Izrada trodimenzionalnoga modela zuba za eksperimentalna biomehanička istraživanja metodom konačnih elemenata

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Sažetak

Problemi s proučavanjem odgovora zuba na djelovanje sustava sila mnogo su složeniji i teže ih rješavamo od jednostavnog mjerenja same sile.

Svrha je ovoga istraživanja razraditi vlastitu metodu trodimenzionalne digitalizacije zuba kako bi se što vjernije mogao izraditi njegov matematički model. Izraditi vlastiti trodimenzionalni matematički model zuba s pripadajućim potpornim strukturama u svrhu biomehaničkih istraživanja metodom konačnih elemenata. Kao predložak za izradu matematičkog modela poslužio je gornji očnjak izvađen zbog parodontoloških razloga. Dobiven je trodimenzionalni matematički model gornjeg očnjaka koji se sastoji od 4000 elemenata oblika heksaedra i 2367 čvorova, što čini ukupno 7101 stupanj slobode cijelog modela. Periodontni ligament izmodeliran je cijelom dužinom korijena u širini od 0,25 mm. Sloj kompakte izmodeliran je u debljini od 2 mm. Zbog mogućnosti simulacije raznih položaja zubi, različite visine alveolarne kosti i terapijske situacije u kojima je izvršena ekstrakcija zubi, očekivati je da će se ova metoda u budućnosti još šire primjenjivati.

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Ortodontska terapija temelji se na primjeni raznih naprava kojima je zadaća stvoriti silu koja će prouzročiti pomake i zubi i čeljusti.

Problemi povezani s proučavanjem odgovora zuba na djelovanje sustava sila mnogo su složeniji i teže ih rješavamo od jednostavnoga mjerenja same sile. Razine proučavanja reakcije zuba na apliciranu silu mogu biti: klinička, stanična, biokemijska, deformacija i naprezanje. Na kliničkoj razini mogu se proučavati veličina pomaka zuba, bol, pomičnost zuba, gubitak alveolarne kosti i resorpcija korijena. Stanična i biokemijska razina daju pregled dinamike promjena unutar potpornog aparata zuba, kosti i periodontnoga ligamenta. Ipak vrlo je važno razumjeti i prijenos sile i naprezanja unutar periodontnoga ligamenta. Veličina naprezanja može se precizno odrediti u raznim područjima ovoga tkiva te može pružiti dobru prigodu za određivanje povezanosti aplicirane sile na zub i njegove reakcije (1). Kako nije moguće unutar periodontnoga ligamenta ugraditi mjerne instrumente koji bi mjerili distribuciju sile i naprezanja, naša znanja o tome dobivamo iz drugih izvora. Tako, primjerice, možemo izraditi matematički model zuba i okolnoga tkiva, na kojem smo u mogućnosti s relativno velikom točnošću i preciznošću simulirati aplikacije ortodontskih sila te proučavati odgovor zuba i potpornih struktura na njih. Svakako valja napomenuti da je takve izračune što je više moguće potrebno provjeriti u kliničkim ispitivanjima.

Budući da još uvijek ne poznajemo dovoljno veličine, smjer i distribuciju sila koje se primjenjuju u ortodonciji, te ne znamo dovoljno o njihovu učinku na zub i okolne strukture, svrha ovog istraživanja je:

- razraditi vlastitu metodu trodimenzionalne digitalizacije zuba kako bi se što vjernije mogao izraditi matematički model zuba,
- izraditi vlastiti trodimenzionalni matematički model zuba s pripadajućim potpornim strukturama u svrhu biomehaničkih istraživanja metodom konačnih elemenata.

Uzorak i postupci

Kao predložak za izradu matematičkog modela poslužio je gornji očnjak izvađen zbog parodontoloških razloga. Dobro očišćen zub uložen je u prozirni akrilat. Paralelometar-frezom (Combilabor CL- MF, Hereaus- Hanau) brušeni su slojevi debljine 0,5 mm okomito na uzdužnu osovinu zuba. Svaki dobiveni presjek snimljen je videokamerom Sony CCD TRV 825 E Hi 8 mm. Snimke su digitalizirane u programu ISSA koji je izradila tvrtka VAMS u suradnji sa Stomatološkim fakultetom Sveučilišta u Zagrebu. Kamera je povezana s računalom (PC Pentium II 64 Mb RAM, 350 MHz, 8,4 Gb HDD) preko S-VHS kabela, a za digitalizaciju slike upotrebljen je frame grabber - videoadapter (Ima Scan, rezolucije 1024x768 u PAL formatu sa 625 vodoravnih linija i 16Mb videomemorije). Definirano je ukupno šezdeset poprečnih presjeka zuba koji su zapisani u slikovnom BMP formatu. Tako definirane konture poprečnoga presjeka zuba učitane su u CAD program AutoCAD Mechanical Deskop 2,0, gdje je iz krivulja poprečnoga presjeka zuba definirana trodimenzionalna geometrija postupkom "loftinga". Crteži su prevedeni u standardni IGES format čime je osigurana njihova čitljivost u raznim CAD aplikacijama, uključujući i program NISA kojim je proveden proračun metodom konačnih elemenata. U programu NISA, iz crteža u IGES formatu definirana je geometrija zuba. Nastavljeno je s definiranjem mreže konačnih elemenata. Ovdje se vodilo računa o kompatibilnosti mreže pojedinih segmenata, jer svako nepoštivanje te kompatibilnosti može prouzročiti numeričke pogrješke. Zbog takovih pogrešaka ne bi bilo moguće provesti proračun. Svakom od segmenata dodijeljen je odgovarajući izotropni materijalni model, što je prikazano u Tablici 1.

