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INJURY BIOMECHANICS RESEARCH
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Evaluation of the Effects on Human Performance Characteristics and Peak Head Acceleration with the Use of Various Intra-Oral Appliances

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ABSTRACT

Various studies have investigated the relationship between the mandibular position and its affect on human performance characteristics. To maintain the jaw in an optimal position Mandibular Orthopedic Repositioning Appliances (MORA) have been produced. A protective mouthguard is an appliance worn in the mouth which helps prevent injuries to the teeth, lips, cheeks, tongue, and jaw as a result of impact. More recently, it has been hypothesized that mouthguards reduce the risk of concussion by attenuating the impact to the jaw rather than transferring the force to the brain. Currently, there are no standards for testing protective mouthguards. Such a test would prove useful to determine maximum acceleration levels of the head.

The aim of this study is to (1) quantify the effectiveness of repositioning the jaw on strength and aerobic potential as well as (2) to determine if a protective mouthguard can give the same affects of a MORA device. In addition, (3) a test protocol will be established for the evaluation of mouthguard performance. The data collected will show how well the EDGE™ Protection performs versus other consumer available mouthguards on the criteria of attenuation of peak head accelerations. After statistical analysis, it was found on a 95% confidence level that the MORA and the protective mouthguard with MORA attributes increase a user's strength. On certain intervals of the aerobic testing there was evidence that the MORA does have an influence on human performance.

INTRODUCTION

As many as 10.8 million people suffer from Temporomandibular Joint (TMJ) disorders. Symptoms associated with TMJ are headaches, facial pain, jaw locking open or closed, bite that feels uncomfortable, as well as pain in the jaw and surrounding tissues. Dentists have found that repositioning the jaw alleviated some of these symptoms. To keep the jaw in this optimal position, Mandibular Orthopedic Repositioning Appliances (MORAs) were developed. It has been shown that such devices prevent the mandible from closing fully. It is believed that if the mandible is over closed, the cervical vertebrae overact causing an excessive stimulation of the sympathetic nervous system which may compromise performance (Stenger, 1977).

For more than a century, MORA devices have been used in the management of TMJ. In the late 1970s and early 1980s dentists began recommending MORA devices to athletes. It was believed that an athlete could see an increase in performance through repositioning the jaw. Many studies have been done in an attempt to validate these claims, but with some inconclusive studies, an increase in performance is not guaranteed.

More recently there has been an interest in incorporating the effects of the MORA device into a mouthguard that is suitable for contact sports. Protective mouthguards are designed to prevent or minimize injuries to the oral area. As of now, there are no standards developed for testing the mechanical performance of protective mouthguards. Such a test would be beneficial in establishing minimal requirements for manufacturers as well as product comparisons.

Aerobic, strength and impact testing will by utilized in this analysis. In the aerobic and strength portions, a MORA device will be tested and compared to a protective mouthguard as well as no mouthguard. In addition, a testing procedure has been developed to investigate the relationship between impact forces and resultant peak head accelerations. Various mouthguards will be tested and compared using this set-up.

Background

MORAs were originally made use of by dentists to help treat patients with Temporomandibular disorders (TMD). "Temporomandibular disorders comprise a group of disorders involving many hard and soft tissues associated with mandibular and masticatory function" (Cooper, 1995). The Temporomandibular joints (TMJ's) are the two joints that connect the mandible to the skull. These joints consist of the mandible and the temporal bone that slide and rotate in front of each ear, see Figure 1. The main components of TMD are the alignment of the teeth when brought together, the masseter muscle, and mandible movement. Dentists believe that repositioning the jaw can eliminate the components of the disorder, hence relieve the patient of some symptoms.

