +/- 9.3^0; CF: 116.3 +/- 9.7^0; P = 0.03; ES: -.27) and the SA condition resulted in significantly higher shoulder extension flexibility than the CF condition (SA: 36.25 + 9.0^o; CF: 34.85 +9.7^o; P = 0.014; ES: -.14). A trend for significance was observed for lumbar spine lateral flexion flexibility as the CF condition had greater ROM than the SA condition (CF: 33.25 + 9.2^o; SA: 31.85 + 9.3^o; P = 0.054; ES: -.15).

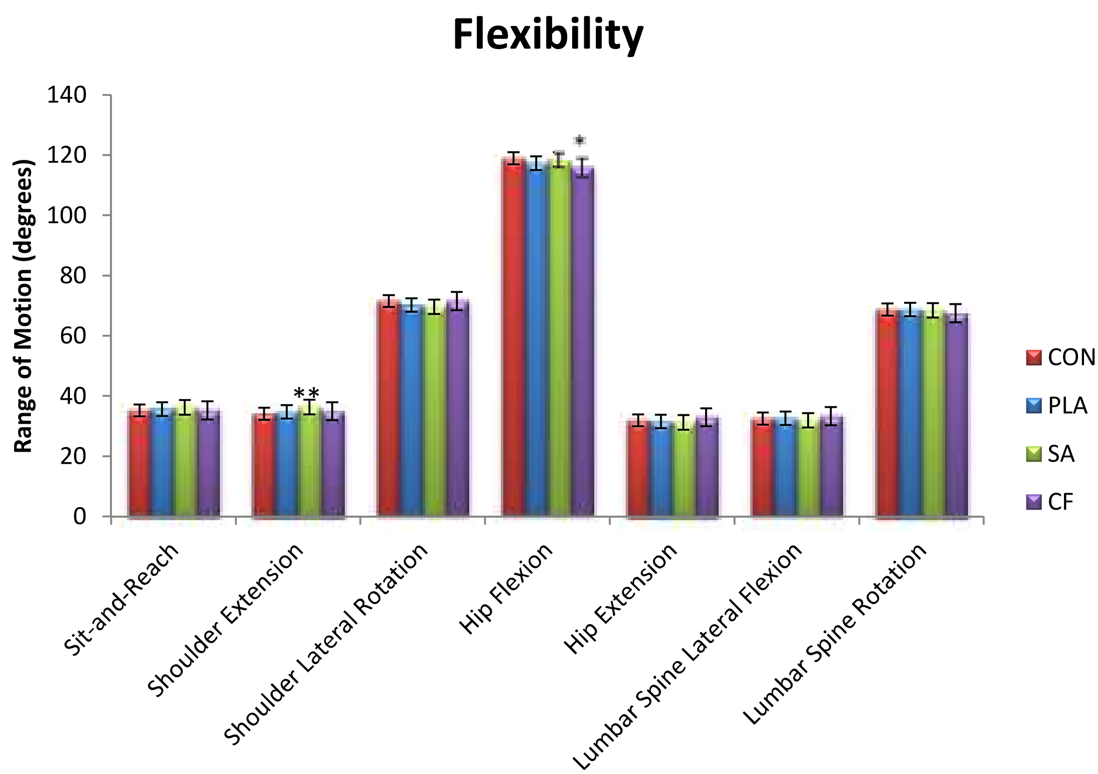


Figure 13. **Flexibility**. The SA condition had significantly higher shoulder extension flexibility compared to the CF condition. The CF condition had significantly lower hip flexion flexibility compared to the CON condition. No other differences in flexibility were observed between conditions. * indicates P <0 .05 compared to CON **P <0 .05 compared to CF

Vertical Jump Height and Power Output

No significant differences were observed regarding vertical jump height between conditions in absolute (CON: 61.0 +/- 7.8 cm; PLA: 60.7 +/- 7.7 cm; SA: 60.5 +/- 8.2 cm; CF: 60.3 +/- 9.1 cm; P =0 .42) or relative terms (CON: 0.78 +/- 0.16 cm/kg; PLA: 0.78 +/- 0.17 cm/kg; SA: 0.77 +/- 0.16 cm/kg; CF: 0.78 +/- 0.18 cm/kg; P =0 .83). No significant effects were observed between groups in terms of absolute power output (CON: 5261.4 +/- 613.7 W; PLA: 5230.1 +/- 555 W; SA: 5243.2 +/- 636.5 W; CF: 5212.1 +/- 613.6 W; P = 0.78) or relative power (CON: 66.49 +/- 7.2 W/kg; PLA: 66.46 +/- 7.6 W/kg; SA: 66.09 +/- 7.6 W/kg; CF: 66.12 +/- 8.5 W/kg; P = 0.88).

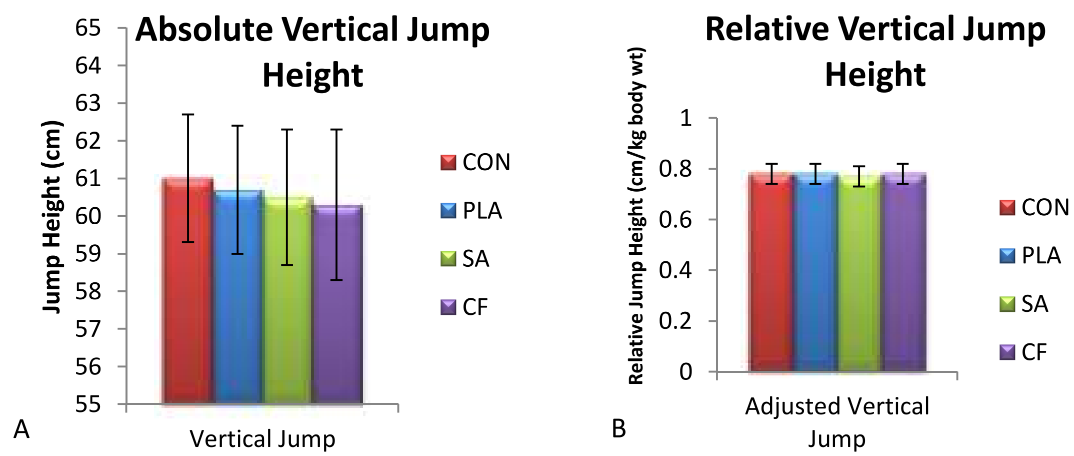


Figure 14. **Vertical Jump Height**. No significant differences between conditions were observed for absolute vertical jump height (A) and adjusted vertical jump height (B).

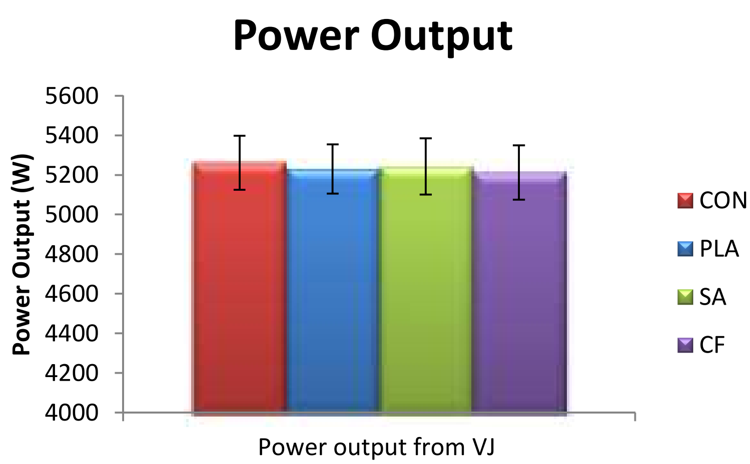


Figure 15. **Power Output**. No significant differences were observed between groups in power output calculated from VJ and body weight.

Agility

No significant differences were observed between conditions for time to completion of the Hexagon agility test (CON: 10.9 +/- 1.6 s: PLA: 10.6 +/- 1.0 s; SA: 10.5 +/- 1.0 s; CF: 10.7 +/- 1.1 s; P = 0.22). Refer to figure 10.

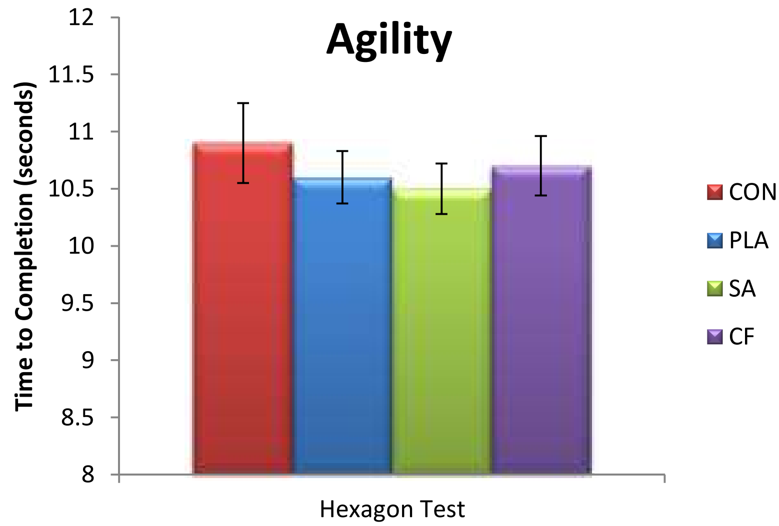


Figure 16. **Agility**. No significant differences in time to completion of the Hexagon agility test were observed between conditions.

Strength

A trend for a significant effect for absolute strength was observed (P =0 .06). Pairwise comparison revealed that the CON condition resulted in a higher absolute strength compared to the PLA condition (CON: 98.8 +/- 17.4 kg; PLA: 97.7 +/- 17.6 kg; P =0.046; ES: -.06), while the absolute strength of the mouthguard conditions did not significantly differ from either CON or PLA conditions (SA: 98.5 +/- 17.3 kg, ES: -.02; and CF: 97.6 +/- 17.6 kg, ES: -.07). No significant differences were observed for relative strength (all conditions: 1.2 +/- .1 kg load/kg body weight; P = 0.47, ES: 0). Refer to figure 11.