Tablica 1. *Vrijednosti Youngova modula i Poissonova koeficijenta upotrijebljene pri izradi modela*

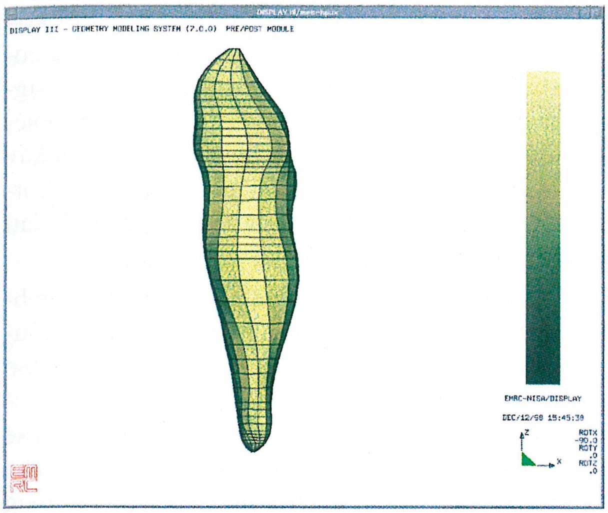
Table 1. *Values of Young's modulus and Poisson's coefficient used during the construction of the model*

	Youngov modul Young's modulus	Poissonov koeficijent Poisson's coefficient
Spongiozna kost Spongiosa/Spongy bone	$0.5 \times 10^9 Nm^{-2}$	0.3
Kortikalna kost Cortical bone	$13.7 \times 10^9 Nm^{-2}$	0.3
PDL	$5 \times 10^6 Nm^{-2}$	0.45
Zub Tooth	$19.6 \times 10^9 Nm^{-2}$	0.3

Za modeliranje su rabljeni trodimenzionalni elementi oblika heksaedra sa šest čvorova i tri stupnja slobode po čvoru (pomaci u pravcu tri međusobno okomite osi). Na taj način dobiven je trodimenzionalni matematički model gornjeg očnjaka. Modelu gornjeg očnjaka dodan je periodontni ligament cijelom dužinom korijena u širini od 0,25 mm. Zatim je izmodelirana potporna kost. Sloj kompakte izmodeliran je u debljini od 2 mm, a ispod njega spongioza. Sav model čini 4000 elemenata oblika heksaedra i 2367 čvorova, što čini ukupno 7101 stupanj slobode cijeloga modela.

Rezultati i rasprava

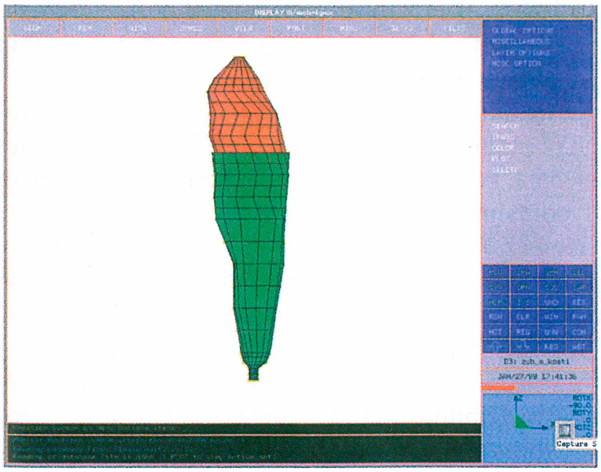
Rezultat istraživanja trodimenzionalni je model zuba prikazan na Slikama 1-4.



Slika 1. *Projekcija matematičkog modela gornjeg očnjaka*

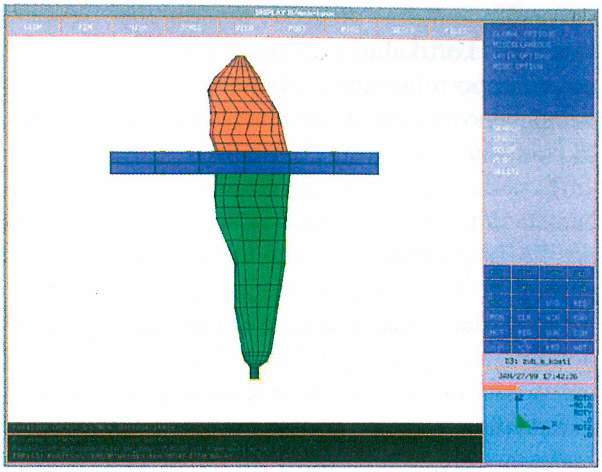
Figure 1. *Projection of the mathematical model of the upper canine.*

Slika 1 prikazuje matematički model gornjeg očnjaka za čije su modeliranje uporabljeni elementi oblika heksaedra s po šest čvorova i tri stupnja slobode po čvoru. Tako izrađenome modelu dodan je periodontni ligament cijelom dužinom korijena u širini od 0,25 mm, što je prikazano na Slici 2. Sloj kompakte izmodeliran je u debljini od 2 mm (Slika 3). Ispod sloja kompaktne kosti izmodelirana je spongiozna (Slika 4). Na taj način dobiven je model koji se sastoji od 4000 elemenata oblika heksaedra i 2367 čvorova, s ukupno 7101 stupnjem slobode.