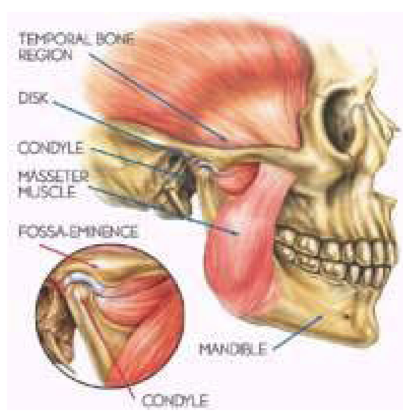

Figure 1: Anatomy of the Temporomandibular Joint

*MORA in Athletics***.** There have been studies published dating back to 1978 which have attempted to determine the relationship between jaw position and strength. Previous studies have generally been lacking in at least one aspect of the analysis. In a previous study, Alexander (1999) compiled a case study of analyses done in this field and their respective short comings. She devised a test to address the criticisms of the previous studies as well as the evaluation of the effectiveness of a self-fit mandibular orthopedic repositioning appliance on athletic performance. The aerobic and strength tests in this study were adapted from her thesis.

*Protective Mouthguards in Sports***.** Mouthguards were first introduced into the sport of boxing in 1913. Since then the National Alliance Football Rules Committee for high school has made the use of mouthguards mandatory in 1962, the NCAA followed in 1974 for football and college hockey in 1976 (Johnsen, 1991). As a result of these regulations, the use of protective mouthguards has been recommended in any sport where a risk of oral injury is significant. These devices have been shown to reduce the frequency of fractures and dislocations to the teeth, protect against bruises and cuts in the mouth, absorb energy from a blow to the chin as well as minimizing upward and backward displacement of the mandibular condyle. Every year an estimated 200,000 football injuries are prevented by mouthguards. Since becoming mandatory safety equipment along with helmets, the probability of a dental injury has been reduced from 10% to 0.4% (Camp, 1991).

There are a variety of protective mouthguards on the market. The most commonly used are the boil-and-bite mouthguards. There are several kinds of boil-and bite, the most fundamental version uses a single type of moldable material while higher end models are a composite of a moldable material that forms to the teeth and another non-moldable material that keeps the jaw from closing completely. Although the apparent safety benefits of mouthguards and with the variety of types saturating the market, there are no standards. If a standard could be developed and implicated, it may improve the quality of mouthguards on the market and increase the protection provided to the user.

*Mechanism of Impact***.** When the mandible suffers an impact it displaces upward and backwards making the mandibular condyles converge with the temporal bone. This convergence causes the energy from the impact to transfer to the brain causing injury. In a study done by Pellman et al. (2003), they determined that the peak head acceleration in concussion was 98 ± 28 g's with a 15 millisecond duration.

METHODS

Experimentation was conducted in two stages. The first stage looked at both strength and aerobic tests and their affects on human performance characteristics. In the second stage, a test was devised to determine the mechanical characteristics of protective mouthguards.

The strength testing protocol was developed to assess the affect of the MORA and the protective mouthguard during an isotonic muscle contraction. An isotonic muscle contraction is a contraction where the muscle tension remains the same as the muscle length shortens. The aerobic portion was adapted from Alexander's evaluation of a MORA device in a double blind study (Alexander, 1999).

In this research, three trials were conducted for each test. The trials varied by the following conditions: no mouthguard, EDGE™ performance, and EDGE™ protection. The EDGE™ performance is a MORA and the EDGE™ protection is a protective mouthguard with MORA attributes. The EDGE™ performance and protection are included in Figures 2(A) and 2(B), respectively. Both are manufactured by EDGE Sports, Incorporated. The participants used in the study were instructed to form their own mouthguards following the manufacturer's instructions. To ensure independence, each trial was conducted at least one day apart with the sequence of the conditions being randomized and the subjects given no instructions on clinching.

Figure 2: (A) EDGE™ Performance; (B) EDGE™ Protection.

The latter stage of testing was developed to determine peak head accelerations as the result of an impact to the jaw. A device was developed such that an impulse could be consistently applied to an instrumented head fitted with a mouthguard. Various mouthguards were tested in order to compare the mechanical performance of the EDGE™ Protection against competitor brands.

Description of Equipment

The blood pressure of the participants was monitored periodically during testing. An OMRON™ Automatic Blood Pressure Monitor was used in this study (see Figure 3). The HEM-712C model automatically inflates the arm cuff to 180 mmHg and produced a digital read out of systolic and diastolic blood pressure as well as the subject's pulse enabling fast and accurate measurements. This particular brand and model was chosen because it was recommended in a previous study done by the British Journal of Medicine (O'Brien et al., 2001).

