Dental Traumatology

Dental Traumatology 2012; **28**: 108–113; doi: 10.1111/j.1600-9657.2011.01046.x

Assessment of nose protector for sport activities: finite element analysis

Neide Pena Coto[1], Josete Barbosa Cruz Meira[1], Reinaldo Brito e Dias[1], Larissa Driemeier[2], Guilherme de Oliveira Roveri[2], Pedro Yoshito Noritomi[3]

[1]Faculdade de Odontologia da Universidade de São Paulo; [2]Departamento de Engenharia Mecatrônica e Sistemas Mecânicos, Escola Politécnica da Universidade de São Paulo; [3]Centro de Tecnologia da Informação Renato Archer, São Paulo, Brazil

Correspondence to: Neide Pena Coto, Cidade Universitária, Av. Lineu Prestes, 2227, CEP: 05508 000, São Paulo, Brazil
Tel./Fax: 0 5511 3091 78 78
e-mail: npcoto@usp.br

Accepted 18 June, 2011

Abstract – There has been a significant increase in the number of facial fractures stemming from sport activities in recent years, with the nasal bone one of the most affected structures. Researchers recommend the use of a nose protector, but there is no standardization regarding the material employed. Clinical experience has demonstrated that a combination of a flexible and rigid layer of ethylene vinyl acetate (EVA) offers both comfort and safety to practitioners of sports. The aim of the present study was the investigation into the stresses generated by the impact of a rigid body on the nasal bone on models with and without an EVA protector. For such, finite element analysis was employed. A craniofacial model was constructed from images obtained through computed tomography. The nose protector was modeled with two layers of EVA (1 mm of rigid EVA over 2 mm of flexible EVA), following the geometry of the soft tissue. Finite element analysis was performed using the LS Dyna program. The bone and rigid EVA were represented as elastic linear material, whereas the soft tissues and flexible EVA were represented as hyperelastic material. The impact from a rigid sphere on the frontal region of the face was simulated with a constant velocity of 20 m s^{-1} for 9.1 μs. The model without the protector served as the control. The distribution of maximal stress of the facial bones was recorded. The maximal stress on the nasal bone surpassed the breaking limit of 0.13–0.34 MPa on the model without a protector, while remaining below this limit on the model with the protector. Thus, the nose protector made from both flexible and rigid EVA proved effective at protecting the nasal bones under high-impact conditions.

There has been a significant increase in the number of facial fractures stemming from sport activities in recent years (1, 2). The nasal bone is in the vulnerable zone of the face and is projected forward in relation to the adjacent structures, making it one of the most affected structures in sport accidents. According to (3, 4), approximately 60% of sport-related injuries to the face occur in the nasal bone, especially in rugby, football (soccer), and basketball (5). Approximately 45% of nasal fractures occur because of impact of either the elbow or head of one athlete against the face of another (6). For adequate repair, the bone must be immobilized during the healing process, which often keeps athletes from practice and competition for a long period of time. This situation can have a negative impact on an athlete's career and cause financial harm to the team (7–11).

Studies have demonstrated that an injured athlete loses his/her physical conditioning and, in many cases, has a tendency toward depression, which hampers his/her physical recovery (8, 9). One of the solutions for avoiding this is the use of a nose protector during the practice of sport activities. A protector can also be used in a preventive fashion in sport modalities that have a high risk of facial fracture. The geometry of the protector and anchoring points on the face should ensure comfort in order not to compromise the athlete's performance during practice and competition.

It is important for the material used in the nose protector to have adequate shock-absorbing capacity. Ethylene vinyl acetate (EVA) meets this requirement and has advantages such as low-temperature conformation, handling ease, reproducibility, satisfactory cohesion between layers, transparency, and low cost (12). In the dentistry market, EVA is used in the form of rigid and flexible flat plates ranging in thickness from one to five millimeters (mm). Flexible plates offer greater comfort, but less protection, as they deform more easily. On the other hand, rigid plates offer greater protection, but comfort is compromised. Clinical experience from the authors (13) has demonstrated that the combination of flexible and rigid layers offers both comfort and safety, especially when the delimitation is established such that peripheral vision and stability of the protector are favored.