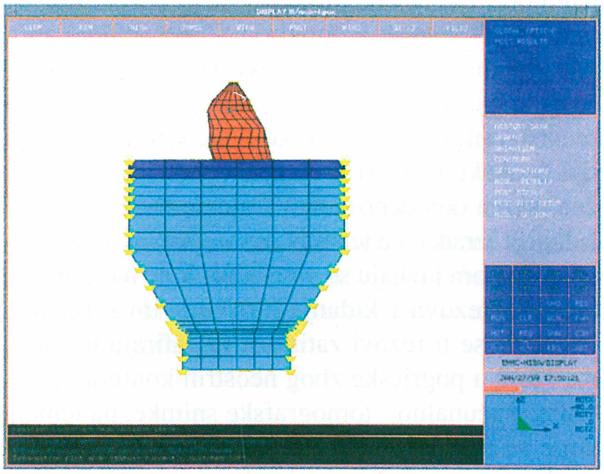
Slika 2. *Projekcija matematičkog modela gornjeg očnjaka s periodontnim ligamentom.*

Figure 2. *Projection of the mathematical model of the upper canine with periodontal ligament.*



Slika 3. *Projekcija matematičkog modela gornjeg očnjaka s periodontnim ligamentom i slojem kompaktne kosti*

Figure 3. *Projection of the mathematical model of the upper canine with periodontal ligament and a layer of compact bone*



Slika 4. *Projekcija matematičkog modela gornjeg očnjaka s periodontnim ligamentom i pripadajućom kompaktnom i spongioznom kosti.*

Figure 4. *Projection of the mathematical model of the upper canine with periodontal ligament and accompanying compact and spongiosa/spongy bone*

Računalni programski paket NISA poslužio je na tako dobivenom trodimenzionalnom modelu gornjeg očnjaka bez pripadajućih potpornih struktura započkusne raščlambe pomaka zuba, deformacija, intenziteta naprezanja, te su izračunana ekvivalentna naprezanja po energetskoj teoriji čvrstoće (Huber- Mises- Hencky teorija).

Budući da se je model zuba u pokusnim eksperimentima pokazao dobrim i odgovarajućim, dodatno su izmodelirane potporne strukture (periodontni ligament, kortikalna i spongiozna kost). Model je učvršćen po rubovima spongioze čime je osigurana nemogućnost pomaka modela kao krutoga tijela koja bi izazvala numeričke singularitete (pogrješke).

U poduzetom se istraživanju osobito vodilo računa o činjenici da rezultati istraživanja, koje će biti poslije provedeno metodom konačnih elemenata, u prvome redu ovise prije svega o načinu kako se je dobio model. Zbog toga je izrada modela ključni trenutak svakoga kasnijeg istraživanja. Navlastito je važno napomenuti na koji se je način došlo do izvora podataka na temelju kojih je model izrađen. Izvor podataka bile su već prije znane dimenzije iz literature, a razmišljalo se i o rezovima preparata (u konkretnom slučaju zuba), ili pak o serijskim računalnim tomografskim snimkama, za što postoji dosta podataka i u recentnoj literaturi (2-16). Problem koji se javlja kada se model izrađuje na temelju kompilata podataka iz literature jest mogućnost nastanka pogrješaka koje se kumuliraju. Zbog velike varijacije pojedinih parametara, tako izrađen model može na kraju ispasti nesuvislo i nelogično. Zato je odabran sigurniji i precizniji, kompliciraniji i dugotrajniji, svakako i znanstveniji pristup, pa je model izrađen prema određenom preparatu, zubu. Kod modela koji je izrađen na temelju rezova napravljenih kriomikrotomom javljaju se netočnosti koje nastaju zbog neoštrih rezova i kidanja na njihovim rubovima. Najčešće se ti rezovi zatim fotografiraju te i u tome nastaju pogrješke zbog neoštrih kontura i povećanja. Računalno - tomografske snimke, na temelju kojih se također može izraditi matematički model, ne daju ispravne dimenzije zbog pogrešaka u rubnim uvjetima. Kakvoća računalno- tomografskih snimaka ovisi i o fotografskom aparatu i njegovoj rezoluciji. Nastale razlike mogu biti bitne za određivanje tako malih debljina kosti i tako maloga prostora kao što je periodontna pukotina. Ni jedan način izrade modela nije apsolutno precizan i točan, no cilj je što više se približiti izvorniku (digitalizirati ga). U poduzetom je istraživanju trebalo naći način kako jedan izvađeni očnjak vjerno prenijeti u računalo. Snimanjem videokamerom i digitalizacijom te slike moguće je unijeti jednu ili više slika toga zuba ili nekoga sličnog objekta u nekom od poznatih formata za pohranu slike (TIF, GIF, JPEG, PCX, BMP). No to ne rješava problem unosa treće dimenzije. Kao što je već spomenuto, kamera kojom smo se služili visoke je rezolucije. Kao i kod svih analognih kamera ovdje CCD chip (charge coupled device) služi za registraciju svjetla, ali je signal koje se upućuje prema računalu analogan (obično VHS ili još bolje sVHS signal). Da bi se takav analogni signal pretvorio u jedan od digitalnih formata potrebno je između kamere i računala dodati uređaj koji će analogni signal digitalizirati.

