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MECHANICAL STRENGTH ANALYSIS OF HUMAN TEETH WITH RESPECT TO PREVENTING SPORTS-RELATED INJURIES

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Abstract

Intoduction: Extreme sports and high-contact sports, all of which are associated with a higher risk of injury, are currently becoming more and more popular. Traumas in the facial and oral region and their consequences are particularly dangerous. Thus, it is important to evaluate the mechanical strength of teeth in order to plan appropriate prophylaxis.

Materials and methods: Study material included 40 phantoms made of human incisors and canines, which were subjected to loading in an Instron testing system until damage occurred.

Results: The mean force causing permanent tooth damage was 0.5322 kN. Statistical analysis based on Pearson's correlation and t-Student test revealed that with increasing tooth cross-section area, parallel to the direction of trauma, the force causing tooth damage, bending moment and S modulus increased, while the bending stress reduced. The study showed that anterior maxillary teeth have low resistance to forces applied perpendicular to their labial surface. Teeth with small bucco-lingual dimensions are especially susceptible to injury.

Conclusions: Promotion of mouthguards is necessary. Sportsmen with small teeth should use mouthguards made of materials with high energy absorption parameters.

***Key words**: teeth trauma; orofacial injury; mouthguards; sport*

Introduction

Participation in various forms of physical activity is beneficial to the respiratory, cardiovascular, muscular and nervous systems. Sports activities prevent diseases of modern civilisation associated with metabolism, and significantly reduce stress, which has a positive effect on emotional and mental health. Extreme sports and those requiring much contact, all of which are associated with increased injury risk, are currently becoming more and more popular. Consequences of oro-facial injuries are particularly dangerous. Anterior maxillary teeth are specifically susceptible to traumatic injuries not only in extreme and contact sports, but also during recreational activities. Data in the available literature indicate that more than 1/3 of all facial injuries occur during sports activity, of which 50% are oral and dental injuries [1]. Author's own survey among young people aged 12-15 and 20-25 revealed that 59% and 34% of the respondents in these age groups, respectively, and almost half of the participants in total (48%) had sustained injuries to the oral cavity or head while practising sport [2]. According to Ferrara et al. [3], 28.8% out of 1189 surveyed sportsmen had suffered oral trauma. Injuries occurred to 41.2% of the subjects who practised jiu-jitsu, 37.1% of handball players, 36.4% basketball players, 23.2% soccer players, 22.3% judo wrestlers and 11.5% field hockey players. On the other hand, a study by Andrade et al. [4] revealed that the most common sports-related injuries affected upper central incisors (56.5%), with enamel fractures occurring in 21.9% of cases. Due to the risk of sustaining oral injuries during sports activities, it is important to estimate forces causing tooth injuries and to determine mechanical parameters of teeth in order to successfully protect them in the future. However, literature lacks specific data on mechanical tooth strength, which would be useful in planning how to prevent injuries, especially with respect to the properties of materials used to manufacture mouthguards. The present study provides an approximate view on mechanical properties of human teeth under static loading, as such conditions differ from *in vivo* conditions to a considerable degree.

The purpose of the present study was to analyse mechanical strength of human teeth subjected to an external force applied perpendicular to their long axis, in a simplified mechanical system comparing to *in vivo* conditions, by recording the applied force and estimating bending moment, section modulus and bending stresses at the moment of tooth damage. These values represent tooth's susceptibility to traumatic injuries, justify the need to use mouthguards during sports activities, and provide guidelines on the amount of protection mouthguards should provide in order to avoid tooth injuries. In addition, the same mechanical parameters were measured for tooth-shaped ceramic phantoms in order to visualise the susceptibility of natural teeth to trauma.