The hypothesis of the present study is that the use of a nose protector made with a 2-mm layer of flexible EVA and overlying 1-mm layer of rigid EVA reduces the risk of nasal bone fracture by reducing the stress when suffering an impact. To test this hypothesis, finite element analysis was employed to simulate the impact of a hard body on a craniofacial model with and without an EVA protector.

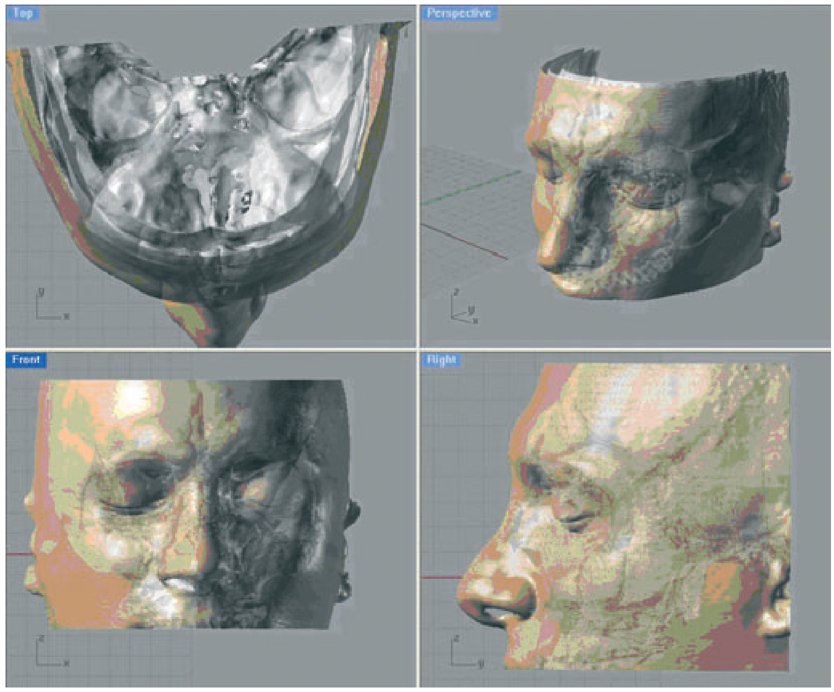

Fig. 1. Image obtained in STL.

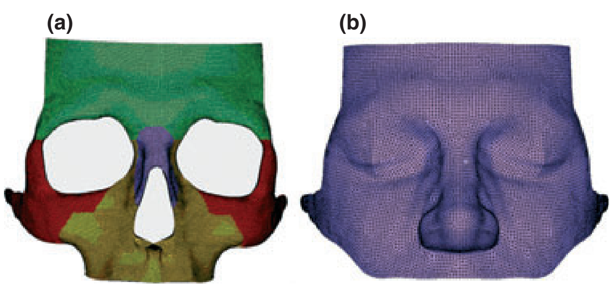

Fig. 2. Geometry mesh obtained after applying BioCAD. (a) bone portion. (b) soft tissue portion.

Finite element is a numerical tool for solving differential equations, which has been increasingly important in the field of dentistry (14). This tool is largely used to determine the distribution of stresses and deformations because of forces applied in structural systems such as tooth, bone, and tissue (15–18). In many practical cases in medicine and dentistry, where research on the mechanism of injuries caused by impact is not viable *in vivo* (19), the results obtained from the virtual FEM are the only available data.

Materials and methods

From a CT (computed tomography) scan, a craniofacial model in STL (stereolithography) format was created (Fig. 1). Although the model perfectly replicates the face, it cannot be used in finite element analysis because of large amount of details. Then, the BioCad (Biological Computer-Aided Design) protocol, developed in CTI (Technology Center Renato Archer, SP, Brazil), was applied to obtain a simplified description of the anatomical structures involved. The simplified format was divided into finite elements, according to Fig. 2a,b. The bone portion has 201,995 shell elements, while soft tissue has modeled with 160 537 shell elements.