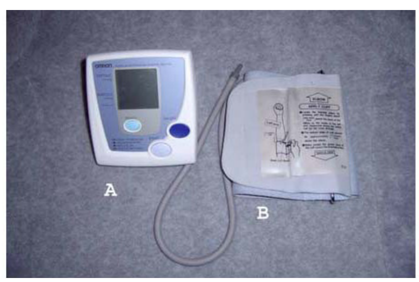

Figure 3: OMRON Blood Pressure Monitor Model HEM-712C.

A Polar S530 Heart Rate Monitor was used for aerobic testing. The heart rate monitor has the ability to record throughout the exercise without interfering with the subject. The coded transmitter is fastened around the subject's abdomen which transmits heart rate data at a rate of 1 measure per 30 seconds to a wrist worn receiver. Following the exercise routine, data was uploaded to a computer where it was post-processed using a custom software application.

Aerobic Test Procedure

A standard runner's treadmill was used to evaluate the aerobic performance of the subjects. The treadmill enabled precise monitoring of the subjects speed. All subjects began at a warm-up pace of 2 miles-per-hour. The pace was increased, per minute, by 0.2 miles-per-hour in order to reach the individual's target heart rate. The target heart rate selected for this test was 75% the maximum heart rate. Maximum heart rate was determined by 220 minus the subject's age. The speed was maintained for ten minutes. After the 10 minutes, the speed was reduced by 0.5 miles-per-hour until either the speed reached 0 mph or 30 minutes had elapsed. Blood pressure of each subject was recorded before and after each test.

Strength Test Procedure

The equipment chosen for the strength testing was a rear delt/pec fly universal weight machine (see Figure 4). In the pectoral fly setting the movement focused on the pectoralis major and anterior deltoid muscles and eliminated the effect of momentum beginning each repetition.

Figure 4: Rear Delt/Pec Fly Universal Weight Machine.

Subjects were instructed to keep good form and do as many as they could until exhaustion. Since all the subjects were at different physical levels, the subjects were tested at 75% of their one-repetition maximum to standardize the testing weights. The one-rep maximum weight was determined using Brzycki's Equation:

$$1RM = \frac{weight}{1.0278 - (.0278 * reps)} \tag{1}$$

where *weight* is the total weight being moved and *reps* is the number of repetitions of the *weight* (Mayhew et al., 1995). Subjects were tested at 75% of their one-rep max each testing day and the total number of complete repetitions was recorded.

Impact Test Procedure

The objective of the impact study was to develop testing equipment as well as a protocol that would measure peak head accelerations after a jaw impact. A bio-fidelic, anthropometric, headform developed by the National Operating Committee on Standards for Athletic Equipment (NOCSAE) was modified to allow for a molded set of upper teeth to be inserted (see Figure 5). Since the headform did not have a functional mandible, the lower jaw was removed and a piece of wood was used to replicate the contact of the lower and upper jaw (see Figure 6). The wood does not have the same characteristics as a human jaw because the jaw bone and tissue would absorb some of the impact. However, the wood provides a greater transfer of energy to the upper jaw thus representing a worse case scenario. The headform was equipped with a triaxial accelerometer to measure peak head accelerations after an impact.

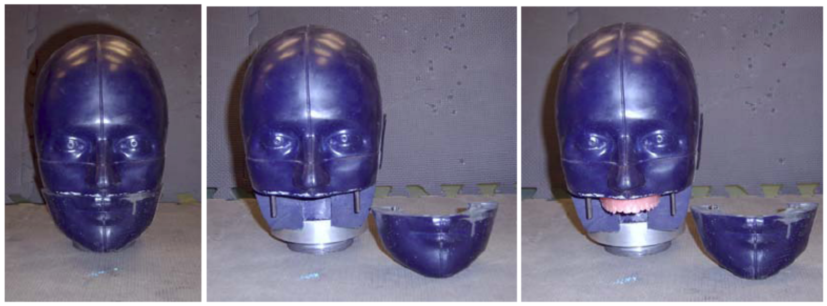

Figure 5: Modified NOCSAE Headform.