Materials and methods

In order to measure the force causing permanent damage to hard tooth structures, 40 phantoms were prepared using human incisors and canines, which had not been treated endodontically, were extracted due to periodontal disease and stored at low temperature in disinfectant solution. Each tooth was centrally embedded with its root in an acrylic cylinder (Duracrol, Spofadental, Czech Republic) (32 mm in diameter, 20 mm in height) and with its coronal part extending 14 mm above the base of the cylinder (Fig. 1). Ceramic phantoms were mounted in a similar manner in acrylic bases. Phantoms had been prepared by copying the shape of the natural maxillary central incisors with silicone impression material (Zeta, Zhermapol, Germany), modelling wax in this form. Wax models were then placed on a cone (IPS Empress EP 500, Ivoclar, Liechtenstein), negative form was cast with investment material (Siladent Premium, Dr. Böhme & Schöps GmbH, Germany) in a casting ring and ceramics was pressed (IPS Empress 2, Ivoclar, Liechtenstein) in the place of burnt-out wax (Fig. 2, 3, 4).

Next, the force causing damage to hard tooth tissue and bending moment, section modulus S and bending stress during loading were measured. Instron 8802 fatigue testing system (I 7653 A 1477- 3033C, Instron, Great Britain) from the Department of Mechanics and Applied Computer Science (Faculty of Mechanical

Fig. 1. *Tooth embedded in an acrylic block*

Fig. 2. *Silicone matrix and wax patterns for preparing ceramic phantoms*

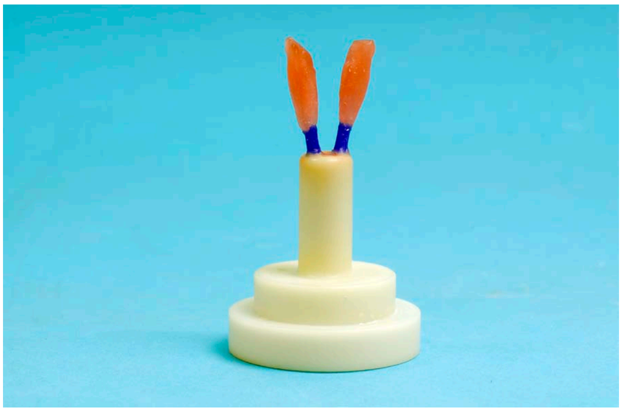

Fig. 3. *Wax patterns embedded on casting cone*

Fig. 4. *Ceramic phantom prior to embedding in acrylic base*

Engineering, Military University of Technology in Warsaw) was used. Teeth were embedded in acrylic bases, which were used to fix them in the testing system. Forces were applied perpendicular to the labial surface of teeth at the mid-length of the coronal part extending above the acrylic cylinder (7 mm above the acrylic base). The external force was applied by a metal rod moving at 1 mm/min (Fig. 5, 6). The measuring system continuously recorded the force until tooth damage occurred. Data were processed in a computer (Intel, fasttrack software). Damaged teeth were measured with an electronic caliper (Kinex, Czech Republic). A total of 40 measurements were made. In some cases intact teeth slid out of their acrylic bases before damage occurred. Failed tests were excluded from analysis. The

