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Relationship between temporomandibular joint dynamics and mouthguards: feasibility of a test method

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Abstract – A test system was developed establishing the feasibility of collecting biomechanical data as they relate to the use of mouthguards. Previous experimental studies have examined the physical and mechanical properties of mouthguard materials. This information has been used as a guide for establishing material standards and specifications for the fabrication of mouthguards, but it lacks the key biomechanical parameters required for a thorough mouthguard evaluation. The current study was designed to assess whether the impact force, condylar deflection, and strain superior to the temporomandibular joint region could be measured. A drop test was conducted on a cadaveric specimen to simulate loading at the chin point. To measure the force of impact, an accelerometer was attached to an impactor of known mass. High-speed biplanar (1000 frames per second) radiographs were used to determine condylar displacement. Radio-opaque markers were inserted into the bone at predetermined locations. Total displacement of these markers was determined in reference to anatomical landmarks. Strain gauges were attached to the mandible and skull to monitor the effects of the condyle impacting the base of the skull. Based on the data collected, forces were calculated by determining the product of the time-based acceleration and known mass. A measurable change in force between the mouthguards and the control (no mouthguard) was demonstrated. The average condylar displacement was successfully measured and indicated as an increase in total deflection for impacts conducted with mouthguards. Quantifiable strain was measured in the region above the mandibular fossa with and without the insertion of a mouthguard at all impact conditions. However, it was determined that additional gauges would provide critical data. Key biomechanical parameters for chin-point impacts were determined in the current study. The technique demonstrated that both displacement within the mandibular fossa and loading of the condyles occur during the impact event. Although the current study established a technique that can be used to examine the relationship between mouthguards and jaw-joint injuries, the role, if any, mouthguards play in the reduction of injuries cannot be established until a thorough analysis is completed.

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There is an estimated 1.5 million traumatic brain injuries (TBI) occurring each year (1). Sports-related activities account for 200–300 thousand of the total number of these injuries (1, 2). The role of a helmet as a protective device has been established for both TBI and facial injury (3, 4). The design of most helmets relies on the retention system or chin-strap to accomplish this task. Under certain impact conditions, a large portion of the impact force can be transferred through the chin-strap to the mandibular structures including the temporomandibular joint (TMJ). Ultimately, the base of the skull and intracranial structures may be affected as a result of the deformation of the temporal bone above the mandibular fossa. This deformation may displace the middle cranial fossa and stretch or damage the middle meningeal artery (5). Damage to this artery can potentially cause bleeding between the dura mater and the periosteum of the internal aspect of the skull, resulting in an extradural hematoma.

Large condylar deflections may lead to impingement-type injuries. These injuries are possible as a result of the close proximity of the auriculotemporal, masseteric, and deep temporal nerves to the TMJ. These nerves innervate several structures, including the TMJ capsule and the tympanic membrane. The close proximity of these nerves to the TMJ may help explain the sharp shooting pain that is sometimes felt after a jaw-joint injury. If the impact and ensuing injury forces the nerves to deviate from their normal sheltered course, normal jaw movements could cause compression and mechanical irritation to the exposed nerves. This irritation in the TMJ region can cause classic symptoms such as pain and other sensations in the area of the ear, temple, cheek, tongue, and teeth (6).

The use of mouthguards to reduce the risk of TMJ injury has been hypothesized. The insertion of a mouthguard creates a recoil space between the condyle and the mandibular fossa by moving the head of the condyle inferiorly and anteriorly (Figs. 1 and 2). The recoil space allows the interface between the mouthguard and bony structure of the maxilla time to dissipate the energy (7, 8). Others have disputed this theory, citing that while effective in reducing dental injuries, the reduction of TMJ-related injuries cannot be accredited to the use of mouthguards. One theory is that the creation of a recoil space gives the mandible room to accelerate, allowing the condyles to impact the base of the skull with a greater force as a result of the increase in momentum (9).

Fig. 1. Position of the condyle without mouthguard.

Fig. 2. Position of the condyle with mouthguard in place.