U konkretnom slučaju primijenjen je frame grabber (videoadapter, digitalizator) vrlo visoke rezolucije, jer prijašnji pokusi s jeftinijim, komercijalno široko dostupnim karticama nisu dali dovoljno oštru sliku. Uporabom digitalnih kamera izbjegla bi se primjena frame grabbera i kompliciranog softwarea za konverziju analognog u digitalni signal, ali zbog lošijeg kontrasta koji takve kamere mogu postići detalji nisu bili dovoljno vidljivi da bi se u njih moglo pouzdati.Trodimenzionalno skeniranje dalo bi dobre rezultate, sigurno se može ustvrditi i najbolje. No nama raspoloživ skener nije imao dovoljno dobru rezoluciju. Kako posljednjih godinu dana i trodimenzionalni skeneri vrlo visoke rezolucije postaju mnogo dostupniji, vjerojatno će u sljedećim istraživanjima to biti metoda izbora.

Treba ipak spomenuti kako vlastita primijenjena metoda ima i drugih prednosti. Rezanjem zuba ili neke slične strukture u tanke slojeve i njihovom digitalizacijom moguće je, osim vanjskog oblika, trodimenzionalno prikazati i unutarnju strukturu, primjerice: pulpnu komoru, korijenske kanale, rubove ili stijenke ispuna, kaviteta ili slično.

Izrada matematičkog modela uz primjenu metode konačnih elemenata, moguća je uz pomoć raznih računalnih programa koji se između sebe više ili manje razlikuju. Razlikuju se u matematičkom pristupu obradbi podataka, prema oblicima konačnih elemenata, koji mogu biti jednodimenzionalni (točka), dvodimenzionalni (crta) ili trodimenzionalni. Takvi elementi mogu imati ravne ili zakrivljene stranice, a broj čvorova varira ovisno o obliku geometrijskog tijela. Čvorovi se mogu nalaziti u kutovima i polovicama stranica prostornog elementa, ali i u njegovu volumenu. Rezultat istraživanja ovisi o navedenoj varijabilnosti oblika konačnih elemenata i broja čvorova. Simulacija sila određenih smjerova, veličina i mjesto aplikacije na takav matematski model rezultirat će deformacijom modela, odnosno pomakom čvorova. Taj pomak može nastati na razne načine i imati različite smjerove, što ovisi o broju stupnjeva slobode koji takav model dopušta. U trodimenzionalnome modelu linearni pomaci čvorova mogu biti definirani ortogonalnim kartezijskim koordinatnim sustavom (x,y,z osi), kao i rotacijom oko svih triju koordinatnih osi. Već ta činjenica potvrđuje kako se kod na taj način složenih struktura i konstrukcija, kao što je to stomatognati sustav, najbolje može primijeniti metoda konačnih elemenata s trodimenzionalnim sustavom elemenata, pri čemu elementi međusobno nisu pravilnog i jednakog oblika, niti imaju jednaki broj čvorova. Pri tome, od strukture do strukture, odnosno od elementa do elementa, variraju i moduli elastičnosti i Poissonovi koeficijenti. Naime, druge metode, između kojih je i fotoelasticimetrija (17-21), ne mogu biti adekvatno primijenjene u ortodonciji, jer ne razlikuju pojedine biološke strukture i međusobne razlike u njihovim mehaničkim svojstvima (caklina, dentin, pulpa, periodontni ligament, kompaktna i spongiozna kost). Također je teško izraditi fotoelastični model koji oblikom odgovara anatomiji stomatognatog sustava. Isto tako i metoda kojom se mjere deformacije s pomoću otporskih mjernih traka (tenzimetrija) (22) provodi se na modelu koji čini anatomski preparat (najčešće lubanja), pri čemu se mjere plošne deformacije u onim točkama na kojima su trake zalijepljene. Ovdje se najčešće upotrebljavaju suhe macerirane lubanje, jer se na njih najlakše mogu zalijepiti otporske trake. Ta metoda dobra je za mjerenje sila koje nastaju aplikacijom određenih ortodontskih naprava na samim napravama. Jasno je kako ni ta metoda ne može analizirati kompleksnost istovremenog djelovanja svih struktura. Takvim postupkom ne bi bilo moguće registrirati pomake zuba okruženog periodontnim ligamentom niti naprezanja i deformacije na udaljenijim strukturama.

Metoda holografske interferometrije (23-36) s dvostrukom ekspozicijom, ili u realnom vremenu, može se primijeniti na model bilo koje strukture, uključujući i kosti i zube, a može se primijeniti i na živu čovjeku kako bi se pri zagrizu registrirao pomak vidljivih zuba. Moguće je registrirati samo ono prostim okom vidljivo, pa se dobiju podatci samo o površini a ne i dubini analizirane strukture.

Pomak zuba pri zagrizu, u sve tri dimenzije, može se izmjeriti i primjenom stereofotogrametrije (37) koja, kao i holografska interferometrija, ima svoje dobre strane u primjeni u stomatološkim istraživanjima, ali sa sličnim ograničenjima.

