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Der implantatversorgte zahnlose Unterkiefer unter traumatischen Bedingungen – Biomechanische Spannungsanalysen mit Hilfe der Finite-Elemente-Methode

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Stefan Krennmair

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Abkürzungsverzeichnis

FEM: Finite-Elemente-Methode

FEA: Finite-Elemente-Analyse

CAD: Computer Aided Design

Publikationsliste

I. Krennmair S, Winterhalder P, Hunger S, Rupperti S, Holberg C. The Effects of Frontal Trauma on 4 Interforaminal Dental Implants: A 3-Dimensional Finite Element Analysis Comparing Splinted and Unsplinted Implant Configurations. J Oral Maxillofac Surg. 2020;78(6):961–72.

II. Krennmair S, Hunger S, Postl L, Winterhalder P, Holberg S, Malek M, Rudzki I, Holberg C. Edentulous mandible with four splinted interforaminal implants exposed to three different situations of trauma: A preliminary three-dimensional finite element analysis. Dental Traumatology. 2020;36(6):607–17.

Beitrag zu den Veröffentlichungen

1.1 Beitrag zu Paper I

Der Eigenanteil zur Publikation beinhaltet die Suche und die Auswahl der Fragestellung, die Erstellung des Studiendesigns sowie die Materialvorbereitungen für die Finite-Elemente-Analyse (FEA). Das umfasst die Bilddatensammlung, das Computer Aided Design (CAD), die Modelldatenbeschaffung sowie die Modellerstellungen für die FEA. Die Softwarebeschaffung für die FEA sowie die Modellbearbeitung und die Modellvorbereitungen für die Simulation gehörten ebenfalls zum Aufgabengebiet. Darüber hinaus schließt der Beitrag zur Veröffentlichung die Durchführung der Simulation der FEA, die Auswertung der Simulationsergebnisse sowie die Durchführung der Datenanalyse und die Vorbereitung und die Mitarbeit bei der statistischen Auswertung ein. Des Weiteren stellten Entwurfsvorbereitungen des Manuskripts der Publikation, der Niederschrieb der Veröffentlichung und die Korrektur nach Supervision wesentliche Beitragsgebiete des Eigenanteils der Veröffentlichung dar. Auch die Einreichung der Publikation sowie die Korrekturen im Reviewprozess im Zuge der Veröffentlichung des Manuskripts waren fester Bestandteil des Eigenanteils zur Publikation.

1.2 Beitrag zu Paper II

Im Eigenanteil an der Veröffentlichung inkludiert sind die Eruierung und die Auswahl des Forschungsvorhabens und der Fragestellung sowie die Erstellung des Studienkonzepts für die FEA. Des Weiteren gehörten bestimmte Materialvorbereitungen, die Bilddatensammlung, die CAD-Modelldatenbeschaffung sowie die Softwarebeschaffung für die FEA zu den Beitragsgebieten des Eigenanteils. Auch die Durchführung der Simulation der FEA mit den damit verbunden

Arbeitsschritten wie Erstellung, Vorbereitung und Bearbeitung der Simulationsmodelle waren Bestandteil des Eigenanteils zum Paper. Darüber hinaus beinhaltete die Eigenleistung die Durchführung der FEA-Simulation sowie eine Auswertung der Ergebnisse der Finite-Elemente-Analyse mit anschließender Datenanalyse. Des Weiteren zählten die Aufbereitung der Daten für die statistische Auswertung und die Mitarbeit bei dieser zu den Beitragsgebieten des Eigenanteils. Die Abfassung des Manuskriptentwurfes sowie Korrekturen nach Supervision und die anschließende Ausarbeitung des Papers waren ebenfalls Teil des Aufgabengebiets ebenso wie die Einreichung der Publikation mit resultierenden Nachbesserungsarbeiten und Korrekturen im Zuge des Veröffentlichungsprozesses des Papers.

2. Einleitung

2.1 Der zahnlose Unterkiefer

Zahnverlust und die Behandlung des zahnlosen Unterkiefers stellen bei einer immer älter werdenden Patientenpopulation wesentliche Gesundheitsprobleme dar (1,2). Obwohl in den letzten Jahren ein gesteigertes Patientenbewusstsein sowie deutlich verbesserte Präventionsmaßnahmen zum Thema Zahngesundheit vorgefunden werden, betrifft der Zahnverlust sowohl europa- als auch weltweit nach wie vor eine große Anzahl an Personen. So wird die Zahl zahnloser Patienten in Europa bei der Alterspopulation der 64- bis 75-Jährigen mit einer Inzidenz von 15 % bis zu 72 % angegeben (1-3).