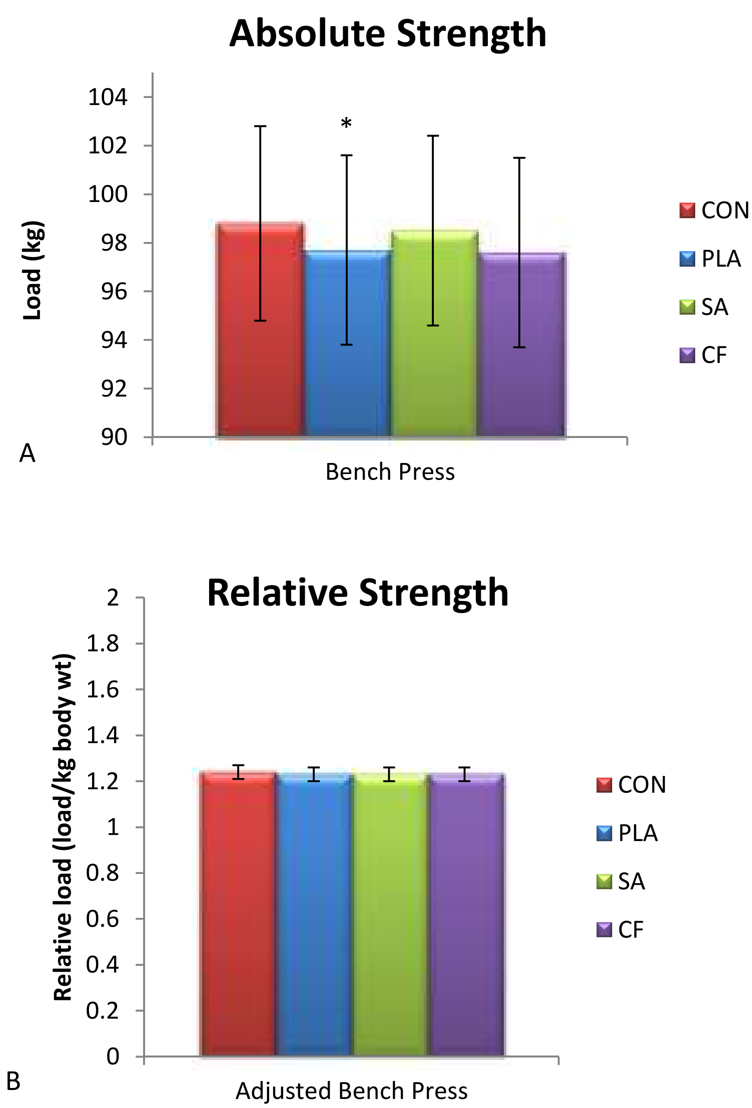


Figure 17. **Strength**. Neither of the mouthguard conditions (SA nor CF) differed significantly from the CON or PLA conditions in absolute (*A*) or relative (*B*) terms of bench press 3-RM performance. The PLA condition had significantly lower bench press performance compared to the CON condition. * indicates $P < 0.05$

DISCUSSION

The dental technique of jaw-repositioning has been used in the development of ergogenic mouthguards. Previous evidence suggested the possibility of improved athletic performance with the use of jaw-repositioning mouthguards (5, 6). The results of this study reveal that neither the self-adapted or custom-fitted jaw-repositioning mouthguards were effective in promoting a change in performance outcomes of balance, flexibility, muscular power, agility, nor strength tests in college-age male athletes.

The results of the current study are consistent with the previous literature in that strength was not affected by jaw-repositioning. However, the lack of effect on muscular power contradicts previous evidence. Bates et al (5) evaluated the effects of a jaw-repositioning appliance, compared to a no-appliance control condition, on upper and lower body power and muscular strength. In that study, each of the 11 college-aged, male subjects completed maximum lifts for bench press and hip sled exercises for strength assessment, as well as vertical jump for power assessment, with and without use of the oral appliance. Performance on bench press and hip sled exercises was not different between the two conditions, indicating the absence of an effect of jaw-repositioning on upper body and lower body strength, respectively. However, a significant increase in vertical jump performance was observed with the use of the oral appliance compared to the control. Use of the jaw-repositioning appliance led to improvements in power but not strength (5). An increase in vertical jump and anaerobic power performance with a jaw-repositioning mouthguard was also observed in our previous study (6).

The lack of performance effects in the current study may be due in part to the standardized method of jaw-repositioning. To decrease costs and increase availability, the manufacturers developed a production system that eliminates the need for dental expertise. However, individuality and precise jaw positioning cannot be acquired without the use of advanced dental techniques and direct contact between dental expert and athlete. More advanced dental techniques that are used in the production of TMD treatment devices, such as transcutaneous electric neural stimulation (TENS) and electromyography (EMG), may be necessary to create an "optimal" jaw-repositioning mouthguard for each individual athlete. Future research should take this into consideration when evaluating the effects of jaw-repositioning mouthguards.

A limitation of the current study is the lack of comparison to a non-jaw-repositioning mouthguard. Another limitation lies within the placebo mouthguard as the design promoted a lack of fit and was claimed to be uncomfortable by most subjects. The absence of blinding could have potentially been another limitation as the subjects may have preferred one condition over others. To address this limitation, the subjects were encouraged to perform to the best of their ability for each test despite the condition. As well, the jaw-repositioning design was not disclosed to reduce subject bias. The limitations in our previous study, including the absence of a no-mouthguard control and possible open-mouth breathing during the bench press test, were addressed in the design of this study. Open-mouth breathing was controlled for during the 3-RM bench press test, along with all other tests, as the subjects were constantly reminded to bite down while exerting effort.

This was the first study to evaluate the effects of jaw-repositioning through a standardized increase in dental occlusion on balance, flexibility, and agility. Although the results were null, the findings lead us to ask other questions regarding the performance claims surrounding these mouthguards and the underlying mechanism of effective jaw-repositioning mouthguards. Future studies should evaluate the effects of these mouthguards on aerobic performance as anecdotal evidence has suggested that small changes in jaw position affect ventilation and gas exchange.

PRACTICAL APPLICATION

The results of the present study indicated that the two standardized, jaw-repositioning mouthguards were ineffective at enhancing performance of dynamic balance, flexibility, power, agility, and strength. The jaw-repositioning method of producing a standardized increase in dental occlusion may explain the difference in the current power results compared to our previous study (6) that utilized EMG to determine an optimal resting jaw position for each individual subject. Perhaps professional manipulation of myofacial activity using advanced dental techniques during mouthguard fitting is necessary to elicit changes in muscular power performance. The purpose of the simplified positioning method used in the mouthguards evaluated in this study was to increase availability and practicality of these jaw-repositioning mouthguards. Eliminating the requirement of dental expertise for the production of these mouthguards enabled the manufacturers to reduce the costs associated with production and sales. These factors make the mouthguards evaluated in this study more practical than the neuromuscular dentistry-designed mouthguards yet less effective as an ergogenic aid in terms of the aspects evaluated in this study.

Although changes in the specific performance aspects of flexibility, balance, agility, power, and strength were not observed with these mouthguards, aerobic performance should not be overlooked. Jaw-repositioning mouthguards may affect aerobic performance in a manner unrelated to proprioceptive movements and therefore may not be affected by method of jaw-repositioning. The technique of jaw-repositioning has been used to treat breathing disorders by increasing respiratory passageways (7, 8, 10). Future research should determine whether these affordable, jaw-repositioning mouthguards affect aerobic performance in athletes.

This study provides additional support to the evidence that promotes mouthguard compliance as negative performance effects were not observed. Despite a decrease observed in hip flexion with the CF condition, mouthguard use did not negatively affect dynamic balance, flexibility, muscular power, agility, or strength kinetics in college-aged, male athletes. The use of mouthguards as a safety device should be encouraged among athletes involved in high dental injury risk sports.

The Effects of a Standardized Jaw-Repositioning Mouthguard on Respiratory Function and Aerobic Capacity

Devon L. Golem and Shawn M. Arent

INTRODUCTION

Many sports involve the combination of explosive and continuous movements which engage both anaerobic and aerobic means of energy metabolism (76). Aerobic metabolism is critical to all sports as it produces more ATP than anaerobic metabolism. The body's demand for oxygen increases during acute bouts of exercise and is directly related to the intensity of the exercise and the amount of muscle involved (76). Several studies have been conducted to examine whether mouthguards impede aerobic performance, aerobic capacity, and respiratory function. These studies are consistent in the finding that well-fitted, smaller mouthguards do not have a negative effect on aerobic performance (18, 37-39, 77). Despite this evidence, non-compliance with mouthguard recommendations continues to place athletes at increased risk of orofacial injuries (16).

Jaw-repositioning is a dental technique that has been incorporated into mouthguard design to promote positive, ergogenic effects on physical performance, including aerobic performance. Evidence strongly suggests a link between jaw position and size of airway openings. Trenouth and Timms found that a large portion of the upper airways, called the oropharyngeal airway (OPA), is positively correlated with the length and position of the mandible (26), indicating that an increase in jaw opening would promote an increase in the upper respiratory airways. For this reason, jaw-repositioning appliances are often used to treat obstructive sleep apnea by enlarging the upper airway area (7, 8, 10).

The jaw-repositioning appliance examined in one study increased the mean pharyngeal cross-section area (CSA) of sleep apnea patients to 28 mm^2, which exceeds the suggested CSA needed to breathe normally (20mm^2) (8). In a recent study involving endurance athletes, computer tomography scans revealed an increase in oropharynx width and diameter with use of a jaw-repositioning mouthpiece at rest (78). The results did not include measures of aerobic performance, but it is inferred that an increase in airway openings promotes improved gas exchange.

The effects of jaw-repositioning mouthguards on aerobic performance have varied. Francis and Brasher observed a *decrease* in oxygen consumption and ventilation during high intensity cycling with the use of jaw-repositioning mouthguards (38). In contrast, a study completed by Garner et al. demonstrated an *increase* in oxygen consumption, carbon dioxide production, and ventilation with use of a jaw-repositioning mouth piece during a 30-min endurance run (77). This study used a lower jaw (mandibular) mouth piece and was plagued with methodological limitations including small sample size, unsupported conclusive statements, and impractical testing methods yielding data that cannot be translated into life-like athletic scenarios. Clearly the relationship between jaw position and aerobic performance has not been fully illuminated and more research is needed. The purpose of this study was to examine the effects of two standardized jaw-repositioning mouthguards on respiratory function, steady-state gas exchange, and maximal aerobic capacity in male athletes. It is hypothesized that these jaw-repositioning mouthguards will improve aerobic performance as evidenced by increased ventilation and oxygen consumption during submaximal and maximal exercise.

METHODS

Experimental Approach

A randomized, blinded, placebo-controlled, crossover design was used to examine the effects of two jaw-repositioning mouthguards on aerobic dynamics at rest, during four incremental stages of submaximal exercise, and during maximal exercise intensity. All subjects completed performance testing with each of the four conditions in a randomized order: self-adapted jaw-repositioning mouthguard (SA); custom-fitted jaw-repositioning mouthguard (CF); placebo mouthguard (PLA); and a no-mouthguard control (CON). The conditions differed in appearance and feel, yet the subjects were blinded to jaw-repositioning design and the placebo condition. All mouthguard fittings were completed in the Human Performance Laboratory at Rutgers University. Guidance and supervision were initially provided by a licensed dentist to ensure research staff provided adequate instruction and aid to the subjects during the fitting process. A familiarization session was paired with the fitting session. The subjects underwent four testing sessions at least 48 hours apart to allow for adequate recovery. During each testing session, subjects completed respiratory functional tests and an aerobic capacity treadmill test. Participants refrained from training for at least 24 hours prior to each testing session, but were otherwise instructed to continue with their normal training regimen during the study. Additionally, each subject was tested at the same time of day each session to control for diurnal variation in physical performance (71, 72).