Za razliku od svih drugih spomenutih i komentiranih metoda, jednom napravljen matematički model konačnih elemenata omogućuje u računalu beskonačan broj promjena oblika pojedinih elemenata i struktura, ali također i bezbroj simulacija aplikacije sila. Rezultat toga su razne mogućnosti deformacija sustava i rasporeda naprezanja unutar takvih struktura. To je i konačni cilj ovakvih istraživanja. Konačna je želja svakog ortodonta kliničara, zbog kojih se ovakva istraživanja i provode, u takav model u praktičnoj primjeni unijeti individualne podatke određenog pacijenta. Na tome bi se onda simulirale razne mogućnosti ortodontskih terapijskih postupaka. Na taj bi se način tim postupkom moglo predvidjeti tijek i rezultate ortodontske terapije, te odabrati najprikladniji terapijski postupak. Pravi cilj toga dijela istraživanja jest metodom konačnih elemenata načiniti takav matematski model koji može biti pogodan za primjenu u ortodonciji, ali ne samo za jedno istraživanje s jasno definiranom svrhom i ciljem nego i poslije primjenjiv na druga istraživanja. I to ne samo u ortodonciji. Na njemu je moguće simulirati razne položaje zubi, različite visine alveolarne kosti i terapijske situacije u kojima je izvršena ekstrakcija zubi. Također je moguće simulirati distribuciju sila i naprezanja koja nastaju tom prigodom, djelovanjem same ortodontske naprave i izmijenjenog položaja zuba. Zbog toga je za očekivati da će se ova metoda u budućnosti još šire primjenjivati.

Literatura

1. DAVIDOVITCH Z. Biologie der Zahnbewegung. U: Schmuth G P F, Vardimon A D. ur. Kieferorthopädie. Stuttgart-New York: Thieme, 1994: 175-183.
2. RICKS-WILLIAMSON LJ, FOTOS PG, GOEL VK, SPIREY JD, RIVERA EM, KHERA S C. A three-dimensional finite element stress analysis of an endodontically prepared maxillary central incisor. J Endod 1995; 21:362-367.
3. MEIJER H JA, STARMANS FJM, BOSMAN F, STEEN WHA. A comparisson of three finite element models of an edentulous mandible provided with implants. J Oral Rehabil 1993; 20:147- 157.
4. ATMARAM G H, MOHAMMED H. Estimation of Physiologic Stresses with a Natural Tooth Considering Fibrous PDL Structure. J Dent Res 1981; 60:873- 877.
5. RUBIN C, KRISHNAMURTHY N, CAPILOUTO E. Stress analysis of the human tooth using a three dimensional finite element model. J Dent Res 1983;62:82- 86.