Aufgrund einer ständig steigenden Lebenserwartung und dem damit verbundenen höheren Risiko, im Laufe des Lebens an zahndestruierenden Veränderungen wie Parodontitis oder Karies zu erkranken, gewinnt die Behandlung von Zahnverlust in der heutigen Zeit zunehmend an Bedeutung (2-4). Ein Zahnverlust bedeutet für die Patienten eine Einschränkung im Bereich des Kauens, der Phonetik, der Ästhetik sowie der Nahrungsaufnahme. Die daraus resultierenden psychologischen und sozialen Effekte haben auch einen Einfluss auf die Lebensqualität der Betroffenen (4,5).

Innerhalb der bekannten Varianten, einen Zahnverlust zu therapieren, nimmt die Anwendung der oralen Implantattherapie sowohl im Fachgebiet der Mund-, Kiefer- und Gesichtschirurgie als auch in der Zahnheilkunde mittlerweile einen fixen Stellenwert ein. Seit Jahrzehnten stellt die Anwendung der enossalen Implantation in Zusammenarbeit mit der Implantatprothetik eine Domäne in der

Rehabilitation von Einzelzahnlücken, teilbezahnter Kieferabschnitte, aber auch des komplett zahnlosen Kiefers dar (5,6).

In der gegenwärtigen Gesellschaft hat sich der Anspruch an einen stabilen Zahnersatz verfestigt. Zusätzlich zeichnet sich das Patientenkollektiv im fortgeschrittenen Lebensalter in der heutigen Zeit durch hohe Aktivität und Vitalität aus. Besonders die erhöhte physiologische Aktivität stellt in diesem Zusammenhang einen wesentlichen traumatologischen Risikofaktor dar (7,8).

2.2 Enossale Implantate als Zahnersatz

Die Verwendung von enossalen dentalen Implantaten gilt als ein wissenschaftlich etabliertes oralchirurgisches Verfahren in der Rehabilitation eines Zahnverlustes (5,9-12). Unter enossaler dentaler Implantologie wird das Einbringen von alloplastischem oder xenogenem Material in knöchernes Gewebe verstanden, um die Basis für eine prothetische oder eine epithetische Versorgung zu schaffen (13).

Die meisten Implantatsysteme bestehen aus einer Implantatfixtur (Implantat), das in den Kieferknochen inseriert wird, sowie aus einem Abutment und einer späteren prothetischen Rekonstruktion (13-15). Zu den Implantatmaterialien zählen Metalle (Titan Niob) sowie Keramikmassen (Aluminiumoxid oder Hydroxylapatit) (16,18). Obwohl Keramikimplantate vermehrt Anwendung finden, stellt nach wie vor das bionierte Titan das am häufigsten verwendete Implantatmaterial dar (16-18).

Das Anwendungsgebiet der dentalen Implantate als Basis für einen Zahnersatz umfasst sowohl den Ersatz von Einzelzahnlücken als auch die Rehabilitation des komplett zahnlosen Gebisses (15,19).

Zu den Zielen der dentalen enossalen Implantation gehört, dass durch deren Anwendung die vorhandene (benachbarte) Zahnhartsubstanz geschont wird, sowie dass die Substanz von Knochen und Weichgewebe erhalten bleibt (19). Vor allem bei kompletter Zahnlosigkeit ermöglicht ein durch Implantate stabil gelagerter Zahnersatz, dass ein Fortschreiten der Kieferatrophie reduziert beziehungsweise sogar verhindert werden kann (20-22).

Im Allgemeinen wird durch die Insertion von Implantaten in einem komplett unbezahnten Ober-/oder Unterkiefer eine Verankerung eines abnehmbaren oder eines festsitzenden Zahnersatzes ermöglicht. Bei der Durchführung einer abnehmbaren implantatprothetischen Versorgung ist anhand der Anzahl der Implantate sowie der Art der verwendeten Verankerungsmöglichkeit zwischen einer rein implantatgetragenen und lediglich einer implantatgehaltenen abnehmbaren Versorgung zu unterscheiden (23-26). Zur Verankerung eines abnehmbaren Zahnersatzes im zahnlosen Unterkiefer werden vorwiegend zwei oder vier (seltener sechs) interforaminale Implantate inseriert (27-34). Diese werden entweder verblockt und mit Stegkonstruktionen versehen oder als unverblockte singuläre Halte- und/oder Retentionselemente verwendet. Aus zahlreichen Meta-Analysen, einzelnen Studien und Review-Artikeln kann entnommen werden, dass – unabhängig davon, ob als verbundene oder singuläre Anwendung – sowohl die Implantate als auch die darauf integrierte Implantatprothetik eine hohe Überlebens- und Erfolgsrate aufweisen (20,27,29).