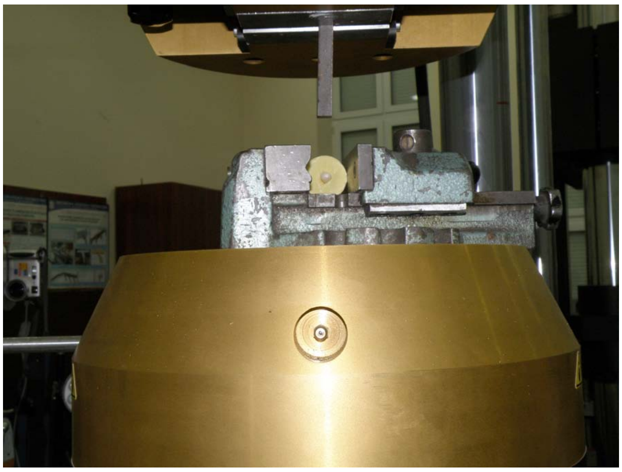

Fig. 5. *Instron 8802 testing system with a fixed sample of natural teeth*

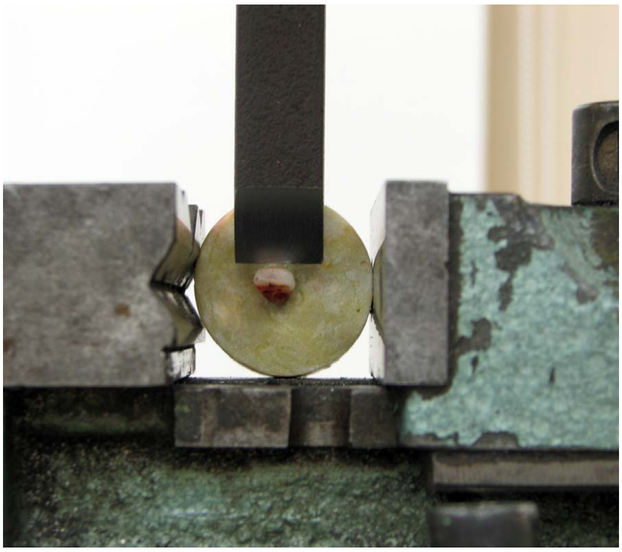

Fig. 6. *The pin of the Instron 8802 testing machine applying load to the sample*

final assessment included 35 measurements, which raised no questions [5]-[8].

Stresses during tooth bending, assuming a simplified elliptical cross-section of the tooth, were determined by calculating the bending moment (M), the moment of inertia (I) and the section modulus (S) for a plane figure with the loading force applied parallel to the long axis [9].

The bending moment was calculated using the following formula:

$$M = P \times L \text{ [N x mm]}, \text{ where:}$$

P – the highest force causing tooth fracture recorded during the strength test

L – the distance between the acrylic base and the point of force application, which was 7 mm.

Section modulus is a quotient of the geometric moment of inertia around a neutral axis and the distance from the extreme cross-section fibre to this axis, calculated using the following formula:

$$S = \frac{l}{y_{max} [mm^3]}, \text{ where:}$$

l – geometric moment of inertia around the x axis running along the neutral axis

y_{max} – maximum distance from the extreme fibres to the neutral axis (=a).

The geometric moment of inertia of an ellipse was calculated using the following formula:

$$I = \pi\, b\, a3\, 4, \text{ where:}$$

a – 1/2 of the long axis of the ellipse, parallel to the loading force

b – 1/2 of the short axis of the ellipse, perpendicular to the loading force.

Modulus of the bending strength of a beam with ellipsoid cross-section is expressed by the following formula:

$$S = \frac{\pi\, b\, a^2}{4}, \text{ where:}$$

a – 1/2 of the long axis of the ellipse, parallel to the loading force

b – 1/2 of the short axis of the ellipse, perpendicular to the loading force.

Stress during bending is expressed by the following formula:

$$\sigma = M \frac{y_{max}}{l} = \frac{M}{S}, \text{ where:}$$

M – bending moment

y_{max} – the maximum distance from the extreme fibres to the neutral axis

l – the geometric moment of inertia around the x axis running along the neutral axis

S – section modulus.

The statistical analysis was carried out using STATISTICA v 8.0 software (significance level α=0.05).

Results

The study results indicate that anterior maxillary human teeth, having the highest risk of traumatic injury during sports activity, demonstrate highly variable mechanical strength values when subjected to an external force applied perpendicularly to their labial surface (Table 1). Statistical analysis of results was performed (Table 2). The mean force causing permanent damage to human teeth was 0.5322 kN. The examined teeth (central and lateral incisors, canines) exhibited a very wide range mechanical strength under loading. The least resistant teeth were damaged by a force of 0.165 kN, while the strongest ones at 1.023 kN. Mean bending force with respect to cross-section area (bending moment) was 3725 Nmm, mean section modulus