6. TANNE K, SAKUDA M, BURSTONE CJ. Three- dimensional finite element analysis for stress in the periodontal tissue by orthodontic forces. Am J Orthod Dentofac Orthop 1987; 92:499-505.
7. Mc GUINNESS N, WILSON AN, JONES M, MIDDLETON J, ROBERTSON NR. Stresses induced by edgewise appliances in the periodontal ligament- a finite element study. Angle Orthod 1992; 62:15-22.
8. WILSON A N, MIDDLETON J, MC GUINNESS N, JONES M. A finite element study of canine retraction with a palatal spring. Br J Orthod 1991; 18:211-218.
9. ANDERSEN K L, PEDERSEN EH, MELSEN B. Material parameters and stress profiles within the periodontal ligament. Am J Orthod Dentofac Orthop 1991; 99:427-440.
10. TANNE K, SHIBAGUCHI T, TERADA Y, KATO J, SAKUDA M. Stress levels in the PDL and biological tooth movement u: Davidovitch Z. The biological mechanismus of tooth movement and craniofacial adaptation. The Ohio State University College of Dentistry, Columbus, Ohio, USA, 1992: 201-209.
11. DARENDELILER S, DARENDELILER H, KINOGLU T. Analysis of a central maxillary incisor by using a three-dimensional finite element method. J Oral Rehabil 1992; 19:371-383.
12. JOST-BRINKMAN PG, TANNE K, SAKUDA M, MIETHKE RR. FEM Studie zum biomechanischen Vergleich von labialem und palatinalem Kraftangriff an oberen Incisivi. Fortschr Kieferorthop 1993; 54:76-82.
13. COBO J, SICILIA A, ARRGUELLES J, SUAREZ D, VIJANDE M. Initial sstress induced in periodontal tissue with diverse degrees of bone loss by an orthodontic force: Trodimensional analysis by means of the finite element method, Am J Orthod Dentofac Orthop 1993; 104:448-454.
14. BRASSE M, TANNE K, MATSUBARA S, SAKUDA M, BRUMANN A. Biomechanische Auswirkung eines Headgears auf Suturen des Viszerocraniums. IOK 1996; 28:253-261.
15. KORIOTH TWP, HANNAM AG. Deformation of the human mandible during simulated tooth clenching. J Dent Res 1994; 73:56-66.
16. KORIOTH TWP, ROMILLY DP, HANNAM AG. Three-dimensional finite element stress analysis of the dentate human mandible. Am J Phys Anthropol 1992; 88:69- 96.
17. ISERI H, ERMAN TEKKAYA A, ÖZTAN Ö, BILGIC A. Biomechanical effects of rapid maxillary expansion on the craniofacial skeleton, studied by the finite element method. Eur J Orthod 1998; 20:347-356.
18. ŠLAJ M, MENIGA A, PLANČAK D. Raspodjela sila aktivnih ploča utvrđena elektrootporničkim davačima. Acta Stomatol Croat 1992; 26:109-116.
19. ŠLAJ M, LAPTER M, RAJIĆ MEŠTROVIĆ S. Raspodjela sila aktivnih ploča s ugrađenim lepezastim Paganijevim vijkom. Acta Stomatol Croat 1998; 32:49-53.
20. STANFORD JW, WEIGEL KV, PAFFENBARGER GC, SWEENEY WT. Compressive properties of hard tooth tissues and some restorative material. J Am Dent Assoc 1960; 60:746-756.
21. ASSIF D, OREN E, MARSHAK BL. Photoelastic analysis of stress transfer by endodontically treated teeth to the supporting structure using different restorative techniques. J Prosthet Dent 1989; 61:535-543.
22. MATTISON G D. Photoelastic stress analysis of cast- gold endodontic posts. J Prosthet Dent 1982; 48:407-411.
23. NAKANISHI Y. Effects of headgeartraction on the human facial skeleton: a study with strain gauges. J Osaka Dent Univ 1973;7:7-30.
24. CAPUTO AA, CHACONAS SJ, HAYASHI RK. Photoelastic visualization of orthodontic forces during canine retraction. Am J Orthod 1974; 65:250-259.
25. CHACONAS SJ, CAPUTO AA, DAVIS JC. The effects of orthopedic forces on the craniofacial complex utilizing cervical and parietal headgear appliances. Am J Orthod 1976; 69:527.
26. CHACONAS SJ, CAPUTO A A. Observation of orthopedic force distribution produced by maxillary orthodontic appliances. Am J Orthod 1982; 82:492.
27. RALPH W J, WILLIAMS J F. Analysis of stresses in alveolar bona-a two dimensional photoelastic model. Arch Oral Biol 1975; 20:411.
28. RAJIĆ Z. Primjena holografske interferometrije u određivanju biomehaničkih svojstava pojedinih krutih dijelova žvačnog aparata. Zagreb: Sveučilište u Zagrebu 1976. Disertacija.
29. PICHLER G, VUKIČEVIĆ D, RAJIĆ Z. Preliminarna holografska mjerenja deformacija zubi. Acta Stomatol Croat 1972/73; 7:68-71.
30. BURSTONE CJ, PRYPUTNIEWITCZ RJ. Holographic determination of centres of rotation produced by orthodontic forces. Am J Orthod 1980; 77:396-408.
31. BURSTONE CJ, PRYPUTNIEWICZ RJ, BOWLEY WW. Holographic measurement of tooth mobility in three dimensions. J Periodont Res 1978; 13:283-294.
32. BURSTONE CJ, EVERY TW, PRYPUTNIEVICZ RJ. Holographic measurement of incisor extrusion. Am J Orthod 1982; 82:1-9.
33. VUKIČEVIĆ S, PAVLIN D, VUKIČEVIĆ D, ŠTERN PADOVAN R, ŠKRINJARIĆ I. Recent advances in holographic investigations of the human skeleton- Investigations of the endocranium. Coll Anthropol 1980; 4:95- 98.
34. PAVLIN D, VUKIČEVIĆ D. Mechanical reactions of facial skeleton to maxillary expansion deterined by laser holography. Am J Orthod 1984;85:498-507.
35. EVANS FG. Methods of studing biomechanical significance of bone form. Am J Phys Anthrop 1953; 11:413.
36. FUCHS P, SCHOTT D. The application of holography to the measurment of deformatioon of human facial bones. Dtsch Zahnärztl Z 1973; 28:90.
37. HEWITT AB. An investigation using holographic interferometry of surface strain in bone induced by orthodontic forces: A preliminary report. Brit J Orthod 1976; 4:39-41.
38. JORGIĆ SRDJAK K. Doprinos biomehaničkom istraživanju resorptivnih procesa potpornih struktura parodonta. Zagreb: Sveučilište u Zagrebu 1986. Disertacija.

Construction of a Three-Dimensional Model of Teeth for Experimental Biomechanical Investigation by the Method of Finite Elements

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Summary

Problems connected with the study of the response of the tooth to the effect of system forces are much more complex and difficult to solve than simple measurement of the forces themselves. The aim of this investigation was to develop a method for three-dimensional digitalization of teeth in order to produce a reliable mathematical model of a tooth. The construction of a three-dimensional mathematical model of a tooth with accompanying supporting structures for biomechanical investigations by the method of finite elements. An upper canine, extracted for parodontal reasons, served as the sample for construction of the mathematical model. A three-dimensional mathematical model of the upper canine was obtained, comprising 4000 elements of hexadic form and 2367 nodes, with a total of 7101 degrees of freedom for the whole model. The periodontal ligament was modelled for the whole length of the root, 0.25 mm in width. The layer of compact was modelled at a depth of 2 mm. It is anticipated that this method will be widely applied in the future, because of the possibility of simulating different positions of the tooth, and different heights of the alveolar bone and therapeutic situations in which teeth extractions are performed.

Key words: *biomechanical investigation, stomatognathic system*

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Orthodontic therapy is based on the application of different appliances, which are used to create force in order to induce movement, both of the teeth and jaws.