Im Gegensatz zu den abnehmbaren Versorgungen kann ein zahnloser Unterkiefer auch festsitzend implantatprothetisch therapiert werden (23). Wurden früher im Unterkiefer für eine festsitzende hybridartige Versorgung fünf bis sechs Implantate verwendet, hat sich seit nahezu 20 Jahren auch die Verankerung auf vier interforaminalen Implantaten als erfolgreiches Konzept erwiesen (23,25,28,33-38). Die vier Implantate werden, um etwaige transversale Defomationen der Mandibula auszugleichen, bevorzugt im interforaminalen Bereich zwischen beiden Foramina mentalia inseriert (33-38). Unabhängig davon, ob die posterioren Implantate schräg oder gerade inseriert werden, kann durch die Verwendung einer streng definierten Prothesenextensionslänge eine zirkuläre distal extendierte Prothese zur festsitzenden Versorgung eingesetzt werden (27,32). Zu erwähnen ist jedoch, dass durch ein schräges Inserieren der distalen Implantate, wie von Malo et al (2003) gezeigt, eine Vergrößerung des Stützfeldes und eine Reduktion der Extensionslänge zustande kommen. Auch für diese Art der festsitzenden implantatprothetischen Versorgung des zahnlosen Unterkiefers wird in zahlreichen Langzeitstudien mit einer Nachuntersuchungsdauer von 15 bis 20 Jahren eine Überlebens- und Erfolgsrate der Implantate und der Implantatprothesen von 94–98 % bzw. 90–94 % angegeben (37,38).

2.3 Trauma im zahnlosen Unterkiefer

2.3.1 Epidemologie

Der Unterkiefer ist bei Gesichtstrauma der am häufigsten gebrochene Knochen mit einer Betroffenheitsrate von 23–97 % (39). Zu den verbreiteten Ursachen von Unterkiefertraumata gehören Verkehrs-, Sport-, Freizeit- sowie Arbeitsunfälle (7,8). Ein Sturzgeschehen als Ursache für ein Trauma im Mund-, Kiefer- und Gesichtsbereich weist in diesem Zusammenhang die größte Bedeutung auf (40-42). Fallneigungen mit ursächlichen Synkopen sind hier als bedeutende Ursachen für allgemeines Sturzgeschehen und das damit verbundene Trauma zu nennen (40-43).

Zum vom zahnlosen Unterkiefergebiss betroffenen Patientenkollektiv zählt vor allem die ältere Patientengeneration. In diesem Kollektiv stellen neurologisch oder cerebro-vaskulär bedingte Synkopen den wesentlichen Risikofaktor für Traumata im Gesichtsbereich dar (7,40-43). Zusätzlich spielt aber auch eine hohe physiologische Aktivität im Alter in der gegenwärtigen Gesellschaft eine bedeutende Rolle für traumatologische Sturzereignisse (7,40-43). Diese Ursachen gewinnen mit der demographischen Verschiebung hin zu einer immer älter werdenden Gesellschaft stätig an Bedeutung (7).

2.3.2 Frakturverhalten des zahnlosen Unterkiefers

Biomechanisch stellen die symphysealen sowie die parasymphysealen Bereiche des Unterkiefers sowie die Unterkieferwinkel die Hauptangriffsbereiche von Unterkiefertrauma dar (44).

Bei appliziertem Trauma weist der zahnlose Unterkiefer im Bereich des Collum Mandibulae das höchste Spannungsaufkommen und somit eine entsprechende Frakturgefahr auf (31-33). Für den Unterkieferhals gelten biomechanisch im Vergleich zum restlichen Unterkiefer dünnere und somit schwächere Knochenverhältnisse (44,47). Diese Verhältnisse sowie die mechanischen Eigenschaften des Knochens in diesem Bereich führen hier zu einem erhöhten Frakturrisiko bei Unterkiefertrauma (44-47).

Bei Unterkiefertrauma bestehen am direkten Ort der Applikation des Traumas ebenfalls erhöhte Spannungswerte. Damit ist der Traumaapplikationsort selbst auch als Frakturrisikobereich zu bewerten (44,48).