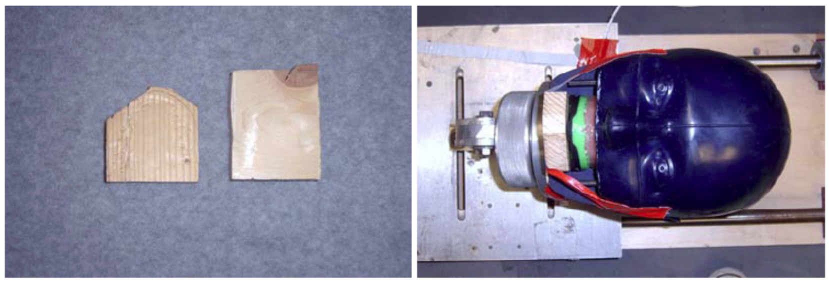

Figure 6: (A) Wood "Mandible" and (B) Headform with teeth, mouthguard and mandible.

The impact was applied via a large sledge hammer instrumented with a piezotronic force transducer (see Figure 7). The hammer was suspended from a steel frame as a pendulum to ensure that the force could be applied repeatedly (see Figure 8).

The force and acceleration data was collected through a KME and a Fluke Scopemeter model 105B series II, respectively (see Figure 9). The KME determined the vector sum of acceleration for the three orthogonal principal axes of the head. The Fluke displayed the peak impact force in the form of voltage.

The EDGE™ protection was tested against no mouthguard and five other competitors' mouthguards. Because the other companies did not give permission for the tests, their names have been kept confidential. Peak acceleration of the head that causes a concussion has been reported to be 98 ± 28g's (Pellman et al., 2003). The impact test was conducted by applying a force that exceeded this level with no mouthguard in place.

Figure 7: Large Sledge Impact Hammer.

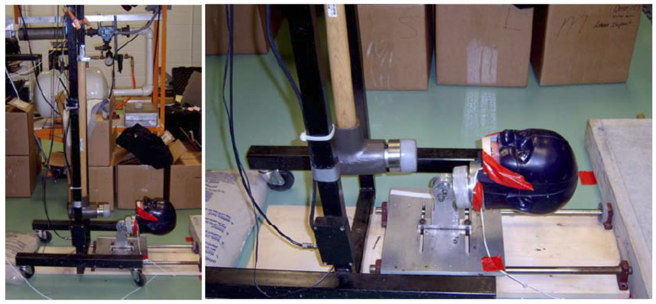

Figure 8: Test Setup.

Figure 9: (A) KME and (B) Fluke Scopemeter model 105B series II.

RESULTS

Data was collected and analyzed statistically to determine its significance. The statistical tests used were the t-test and the Wilcoxon signed-rank test. Microsoft Excel and a statistics software JMP version 5.1 were utilized in the analysis.

Aerobic Test Results

The heart rate data collected in the aerobic test was split into three intervals: warm up, 10 minute running interval, and cool down. An example of an individual heart rate graph is shown in Figure 10. The data for subject number 16 was thrown out of the calculations for the warm up and the running as an outlier because of a malfunction with the heart rate monitor in the first trial. Subject number 7's heart rates for the cool down were also thrown out because of a lack of data from the first trial. All three hypotheses were analyzed for each interval to determine if it had statistical significance. A summary of the t-test can be found in Table 1.