Problems connected with studying the responses of teeth to the effect of a system of forces are much more complex and difficult to solve than simple measuring of the force itself. The levels of studying the reaction of teeth to the applied force can be clinical, cellular, biochemical, deformation and stress. At the clinical level it is possible to study the extent of tooth movement, pain, tooth mobility, loss of alveolar bone and root resorption. The cellular and biochemical levels give information on the dynamics of change within the supporting apparatus of the teeth, bone and periodontal ligament. However, it is very important to understand the transfer of force and stress within the periodontal ligament. The extent of stress can be precisely determined in different areas of this tissue, and can offer a good opportunity to determine the correlation between the applied force to the tooth and its reaction (1). As it is impossible to incorporate measuring instruments within the periodontal ligament which would measure the distribution of force and stress, our knowledge is therefore obtained from other sources. For example, we can construct a mathematical model of the tooth and surrounding tissue, on which it is possible, relatively accurately, to simulate application of orthodontic forces and to study the response of the tooth and supporting structures. It should also be stressed that such calculations, whenever possible, should be checked in clinical investigations.

As the extent, direction and distribution of forces applied in orthodontics are still unknown and there is still insufficient knowledge of their effect on the tooth and surrounding structure, the object of this investigation was to:

- develop a method of three-dimensional digitalization of teeth in order to construct a reliable mathematical model of teeth.
- construct a three-dimensional mathematical model of teeth with relevant supporting structures for biomechanical investigations by the method of finite elements.

Material and methods

An upper canine, extracted for parodontal reasons, served as the sample for construction of a mathematical model. The tooth was cleaned and placed in clear acrylic. A paralelometar - freezer (Combilabor CL- MF, Hereaus- Hanau) was used to grind layers, 0.5 mm thick, vertically on the longitudinal axis of the tooth. Each section obtained was recorded by a video camera Sony CCD TRV 825 E Hi 8 mm. The pictures were digitalized in a ISSA programme which was developed by the firm VAMS in cooperation with the School of Dental Medicine University of Zagreb. The camera was connected to a computer (PC Pentium II 64 Mb RAM, 350 MHz, 8.4 Gb HDD) via S-VHS cable, and a frame grabber - video adapter used for digitalization of the picture (Ima Scan, resolution 1024x768 in PAL format with 625 horizontal lines and 16Mb video memory). Sixty cross-sections of the tooth were defined and recorded in pictorial BMP format. These defined contours of a cross-section of the tooth were entered into the CAD programme AutoCAD Mechanical Desktop 2.0, where three-dimensional geometry was defined from the curve of the cross-section tooth cut by "lofting" procedure. The drawings were translated into standard IGES format which ensured their readability in different CAD applications, including the NISA programme, with which calculation was performed by the method of finite elements. Tooth geometry was defined from the drawings in IGES in the NIS programme and definition of a network of finite elements was continued. Care was taken with regard to the compatibility of the network for individual segments, because any disregard for this compatibility can lead to numerical errors, and such errors would make it impossible to complete the estimate. Each of the segments was provided with a relevant isotropic material model as shown in Table 1.

Three-dimensional elements of hexadic form were used for the modelling, with six nodes and three degrees of freedom for each node (movements in the direction of three mutually vertical axes). In this manner a three-dimensional mathematical model of an upper canine was obtained. A periodontal ligament was added to the model of the upper canine for the whole length of the root, 0.25 mm in width, and supporting bone was then modelled. The layer of compact was modelled 2 mm thick and beneath it spongiosa. The whole model consists of 4000 elements of hexadic form and 2367 nodes, making a total of 7101 degrees of freedom for the whole model.

Results and discussion

The result of the investigation is a three-dimensional model of a tooth, presented in Figs. 1-4. Fig. 1 shows a mathematical model of an upper canine, for which elements in hexadic form, with six nodes and three degrees of freedom for each node were used. Periodontal ligament was added to this constructed model for the whole length of the root, 0.25 mm wide, as shown in Fig. 2. The compact layer was modelled 2 mm thick (Fig. 3) and beneath the compact layer spongiosa was modelled (Fig. 4). In this way a model was obtained with 4000 elements in hexadic form and 2367 nodes, with a total of 7101 degrees of freedom.

The computer programme packet NISA was used on this three-dimensional model of an upper canine, without relevant supporting structures, for test analyses of tooth movement, deformation, stress intensity and equivalent stresses were calculated according to the energy theory of hardness (Huber-Mises-Hencky theory).

After the tooth model had proved satisfactory in test experiments, supporting structures were modelled (periodontal ligament, cortical and spongiosa). The model was secured at the edges of the spongiosa, which ensured that there was no movement of the model as a solid body which could cause numerical singularity (errors).

During the investigation particular consideration was taken of the fact that the results of the investigation which would later be performed by the method of finite elements, depend primarily on the manner in which the model was obtained. Thus, the construction of the model is the key for all further investigations. The sources of data, based on which the model was constructed, were previously known dimensions from literature, and consideration was also taken of sections of specimens (in this case the tooth), or even serial computer tomographic recordings, for which there is sufficient data in recent literature (2-16). A problem which occurs when the model is constructed on the basis of a compilation of data from literature is the possibility of cumulating errors. Due to the great variety of certain parameters such a constructed model may finally look incoherent and illogical. We, therefore, chose a safer and more precise approach, which is more complicated and lengthy and certainly more scientific, i.e. the model was constructed according to a determined specimen, the tooth. In the case of a model which is constructed on the basis of sections made by criomicrotomy, inaccuracy occurs because of the unsharp sections and breaking on their edges. Usually the sections are photographed, and here also errors occur because of the unsharp contours and enlargement. Computer-tomographic recordings, on the basis of which a mathematical model can also be constructed, do not give correct dimensions because of errors in the edge conditions. The quality of computer-tomographic recordings also depends on the camera and its resolution. The resulting differences can be essential for determining such small thickness of bone and such a small area such as the periodontal gap. As there is no method for constructing a model which is completely precise and correct, the aim is to be as close as possible to the original (digitalize it). In the present investigation the aim was to find a method to authentically transfer an extracted canine into the computer. By recording with a video camera and digitalization of the pictures it is possible to transfer one or more pictures of a tooth or similar object into one of the known formats for storing pictures (TIF, GIF, JPEG, PCX, BMP). However, this does not solve the problem of third dimension. As earlier mentioned, a video camera of high resolution was used and, as in the case of all analogous cameras, a charge coupled device (CCD) chip was used for light registration, although the signal directed to the computer was analogous (usually VHS or still better sVHS signal). In order to change this analogous signal into one of the digital formats additional apparatus is necessary between the camera and computer, to digitalize the analogous signal.