2.3.3 Einfluss von Implantaten bei Trauma

Unter den bekannten möglichen Komplikationen von implantologisch-chirurgischen Eingriffen wie Blutungen und Infektionen kann auch das Auftreten einer Alveolarkamm- oder Kieferfraktur genannt werden (42,43,48,49). Im zahnlosen Unterkiefer kann ein Frakturgeschehen in seltenen Fällen durch den Eingriff selbst oder als Folge von Unterkiefertrauma im Bereich der Implantate auftreten (48,49). Auch infolge einer durch eine peri-implantäre Entzündung verursachten Knochenresorption kann eine Unterkieferfraktur stattfinden (50,51).

Biomechanisch weisen Implantate im zahnlosen Unterkiefer im Falle einer Traumabelastung eine Spannungsverschiebung in die knöcherne Region um die Implantate auf (48,49).

In klinischen sowie in biomechanischen Studien konnte gezeigt werden, dass die Länge der Implantate einen Einfluss auf die peri-implantäre Spannungsreaktion bei Traumaapplikationen hat (48,49). Dabei weisen kürzere monocorticale Implantate eine geringere Belastung in der knöchernen Umgebung auf als lange bicorticale Implantatsysteme (48,49). Insgesamt führt das in den Knochen eingebrachte Implantat zu einer Spannungserhöhung und somit zu einer Schwächung des Unterkiefers unter traumatischen Bedingungen (48,49).

2.4 Finite-Elemente-Methode in der Traumaanalyse

Die Finite-Elemente-Methode (FEM) ist ein Verfahren, bei dem Fragestellungen durch komplexe mathematische Gleichungen umschrieben werden. Die Berechnung dieser Gleichungssysteme führt dann zu approximierten Lösungen. Im medizinischen Anwendungsgebiet stellt diese Methode eine innovative Möglichkeit dar, um biomechanische Untersuchungen sowie Entwicklungen mathematisch zu simulieren und zu lösen (45,46,48,49).

Die FEM ist ein anerkanntes Instrument der Grundlagenforschung zur Analyse von Spannungs- sowie Belastungsuntersuchungen von Materialien wie Knochen und Implantate (45,46,48,49).

In der Vergangenheit konnten durch die FEM wesentliche Erkenntnisse im Bereich der Trauma- und der Belastungsanalyse des Unterkiefers gewonnen werden. Insgesamt hat sich die Finite-Elemente-Analyse als akkurate, nichtinvasive, reproduzierbare Methode für Untersuchungen des biomechanischen Verhaltens des Unterkiefers unter traumatischen Belastungen in der Literatur etabliert (45,46,48,49).

Im Gegensatz zu menschlichen oder tierischen Kadaverstudien kann das biomechanische Verhalten in FEM-Studien in ethisch unbedenklicher Weise vollständig computerisiert simuliert werden.

2.5 Übergeordnete Fragestellung des Forschungsvorhabens

Durch die FEM-Traumanalysen konnten bisher neue Erkenntnisse über das biomechanische Verhalten des komplett zahnlosen Unterkiefers im Allgemeinen unter verschieden traumatischen Bedingungen vorgelegt werden. Zusätzlich wurde in der Literatur der Einfluss einzelner Implantate auf den zahnlosen Unterkiefer im Trauma beschrieben. Dennoch bleibt angesichts der Erkenntnisgewinne aus der Literatur die Fragestellung offen, wie sich die Spannungsverteilung im zahnlosen Unterkiefer bei vier interforaminal inserierten Implantaten verändert und ob eine prothetische Maßnahme wie etwa Verbindung zwischen den Implantaten einen Effekt auf das biomechanische Verhalten haben könnte.

Beide Publikationen befassen sich mit der Kernfragestellung, wie sich das etablierte Behandlungskonzept des zahnlosen Unterkiefers bei vier interforaminalen Implantaten unter traumatischen Bedingungen biomechanisch auf den knöchernen Kiefer auswirkt.

2.6 Aspekte der einzelnen Publikationen

Die Analyse der Spannungsverteilung im zahnlosen Unterkiefer bei vier interforaminalen Implantaten und der Einfluss einer Verbindung zwischen den Implantaten bei frontalem Unterkiefertrauma ist Gegenstand der Publikation: „The Effects of Frontal Trauma on 4 Interforaminal Dental Implants: A 3-Dimensional Finite Element Analysis Comparing Splinted and Unsplinted Implant Configurations“. Dabei werden traumatischen Spannungsanalysen, die an einem zahnlosen Unterkiefermodell sowie an einem Modell mit vier unverblockten Implantaten und an einem mit vier verbundenen (mit Stegprothese verblockten) Implantaten durchgeführt wurden, evaluiert und einander gegenübergestellt.