Table 1. *Characteristics of anterior maxillary teeth*

No.	Sample no.	Long axis of ellipse to the force [mm]	Short axis of ellipseto the force [mm]	Maximum force P [kN]	Bending moment M [Nmm]	Section modulus S [mm3]	Bending stress σ [MPa]
1	1	6.65	5.71	0.587	4111	24.79	165.8
2	2	7.31	5.59	0.840	5877	29.33	200.4
3	3	6.35	3.02	0.226	1584	11.96	132.5
4	4	5.17	3.21	0.165	1157	8.42	137.4
5	7	6.29	4.23	0.173	1209	16.43	73.6
6	8	6.54	3.15	0.514	3600	13.23	272.2
7	9	5.47	5.92	0.321	2248	17.39	129.3
8	10	7.07	5.34	0.237	1658	26.20	63.3
9	11	5.19	4.98	0.371	2594	13.17	197.0
10	13	5.90	4.96	0.668	4677	16.95	275.9
11	15	4.92	3.65	0.365	2556	8.67	294.7
12	16	5.75	4.29	0.297	2079	13.92	149.3
13	17	4.86	6.04	0.459	3210	14.01	229.2
14	18	5.75	3.82	0.347	2426	12.40	195.7
15	19	5.49	5.54	0.165	1158	16.39	70.7
16	20	5.80	5.78	0.593	4150	19.09	217.4
17	22	6.42	4.27	1.023	7159	17.28	414.4
18	24	6.50	4.95	0.800	5602	20.53	272.9
19	25	6.13	5.86	0.871	6098	21.62	282.1
20	26	7.60	4.18	1.007	7050	23.70	297.4
21	27	5.98	5.24	0.310	2173	18.40	118.1
22	28	6.37	5.13	0.475	3324	20.44	162.6
23	29	8.11	5.38	0.644	4508	34.74	129.8
24	30	6.04	4.87	0.365	2558	17.44	146.7
25	31	7.47	4.63	0.43	2989	25.36	117.8
26	33	6.39	3.70	0.71	4949	14.83	333.7
27	34	4.77	3.53	0.76	5285	7.89	670.2
28	35	5.68	4.76	0.52	3640	15.08	241.4
29	36	5.56	4.84	0.53	3724	14.69	253.5
30	37	5.67	4.78	0.49	3395	15.09	225.0
31	38	6.84	4.82	0.92	6405	22.14	289.3
32	39	6.82	5.22	0.95	6622	23.84	277.8
33	40	4.70	3.07	0.47	3269	6.66	491.0
34	41	5.50	6.12	0.52	3633	18.18	199.9
35	42	4.99	3.35	0.53	3703	8.19	452.2

Table 2. *Characteristics of anterior maxillary teeth. Basic statistics*

Variable	n	mean	std	min	median	max
Long axis [mm]	35	6.059	0.846	4.70	5.980	8.11
Short axis [mm]	35	4.684	0.927	3.02	4.840	6.12
Max force P [kN]	35	0.5322	0.2458	0.165	0.5143	1.023
Bending moment M [Nmm]	35	3725.2	1720.7	1157	3599.9	7159
Section modulus S [mm^3]	35	17.384	6.351	6.66	16.951	34.74
Bending stress σ [MPa]	35	233.72	126.79	63.3	217.43	670.2

Table 3. *Ceramic phantom characteristics*

Sample no.	Long axis of ellipse [mm]	Short axis of ellipse [mm]	Maximum force P [kN]	Bending moment M [Nmm]	Section modulus S [mm^3]	Bending stress σ [MPa]
5	6.30	4.21	0.780	5463	16.40	333.0
6	6.85	4.10	0.958	6709	18.89	355.2
Mean	6.575	4.15	0.869	6086	17.645	344

was 17.384 mm^3, while mean bending stress was 233.72 MPa. The force causing damage to ceramic teeth was 0.869, which is considerably higher comparing to natural teeth. However, the section modulus had almost the same mean value in both groups: 17.38 mm^3 for natural teeth and 17.64 mm^3 for ceramic teeth. Phantoms also had higher stress levels - 344 MPa (Table 3).

Tooth fractures occurred most frequently (in more than 30% of cases) within a force range of 240-720 N (Fig. 7). The bending moment, which describes the force in relation to area, varied from 2500 to 4000 N/mm in most cases (approximately 30%), (Fig. 8). Section modulus (S) was approximately 17 mm^3 in most cases (Fig. 9). The most frequent stress levels under loading were around 125-250 MPa (Fig. 10).

Four straight-line regression models were constructed, which are presented in figures 11, 12, 13, 14. Dependent variables included: maximum force (P), bending moment (M), section modulus (S), stress (σ). The independent variable was the long axis of the ellipse parallel to the loading force. Statistical analysis based on Pearson's correlation coefficient and t-Student test showed a stronger relationship of the damaging load with the length of the cross-section axis parallel to the loading force than with the length of the axis perpendicular to this force. The longer the axis of tooth cross-sections, parallel to the loading force, the higher is the force causing damage, bending moment, section modulus (S), and the smaller is the internal stress.