Presently, hockey and football players wear mouthguards in conjunction with facemasks to protect their teeth. Many of these players believe that these mouthguards are also protecting them from temporomandibular-related injuries (10). This belief is based primarily on epidemiological studies (11, 12) and few experimental studies. Most of the epidemiological studies have involved small samples of players in which information on the injury and mouthguard is retrospectively collected. This requires players to recall the events surrounding their injury, which may compromise the quality of the data collected.

Several experimental studies have examined the physical and mechanical properties of mouthguards (13–15). These tests have been conducted using standards prescribed by the American Society for the Testing of Materials (ASTM) for strength, hardness, water absorption, and energy dissipation. This information has been used as a guide for establishing material standards (16), but it lacks requirements for a biomechanical evaluation of mouthguards.

In 1967, Hickey et al. (17) studied the relationship between mouthguards and cranial pressure and deformation. A dynamic force was applied to the chin of an intact embalmed cadaver with and without a mouthguard. While the biomechanical response of an embalmed cadaver is not the same as human tissue (18), their results indicated a decrease in the measured parameters. A decided reduction in the amplitude of

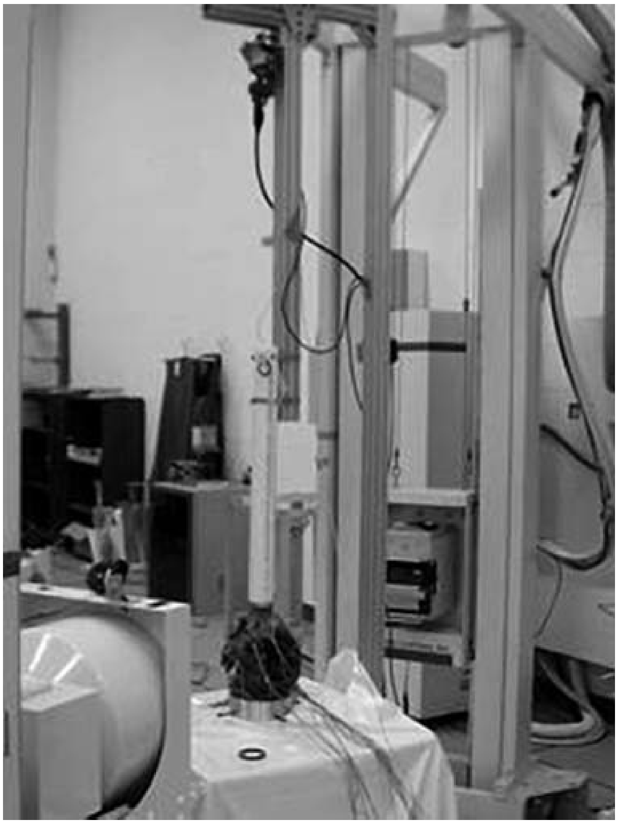

Fig. 3. Specimen attached to impact fixture and positioned in front of high-speed biplanar X-ray machine.

the intracranial pressure wave, when the mouthguard was in place, and a moderate decrease in bone deformation was noted. Although this study demonstrated a protective role of mouthguards, the use of an embalmed specimen remains in question. Research has shown that unembalmed tissue more closely represents living tissue (18).

A test system was developed to establish the feasibility of collecting biomechanical data related to the use of mouthguards. The study was developed to determine if this system was sensitive enough to collect critical biomechanical parameters. Based on the findings of this study, future studies can be conducted to determine the level of injury protection mouthguards offer to the TMJ region.

Methods and materials

To determine the feasibility of collecting biomechanical properties of mouthguards, three parameters were investigated: impact force, condylar deflection, and principle strain above the jaw-joint region. The impact force was calculated using an accelerometer attached to an impactor of known mass. To verify the 3D-motion of the mandible, the head of the condyle was tracked with high-speed biplanar X-ray. The effects of the mandible impacting the base of the skull were measured by strain gage rosettes attached to the mandible and skull.