Subjects

Healthy, male collegiate athletes (N = 20; M_{weight} = 79.8 +/- 11.7 kg; M_{height} = 176.5 +/- 6.5 cm; M_{age} = 21.5 +/- 2.7 years) with 12.4 +/- 4.5 years of training/conditioning experience participated in this crossover study. All subjects participated in sports with which mouthguard use was recommended and were required to have worn mouthguards during their athletic career ($MG_{experience}$ = 7.9 +/- 5.4 years). The sports represented by the subject population included mixed martial arts, wrestling, football, soccer, and lacrosse. This study was limited to males in order to control for pulmonary function differences that exist between genders (68, 79, 80). Risks and benefits were explained to the subjects and each of them gave written informed consent prior to participation in the study. All individuals were free from current injuries, dental conditions, and health conditions limiting their ability to complete physiological testing. A health screening was completed with each subject in accordance with American College of Sports Medicine exercise testing procedures. Refer to appendix 4 to review the medical questionnaire. A temporomandibular joint disorder screening was completed to ensure adequate dental health (3, 69). The medical questionnaire ruled out asthma or any lung conditions that may affect performance or be affected by jaw-repositioning. The study was approved by the Rutgers University Institutional Review Board.

Conditions

A standardized increase between the upper and lower molars (dental occlusion) was the jaw-repositioning method used in the design of the two mouthguards evaluated in this study. Two different polymer materials were incorporated into each mouthguard: a soft, shape-conforming polymer that fits around the teeth and a hard polymer material that promotes a change in jaw position by stabilizing the upper and lower molars at least 2 mm from each other. To reduce cost and increase availability, the jaw-repositioning mouthguards evaluated in this study were designed to be constructed without advanced dental equipment and the professional judgment of a dentist. However, a consulting dentist provided training and guidance to the research staff regarding temporomandibular joint disorder assessment, occlusion measurement, and mouthguard fittings.

Both an SA (a.k.a. boil-and-bite) and CF jaw-repositioning mouthguard were compared to PLA and CON (no-mouthguard) conditions. As seen in the picture below, the PLA was fitted to the upper teeth yet lacked material between upper and lower molars preventing change in jaw position. Dental occlusion under each condition was measured and recorded.

Figure 18. **Mouthguard Conditions**. From right to left, the custom-fitted jaw-repositioning mouthguard (CF), the self-adapted jaw-repositioning mouthguard (SA), and the placebo mouthguard control (PLA).

Procedures

After screening, each subject was fitted for mouthguards and completed a familiarization session to control for learning effects (44). The SA jaw-repositioning mouthguards were fitted using a boil-and-bite process. Trained research staff assisted the subjects to ensure proper fit. The fitting of the CF jaw-repositioning mouthguard consisted of two steps: 1) dental impressions were made in the Human Performance Laboratory by the subject under research staff supervision, and 2) these impressions were shipped to the manufacturer for mouthguard construction. The manufacturer used the impressions to construct the CF and the PLA mouthguards for each subject. These were then mailed back to the Human Performance Laboratory. The first session also consisted of a familiarization practice of the resting oral airflow dynamic tests. Verbal instructions and a demonstration were provided by trained research staff. Each subject completed the respiratory function tests and the results were recorded.

Subjects were instructed to arrive for testing normally hydrated, to have eaten and slept per usual regimen, to maintain consistency in footwear, and to refrain from vigorous exercise training at least 24 hours prior to the testing session. Records of these daily patterns were obtained at the beginning of each testing session and were used to ensure compliance. No significant differences in energy or macronutrient intake per kilogram body weight were observed between conditions ($P = 0.74$). No significant differences between conditions were observed for number of hours of sleep ($P = 0.86$) or for body weight ($P = 0.19$).

Performance Measures

Respiratory Function Tests: The subjects first underwent respiratory function tests to assess lung capacity. Dynamic pulmonary measures were assessed through direct gas exchange on an open circuit spirometer (Parvo Medics Sandy, Utah). These measures included functional vital capacity (FVC), forced expiratory volume in 1 second ($FEV_{1.0}$), peak expiratory flow rate (PEFR), and maximum voluntary ventilation (MVV). FVC (L) is defined as the total amount of air moved in one breath cycle from full inspiration to full expiration. The $FEV_{1.0}$ is the volume of air expired (L) in 1 second which is typically 85% of the FVC in healthy adults (76). PEFR (L/s) evaluates the maximum speed of expiration from the lungs during a full expiration. FEV, FVC, and PEFR were measured simultaneously over a single breath. While seated, each subject was instructed to take a full inspiration followed by a full expiration into the flow meter mouthpiece. The subjects completed 3 trials with a 30 second rest between each trial. The highest values were recorded. The MVV (L/min) evaluates ventilatory capacity over 15 seconds as the subject breathes as deeply and as rapidly as possible. The value was multiplied by four in order to calculate liters of air moved per minute. MVV was measured one time per condition and followed by a 2 min rest (76). All oral airflow measures were obtained solely from the mouth as the subjects wore a nose plug for these tests.

Blood Lactate Analysis: Capillary blood samples (10-15 ul) were obtained from the fingertips immediately before, 0, 5, and 10 min post-exercise to assess blood lactate values. Whole blood lactate content (mmol/L) was determined using the Lactate Pro (Arkay, Japan) portable analyzer (r =0.99) (81). Resting and peak blood lactate values were determined for each condition. An adjusted peak lactate value (peak minus resting) was calculated and analyzed for each condition.

Submaximal and Maximal Aerobic Capacity: Oxygen consumption (VO_2), carbon dioxide production (VCO_2), and ventilation (V_E) were assessed through direct gas exchange on an open circuit spirometer (Parvo Medics; Sandy, Utah). The subjects wore a face mask, encasing the mouth and nose, which was secured in place with a head net. The face mask was attached to a one-way breathing valve that allowed ambient air to be inhaled and directed the expired air to a mixing chamber prior to analysis. The subjects completed a modified Bruce treadmill test protocol (82) that included 3-min stages of increasing intensity until exhaustion. Data from the first four submaximal stages was used to assess submaximal ventilation and gas exchange using the last 30s interval of each stage. Refer to the table below for absolute workload of each submaximal stage.

Stage	**Speed** (mph)	**Incline** (%)
1	1.7	10
2	2.5	11
3	3.4	12
4	4.2	13

Maximal aerobic capacity (ml oxygen consumption/kg body weight/min) was determined through analysis of expired air volume and content. Fifteen second averages of breath-by-breath measurements were used to determine the VO_{2max} for each condition.

Comfort Visual Analog Scale: A subjective assessment of fit and comfort of each condition was obtained using a visual analog scale (VAS). The VAS consisted of 100 mm horizontal lines with least to greatest ratings directed left to right for each of 8 comfort variables. Refer to Appendix 7. The comfort variables consisted of ability to breathe, ability to speak, level of comfort, level of dry mouth, taste, level of nausea, interference with performance, and ability to adapt to the mouthguard. Upon completion of the testing session, the subjects were instructed to make a vertical mark at a point on each 100 mm horizontal line indicating their feelings. The larger the distance from the left anchor point to the vertical marking, the more positive the feelings the subject was considered to have in each comfort category. For example, the larger the value for "nausea", the less likely the condition is causing nausea while the larger the value for "comfort", the more comfortable the condition is.

<u>Centric Occlusion</u>: To determine whether the jaw-repositioning mouthguards were effective at promoting a change in jaw position, centric occlusion was measured for each condition. A mark was made at two points on each subject's face, one on the tip of the nose and one at the largest projection of the chin. The two points of a Jameson caliper were aligned with the marks to determine the length (mm) at each condition. Subjects were instructed to relax facial muscles and soft tissues, part lips, and to bite down for each measurement. The measurements for all conditions were obtained together at the last testing session.

Statistical Analyses

All statistical analyses were completed using SPSS statistical software (IBM®, SPSS® version 20). Separate repeated measures multivariate analysis of variance (RM MANOVA) were used to assess the effects of the four different conditions (CON, PLA, SA, and CF) on respiratory function tests at rest (FVC, $FEV_{1.0}$, PEFR, and MVV), submaximal aerobic measures (V_E, VO_2, and VCO_2) and lactate values (pre-exercise, 0, 5, 10 min post exercise, peak, and adjusted peak values). Significant multivariate effects were followed by univariate tests. A RM ANOVA was used to assess the effect of the four conditions on VO_{2max}. For each univariate analysis, the Huynh-Feldt epsilon was calculated to test the assumption of sphericity. If this statistic was > .75, sphericity was assumed and the unadjusted statistic was used. If this statistic was < .75, then sphericity was considered to have been violated and the Huynh-Feldt adjusted statistic was used to test significance.

Simple contrasts were used to compare all conditions to the CON condition while pairwise comparison was used to compare conditions. A Least Significant Difference (LSD) post hoc test was used based on a priori hypotheses. Small effects may have a large impact in this subject population therefore effect sizes (ES) were calculated for all variables using Hedges' *g* formula (48). Data are expressed as mean $\pm$ SD and statistical significance was set at $\alpha < 0.05$.

RESULTS

Jaw Position

RM ANOVA revealed a significant difference between conditions (P < .001) with CON and PLA having a significantly lower occlusion than the SA and CF conditions (CON: 72.8 +/- 4.9 mm; PLA: 73.1 +/- 4.7 mm; SA: 75.5 +/- 5.0 mm; CF: 75.9 +/- 4.8 mm; P < 0.001). The mouthguards effectively increased dental occlusion 2-3mm.

Respiratory Function Tests

No significant differences between conditions were observed for FVC (CON: 5.15 +/- .74 L; PLA: 5.02 +/- .67 L; SA: 5.05 +/- 1.05 L; CF: 5.02 +/- .54; P = 0.77) and $FEV_{1.0}$ (CON: 4.45 +/- .66 L; PLA: 4.26 +/- .70 L; SA: 4.2 +/- .98 L; CF: 4.23 +/- .62 L; P = 0.25). Univariate analysis revealed significant differences between conditions for MVV (P = 0.02) and PEFR (P = 0.03). Pairwise comparison indicated that CON had significantly higher PEFR values than the other conditions (CON: 9.16 +/- 2.0 L/s; PLA: 8.16 +/- 1.98 L/s, P = 0.025; SA: 7.91 +/- 2.63 L/s, P = 0.011; CF: 8.39 +/- 2.34 L/s, P = 0.027). MVV values for PLA and SA were significantly lower compared to CON (CON: 164.8 +/- 24.4 L/min; PLA: 147.8 +/- 26.1 L/min, P = .008; SA: 136.9 +/- 43.5 L/min, P = 0.015; and CF: 155.2 +/- 26 L/min, P = 0.095). Refer to the figures below.

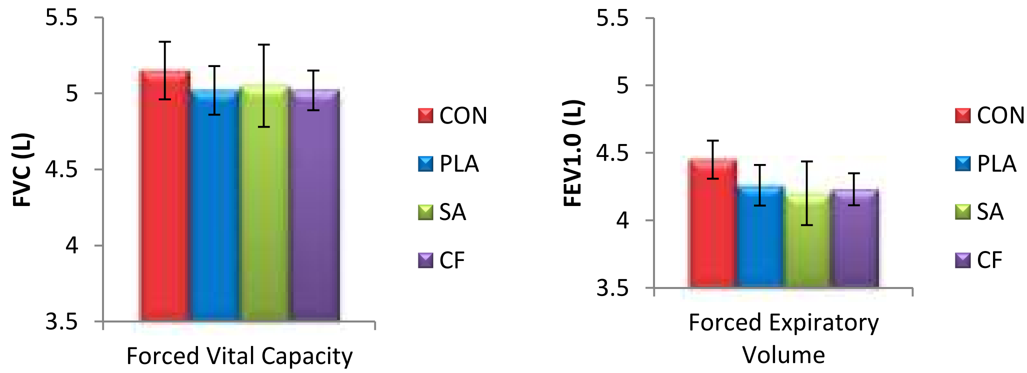


Figure 19. **FVC and FEV$_{1.0}$.** No significant differences were observed with the volume of air expired in a full expiration (FVC) between conditions or with volume of air expired per second of a single breath (FEV$_{1.0}$) were observed between conditions.