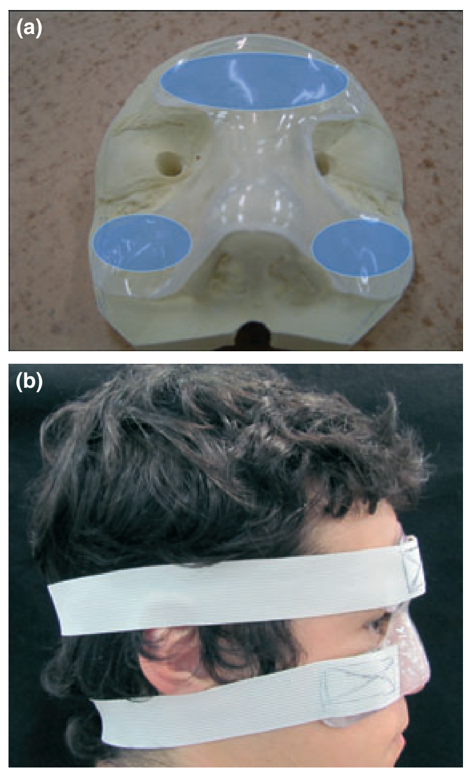

Fig. 3. (a) Nasal protector with support points. (b) Nasal protector fixation in the head by elastic straps.

A nose protector composed by a 2-mm layer of flexible EVA with a 1-mm layer of rigid EVA was laid

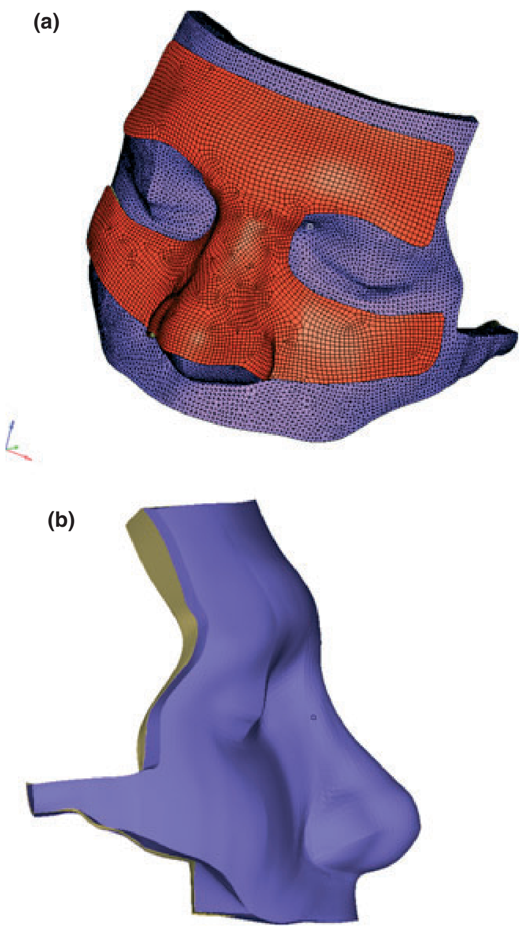

Fig. 4. (a) Facial model used in the study with protector. (b) Facial model used in the study without protector.

Table 1. Material model for bone

Elastic parameters			Failure criterion
ρ(t mm^{-3})	E (MPa)	ν	Maximum main stress (MPa)
7.85E-04	1300.00	0.30	0.13–0.34

Table 2. Material model for soft tissue

Ogden parameters				Elastic parameters		
μ_2	μ_4	α_2	α_4	G (MPa)	ρ (t mm^{-3})	ν
0.0059	0.0236	2.00	4.00	0.69	9.5E-10	0.30

Table 3. Material model for EVA flexible

Ogden parameters				Elastic parameters		
μ_1	μ_2	α_1	α_2	G (MPa)	ρ (t mm^{-3})	ν
7.00	2.60	0.80	2.60	10	2.00–0.9	0.48

EVA, ethylene vinyl acetate.