Data were collected during chin-point impacts given to a 67-year-old male cadaver from the Wayne State University Willed Body Program, using a 1-kg mass. The specimen was treated with respect in accordance to ethical practices of cadaver usage (19). The goal of the tests was not to cause fracture, but to load the mandible to a subfracture level, similar to what might be seen in sports.

The initial, preimpact position of the mandible was maintained by stretching surgical thread from the angle of the mandible up to the zygomatic arch. The thread was tied tightly to hold the jaw in a natural occlusion. When an oral appliance was inserted, the mandible was drawn up with the thread so that the teeth of the lower arch came naturally in contact with the bottom of the mouthguard.

The direction of this impact was estimated as the straight line from the chin point, through the head's center of gravity (cg). To position the head for impact and isolate the motion of the jaw, the apex of the specimen was potted in polyester resin and securely bolted to a rigid table (Fig. 4). Once oriented, the projectile was released and allowed to free-fall onto the chin point. The projectile was instrumented with an accelerometer so that the peak force of the impact could be calculated by

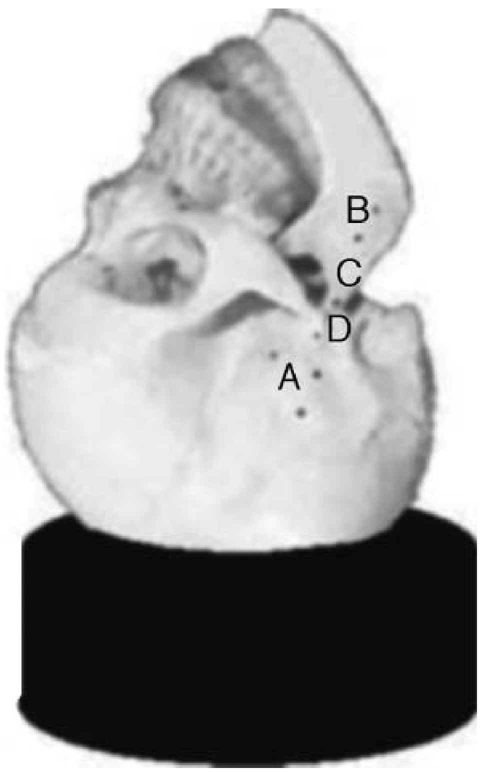

Fig. 4. Schematic showing position of the X-ray markers on the specimen.

multiplying the mass of the projectile by its acceleration. The mass was dropped from three heights (0.2, 0.3, and 0.4 m) so that a variety of impact conditions could be evaluated. This procedure was duplicated with and without a mouthguard in place. After each impact, the specimen was examined to determine if there was a palpable change in the mandible and TMJ. If no change was detected, the testing continued.

To measure the motion of the mandible, the bones surrounding the jaw joint were tracked with a high-speed biplanar X-ray system (Fig. 3) located at the Motion Analysis Laboratory at Henry Ford Hospital, Detroit, Michigan. The system emits a continuous X-ray beam with the output collected by an image intensifier. Two sets of X-ray heads and intensifiers utilized to conduct 3D-motion analysis. Images were captured from the rear of the intensifiers by digital video cameras (JCL) with a resolution of 384 × 240 pixels at a rate of 250 frames per second. This high-speed X-ray has been previously used to measure 3D-brain motion in cadaveric specimens (20).

Lead balls ranging from 2 to 3 mm in diameter were fixed to the specimen for tracking with the high-speed biplanar X-ray machine. To fix the targets to the bone, holes were drilled into the bone, and a lead ball was inserted into each hole. The balls were arranged in five-ball arrays, with two axes (Fig. 4). The center ball of each array was used as the origin for the local coordinate system, with two additional balls defining each axis. One of the two axes was aligned parallel to the Frankfort plane of the head. The spacing of the targets was held constant by using a drill template. After the targets were positioned, the holes were filled with dental acrylic to minimize the possibility of stress risers created by the holes. Arrays were placed in two locations. The first array (Fig. 4A) was drilled into the temporal bone to provide a fixed reference point from which the displacement of the mandible would be calculated. The second array (Fig. 4B) was drilled into the mandible in the subcondylar region to track gross linear translation and rotation of the mandible during impact.