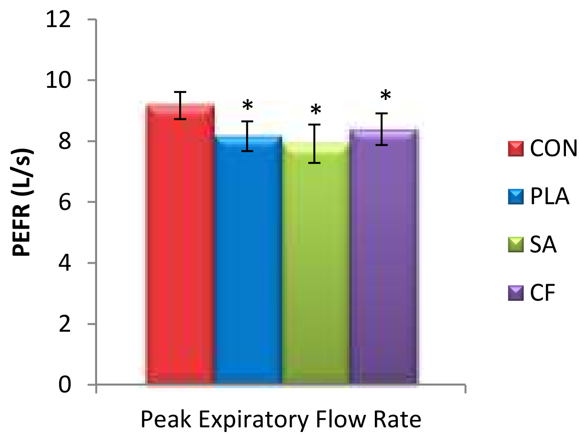


Figure 20. **Peak Expiratory Flow Rate.** Compared to CON, all other conditions had a significantly lower peak force during a full expiration. * indicates P < 0.05 compared to the CON condition

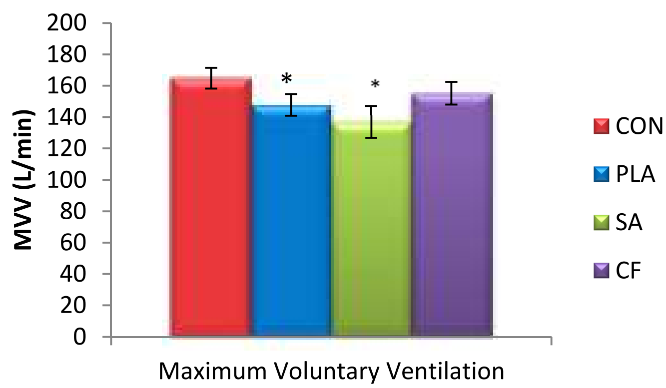
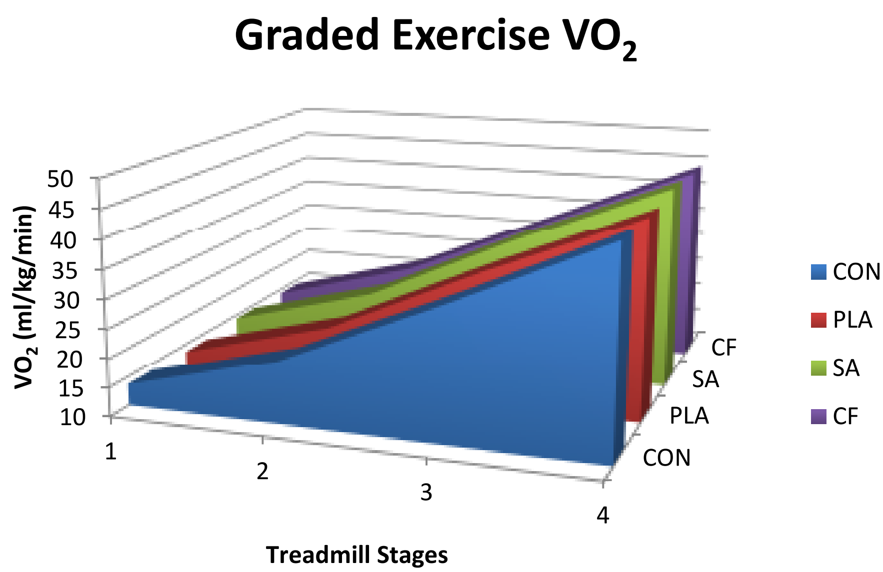


Figure 21. **Maximum Voluntary Ventilation**. The CON condition had a significantly higher MVV than the PLA and SA conditions. * indicates P < 0.05 compared to the CON condition

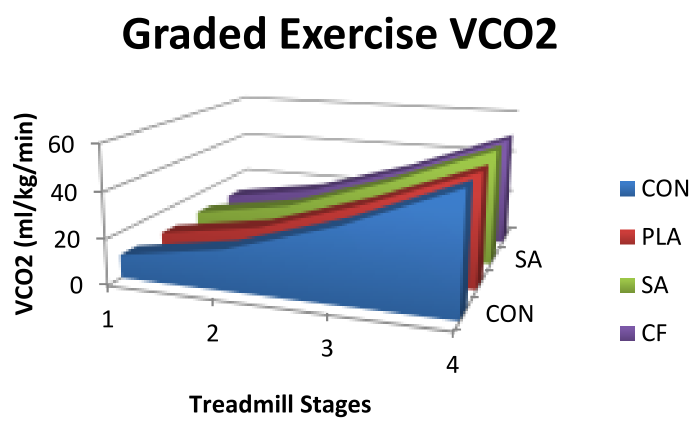
Ventilation and Gas Exchange During Exercise

No significant multivariate effects were observed between conditions for ventilation and gas exchange during submaximal exercise (P = 0.81). Univariate analysis revealed no significant differences between conditions across all stages in VO_2 (P = 0.72), VCO_2 (P = 0.63), and V_E (P = 0.35) Refer to the figures below.



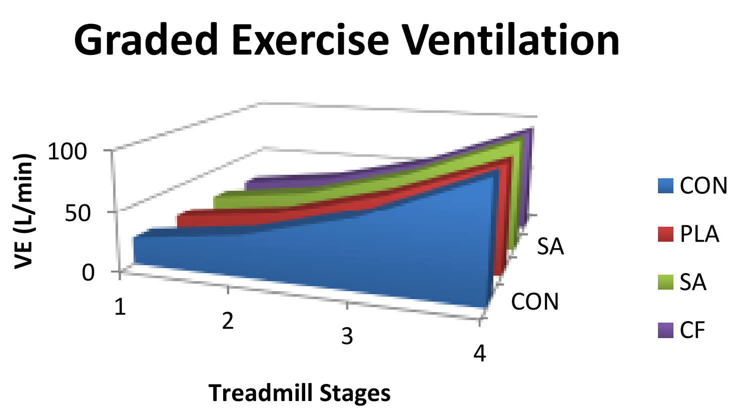
	CON		PLA			SA			CF		
VO_2 (ml/k	mean	SD	mean	SD	ES	mean	SD	ES	mean	SD	ES
stage 1	13.83	1.9	13.79	1.6	-0.02	14.31	0.8	0.33	14.53	1.7	0.37
stage 2	20.7	1.9	20.63	2.2	-0.05	21.23	1.9	0.28	21.09	1.7	0.22
stage 3	31.69	3.7	31.71	3.9	0	32.5	4.1	0.21	31.93	3.4	0.06
stage 4	43.68	4.6	43.06	5	-0.12	43.6	4.1	-0.02	43.18	4	-0.11

Figure 22. **Oxygen Consumption During Graded Exercise.** No significant difference in oxygen consumption were observed between conditions across four submaximal exercise stages.



	CON		PLA			SA			CF		
VCO_2 (ml/	mean	SD	mean	SD	ES	mean	SD	ES	mean	SD	ES
stage 1	10.27	1.6	10.25	1.4	-0.01	10.59	1	0.24	10.71	1.5	0.28
stage 2	17.44	1.9	17.22	2.1	-0.11	17.82	2	0.2	17.5	1.6	0.03
stage 3	30.62	4.5	30.51	4.4	-0.02	31.47	5	0.18	30.67	4.3	0.01
stage 4	48.58	8	47.67	7.3	-0.12	48.71	7.1	0.02	47.74	7	-0.1

Figure 23. **Carbon Dioxide Production During Graded Exercise.** No significant difference in carbon dioxide production was observed between conditions across four submaximal exercise stages.



	CON		PLA			SA			CF		
VE (L/min)	mean	SD	mean	SD	ES	mean	SD	ES	mean	SD	ES
stage 1	23.12	4.5	23.1	4.5	0	24.34	3.31	0.31	23.72	3.67	0.15
stage 2	34.99	4.84	34.43	6.47	-0.1	36.05	5.48	0.21	34.96	5.67	0
stage 3	57.24	11.14	56.98	10.66	-0.02	59.1	9.73	0.18	56.83	11.6	-0.04
stage 4	94.15	18.27	91.18	17.63	-0.17	94.33	16.51	0.01	92.13	18.7	-0.11

Figure 24. **Ventilation During Graded Exercise.** No significant differences were observed in ventilation between conditions across four submaximal exercise stages.

Maximal Aerobic Performance

No significant difference in maximal oxygen consumption was observed between conditions (CON: 49.9 +/- 4.5 ml/kg/min; PLA: 50.0 +/- 5.7 ml/kg/min; SA: 50.2 +/- 4.5 ml/kg/min; CF: 48.7 +/- 5.1 ml/kg/min; P = 0.35). Refer to figure 19.

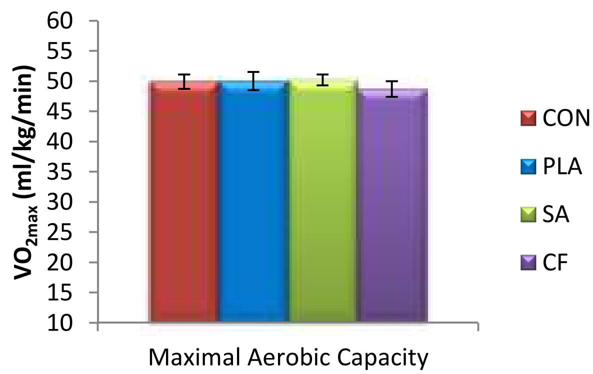


Figure 25. **Maximal Aerobic Capacity**. No significant differences between conditions were observed for VO_{2max} values.

Blood Lactate

No significant differences were observed in the pre-exercise lactate levels between conditions (CON: 3.2 +/- 1.7 mmol/L; PLA: 2.96 +/- .80 mmol/L; SA: 2.9 +/- 1.2 mmol/L; CF: 2.9 +/- 1.1 mmol/L; P = 0.92). No significant differences between conditions were observed in post-exercise lactate levels at 0-min (CON: 13.3 +/- 3.2 mmol/L; PLA: 11.7 +/- 3.0 mmol/L; SA: 11.3 +/- 3.3 mmol/L; CF: 12.2 +/- 3.5 mmol/L; P = 0.10); 5-min (CON: 11.5 +/- 3.1 mmol/L; PLA: 11.7 +/- 3.6 mmol/L; SA: 11.4 +/- 3.0 mmol/L; CF: 11.3 +/- 3.5 mmol/L; P = 0.10); and 10-min (CON: 5.8 +/- 5.1 mmol/L; PLA: 7.7 +/- 5.6 mmol/L; SA: 6.4 +/- 6.1 mmol/L; CF: 6.8 +/- 6.1 mmol/L; P = 0.69). The peak lactate levels measured within the 10-minute post-exercise period did not differ significantly between conditions (CON: 13.7 +/- 2.8 mmol/L; PLA: 12.6 +/- 3.1 mmol/L; SA: 12.6 +/- 3.0 mmol/L; CF: 12.8 +/- 3.7 mmol/L; P = 0.30). Significant differences between conditions were not observed in the adjusted peak lactate levels, which accounted for pre-exercise lactate levels (CON: 10.5 +/- 3.5 mmol/L; PLA: 9.6 +/- 3.3 mmol/L; SA: 9.7 +/- 3.9 mmol/L; CF: 9.9 +/- 3.8 mmol/L; P = 0.63). Of all post-exercise peak lactate measures, 69% were obtained immediately after exercise at the 0-min time point (CON: 85%; PLA: 55%; SA: 70%; CF: 65%).