Im Artikel „Edentulous mandible with four splinted interforaminal implants exposed to three different situations of trauma: A preliminary three-dimensional finite element analysis“ werden die Auswirkungen des biomechanischen Verhaltens eines mit vier verblockten interforaminalen Implantaten versorgten zahnlosen Unterkiefers auf drei verschiedene traumatische Bedingungen untersucht. In dieser Studie nimmt die Einflussnahme der Versorgung des zahnlosen Unterkiefers mit vier Implantaten und einer Stegprothesenverbindung verglichen mit dem zahnlosen Unterkiefermodell die zentrale Rolle ein. Für beide Modelle wurden jeweils drei traumatische Bedingungen vereinfacht simuliert, für die FEM-Traumaanalysen durchgeführt wurden. Dabei wurden die Simulation von frontalem Trauma, von parasymphysealem und von seitlichem Trauma als traumatische Expositionsorte gewählt. Der frontale Kraftangriff sollte einen Sturz und die seitlichen Angriffspunkte sollten einen Schlag simulieren.

Aus beiden Artikeln sind neue Erkenntnisse in Bezug auf das Traumaverhalten eines zahnlosen Unterkiefers mit interforaminaler Implantatversorgung zu gewinnen. Für beide Studien wurde die FEM als Simulationsmethode für die biomechanischen Traumaanalysen gewählt.

3. Zusammenfassung

Durch die Ergebnisse aus der biomechanischen Studie ließ sich zeigen, dass durch eine frontale Kraftapplikation in allen Unterkiefermodellen – sowohl mit interforaminalen Implantaten als auch ohne – die höchsten Spannungswerte immer im Bereich des Kondylenhalses verursacht werden. Auffallend ist jedoch, dass die Spannungswerte im Kondylenhals in den Modellen mit Implantaten (prothetisch verbunden und unverbunden) signifikant geringer waren als im (imlantatfreien) zahnlosen Modell. Für diese Unterschiede hinsichtlich des Stressmusters im Kondylenhals zwischen implantatversorgten und implantatunversorgten Unterkiefermodellen kann die Absorption der kinetischen Energie und der Spannung im Bereich um die inserierten interforaminalen Implantate verantwortlich gemacht werden.

Anhand der Ergebnisse wird aber auch deutlich, dass durch die Simulation einer frontalen Kraftapplikation in beiden Implantatmodellen ein erhöhtes Spannungsaufkommen und somit ein erhöhtes Frakturrisiko im Bereich um des Foramen mentale entstehen. Hier scheinen das Zusammenwirken von Energieabsorption und Deformationsveränderungen des implantatversorgten Unterkiefers sowie der anatomische Schwachpunkt der knöchernen Region um das Foramen mentale eine wesentliche Rolle zu spielen.

Aus der biomechanischen Analyse der frontalen Traumasimulation ergibt sich zudem, dass im Bereich der Symphyse im Unterkiefermodell mit unverbundenen interforaminalen Implantaten höhere kortikale Belastungswerte auftreten als im Unterkiefermodell mit verblockten Implantaten. Eine (prothetische) Implantatverblockung geht somit mit der Ausbildung von vorteilhaften, geringeren Belastungswerten und einem geringeren Frakturrisiko im Bereich der Symphyse einher. Das

Spannungsaufkommen in der Symphyse in einem verblockten Implantatmodell ist dabei mit dem Belastungsniveau eines insgesamt implantatfreien zahnlosen Unterkiefermodells vergleichbar.

Es kann davon ausgegangen werden, dass die bewertete Belastung auf die prothetisch-schienende Suprastruktur/die Gerüstvorrichtungen und somit nicht – wie beim prothetisch unverbundenen implantantversorgten Modell – vollständig in den symphysealen kortikalen Knochenbereich übertragen wird. Die Verwendung einer prothetischen Implantatverblockung scheint nicht nur als geeigneter Behandlungsansatz für den zahnlosen Unterkiefer zu dienen, sondern darüber hinaus eine Reduktion des Frakturrisikos im Bereich der Symphyse unter frontalen traumatischen Bedingungen zu ermöglichen.

Zusätzliche Untersuchungen über drei unterschiedliche Lokalisation von Traumaapplikation haben ergeben, dass das prothetische Verbinden der interforaminalen Implantate nur bei frontalen Traumasituationen einen vorteilhaften Einfluss auf die Stressabsorption hat.