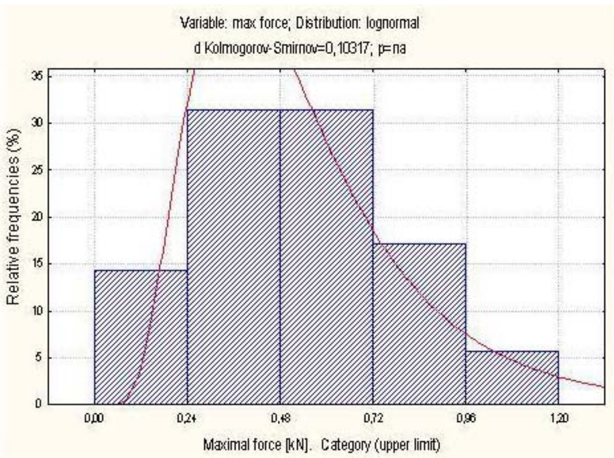

Fig. 7. *Distribution of frequencies. Maximum force [kN]*

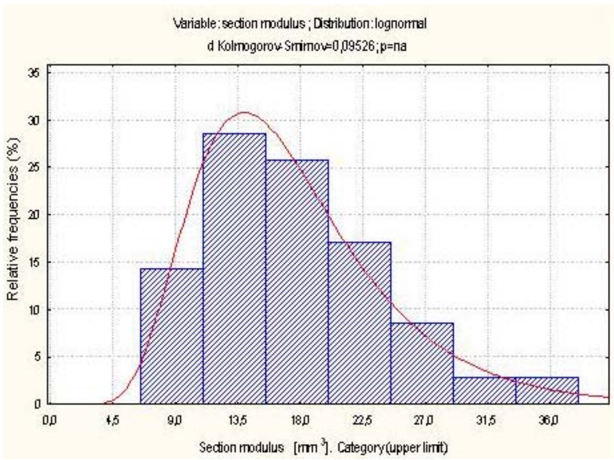

Fig. 9. *Distribution of frequencies. Section modulus S [mm^3]*

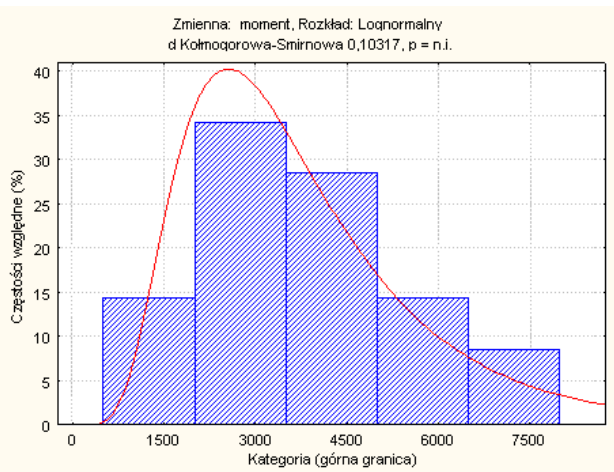

Fig. 8. *Distribution of frequencies. Bending moment [Nmm]*

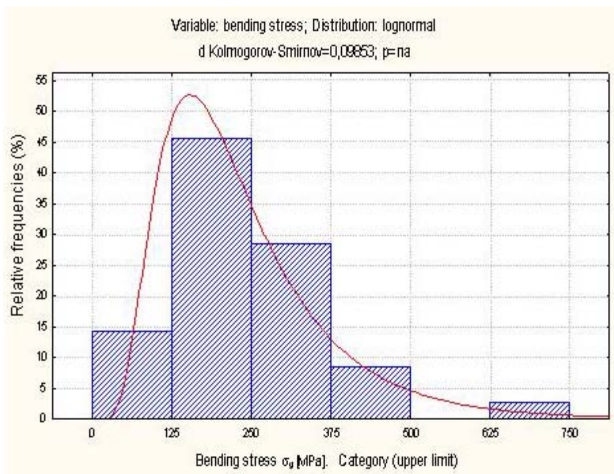

Fig. 10. *Distribution of frequencies. Bending stress σ [MPa]*

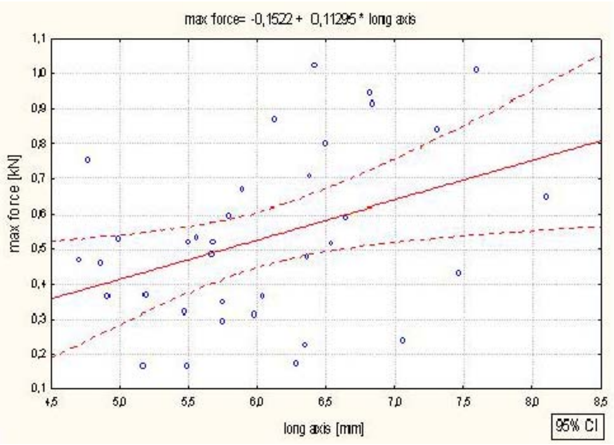

Fig. 11. *Relationship between the force causing fracture and the long axis length of teeth cross-section, parallel to the exerted force*