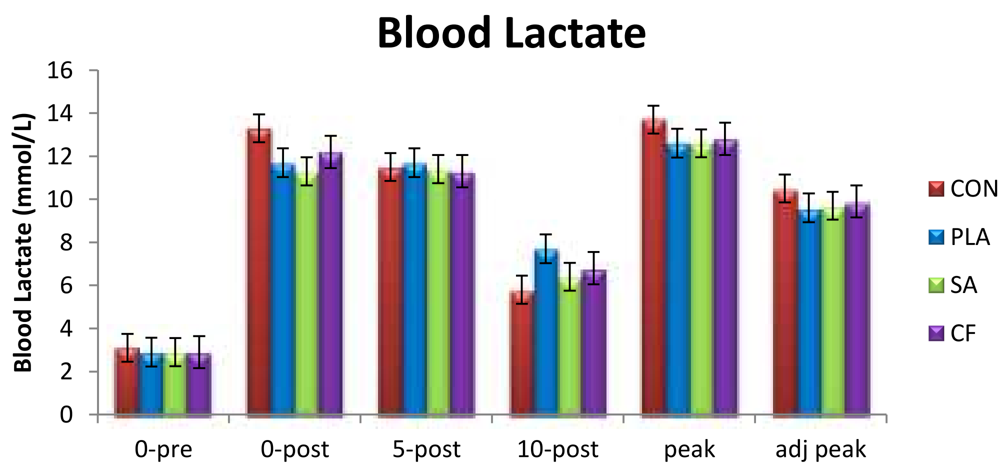


Figure 26. **Blood Lactate Levels.** No significant differences in lactate levels were observed between conditions.

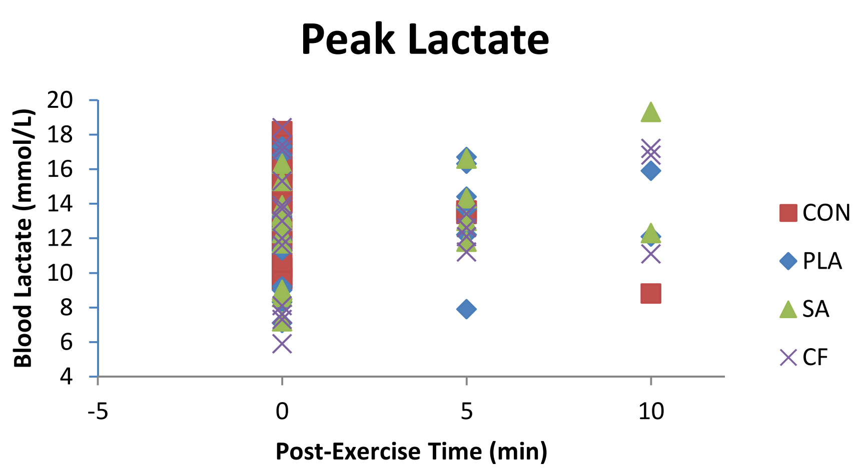


Figure 27. **Peak Lactate Levels.** Peak lactate levels were obtained within a 10 min post-exercise duration with a majority observed immediately post.

Comfort Ratings

A significant condition multivariate effect was observed between conditions for comfort ratings ($P < 0.001$). Univariate analysis revealed that feelings of nausea ($P = 0.12$) was the only variable in which no significant difference was observed between conditions while significant univariate effects were observed between conditions in ability to breathe ($P < 0.001$), ability to speak ($P < 0.001$), overall comfort ($P <0.001$), dry mouth ($P = 0.02$), taste ($P < 0.001$), adaptability ($P < 0.001$), and interference ($P < 0.001$). Pairwise comparison revealed that compared to the CON condition the ratings for all other comfort variables were lower in the other conditions. Refer to Figure 22.

Ability to Breathe

The PLA, SA, and CF conditions had significantly lower ratings of ability to breathe compared to the CON condition (CON: 86.7 +/- 17.2 mm; PLA: 57.8 +/- 28.7 mm, $P = 0.003$; SA: 54.8 +/- 23.8 mm, $P < 0.001$; CF: 70.1 +/- 15.9, $P = 0.001$). SA had significantly lower breathing ratings than CF ($P = 0.003$).

Ability to Speak

Significantly lower ratings of ability to speak with mouthguard were observed with all mouthguard conditions compared to the CON condition (CON: 91.2 +/- 18.8 mm; PLA: 43.6 +/- 28.4 mm, $P < 0.001$; SA: 44.4 +/- 27.4 mm, $P < 0.001$; CF: 56.7 +/- 20.1 mm, $P < 0.001$). A trend for significant difference between PLA and CF was observed ($P = .057$) with PLA having lower ability to speak ratings. No significant differences were found between the mouthguard conditions regarding ratings of ability to speak.

Overall Comfort During Exercise

Significantly lower comfort ratings were observed for all mouthguard conditions compared to the no-mouthguard control (CON: 88.9 +/- 20.7 mm; PLA: 38.2 +/- 28.6 mm, $P < 0.001$; SA: 49.5 +/- 27.7 mm, $P < 0.001$; CF: 61.5 +/- 28.2 mm, $P < 0.001$). PLA had significantly lower comfort ratings compared to SA ($P = 0.004$). No significant differences among SA and CF were observed in regards to comfort ratings.

Dry Mouth

Significantly higher ratings (less dry mouth) were observed for the CON condition compared to the other conditions (CON: 79.8 +/- 22.5 mm; PLA: 62.8 +/- 26.4 mm, $P = 0.044$; SA: 61.9 +/- 25.7 mm, $P = 0.015$; CF: 64.9 +/- 26.4 mm, $P = 0.043$). The mouthguard conditions did not significantly differ in regards to dry mouth ratings.

Taste

All mouthguard conditions had significantly lower average taste ratings compared to the CON condition (CON: 83.1 +/- 20.1 mm; PLA: 58.4 +/- 15.6 mm, $P < 0.001$; SA: 60.8 +/- 18.9 mm, $P = 0.001$; CF: 63.9 +/- 19.0 mm, $P = 0.004$). No significant differences were observed for mouthguard taste ratings between the mouthguard conditions.

Interference with Performance

The mouthguard conditions were rated as more interfering than the CON condition as evidenced by lower interference scores (CON: 91.8 +/- 19.6 mm; PLA: 61.3 +/- 27.9 mm, P =

0.001; SA: 65.7 +/- 24.0 mm, P < 0.001; CF: 80.5 +/- 20.8 mm, P = 0.001). CF was rated to interfere less with performance than the PLA (P = 0.031) and SA (P = 0.002) conditions.

Adaptability to the Mouthguard

Compared to CON, all mouthguard conditions had significantly lower adaptability ratings (CON: 92.6 +/- 19.1 mm; PLA: 52.4 +/- 32.0 mm, P < 0.001; SA: 56.8 +/- 27.3 mm, P < 0.001; CF: 77.5 +/- 22.1 mm, P = 0.001). CF had significantly higher adaptability ratings compared to PLA (P = 0.003) and SA (P = 0.004).

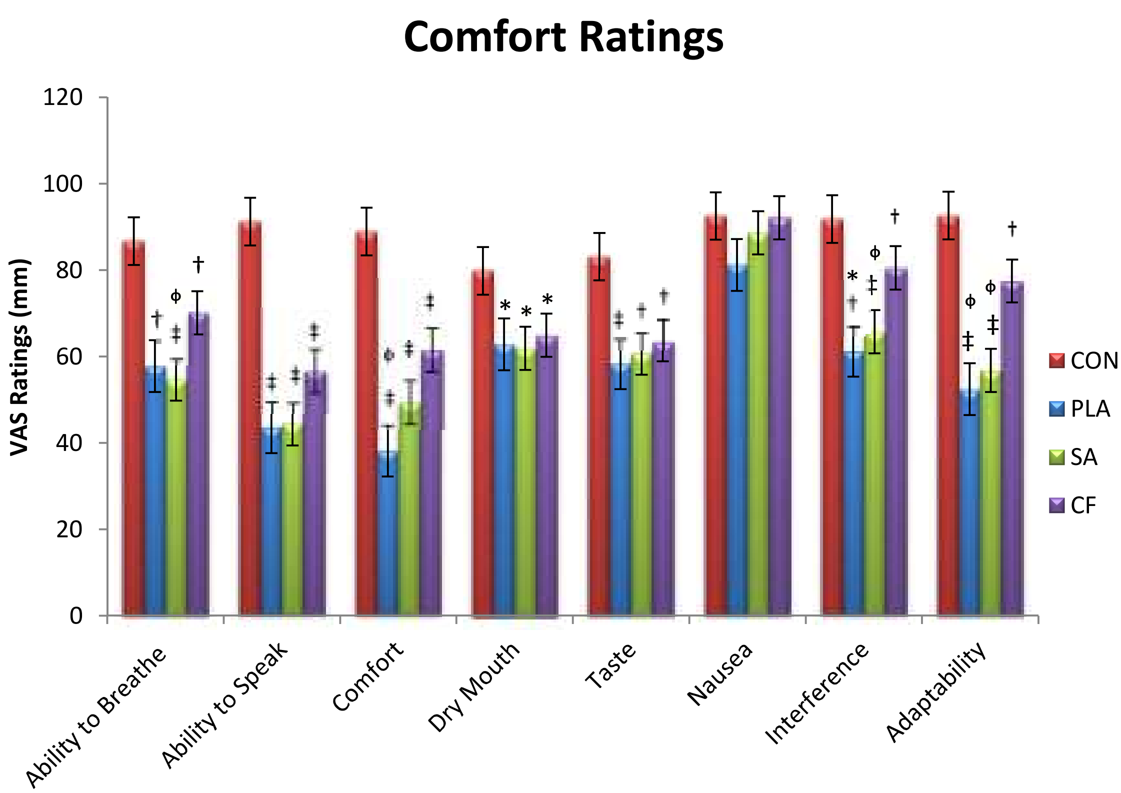


Figure 28. **Comfort VAS Ratings.** The scale provides a postive association with score and constructive ratings. CON received higher ratings on all categories except Nausea.
* indicates P < 0.05 difference compared to CON
† indicates P < 0.01 difference compared to CON
‡ indicates P < 0.001 difference compared to CON
ᶲ indicates P < 0.01 difference compared to CF

DISCUSSION

To determine the effect of standardized jaw-repositioning mouthguards on aerobic performance, respiratory functional tests were assessed at rest, ventilation and gas exchange were assessed during four submaximal exercise stages, and oxygen consumption was assessed at maximal exercise intensity in collegiate male athletes. Increased centric occlusion was confirmed with the use of the jaw-repositioning mouthguards.