Table 4. Materia model for EVA rigid

Ogden parameters			Elastic parameters		
E (MPa)	σ Flow (MPa)	Tangent modulus (MPA)	Strain at failure	ρ (t mm^{-3})	ν
480	46	0.80	1.2	9.4E-10	0.48

EVA, ethylene vinyl acetate.

over the face. Because the material is thermoplastic, it is not necessary to use a bonding agent. Among the main features of the EVA, the high elasticity, flexibility, high mechanical and fracture resistance at low temperatures can be highlighted. The protector geometry guarantees its support in the strength zone of the face (Fig. 3a). The Fig. 3b shows the straps used to fix the protector in the head of the athlete. A mesh was generated over the digitized geometry on the Hyper Mesh program, totaling 735 793 shell elements (Fig. 4a). A model without a protector was used as the reference (control) (Fig. 4b).

Moreover, material properties for the soft tissue and bones model were determined based on published literature. Table 1 presents the material models for the bone, which were modeled as elastic linear, with a failure criteria of maximum principal strain (20, 21). According to the literature, a linear law does not account properly for the mechanical behavior of the human soft tissues, while a hyperelastic material seems to be well adapted, showed in Table 2 (21–24). Among the various strain-energy functions that can describe such a mechanical response (see, for example Bonet and Wood, 1997) (25), we focused on the Ogden model and Table 3 resumes the parameters (26). And EVA rigid was modeled as Von Mises bilinear elastoplastic (Table 4).

As show in Fig. 5a, impact from a rigid sphere with radius of 30 mm was simulated on the frontonasal region for 9.1 μs, with constant velocity and mass (20 m s^{-1} and 0.025 kg, respectively). The time interval is defined by numerical analysis. Without considering rebounding, the phenomenon is analyzed until the instant the projectile begins to move away from the face, decreasing the stress at the contact point.

The analysis was carried out using the LS Dyna® program (Livermore Software Technology Corporation, Livermore, CA, USA). The Hyper View® was used as the postprocessor. The distribution of maximum main stress of the facial bones in the model with the protector was compared with that of the control. Moreover, regions where the main stress reached the failure values reported in the literature were determined. Figure 5b shows the model without nose protector that is used as reference.

Results

The maximum main stress on the nasal bone surpassed the fracture range of 0.13–0.34 MPa (20, 21) on the model without the protector (Fig. 6a), whereas the stresses remained below this range on the model with the protector (Fig. 6b). Figure 6c displays the overlay of

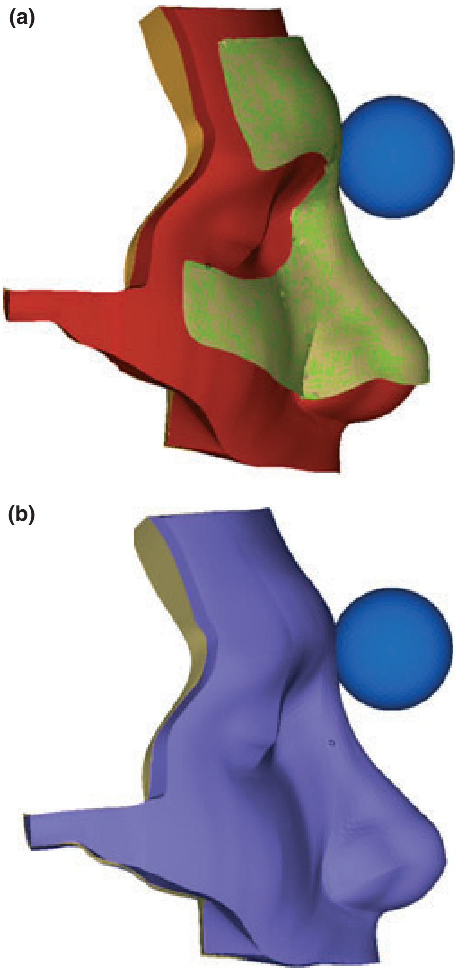

Fig. 5. (a) Facial model with nose protector. (b) Facial model without protector.

the mesh with the respective bone divisions (frontal and nasal), revealing that the failure without the protector occurred in the region of the nasal bones, with stress values > 0.34 MPa. Figure 6d illustrates the model with the protector, revealing that no fracture of the nasal bone had occurred. The influence of the nose protector in the prevention of injuries in the soft tissues of the face is shown in Fig. 7a,b (control, with protector).The stress of rigid and flexible EVA are shown in Fig. 8a,b, respectively.