Die biomechanische Analyse zeigt dabei, dass die anteriore Schienung von vier interforaminalen Implantaten – wie sie klinisch im ‘All-on-four‘-Konzept verwendet wird – bei direkter lateraler (traumatischer) Krafteinwirkung im Unterkieferkörperbereich und im Unterkieferwinkel keinen Einfluss auf die Spannungsverteilung in diesen Bereichen hat. In diesen Situationen von Krafteinwirkungen bleiben das Belastungsniveau und das Frakturrisiko auf den Ort der Krafteinwirkung beschränkt.

4. Abstract (English)

The results of the biomechanical study demonstrate that the application of frontal force in all mandibular models – both with and without interforaminal implants – always indicates the highest stress values in the area of the condylar neck. However, notably, the stress values in the condylar neck are significantly lower in the models with implants (both prosthetically connected and unconnected) than in the (implant-free) edentulous model. These differences in the stress pattern in the condylar neck between implant-supported and implant-unsupported mandibular models can be attributed to the absorption of kinetic energy and stress in the region around the inserted interforaminal implants.

However, the results also demonstrate that the simulation of frontal force application in both implant models leads to increased stress and thus an increased risk of fracture in the area around the mental foramen. The interaction of energy absorption and deformation changes in the implant-supported mandible and the anatomical weakness of the bony region around the mental might be considered for significance.

The biomechanical analysis of the frontal trauma simulation also shows that higher cortical load values occur in the symphysis region in the mandibular model with unconnected interforaminal implants than in the mandibular model with splinted implants. (Prosthetic) implant splinting is thus associated with the formation of advantageous lower load values and a lower risk of fracture in the symphysis region. The stress level in the symphysis in a splinted implant model is comparable to the stress level in an implant-free edentulous mandible model.

The evaluated load can be assumed to be transferred to the prosthetic-splinting superstructure or framework devices and, therefore, not completely into the symphyseal cortical bone region, as in the prosthetically unconnected implant-supported model. The use of prosthetic implant splinting not only appears to be a suitable treatment approach for the edentulous mandible but also to reduce the risk of fracture of the symphysis under frontal traumatic conditions.

Additional studies on three different localizations of trauma application have shown that the prosthetic connection of interforaminal implants only has a beneficial effect on stress absorption in frontal trauma situations.

The biomechanical analysis reveals that the anterior splinting of four interforaminal implants – as clinically used in the “all-on-four” concept – with the application of direct lateral (traumatic) force in the mandibular body region and mandibular angle does not influence the stress distribution in these areas. In these situations of force application, the stress level and fracture risk remain restricted to the site of force application.

5. Publikation I

The Effects of Frontal Trauma on 4 Interforaminal Dental Implants:

A 3-Dimensional Finite Element Analysis Comparing

Splinted and Unsplinted Implant Configurations

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Holberg Christof

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The Effects of Frontal Trauma on 4 Interforaminal Dental Implants: A 3-Dimensional Finite Element Analysis Comparing Splinted and Unsplinted Implant Configurations

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Purpose: With increased implant-prosthodontic rehabilitation for mandibular edentulism together with the increased life expectancy and activity of the elderly population, a greater number of implant patients may be at risk of facial trauma. The aim of this 3-dimensional (3D) finite element analysis (FEA) was to evaluate the biomechanical effects of the edentulous mandible (EM) with and without implants exposed to frontal facial trauma including assessment of the fracture risk of different mandibular areas.

Materials and Methods: By use of a 3D FEA, our experimental study design comprised 3 different models (model A, EM; model B, EM with 4 unsplinted interforaminal implants; and model C, EM with 4 splinted interforaminal implants) exposed to application of symphyseal frontal trauma of 2 MPa. In 3 defined regions of interest (ROIs) (ROI 1, symphyseal area; ROI 2, mental foraminal area; and ROI 3, condylar neck), the effective stress was measured at predefined sites in the superficial cortical mandibular area. The stress values of all ROIs evaluated were compared within each model (intramodel) as well as between the 3 models (intermodel).

Results: For all models evaluated, a frontal traumatic load generated the highest stress levels in the condylar neck. However, for both models with implants (models B and C), the stress values were reduced significantly ($P < .01$) in the condylar neck region (ROI 3) but increased significantly ($P < .001$) in the mental foraminal area (ROI 2) compared with the EM model without implants. For the symphyseal area (ROI 1) evaluated, the unsplinted 4-implant model (model B) presented significantly ($P < .001$) higher stress values than the splinted implant model (model C) when frontal forces were applied.

Conclusions: Regardless of splinting or lack of splinting of 4 interforaminal implants, force absorption or transmission may shift the predominant risk factor from the condylar neck to the corpus or foramen mandibulae. However, splinting of 4 interforaminal implants may be beneficial in reducing the risk of bone fracture by providing protection for anterior risk situations.