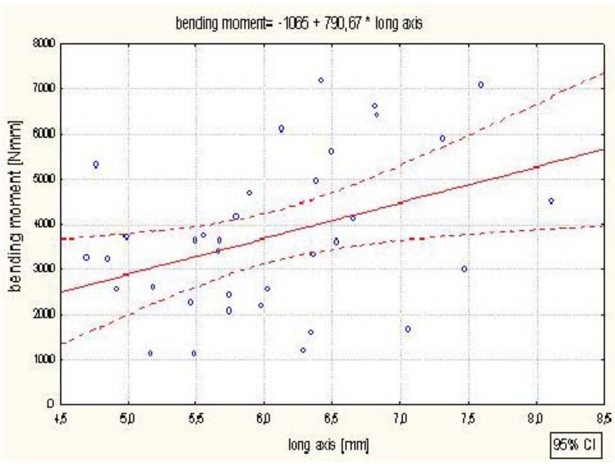

Fig. 12. *Relationship between the bending moment and the long axis length of teeth cross-section, parallel to the exerted force*

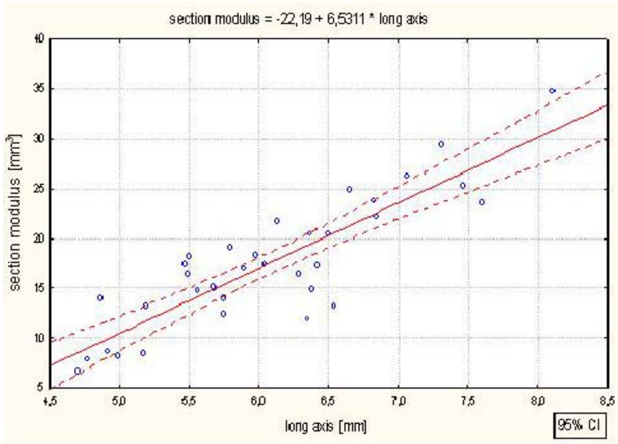

Fig. 13. *Relationship between the section modulus and the long axis length of teeth cross-section, parallel to the exerted force*

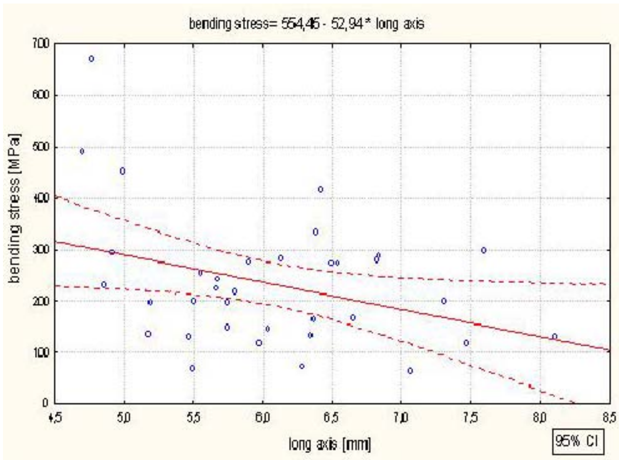

Fig.14. *Relationship between the bending stress and the long axis length of teeth cross-section, parallel to the exerted force*