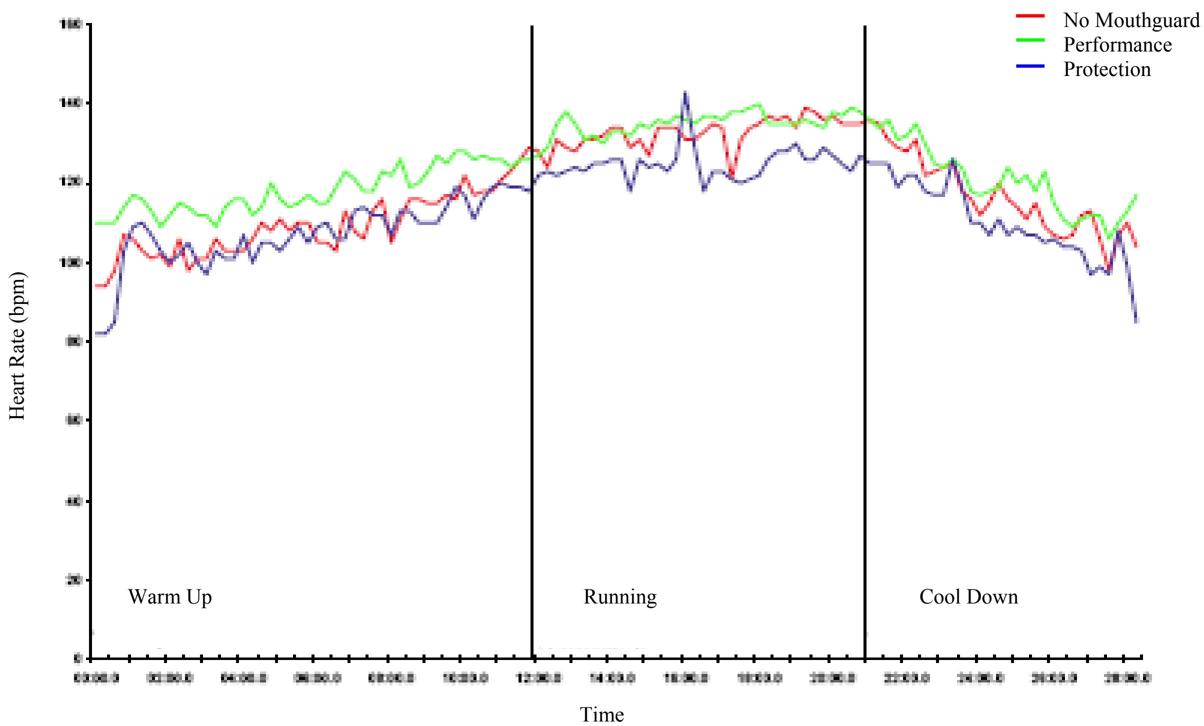

Figure 10: Aerobic Data for Subject #5.

For the warm up interval of the aerobic testing it was found that there was no statistically significant difference in the heart rate when the subject had no mouthguard and when the subject was wearing the EDGE™ performance. It was also found that the heart rate of a subject with no mouthguard was higher than the heart rate when the subject was wearing the EDGE™ protection. No statistical difference could be found between the heart rates of the EDGE™ performance and the EDGE™ protection.

Table 1. Summary of t-test Results for the Aerobic Data.

Test Interval	Null Hypothesis (H_o)	p-value	comparison	alpha (α)	conclusion
Warm Up	No Mouthguard ≤ Performance	0.1278	>	0.05	cannot reject null
	No Mouthguard ≤ Protection	0.0014	<	0.05	reject null
	Performance = Protection	0.0833	>	0.05	cannot reject null
Running	No Mouthguard ≤ Performance	0.0001	<	0.05	reject null
	No Mouthguard ≤ Protection	0.3245	>	0.05	cannot reject null
	Performance = Protection	0.0072	<	0.05	reject null
Cool Down	No Mouthguard ≤ Performance	0.0001	<	0.05	reject null
	No Mouthguard ≤ Protection	0.0345	<	0.05	reject null
	Performance = Protection	0.0356	<	0.05	reject null

In the running interval there was no statistical difference in the heart rate with no mouthguard and that of the heart rate with the EDGE™ protection. There was statistically significant proof that the heart rate with no mouthguard was different from that with the EDGE™ performance. With regards to the heart rate with the EDGE™ performance compared to the heart rate with the EDGE™ protection, there was a statistical difference.

For the cool down there was a statistical difference noted for two of the three hypotheses. On a 95% confidence interval, the heart rate of the subject with no mouthguard was higher than the heart rate with the EDGE™ performance and protection. When the heart EDGE™ performance was compared to the protection, there was a statistical difference.

Strength Test Results

Because of the small sample size of the strength data the t-test used for the aerobic data analysis was inappropriate. Therefore, the Wilcoxon signed-rank test was chosen. With this test, the differences in the sets of data can be ranked and their significance can be determined. Table 2 contains a summary of the test for significance. For both the EDGE™ performance and the EDGE™ protection, there was statistically significant proof that the number of repetitions was different than those performed without a mouthguard.