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Mandibular fractures represent one of the most common types of facial injuries and are predominately related to vehicular accidents, violent crimes, injuries, sports injuries, and work accidents.[1-3] According to several epidemiologic studies, fractures of the atrophic edentulous mandible are fairly common in elderly persons, in whom atrophy and weakening tend to occur as a result of reduced vascularity and decreased blood flow.[3-7]

The application of dental implants has become a well-accepted standard treatment modality for oral rehabilitation of edentulous mandibles.[8,9] According to the results of several meta-analyses, individual studies, and consensus statements, the use of 2 interforaminal implants has been postulated as a standard treatment procedure for stabilization of an implant-retained overdenture.[10-12] In addition, numerous studies have reported that placement of 4 interforaminal implants used for either fixed or removable denture anchoring provides more denture (occlusion) stability, denture retention, and patient satisfaction than removable 2-implant–retained restorations.[13-15] Therefore, the increasing use of 4 connected interforaminal implants—for either fixed implant-supported prostheses in the widely accepted "all-on 4" concept or milled bars—has received increased attention within the wide range of different implant-prosthodontic rehabilitation modalities.[14-16]

Considering the fact that the use of dental implants will continue to increase because of substantial clinical implant-prosthodontic advancements, maxillofacial surgeons will encounter an increased rate of maxillofacial trauma in patients with previous dental implant treatment. Dental implants and trauma are rarely reported covariables evaluated in edentulous patients.[17,18] Although there are only isolated reports of mandibular fractures induced by or occurring during or after an implant placement procedure, there is still a lack of information on how osseointegrated dental implants may influence the stress modulation of an edentulous mandible in the presence of traumatic forces.[17,18]

In the scarce literature available, only Kan et al[19] and Ayali and Bilginaylar,[20] in separate studies, have reported on unsplinted implants exposed to traumatic situations using finite element analysis (FEA). According to their findings, a more beneficial stress modulation was found for implants placed in the lateral incisor region than for those placed in the canine region when frontal trauma was present.[19,20] However, no study to date has evaluated and compared the effect on interforaminal implants with or without splinting exposed to frontal trauma. Moreover, there is no information available describing whether implant splinting may be advantageous and would have a beneficial effect serving as external fixation or whether this configuration would alter the fracture patterns in a favorable or unfavorable manner.[21,22] Assuming that splinting 4 interforaminal implants may provide biomechanical benefits, clinicians will prefer splinting the implants, especially in at-risk patients for whom traumatic situations may be expected. Thus, patients at risk, that is, patients with falls induced by syncope as a result of cardiovascular or neurologic disorders, as well as elderly patients with high physiological activity levels, may benefit from the splinting technique as it will provide for a more favorable fracture pattern than other treatment modalities.

On the basis of previous studies and considering the lack of clinical data, this topic of interest needs to be evaluated using FEA.[19,20,23] It must be pointed out that the use of FEA has already become widely accepted and features a noninvasive tool, providing valuable results for estimating different parameters of the complex biomechanical behavior of the mandible.[19,20,23]

The aim of this 3-dimensional (3D) FEA study was to evaluate and to compare the biomechanical effects of either a splinted or unsplinted implant configuration of 4 interforaminal implants inserted in an edentulous mandible in a setting with frontal facial trauma. It was initially hypothesized that 4 splinted implants would provide for a more beneficial stress pattern than unsplinted implants in edentulous mandibles exposed to frontal facial trauma for areas with a predilection for fractures such as the mandibular symphysis, mandibular corpus, and condylar neck region.

Materials and Methods

DATA ACQUISITION

This study was conducted using a scanned computed tomography image of a completely edentulous mandible (ProMax; Planmeca, Helsinki, Finland). The raw image data were exported to a computer in DICOM (Digital Imaging and Communications in Medicine) format with a pixel resolution of 651 × 651, at 96 kV, and with increment slices of 0.2 mm in thickness. Acquisition of the anatomic data of the cortical and cancellous mandibular structures was performed by manual segmentation using Amira software (Visage Imaging, Berlin, Germany). By merging point clouds (Delaunay triangulation) to 3D polygon meshes, morphologically identical models of the cancellous and cortical mandible were generated (Fig 1).[24-26] This study was approved by the Ludwig Maximilian University of Munich (NumBioLab), and all participants signed an informed consent agreement. The study design for FEA simulation did not require ethical approval. We used no human (patient) or animal in vivo model when conducting the study.