At rest, the jaw-repositioning mouthguards did not influence the volume of air that was moved by the lungs during a full exhalation (FVC) nor did they interfere with the average rate at which that exhalation took place ($FEV_{1.0}$). However, all mouthguard conditions impeded the *peak* rate of that exhalation (PEFR) compared to the no-mouthguard condition. The SA and the PLA mouthguards significantly decreased the maximum volume of air that was voluntarily moved by the lungs (MVV) compared to CON, however the CF jaw-repositioning mouthguard did not influence MVV. These results indicate that mouthguards as oral appliances may decrease the rate at which forceful ventilation occurs and may therefore lower forceful ventilatory volume. These measures were obtained during a rested state and may not directly translate to ventilation during exercise. The jaw-repositioning mouthguards did not have differing effects when compared to the PLA mouthguard which indicates that the standardized increase in centric occlusion did not lead to changes in oral airflow dynamics at rest.

During four submaximal stages of treadmill exercise, no differences between conditions were observed in ventilation, oxygen consumption, or carbon dioxide production. Neither the increase in centric occlusion promoted by the jaw-repositioning mouthguards nor the presence of a mouthguard influenced submaximal ventilation or gas exchange. Taken with the PEFR and

MVV results, these findings indicate that the impedance on oral airflow at rest did not carry over to the airflow during exercise. This is confirmed through the maximal aerobic capacity results.

No significant differences in VO_{2max} values were observed between conditions, indicating that the jaw-repositioning mouthguards did not influence aerobic capacity. Maximal oxygen consumption is typically attained prior to exhaustion as increased energy demands are met through anaerobic processes. Pyruvate is converted to lactic acid following glycolysis and this metabolite can travel, as lactate, to other muscle cells or to the liver where it can further contribute to energy provision. The accumulation of the by-products of anaerobic metabolism (i.e. lactic acid) promotes an acidic environment that leads to eventual fatigue and exhaustion. Motivation plays a large part in maximal exercise testing and may be a confounding factor. However, blood lactate values did not differ between conditions indicating that similar levels of anaerobic metabolism and effort were applied across all conditions. Blood lactate was sampled at three time points (0, 5, and 10-min) after the exercise test in efforts to obtain a peak lactate level. Peak lactate levels did not differ between conditions even when accounting for pre-exercise lactate levels. A time trend is visible in the post-exercise lactate levels as an average decline was observed by 10-min post.

The results of the comfort ratings revealed that the subjects preferred the no-mouthguard condition, which is not surprising. However, CF received the next highest ratings in all categories while the SA was comparable to the PLA. The CF jaw-repositioning mouthguard had a more advanced fitting process promoting better fit to the maxillary teeth. Perhaps this explains the improved ratings of comfort. The lower ratings of comfort did not influence aerobic exercise performance.

This study revealed that use of the two standardized, jaw-repositioning mouthguards did not promote any changes in aerobic exercise performance compared to the placebo and no-mouthguard controls. Ventilation and gas exchange during exercise were not affected by the standardized change in jaw position promoted by either of these two mouthguards. The results support previous literature indicating that well fitted, small sized mouthguards do not impede aerobic performance during exercise (17, 18, 37, 39).

Very little literature is available regarding the effects of jaw position on aerobic performance. Consistent with our findings, a recent study compared the aerobic effects of a custom-fitted mouthguard, self-adapted mouthguard, and a no-mouthguard control in healthy athletes (17). The custom-fitted mouthguard in this study raised the dental occlusion 2mm for the purpose of creating a gap to ease breathing with a closed jaw, and therefore is considered a type of jaw-repositioning appliance. The respiratory functional tests did not differ between conditions. As well, the ventilation and oxygen consumption values during submaximal and maximal exercise intensities did not differ between conditions. These results are consistent with other mouthguard studies and indicate that well fitted mouthguards do not interfere with aerobic performance (17). However, this study may also indicate that changing jaw position does not affect aerobic performance or respiratory functional tests.

Recently, another study used a mandibular mouthpiece that provided a vertical increase gap for breathing ease. Fourteen aerobically active college-aged subjects participated in this crossover study (77). The subjects ran at 6.5mph and 0% incline on a treadmill for 10 min with each of 3 conditions: 1) biting down on mouthpiece with nose clamped; 2) no mouthpiece, mouth open with nose clamped; and 3) nose-breathing with mouth taped (77). The authors observed a decrease in all aerobic variables with nose-breathing compared to both mouth-breathing conditions. The mouthpiece condition had higher oxygen consumption and carbon dioxide production than the no-mouthpiece condition while ventilation, respiratory rate, and tidal volume were similar between these two groups (77). The results suggest that mouth-breathing while clenching teeth on a mouthpiece and nose clamped requires more respiratory work than open mouth breathing or nose breathing. The respiratory muscles typically consume 10% of the oxygen needs during strenuous exercise (83). Forcing air through small openings increases respiratory muscle work leading to increased energy expenditure (83). Increasing the breathing work rate would lead to an increase in oxygen consumption and ventilation (84). Although the jaw of the subjects may have been repositioned with use of the mouthpiece, the use of nose clamps and instruction to keep teeth clenched reduced the practical value of these results.

The current study measured aerobic parameters using a mask that encompassed both oral and nasal passages. This allowed the subjects to use both airways in combination during exercise to promote a more realistic exercise testing scenario. During graded exercise, nose-breathing typically shifts to mouth-breathing or a combination of the two at ventilation rates of 30-40 L air/min (38). By allowing the subjects to transition from nose to mouth breathing with or without the presence of a mouthguard, we promoted consistency in the breathing work rates.

In conclusion, similar to previous mouthguard literature, this study indicates that well-fitted mouthguards do not promote changes in airflow or gas exchange during aerobic exercise. The standardized jaw-repositioning mouthguards were not effective in promoting a change in aerobic dynamics in college-aged male athletes. A limitation of this study was the lack of upper respiratory airway measurements. Although the change in centric occlusion needed to promote jaw-repositioning was confirmed, it is possible that the particular position of the mandible was not effective in increasing the size of upper respiratory airways. Future research should examine the effect of various jaw-repositioning methods and jaw positions on airway openings and aerobic performance to determine if a relationship exists.

PRACTICAL APPLICATION

The results of the present study indicated that the two standardized, jaw-repositioning mouthguards were ineffective at enhancing aerobic performance. It is possible that the advanced jaw-repositioning techniques used to construct the mandibular advancement devices that treat sleep disordered breathing may be required to promote a change in aerobic performance. The premise behind the design of these devices is that manipulation of the tissue around the jaw affects adjacent tissues (11). Future research should evaluate the relationship between the masticatory/facial muscle activity, airway size, and aerobic performance. Despite the lower comfort ratings and reduced forceful breathing at rest, the mouthguards in this study did not affect aerobic performance during exercise and therefore the results of this study should encourage mouthguard compliance. Athletes should consider this information and use mouthguards as a safety device to reduce the risk of orofacial injuries.

Concluding Comments and Future Research Directions

Jaw-repositioning is a dental technique that is used to treat temporomandibular disorders (TMD) and sleep disordered breathing conditions by directly affecting orofacial musculature and upper respiratory airway size, respectively. Improved body posture and proprioception with the use of jaw-repositioning devices have been repeatedly observed in both TMD and non-TMD sufferers (1-4, 29, 53). It has been established that jaw-repositioning increases upper respiratory airway size in both apneic (7, 9-11, 21, 22, 25) and nonapneic populations (21, 26). Whether these physiological effects elicited by jaw-repositioning translate into improved athletic performance has been a question of research in the exercise science field for over two decades.

Most of the early exercise research on this topic evaluated the effects of jaw-repositioning on muscular strength through the use of mandibular orthopedic repositioning appliances in athletic populations. This cluster of studies collectively indicated that jaw-repositioning did not have any effect on strength (5, 54-56, 58-60). Although an improvement in muscular power was observed in one of these studies (5), the influence of the lack of strength observations led to a waning of the evaluation of jaw-repositioning until recently. Jaw-repositioning and mandibular orthopedic repositioning appliances appear to have made a "comeback" in the mouthguard market in response to decreased mouthguard use by athletes, which is typically attributed to concerns of negative impacts on performance despite safety recommendations (16). Anecdotal evidence and case studies have exposed the need for well-controlled studies that evaluate the performance effects of jaw-repositioning mouthguards. The purpose of the first study in this dissertation was to further evaluate the performance effects of jaw-repositioning on muscular power through the use of a neuromuscular dentistry-designed mouthguard. The second study evaluated more affordable, standardized jaw-repositioning mouthguards on power as well as other aspects of physical performance including dynamic balance, flexibility, agility, and strength. The third study evaluated the effects of the affordable, standardized jaw-repositioning mouthguards on respiratory dynamics and aerobic performance.

A neuromuscular dentistry-designed jaw-repositioning mouthguard was effective at improving muscular power performance compared to a standard custom-fitted mouthguard as evidenced by vertical jump and Wingate Anaerobic Test results of healthy, male athletes (6). Similar vertical jump improvements were not observed using standardized, jaw-repositioning mouthguards when compared to a no-mouthguard and a placebo control. It is important to note that although the vertical jump test is easy to administer in a battery of tests and is sport-specific, it only measures jump height and does not take body mass into consideration. For example, two subjects with the same jump height appear to have the same power output, yet this only holds true if the two subjects have the same body weight. If not, the subject that has a larger body weight is exerting greater power output. To address this issue, a prediction equation was used to calculate peak power output (W) using vertical jump height and body weight (75). Evaluating vertical jump height (cm) and peak power output (W) provides a more comprehensive assessment of muscular power.

MANOVAs were used to separately compare the effects of the six mouthguards/conditions (PPM, CFM, CON, PLA, SA, and CF) on VJ height and calculated peak power output. No significant differences in body weight were observed between groups (PPM & CFM: 86.2 +/- 13.7 kg; CON: 79.8 +/- 11.7 kg, $P = 0.12$; PLA: 79.5 +/- 11.4, $P = 0.10$; SA: 80 +/- 11.5 kg, $P = 0.13$; CF: 79.6 +/-11.3 kg, $P = 0.11$). Significant multivariate effects were observed between the PPM group and each of the other groups: the CON group ($P = 0.05$), the PLA group

(P = 0.03), the SA group (P = 0.047), and the CF group (P = 0.016). Univariate follow-ups revealed that the PPM group had significantly higher VJ heights than each of the other groups (PPM: 67.2 +/- 7.4 cm; CON: 61.0 +/- 7.8 cm, P = 0.02; PLA: 60.7 +/- 7.7 cm, P = 0.01; SA: 60.5 +/- 8.2 cm, P = 0.01; CF: 60.3 +/- 9.1 cm, P = 0.02). The PPM group also had significantly higher peak power outputs than each of the other groups (PPM: 5929.4 + /- 866.3 W; CON: 5261.4 +/- 613.7 W, P = .008; PLA: 5230 +/- 555 W, P = 0.004; SA: 5243.2 +/- 636.5 W, P = .007; CF: 5212.1 +/- 613.6 W, P = 0.004). Refer to Appendix 2 for effect sizes.