Table 2. Wilcoxon Signed-rank Summary for the Strength Test.

Condition	n	T	p-value
EDGE™ Performance to No Mouthguard	11	2.5	0.0040
EDGE™ Protection to No Mouthguard	10	0	0.0001
EDGE™ Protection to EDGE™ Performance	8	12	0.4610

Impact Test Results

The impact data consisted of 10 hits of 460 pounds force (lbf) to each of the protective mouthguards. The peak head accelerations were averaged and compared to the average acceleration to the head without a mouthguard. One impact was thrown out because the wood used to transfer the force to the teeth cracked. Percentage reduction on peak head acceleration was calculated and used to compare the protective mouthguards. These values are found in Table 3.

Table 3: Summary of Impact Data.

Mouthguard	Average g's	% reduction
None	117.4	---
EDGE™	91.1	22.40%
2	74.8	36.29%
3	85.1	27.51%
4	92.3	21.38%
5	96.0	18.23%
6	122.1	-4.00%

CONCLUSIONS

From the aerobic data there was no statistically significant decrease in the heart rate for the EDGE™ Performance compared to that of no mouthguard for the warm up. There was a statistically significant decrease in the heart rate with the EDGE™ Protection to that of no mouthguard. For the heart rates of EDGE™ performance and the EDGE™ protection, there was no statistical difference in the warm up.

The running interval had opposite results from the warm up. There was an increase in the heart rate with no mouthguard compared to that with the EDGE™ performance. The EDGE™ protection had a higher heart rate than without a mouthguard and there was statistical proof that the EDGE™ performance heart rates and the EDGE™ protection heart rates were not the same.

In the cool down interval, both the EDGE™ performance and protection had significantly lower heart rates than that with no mouthguard. Although both of these products had lower heart rates, there was no statistical proof they were the same.

Although the EDGE™ protection was found to be beneficial in the warm up, further tests should look at factors besides heart rate. Heart rate can vary dramatically at the start by conditions uncontrollable. For some of the subjects their starting heart rates were as much as 20 beats apart depending on the day. One option would be to test the subject to the same heart rate each day, instead of the same speed, and compare the work loads. Because the EDGE™ protection did not show the same results as the EDGE™ performance in the running interval, oxygen intake may be a factor. A follow up study could include testing VO2max. VO2max is the maximum amount of oxygen in milliliters one can use in one minute per kilogram of body weight. If more tests can be done to determine the affect of a MORA on human performance, the results would be beneficial to any active individual.

Once the strength data was analyzed, it was determined that there was a difference in the data. Under a 95% confidence level it was statistically significant that the EDGE™ performance and the EDGE™ protection increase the muscle threshold.

Once the apparatus was impacted when the various mouthguards were in place, the percentage in reduction of g's was calculated. The mouthguards that were comparable to the EDGE™ were numbers 2 and 3. These mouthguards reduced the peak head acceleration 36.3% and 27.5%, respectively. Both showed a greater reduction in acceleration when compared to the EDGE™ which performed with a 22.4% reduction in peak head acceleration. While this is a significant reduction in the acceleration of the head to below the threshold of 98 g's, the rigid bite plate used to make the EDGE™ protection perform like a MORA device may have compromised its protective characteristics as a mouthguard. The bite plate used on the EDGE™ protection was not as hard as the bite plate used on number 4. Mouthguard #4 indented the wood, which would most likely damage a user's lower teeth if impacted with the same force.

Further studies on the effectiveness of protective mouthguards need to be done. In addition to peak head accelerations, a velocity gate could be used on the impact hammer as well as the head to get velocity data that would be used along with momentum. A better representation of the mandible also needs to be developed. If a head could be equipped with a Temporomandibular joint, force measurements could be taken on the mandibular condyles. This study and future studies could have an impact on the manufacturing and marketing of protective mouthguards. An athlete's safety in impact sports would be greatly benefited by standardization of protective mouthguards.

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DISCUSSION

PAPER: **Evaluation of the Effects on Human Performance Characteristics and Peak Head Acceleration with the Use of Various Intra-oral Appliances**

PRESENTER: ***Katie Padgett, US Army Aeromedical Research Research Lab***

QUESTION: (NONE)