A single lead target was implanted approximately at the center of the condylar head to measure the motion of the mandible within the fossa (Fig. 4C). Additional targets were fixed to the skull to measure relative distances between the head of the mandible and important bony landmarks. Targets were fixed to the temporal bone in the region posterior to the external acoustic meatus (Fig. 4D), as well as the base of the skull in the region of the jugular foramen, where the jugular vein and cranial nerves exit.

Fig. 5. Location of the strain gage rosette attached to the inside of the skull above the mandibular fossa.

The contents of the cranial cavity were removed so that a strain gage rosette could be attached to the floor of the cranial vault above the mandibular fossa to track skull deformation upon impact (Fig. 5). It was hypothesized that the amount of skull deformation in the region above the mandible should be reduced with the insertion of a mouthguard. The reduction in strain should correlate to a smaller amount of energy being passed through this region to the base of the skull. The primary goal of the current research was to determine if a difference in skull deformation could be measured. Although this approach did not determine the absolute amount of force transferred through the TMJ, it did signal as to when the mandible loaded the base of the skull. This data along with the targets indicate the time when the mandible contacts the walls of the fossa. The current study used a generic boil-and-bite mouthguard (appliance A) and a bimaxillary mouthguard (appliance B). Both were made of a thermoplastic material, formed by immersing them in boiling water, and formed in the mouth using fingers, tongue, and biting pressure. The bimaxillary mouthguard is a special type of boil-and-bite mouthguard that covers both the upper and lower dental arches.

Results

The data showed a difference in force measured between the mouthguards and unprotected conditions for all drop heights (Table 1). The peak forces ranged from 778 to 1112 N with no guard, and from 334 to 1289 N and 222 to 556 N for

Table 1. Force and deflection results at various impact conditions

	No protection	Appliance A	Appliance B
0.2-m drop (28 J)			
Impact force (N)	778	334	222
Condylar deflection (mm)	0.7	1.6	2.2
0.3-m drop (43 J)			
Impact force (N)	1245	498	400
Condylar deflection (mm)	0.7	1.6	1.8
0.4-m drop (58 J)			
Impact force (N)	1112	1289	556
Condylar deflection (mm)	0.8	0.7	2.4

appliances A and B, respectively. The insertion of an oral appliance increased the duration of the impact event (Fig. 6). For the 0.4-m drop height, the use of appliance B increased the duration of impact to almost double than that seen when no appliance was used. This increase in duration was observed at all drop heights when a mouthguard was inserted.

The condylar displacement when no guard was inserted was similar at all drop heights (0.7–0.8 mm). The condylar displacement was measured to be over 1.6 mm for all impacts where mouthguards were used, with the exception of the 0.4-m drop with appliance A. Figure 7 shows a condylar motion with the insertion of appliance B three times greater as compared to the no-guard condition for the 0.4-m drop condition. This condylar motion (2.4 mm) corresponded to an impact force of 556 N and a calculated principle strain of 25 μm in the region above the mandibular fossa. This compares to a condylar motion of 0.7 mm with an impact force of 1112 N for the no-guard condition at the same drop height.

The data show that the strain was measured in the region above the mandibular fossa with and without the insertion of a mouthguard for all drop conditions. For the 0.4-m drop, the maximum principle strain in the fossa was 350 μm with the use of appliance A and 25 μm with appliance B. The strain was 250 μm when no mouthguard was inserted for the same drop condition.