Multivariate effects were observed when comparing the CFM group to the PLA group (P = 0.037) and the CF group (P = 0.041). Univariate follow-ups indicated that CFM had significantly higher peak power outputs than each of the other groups (CFM: 5756.7 +/- 910.7 W: CON: 5261.4 +/- 613.7 W, P = 0.05; PLA: 5230 +/- 555 W, P = 0.03; SA: 5243.2 +/- 636.5 W, P = 0.05; CF: 5212.1 +/- 613.6 W, P = 0.03). No significant differences in VJ height were observed between CFM and each other group. Refer to the figures below.

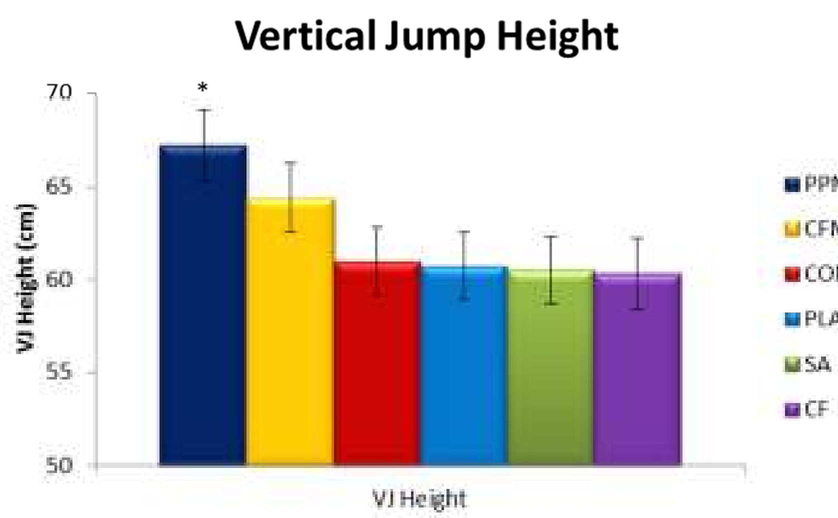


Figure 29. **VJ Height Comparison.** Separate analyses revealed that the PPM group jumped significantly higher than the each of the other groups. CFM did not significantly differ from CON, PLA, SA, or CF groups. * indicates P < .02

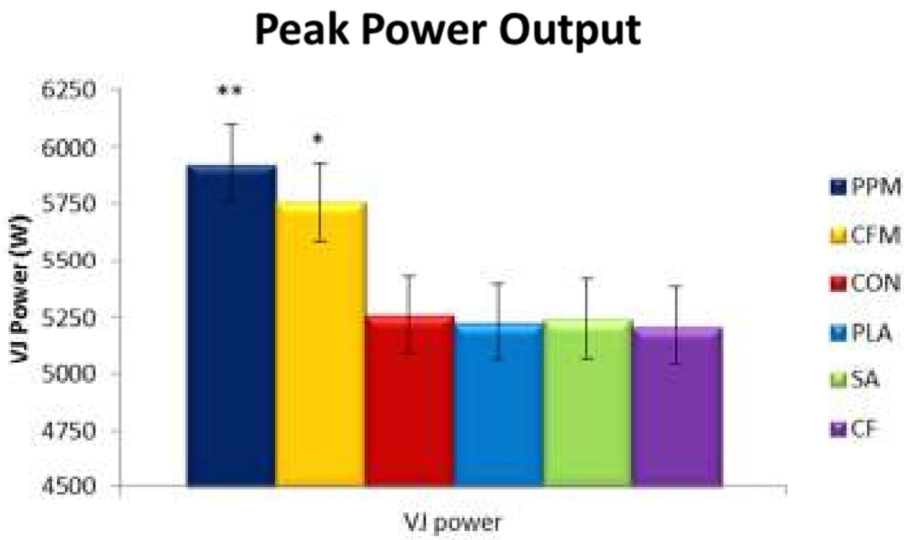


Figure 30. **Peak Power Output Comparison**. Taking body weight and VJ height into account, peak power output provides an estimate of absolute power needed to move a specific body mass to its highest VJ height. The PPM group and the CFM group each had significantly higher power output than CON, PLA, SA, and CF groups.
** indicates P < .01
* indicates P $\leq$ .05

This analysis extends the practical significance of the results in the first study. The significantly higher peak power output exhibited by the CFM group in comparison to the CON, PLA, SA, and CF groups indicates that there was much less room for improvement. However, utilization of the PPM led to even higher vertical jumps and greater peak power output. The effect sizes associated with these differences indicate a large magnitude of difference that can lead to practical applications in athletic power performance.

The three completed studies in this dissertation have contributed to the scientific and athletic communities by indicating the need to apply advanced dental techniques for jaw-repositioning in order to obtain positive changes in performance. The use of TENS and EMG to determine an optimized jaw position for each individual was the technique used in the study that observed positive performance results, specifically in muscular power performance. It is possible that the underlying mechanism responsible for change in power performance is associated with alterations in muscle activity linked with the jaw position. Perhaps relaxing the facial musculature through an optimized jaw position promotes changes not only in the surrounding structures, but in neuromuscular communication. Future studies can use multiple EMG readings to evaluate muscular activity changes during performance of a power movement with and without utilization of a neuromuscular dentistry-designed mouthguard. These changes in muscle activity during exercise would provide information regarding reaction time of muscle action, which is vital to athletic performance. The performance aspects involved in the second and third study should be evaluated with an advanced jaw-repositioning mouthguard that has been previously shown to affect performance.

Expensive, advanced dental techniques may be impractical for public use as an ergogenic aid and may be more appropriate for use as an orthotic. Individuals suffering from mobility impairment and physical disabilities may benefit from an oral appliance that promotes improved posture, proprioception, reaction time, balance, and flexibility. Therefore, it remains reasonable to continue research efforts regarding the effects of jaw-repositioning on physical performance.

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Appendix 1

Abbreviations

CNS	Central Nervous System
EMG	Electromyography
$FEV_{1.0}$	Forced Expiratory Volume over 1 $_{second}$
FVC	Forced Vital Capacity
GTO	Golgi Tendon Organ
MAD	Mandibular Advancement Device
MORA	Mandibular Orthopedic Repositioning Appliance
MVV	Mean Voluntary Volume
OPA	Oropharyngeal Airway
OSA	Obstructive Sleep Apnea
PEFR	Peak Expiratory Flow Rate
RM	Repetition Maximum
SDB	Sleep Disordered Breathing
T1	Testing session one
T2	Testing session two
TMD	Temporomandibular joint disorder
VO_2max	Maximal Aerobic Capacity or Maximal Oxygen Consumption
WAnT	Wingate Anaerobic Test

Appendix 2

Effect Size Tables

All effect size values are in comparison to the CON condition.

Dynamic Balance

Time in Center Balance	PLA	SA	CF
	.01	.03	.03

Flexibility

	PLA	SA	CF
Sit-and-Reach	.05	.12	.01
Shoulder Extension	.06	.22	.07
Shoulder Lateral Rotation	-.11	-.15	0
Hip Extension	-.02	-.04	.06
Hip Flexion	-.17	-.03	-.27
Lumbar Spine Lateral Flexion	.01	-.07	.08
Lumbar Spine Rotation	0	-.02	-.07

Vertical Jump Height

	PLA	SA	CF
Absolute VJ height	-.04	-.06	-.08
Relative VJ height	0	-.06	0
Power Output	-.05	-.03	-.08
Relative Power Output	0	-.05	-.05

Hexagon Agility Test

	PLA	SA	CF
Agility Time	-.22	-.30	-.15

Strength

	PLA	SA	CF
Absolute load	-.06	-.02	-.07
Relative load	0	0	0

Aerobic Dynamics

	PLA	SA	CF
Forced Vital Capacity (FVC)	-.18	-.11	-.20
Forced Expiratory Volume ($FEV_{1.0}$)	-.28	-.98	-.34
Peak Expiratory Flow Rate (PEFR)	-.50	-.54	-.35
Maximum Voluntary Ventilation (MVV)	-.67	-.79	-.38
Maximal Oxygen Consumption (VO_{2max})	.02	.07	-.25

Effect Size Tables continued

Blood Lactate

	PLA	SA	CF
Pre-exercise	-.18	-.20	-.21
0 min post-exercise	-.52	-.62	-.33
5 min post-exercise	.06	-.03	-.06
10 min post-exercise	.35	.11	.18
Peak lactate	-.37	-.38	-.27
Adjusted peak lactate	-.26	-.22	-.16

Comfort Visual Analog Scale Ratings

	PLA	SA	CF
Ability to Breathe	-1.22	-1.54	-1.0
Ability to Speak	-1.98	-1.99	-1.77
Overall Comfort	-2.03	-1.6	-1.1
Mouth Dryness	-.69	-.74	-.61
Taste	-1.4	-1.1	-.98
Interference with performance	-1.3	-1.2	-.56
Adaptability	-1.5	-1.5	-.73

VJ Comparison Effect Sizes

	VJ height vs. PPM	Peak Power Output vs. PPM	VJ height vs. CFM	Peak Power Output vs. CFM
CON	-.78	-.89	-.44	-.64
PLA	-.82	-.96	-.50	-.70
SA	-.82	-.90	-.50	-.65
CF	-.80	-.96	-.49	-.70

Appendix 3

The effects of different mouthguards on various physical performance measures

Informed Consent Form

It is the policy of Rutgers University that all subjects participating in research read and sign an informed consent form prior to participation. Read the following carefully, initial the first page, and sign the form if you understand it.

I have been informed that:

1) Dr. Shawn Arent, a professor in the Department of Exercise Science and Sport Studies at Rutgers University, has identified me as a potential participant in a research study at this institution.
2) The purpose of this study is to examine the effects of three different mouthguards on my balance, vertical jump, strength, flexibility, and cardiovascular exercise capacity.
3) My participation in the study is completely voluntary and will involve five separate days of fitness testing, three of which will involve wearing a mouthguard while being tested. I will be using all three mouthguards included in the study, but I won't be told in which order I am wearing them or what each one is expected to do. I will need to refrain from training for 24 hours prior to my assigned testing time on each occasion. I should make sure that I eat a high carbohydrate meal about 2 hours before each test and refrain from nicotine, caffeine, or alcohol on those days.

On the first day of the study, I will report to the Human Performance Lab at Rutgers for a health screening and to go through the fitting process for the mouthguards. The initial fitting for the mouthguards will first involve taking a standard dental mold of my teeth. This will be used to manufacture each of the custom mouthguards. The total fitting process takes about 15-20 minutes. Following this, I will practice performing the balance test, vertical jump, bench press, and squats that I will be doing on the other 4 testing days. This first session will take about 1 to 1.5 hours. After the mouthguards are made, I will return to the lab on four separate occasions (2-3 days apart) to complete the testing for the balance, vertical jump, bench press and squats for my 3 repetition maximum (3RM), upper and lower body flexibility tests, and a treadmill test to measure my cardiovascular capacity. At the end of the treadmill test, I will have a very small amount of blood tested using a finger prick (1 drop of blood) to measure my blood lactate levels. On three of the testing days, I will do these tests while wearing a mouthguard. The entire trip to the lab on each day that I'll be tested will take about 1-1.5 hours.