Discussion with conclusions

The need to introduce preventive measures for sports-related injuries remains unquestionable. It is supported not only by mandatory regulations in some highly-developed countries [10],[11], but also by numerous literature reports on the high incidence of injuries suffered by people during sports activities [12],[13]. A survey conducted among sports trainers by Berg et al. [14] showed that 48% people practising sports who did not use mouthguards suffered injuries. In addition, Berg et al. assessed frequency of the most common injuries, which revealed that 14% of study participants reported tooth loss or fracture [14]. The frequency of tooth injuries among people practising winter sports reaches as much as 24.3% [15],[16]. More than 80% of injuries sustained during soccer games concerned teeth or the upper or lower alveolar process [17].

Analysis of injuries sustained during snowboarding performed in Turkey revealed that approximately 20% subjects suffered facial trauma, of which 2.3% were tooth injuries [18].

A large screening study performed in Rio de Janeiro in 2007, which included 409 athletes from 42 countries, showed the following sports disciplines to have the highest rates of head injuries: wrestling (83.3%), boxing (73.7%), basketball (70.6%) and karate (60%). Enamel fractures occurred in 21.9% of cases, enamel and dentin fractures in 20%, and tooth dislocation in another 9%. Injury rate for upper incisors was 56.5%, and 9.5% for lower incisors. Overall, 49.6% of study participants sustained oral injuries [4]. A similar study was conducted among German, Italian, Austrian and Swiss mountain bikers. Tooth injuries occurred in 5.7% of the 423 participants [19]. A very thorough study was also carried out in Norway, in which ice hockey was shown to be the discipline linked with the highest numbers of tooth injuries [20].

Research on sports-related injury prevention aims to develop standards for polymer materials used to manufacture mouthguards [21]-[23]. For these purposes, special models simulating natural anatomical conditions have been developed to test mechanichal strength of mouthguards [23]. However, it is difficult to determine the most desirable material properties unless values of forces causing tooth damage remain unknown. In 1967 Hodgson provided a simplified model, in which a force of 3000 N caused mandibular fracture, which can serve as reference [24]. Available studies on mechanical strength of hard tooth tissues were mostly conducted with the aim of improving restorative dental materials and usually estimated forces that cause damage to specific tooth tissues (enamel, dentin) and are axially applied to teeth [25], [26]. The most commonly assessed coefficient is K_{ic}, which describes brittle strength rather mechanical strength under dynamic loading. As a consequence, the main objective of the mentioned studies is to simulate loading during mastication and compare the strength of tooth tissues and restorative materials instead of estimating their resistance to injuries. Schatz et al. [27] are among authors who provided data on mechanical properties of teeth that are useful for assessing polymer materials with respect to manufacturing mouthguards. They compared strength of human teeth (incisors, canines and premolars) upon striking depending on the presence of cracks, abrasion, erosion, restorations and root length. A pendulum was used for measurements, and mechanical strength was compared between groups basing on percentile values. However, these studies are associated with high probability of observational errors due to questionable precision of energy absorption calculations, which results from large amounts of measurement data - mass, pendulum length and the great difficulty in reliably assessing the pendulum rebound angle after striking. Author's own study conducted with Instron system provides precise force values that cause damage to anterior maxillary teeth. In addition, teeth were embedded in acrylic bases, which have higher elasticity values (Young's modulus 2.4-3.1 GPa) compared to epoxy resin (Young's modulus up to 5.5 GPa) used by Schatz [27], providing closer resemblance to natural conditions in the present study. Instron system was also used by: Ehrnford and Fransson [6], who compared strength of teeth restored with cermet and composite resins; Potiket et al. [8], who assessed strength of teeth restored with a variety of ceramic systems; and Castelnuovo et al. [5], who assessed strength of ceramic restorations in relation to preparation methods. A study by Hernandez et al. [7] assessed strength of endodontically treated teeth restored with various adhesive systems and composite resins. The mean forces causing tooth damage depended on the restorative material: 104, 161, 151, 180, 175, 148 lbf (1 lbf = 4.448 N), i.e. 462-800 N, which is very similar to present study's results.