Discussion

The current study demonstrates that a simple drop apparatus can be used to determine key biomechanical parameters for chin-point impacts. This

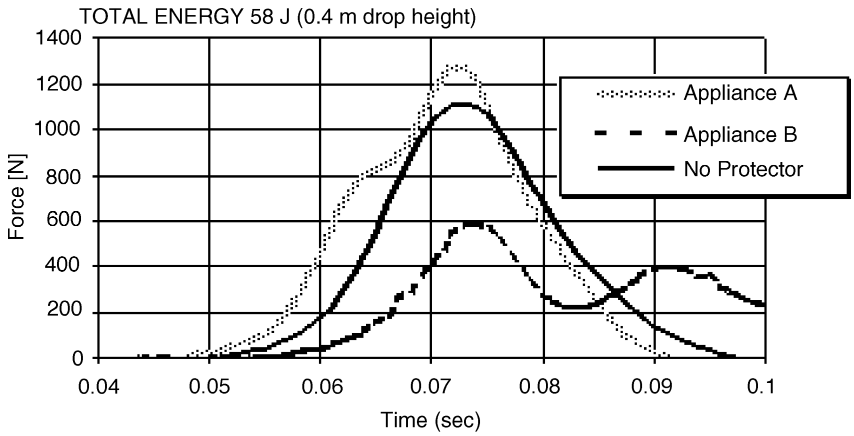

Fig. 6. Impact forces with and without mouthguard.

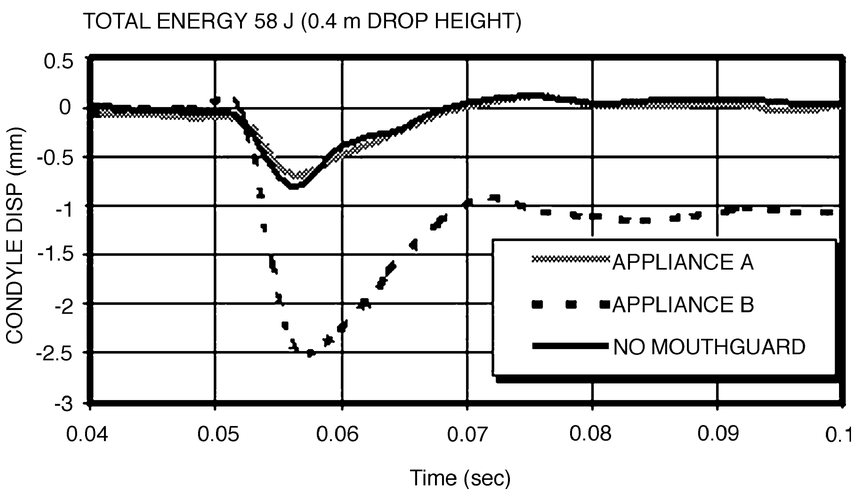

Fig. 7. Absolute deflection of the condyle with and without mouthguard.

technique demonstrated both displacement within the mandibular fossa and loading of the condyles during impact events. Strain in the region above the mandibular fossa was measured for all drop conditions; however, given the current test set-up, additional regions of high-strain areas were not identified. Additional gauges are warranted to delineate high-strain regions within the cranial vault.

Based on the current research, the shock-attenuating properties of the oral appliances appear to diminish. These results are consistent with the conclusions of Hoffman & Goz (21) in their study of the protective capabilities of mouthguards in the prevention of dental injuries. This observation requires further investigation because, in the current study, boil-and-bite-type guards were used and the dental impressions taken were not optimal as the thermoplastic material was set very quickly in the cadaver because of its low body temperature.

Although condylar displacement was determined, difficulties were encountered with the JCL cameras because of the low frame rate and limited dynamic range. Targets were often difficult to track and required digital enhancement prior to analysis. Advances in technology related to high-speed video cameras offer a wider dynamic range resolving tracking problems which were previously encountered. Newer VR4 cameras are currently installed with a 512×512-pixel resolution using a frame rate of 1000 frames per second. These improvements will allow for tracking of the targets with greater precision.

The current study demonstrates the feasibility of a test system in collecting key biomechanical data in the jaw-joint complex. The collection of these parameters is essential to complete a through analysis of the conditions that lead to TMJ injuries. Determining these conditions allows for protective ability of mouthguards to be established in future studies.

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