Discussion

The hypothesis of the present study was confirmed. The use of a protector made with a 2-mm layer of flexible EVA and overlying 1-mm of rigid EVA reduced the risk of nasal fracture by diminishing the stresses in this bone during impact. These results are expected, because the rigid portion offers resistance to deformation and decelerates the impact, while the flexible portion deforms considerably, distributing, and absorbing the energy received in a larger time interval.

The craniofacial model employed respected the actual measurements of the human face regarding the bone and soft tissue portions, as indicated by tomography. Colors were used to differentiate the zones of strength and fragility.

The bone failure criterion used in this study was the maximum main stress, with the critical value range reported in the literature of 0.13–0.34 MPa. Although current articles suggest the use of maximal deformation as the criterion of bone failure, results differing from those obtained in the present study would only be possible with models containing more elaborate materials than the linear elastic model used herein(16, 19, 27–29).

Because of the trajectory of a projectile and the anatomy of the face, the frontal bone is affected as well. Figure 4b illustrates the overlaying of the mesh with the bone division, demonstrating that the failure without the protector occurred in the region of the nasal bones, while Fig. 4d reveals no fracture in the nasal bone fracture with the use of the protector. It should be emphasized that the strength of the frontal bone is up to 70-fold greater (≥7.58 MPa).

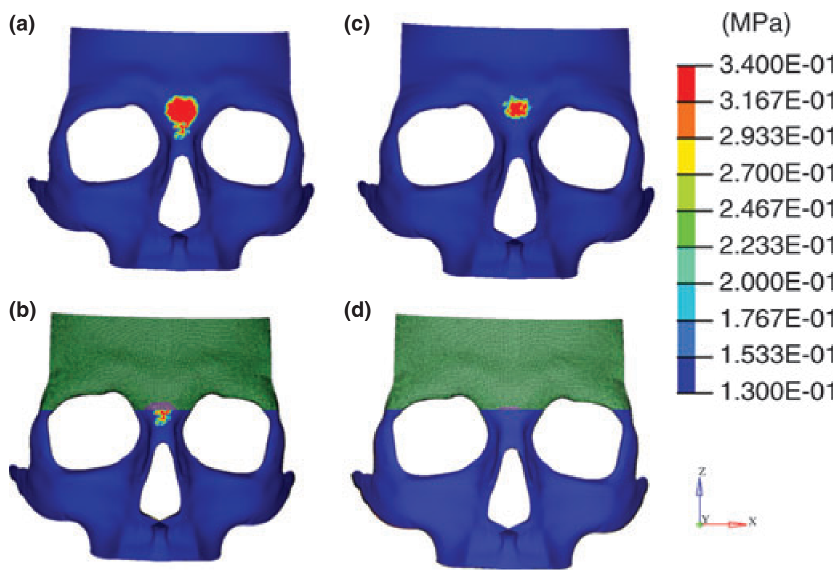

Fig. 6. (a) Bone portion without protector; (b) Overlap model of stresses analysis without protector, demonstrating nasal bone failure; (c) Bone portion with protector; (d) Overlap model of stress analysis with protector, demonstrating absence of nasal bone failure.

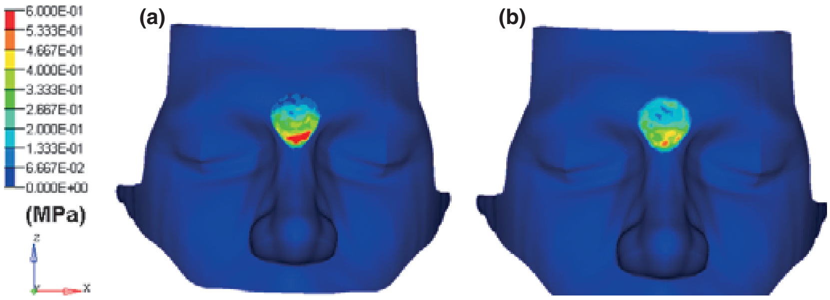

Fig. 7. (a) Stress analysis in soft tissue region nasal without protector (MPa); (b) Stress analysis in soft tissue region nasal with protector (MPa).