Other authors also have carried out experiments on the resistance of teeth restored with various materials to dynamic loading by a striking pendulum [28], [29]. Results from such studies tend to demonstrate that teeth are weakened after treatment, but do not provide data on maximum resistance to loading. In the previously cited study, Schatz et al. [27] reported that the highest shock absorption (E_a), which they defined as fracture resistance, was observed in maxillary canines (E_a = 1.26 J). According to their results, E_a for central maxillary incisors was 0.3 J, and 0.28 J for lateral maxillary incisors. However, these results cannot be compared to those from the present study as it involved measuring force expressed in Newtons, as opposed to energy expressed in Joules in the former study.

Strength values for dental ceramics are comparable to those from other studies. IPS Empress 2 samples examined by Nakamura et al. [30] showed mean stress values of 329 MPa, while study by Dejak et al. [31] reported a value range of 329 - 400 MPa.

It is worth noting that the fundamental objective of the present study was to estimate forces causing damage to hard tooth tissues, which constitute the lower limit of force reduction range by mouthguards. This will allow to develop qualitative standards for materials used in various mouthguard manufacturing methods. Materials incapable of absorbing the aforementioned forces should not be used in preventing sports-related injuries. The section modulus of mouthguard materials should be higher than the mean section modulus of teeth obtained in the study. In addition, experiments with ceramic phantoms, in which damage occurred under higher forces than in natural teeth, confirmed the fragility of natural teeth, their susceptibility to fracture and the need to take preventative measures during sports activities.

The study revealed that anterior maxillary teeth have low strength to forces applied perpendicular to their labial surface. They are damaged under a mean loading force of 532 N. Teeth with small bucco-lingual dimensions were especially susceptible to injury. People with smaller teeth should use mouthguards, which significantly reduce forces during impact [32], [33].

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ANALIZA MECHANICZNEJ WYTRZYMAŁOŚCI ZĘBÓW LUDZKICH W ASPEKCIE PROFILAKTYKI OBRAŻEŃ SPORTOWYCH

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Streszczenie

Wstęp: Uprawianie różnych form aktywności ruchowej jest korzystne dla fizycznego i psychicznego rozwoju organizmu. Obecnie coraz częściej są jednak rozpowszechniane dyscypliny nadmiernie kontaktowe i ekstremalne, których uprawianie niesie ryzyko odniesienia obrażeń. Szczególnie niebezpieczne są skutki urazów doznawanych w obrębie twarzy i jamy ustnej. Istotne jest w związku z tym określenie wytrzymałości mechanicznej zębów obciążanych siłą skierowaną w taki sposób, w jaki najczęściej dochodzi do urazu – prostopadle do ich długiej osi, w dążeniu do zaplanowania odpowiedniej profilaktyki, zapobiegającej siłom powodującym uszkodzenie struktur twardych tkanek zębów.

Materiał i metody: Materiał do badań stanowiło 40 fantomów składających się z ludzkich zębów siecznych i kłów, które poddawane były obciążeniu z zastosowaniem urządzenia Instron, aż do zniszczenia.

Wyniki: Średnia wartość siły powodującej trwałe uszkodzenie zębów ludzkich wyniosła 0,5322 kN. Analiza statystyczna oparta o współczynnik korelacji Pearsona i test t-Studenta wykazała, że wraz ze wzrostem długości osi przekrojów poprzecznych zębów, równoległych do działającego obciążenia, wzrasta wartość siły powodującej ich zniszczenie, momentu gnącego, wskaźnika S, a maleje powstające w ich strukturze naprężenie.

Wnioski: W toku przeprowadzonych badań stwierdzono, że zęby ludzkie przedniego odcinka szczęki wykazują małą wytrzymałość wobec siły skierowanej prostopadle do powierzchni wargowej. Szczególnie narażone na uraz są zęby o małym wymiarze wargowo- podniebiennym. Konieczne jest więc propagowanie użytkowania ochraniaczy wewnątrzustnych, których wytrzymałość mechaniczna jest większa od siły uszkadzającej struktury zębów. Sportowcy posiadający drobne zęby powinni użytkować ochraniacze o wysokiej pochłanialności energii.

***Słowa kluczowe**: urazy zębów i części twarzowej czaszki, ochraniacze jamy ustnej, sport.*

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