In this case a frame grabber was used (video adapter, digitalizer) of very high resolution, because previous tests with cheap, commercially widely available cards, had not given a sufficiently sharp picture. By using a digital camera the application of a frame grabber and complicated software for conversion of the analogue signal into a digital signal is avoided. However, because of the poorer contrast achieved with this camera the details are not sufficiently visible to be reliable. Thus it can be said that three-dimensional scanning gives good, or possibly even the best, results. However, the scanner used in this investigation did not have sufficiently good resolution. As over the last year three-dimensional scanners of very high resolution have become available, they will probably be the method of choice in future investigations.

However, the method used here has other advantages. Namely, by cutting a tooth or similar structures into thin layers and their digitalization it is possible to show, apart from the external form, the internal structure three-dimensionally: for example the pulp chamber, root canals, edges or fillings walls, cavities etc.

The construction of a mathematical model by means of the method of finite elements is possible through various computer programmes. These programmes differ in their mathematical approach to the analysis of data, according to the forms of finite elements which can be one-dimensional (point), two-dimensional (line) or three-dimensional. Such elements can have straight or curved sides, and the number of nodes varies, depending on the form of the geometric body. Nodes can be present in angles and halves of sides of the spatial element, and also in its volume. The result of the investigation depends on the mentioned variability of the form of finite elements and the number of nodes. Simulation of forces of determined directions, the magnitude and site of the application on such a mathematical model results in deformation of the model, i.e. movement of nodes. This movement can occur in different ways and have different directions, depending on the number of degrees of freedom which such a model allows. In the three-dimensional model linear movements of nodes can be defined by orthogonal Cartesian coordinate system (x,y,z axes), and rotation around all three coordinate axes. This fact confirms that in the case of complex structures and constructions such as the stomatognathic system the method of finite elements with three-dimensional system elements can best be applied, during which the elements are not mutually uniform, and neither do they have an identical number of nodes. In this connection the moduli of elasticity and Poisson's coefficients vary from structure to structure, i.e. from element to element. Namely, other methods, such as photoelasticitimetry (17-21) cannot be adequately applied in orthodontics, as they do not differentiate individual biological structures and mutual differences in their mechanical characteristics (enamel, dentine, pulp, periodontal ligament, compact and spongy bone). It is also difficult to construct a photoelastic model, whose form corresponds to the anatomy of the stomatognathic system. In the same way the method used to measure deformation by means of resistant measuring tapes (tensimetry) (22) is carried out on a model which comprises an anatomic specimen, most often the skull, during which flat deformations are measured at those points on which the tapes are stuck. Here dry macerated skulls are most frequently used, because it is easiest to stick the resistant tapes onto them. This method is good for measuring forces which occur during the application of some orthodontic appliances on the appliances themselves. Clearly, neither can this method analyse the complexity of the simultaneous effect of all structures, and by using this procedure it would be impossible to register movements of a tooth surrounded by periodontal ligament, or the stress and deformation on distant structures.

The method of holographic interferometry (23-36) with double exposure or in real time, can be applied on a model of any structure, including bones and teeth, and can be applied "in vivo" in man, in order to register the movement of visible teeth during mastication. As it is only possible to register that which can be seen with the naked eye, only information about the surface is obtained and not the depth of the analysed structures.

Movement of the tooth during mastication can be measured by the application of stereophotogrametry in all three dimensions (37), which like holographic interferometry has its good points for application in dental investigations, although it has similar limitations.

In contrast to all the other methods mentioned a mathematical model of finite elements enables an endless number of changes in the form of certain elements and structures in the computer, including countless simulations of force application. This results in different possibilities for the formation of systems and distribution of stress within such structures. This is the main aim of investigations such as this. The goal of every orthodontist-clinician, for whom such investigations are performed, is the transfer of individual data of a particular patient into such a model, on which different possibilities of orthodontic therapeutic procedures could be simulated. In this way it would be possible to envisage the course and result of orthodontic therapy, and to chose the most suitable therapeutic procedure. The object of this part of the investigation was to produce such a mathematical model, by using a method of finite elements, which would be suitable for application in orthodontics and not restricted to one investigation with a clearly defined aim but for later application in other investigations, not only in orthodontics. Simulation of different positions of the teeth is possible on such a model, including different heights of the alveolar bones and therapeutic situations in which tooth extraction is performed. It is also possible to simulate distribution of forces and stress which occur at that time, by the orthodontic appliances and changed position of the tooth. It is therefore anticipated that this method will be applied even more widely in the future.