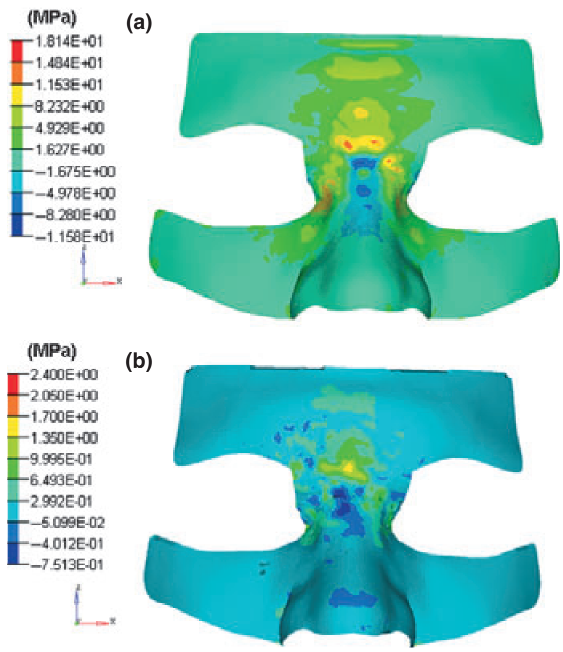

Fig. 8. (a) Stress analysis in portion ethylene vinyl acetate (EVA) rigid of the protetor (MPa); (b) stress analyses in EVA flexible of the protector(MPa).

The analyses obtained through computed tomography required a long computational time using a server Intel Xeon E5520, 2.27 GHz (two processors, eight cores, 16 logical processors), L3 cache 8 MB, 24 GB RAM memory, Windows 7 Enterprise (64-bits) computer. For example, it took 15 days to complete the impact simulation in the face with the protector. This was because of the large number of elements, the non-linear model of the materials (soft tissues and EVA), and contact between the different layers. Thus, the material and geometry of the projectile were limited as rigid and with small dimensions, respectively.

Therefore, with the present model, continuity to this line of research can be considered. Moreover, projectiles with different shape, material, velocity, and angle impacting even nasal bone undergoing healing process can be analyzed. Finite element analysis proved to be an important tool in the optimization of a nose protector made from EVA. The simulations showed the capability of the device in protecting facial bones, in the proposed critical situation.

Conclusion

The nose protector made from both flexible and rigid EVA proved effective at protecting the nasal bones under high-impact conditions.