The total length of the study is expected to be about 21 days (5 total days in the lab) with approximately 6.5-7 hours spent in the lab during the actual testing. I will be paid up to $100 for my participation, but this will be prorated if I do not complete testing for each phase of the study.

I have been informed that my participation in this study is voluntary and that I can choose to withdraw at any time without consequence. I also understand that I won't be told what the different mouthguards were or which order I'm using them until the study is over.

4) During the performance tests, there may be certain risks due to the exertion of the exercise. These include such things as shortness of breath, abnormal blood pressure responses, fainting, nausea/vomiting, irregularities in heartbeat, or injury. However, I understand that steps will be taken to minimize all of these risks and that emergency protocols and trained personnel are available to deal with the situations if they arise.
5) The possible benefits of my participation in this study include assessing the performance effects of these mouthguards and to gain knowledge of my work capacity and fitness in order to optimize my own training program. It is also possible that one or all of these mouthguards will enhance my own training and I am free to keep the mouthguards upon completion of the study if I want. If these things are understood, then athletes, coaches, and researchers may find ways to alter sports performance to better serve athletes in training more effectively. My individual results will be provided to me upon completion of the testing upon my request.
6) The results of this research may be published, but my name or identity will not be revealed. In order to maintain confidentiality of my records, my data will be reported in group form only. No subject will be identified individually. Dr. Arent and his immediate research team will be the only people with direct access to the subject number decoding list.
7) In case of injury, I can expect to receive the following treatment or care: first aid will be administered and transportation to a hospital will be arranged if necessary. I am aware that facilities and professional care, which are available, will not be provided free of charge and that monetary compensation will not be made.
8) Any questions regarding my participation in the study, before or after my consent, will be answered by Dr. Shawn Arent, who can be contacted at (732) 932-8669 in the Department of Exercise Science and Sport Studies, 70 Lipman Dr., New Brunswick, NJ, 08901-8525 x.28 or at shawn.arent@rutgers.edu.
9) In case of injury, if I have questions about my rights as a participant in this research, or if I feel I have been placed at risk, I can contact the Sponsored Programs Administrator at Rutgers University at (732) 932-0150 x.2104 in ASB III, 3 Rutgers Plaza, New Brunswick, NJ 08901 or at humansubjects@orsp.rutgers.edu.
10) The nature, demands, benefits, and any risk of the project have been explained to me. I knowingly assume any risks involved. I UNDERSTAND THAT MY PARTICIPATION IS VOLUNTARY AND THAT I MAY WITHDRAW MY CONSENT AND DISCONTINUE PARTICIPATION AT ANY TIME WITHOUT PENALTY OR LOSS OF BENEFIT. In signing this consent form, I am not waiving any legal claims, rights, or remedies. A copy of this consent form will be offered to me.

I have read the above informed consent form.

Participant's
Signature ____ Date ______________

"I certify that I have explained to the above individual the nature and purpose, the potential benefits and possible risks associated with participation in this research study, have answered any questions that have been raised, and have witnessed the above signature."

Signature of
Investigator ____ Date ______________

Appendix 4

Medical History Questionnaire

Demographic Information:

Last Name ____________ First Name ____________

Date of Birth ____________ Gender ____________ Phone: Cell / Home / Work ____________

Section A

When was the last time you had a physical examination? ________________________________
Are you allergic to any medications, foods, or other substances? __________________________
Have you been told you have any chronic or serious illnesses? If so, what are they? __________
Give the following information pertaining to the last 3 times you have been hospitalized:

	Hospitalizations 1	**Hospitalizations 2**	**Hospitalizations 3**
Reason:	________________	________________	________________
Month/year:	________________	________________	________________
Location:	________________	________________	________________

Section B

During the past 12 months:

1. Have you been prescribed any form of medications?
   YES NO
2. Has your weight fluctuated more than a few pounds?
   YES NO
3. If yes, did you attempt to bring about this weight change through diet or exercise?
   YES NO
4. Have you experienced any faintness, light headedness, or blackouts?
   YES NO
5. Have you occasionally had trouble sleeping?
   YES NO
6. Have you experienced any blurred vision?
   YES NO

7. Have you had any severe headaches?
   YES NO
8. Have you experienced chronic morning cough?
   YES NO
9. Have you experienced any temporary change in your speech pattern, slurring or loss of speech?
   YES NO
10. Have you felt unusually nervous or anxious for no apparent reason?
   YES NO
11. Have you experienced unusual heartbeats such as skipped beats or palpitations?
   YES NO
12. Have you experienced periods of your heart racing for no apparent reason?
   YES NO

At Present:

1. Do you experience shortness or loss of breath while walking?
   YES NO
2. Do you experience sudden tingling, numbness, or loss of feeling in your arms, hands,
   YES NO
   legs, feet, or face?
3. Have you ever noticed that your hands or feet sometimes feel cooler than other parts of
   YES NO
   your body?
4. Do you experience swelling of your feet or ankles?
   YES NO
5. Do you get pains or cramps in your legs?
   YES NO
6. Do you experience any pain or discomfort in your chest?
   YES NO
7. Do you experience any pressure or heaviness in your chest?
   YES NO
8. Have you ever been told that your blood pressure was abnormal?
   YES NO
9. Have you ever been told that your serum cholesterol or triglyceride level was high?
   YES NO
10. Do you have diabetes?
   YES NO
   If yes, how is it controlled?
   ☐ Dietary means ☐ Insulin injections ☐ Oral Meds ☐ Uncontrolled
11. How often would you characterize your stress level as being high?
   ☐ Occasionally ☐ Frequently ☐ Constantly

12. Have you ever been told that you have any of the following illnesses?

YES NO

☐ Myocardial Infarction Disease	☐ Atherosclerosis	☐ Heart Disease	☐ Thyroid
☐ Coronary Thrombosis	☐ Rheumatic Fever	☐ Asthma	☐ Epilepsy
☐ Coronary Occlusion	☐ Heart Failure	☐ Osteoporosis	☐ Heat Stroke
☐ Heart Block	☐ Aneurysm	☐ Fibromyalgia	☐ TMJ Dysfunction

13. Have you ever had any of the following medical procedures?

YES NO

☐ Heart Surgery	☐ Pacemaker Implant	☐ Cardiac Catheterization
☐ Defibrillator	☐ Coronary Angioplasty	☐ Organ Transplantation

Section C

Do you suffer from any of the following signs and symptoms? (Check the appropriate selection)

___ Chronic, Generalized Pain, Muscle Soreness, and or joint pain

___ Osteoarthritis or Osteoporosis

___ Foot injuries
(plantar fasciitis, plantar fascia strain, heel pain, metatarsalgia, metatarsal fracture, Morton's neuroma, Turf toe, etc.)

___ Lower leg & Ankle injuries
(ankle pain, sprained ankle, broken ankle, shin splints, calf strain, Achilles tendon rupture, Achilles pain, Sever's disease, anterior compartment syndrome, peroneal tendinopathy, etc.)

___ Knee Injuries
(knee pain, patella pain, ACL injury, Iliotiabial band syndrome, Osgood-Schlatters disease, posterior cruciate or medial ligament injury, medial cartilage meniscus injury, articular cartilage injury, quadriceps tendon inflammation, etc)

___ Thigh injuries
(hamstring strain, quadriceps strain, quadriceps contusion, myositis ossificans, rectus femoris rupture, stress fracture of the femur, tight hamstrings, etc)

___ Hip and Groin Injuries
(groin strain, Gilmores groin, hernias, ostetitis pubis, hip bursitis, labral tear, snapping hip, etc.)

___ Buttock Injuries
(piriformis syndrome, sciatica, sacroiliac joint pain, myofascial pain, ischiogluteal bursitis, ischial bursitis, etc.)

___ Lower Back Pain
(lumbago, scoliosis, sciatica, facet joint pain, muscle strains, slipped disc, pinched nerve, etc.)

___ Upper Back & Neck Pain
(whiplash, cervical posture syndromes, Scheuermanns disease, etc.)

___ Head Injuries
(facial injuries, concussion, headaches, etc.)

___ Chest & Abdominal Injuries
(abdominal strain, rib fracture, sternoclavicular joint sprain, thoracic spine pain, costochondritis, chest pain, thoracic outlet syn etc.)

___ Shoulder Injuries
(shoulder pain, rotator cuff injury, dislocated shoulder, impingement syndrome, clavicle fracture, AC joint injury, frozen shoulder, winged scapular, inflammation of bicep long head, etc.)

___ Elbow Injuries
(Tennis elbow, golfer's elbow, tricep tendon rupture, hyperextension injury, students elbow, etc.)

___ Wrist & Hand Injuries
(wrist bursitis, carpal tunnel syndrome, repetitive strain injuries, fractured scaphoid, metacarpal fracture, sprained thumb, de quervains tenosynovitis, etc.)

____ TMD Assessment _____ Investigator Initials

1. Able to increase dental occlusion at least 3.5 inches ____
2. Able to move mandible left and right at least 1 inch ____
3. Any signs of jaw pain or soreness ____
4. Any current or previous diagnosis of jaw or dental disorders ____
5. Audio/visual assessment of jaw misalignment/clicking noise ____

I certify that the above questionnaire was filled to the extent of my knowledge and that I have informed the researchers of any medical conditions that may impede my ability to participate in this study.

Print Name: ____

Signature: ____ Date:_____________

Investigator Signature: _______________________________________ Date: ____________

Appendix 5

Background Information

1. What sport do you currently participate in? With which team?

2. Does this sport require use of a mouthguard?

3. How many seasons or years experience do you have competing in this sport?

4. How many years experience do you have wearing mouthguards during sport activities?

Appendix 6

Diet, Sleep, Exercise Subject: Date:

1. Please list the foods and amounts of foods consumed today.

2. How many hours of sleep did you obtain yesterday? Please include the approximate times that you fell asleep and the time you woke up this morning.

3. What shoes are you wearing today?

4. Did you participate in moderate-to-vigorous exercise in the past 24-hours?

Appendix 7

Comfort Visual Analog Scale

Name: **Condition:** **Date:**

Extremely Difficult to Breathe Extremely Easy to Breathe

0 100

Extremely Difficult to Speak Extremely Easy to Speak

0 100

Extremely Uncomfortable Extremely Comfortable

0 100

Extreme Oral Dryness Absolutely No Oral Dryness

0 100

Extremely Bad Taste Extremely Good Taste

____

0 100

Extreme Feelings of Nausea No Feelings of Nausea

____

0 100

Extremely Interferes with Performance No Interference with Performance

____

0 100

Extremely Difficult to Adapt To Extremely Easy to Adapt To

____

0 100

Appendix 8

Addendum to Chapter 1: "Effects of a neuromuscular dentistry-designed mouthguard on muscular endurance and anaerobic power."

The improvement in power observed with use of the PPM compared to the CFM may be due to improved neuromuscular communication. In anticipation of a power movement, the central command sends signals via motor neurons to initiate and follow through. Mechanoreceptors, such as the muscle spindles and golgi tendon organs, provide feedback to the CNS regarding intensity and speed of the movement. The CNS responds by adjusting motor neuron communication to recruit more muscle fibers or increase the speed of action potential firing rate. Jaw-repositioning influenced a part or the entire chain of neuromuscular communication. Future research will need to evaluate muscle fiber recruitment rate and action potential firing rate to determine the differences in communication to the muscle.