References

1. Antoun JS, Lee KH. Sports-related maxillofacial fractures over an 11-year period. J Oral Maxillofac Surg 2008;66:504–8.
2. Linn EW, Vrijhoef MM, de Wijn JR, Coops RP, Cliteur BF, Meerloo R. Facial injuries sustained during sports and games. J Maxillofac Surg 1986;14:83–8.
3. Frenguelli A, Ruscito P, Bicciolo G, Rizzo S, Massarelli M. Head and neck trauma in sporting activities. Review of 208 cases. J Craniomaxillofac Surg 1991;19:178–81.
4. Carroll SM, Jawad MA, West M, O'Connor TP. One hundred and ten sports related facial fractures. Br J Sports Med 1995;29:194–5.
5. Flanders RA, Bhat M. The incidence of orofacial injuries in sports: a pilot study in Illinois. J Am Dent Assoc 1995;126:491–6.
6. Delilbasi C, Yamazawa M, Nomura K, Iida S, Kogo M. Maxillofacial fractures sustained during sports played with a ball. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2004;97:23–7.
7. Levin L, Friedlander LD, Geiger SB. Dental and oral trauma and mouthguard use during sport activities in Israel. Dent Traumatol 2003;19:237–42.
8. Garza JR, Baratta RV, Odinet K, Metzinger S, Bailey D, Best R et al. Impact tolerances of the rigidly fixated maxillofacial skeleton. Ann Plast Surg 1993;30:212–6.
9. Ellis E, 3rd, Kittidumkerng W. Analysis of treatment for isolated zygomaticomaxillary complex fractures. J Oral Maxillofac Surg 1996;54:386–400; discussion -1.
10. Cascone P, Petrucci B, Ramieri V, Marianetti TM. Security Hi-tech Individual Extra-light Device Mask: a new protection for [soccer] players. J Craniofac Surg 2008;19:772–6.
11. Ranalli DN, Demas PN. Orofacial injuries from sport: preventive measures for sports medicine. Sports Med 2002;32:409–18.
12. Coto NP, Dias RB, Antoniazzi TF, Costa RA, Carvalho EPC. Mechanical behaviour of ethylene vinyl acetate copolymer (EVA) used for fabrication of mouthguards and interocclusal splints. Braz Dent J 2007;18:324–8.
13. Coto N, Dias R, Reis R, Oliveira C. Protetor facial em atleta: contribuição da odontologia. Informe News2006.
14. Hannam A. Current computational modelling trends in craniomandibular biomechanics and their clinical implications. J Oral Rehabil 2011;38:217–34.
15. King AI. Progress of research on impact biomechanics. J Biomech Eng 1993;115:582–7.
16. Kosmopoulos V, Schizas C, Keller TS. Modeling the onset and propagation of trabecular bone microdamage during low-cycle fatigue. J Biomech 2008;41:515–22.

17. Witzel U, Preuschoft H. Finite-element model construction for the virtual synthesis of the skulls in vertebrates: case study of Diplodocus. Anat Rec A Discov Mol Cell Evol Biol 2005; 283:391–401.
18. Field C, Ichim I, Swain MV, Chan E, Darendeliler MA, Li W et al. Mechanical responses to orthodontic loading: a 3-dimensional finite element multi-tooth model. Am J Orthod Dentofacial Orthop 2009;135:174–81.
19. Rincon-Kohli L, Zysset PK. Multi-axial mechanical properties of human trabecular bone. Biomech Model Mechanobiol 2009; 8:195–208.
20. Hodgson VR, Nakamura SM, Nakamura GS. Mechanical impedance and impact response of the human cadaver zygoma. J Biomech 1968;1:73–8.
21. Hampson D. Facial injury: a review of biomechanical studies and test procedures for facial injury assessment. J Biomech 1995;28:1–7.
22. Holberg C, Heine AK, Geis P, Schwenzer K, Rudzki-Janson I. Three-dimensional soft tissue prediction using finite elements. Part II: clinical application. J Orofac Orthop 2005; 66:122–34.
23. Holberg C, Schwenzer K, Rudzki-Janson I. Three-dimensional soft tissue prediction using finite elements. Part I: implementation of a new procedure. J Orofac Orthop 2005; 66:110–21.
24. Lapeer R, Gasson P, Karri V. A hyperelastic finite-element model of human skin for interactive real-time surgical simulation. IEEE Trans Biomed Eng 2010;58:1013–22.
25. Bonet J, Wood RD. Non-linear continuum mechanics for finite element analysis. Cambridge University Press 1997;sect:248.
26. Verdejo R, Mills NJ. Heel-shoe interactions and the durability of EVA foam running-shoe midsoles. J Biomech 2004;37:1379–86.
27. Schileo E, Taddei F, Cristofolini L, Viceconti M. Subject-specific finite element models implementing a maximum principal strain criterion are able to estimate failure risk and fracture location on human femurs tested in vitro. J Biomech 2008;41:356–67.
28. Gerard JM, Ohayon J, Luboz V, Perrier P, Payan Y. Non-linear elastic properties of the lingual and facial tissues assessed by indentation technique. Application to the biomechanics of speech production. Med Eng Phys 2005;27:884–92.
29. Wang S, Yang J, Gee JC. Advances in collision detection and non-linear finite mixed element modelling for improved soft tissue simulation in craniomaxillofacial surgical planning. Int J Med Robot 2009;6:28–41.