COMPUTER-AIDED DESIGN MODELING

The resulting rough polygon mesh model was converted to DXF (drawing exchange format) and exported to the reverse-engineering software Geomagic Wrap (Geomagic Studio, Rock Hill, SC) to generate a smooth computer-aided design (CAD) model of the mandible.[27] All constructible elements of the model, such as implants, abutments, and the suprastructure, were designed virtually using established CAD tools in Inventor software (Autodesk, Munich, Germany).[24-26] Dental implants were modeled based on the dimensions of a Camlog Screw Line Promote dental implant (Camlog, Winsheim, Germany) 3.8 mm in diameter and 13 mm in length. Implant modeling included detailed assessments as external thread as well as internal housing. In addition, corresponding abutments were modeled based on imported Camlog CAD data.

Consecutively, 4 implants were placed in the interforaminal region in the model of the edentulous mandible. The 2 anterior implants were positioned vertically at the lateral incisor region, and both posterior implants were placed parallel to the anterior implants in the region of the first premolar about 5 mm mesial to the mental foramen.[28] The 2 anterior implants were placed with an interimplant distance of 13 mm, and the distance of the lateral implants to the anterior had a constant dimension of 12.5 mm as previously reported.[28]

The model with 4 incorporated interforaminal implants was duplicated, and additional modeling was performed with a splinted suprastructure. The suprastructure corresponded to a splinted fixed construction of a titanium framework similar to a bar or fixed implant-prosthodontic reconstruction.

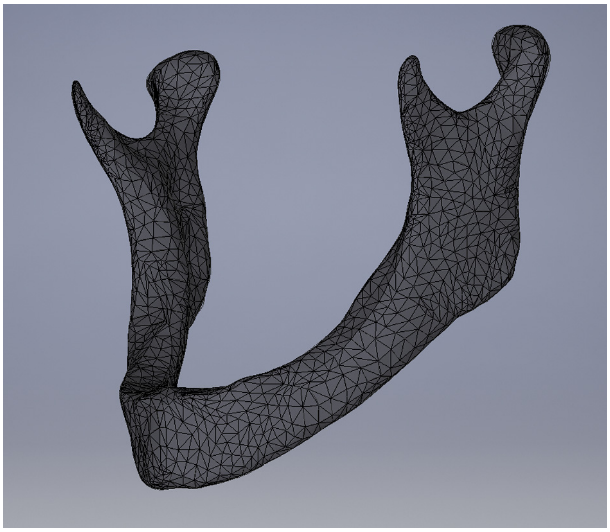

FIGURE 1. Three-dimensional polygon meshes of model of edentulous mandible.

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All solid models were combined by Boolean operations (addition and subtraction) using Inventor software.[24-26] The experimental study design consisted of 3 different models: model A, edentulous mandible without dental implants (Fig 2A); model B, edentulous mandible with 4 unsplinted interforaminal implants (Fig 2B); and model C, edentulous mandible with 4 splinted interforaminal implants (Fig 2C).

FINITE ELEMENT METHOD MODELING AND FORCE SIMULATION

The resulting models (models A, B, and C) were imported into the finite element method Simulation section of Inventor software and cross-linked in 3 dimensions to corresponding finite element method models.[8] FEA represents a mathematical technique that allows complex geometries to be reduced into a finite number of elements (voxels), each with a simple geometry. The elements used for cross-linking were parabolic tetrahedrons with 4 nodes at each corner and 1 node in the center.[20,24-26] The numbers of tetrahedrons and noduli of the 3 models are presented in Table 1.

The model was based on the mechanical properties of cortical bone and cancellous bone, which were characterized as isotropic and elastic structures, respectively. Material properties of the materials that were simulated were taken from the literature and are presented in Table 2.[23] The high mechanical and dynamic reliability of titanium used for the restoration with high tensile strength ensured an intact and stabile restoration under simulated trauma.[29]

On the basis of the studies of Kan et al[19] and Ayali and Bilginaylar,[20] a static force of 2,000 N was applied frontally to the symphyseal mandibular region (Fig 3) for each model simulated. The condyles were constrained to prevent free movement in the x-, y-, and z-axes during traumatic loading to simulate the presence of masticatory muscles during trauma.[30-32] Contact between the implants, abutments, and suprastructure was defined as fixed, and the bone-implant interfaces were treated as fully bonded (ie, implants with 100% osseointegration).

STRAIN MEASUREMENTS

For each model, the cortical stress pattern was evaluated in detail for 3 regions of interest (ROIs) representing areas with a predilection for mandibular fractures as described in previous studies.[20,33] The 3 ROIs showed a homogeneous area dimension of 15 × 7 mm and were

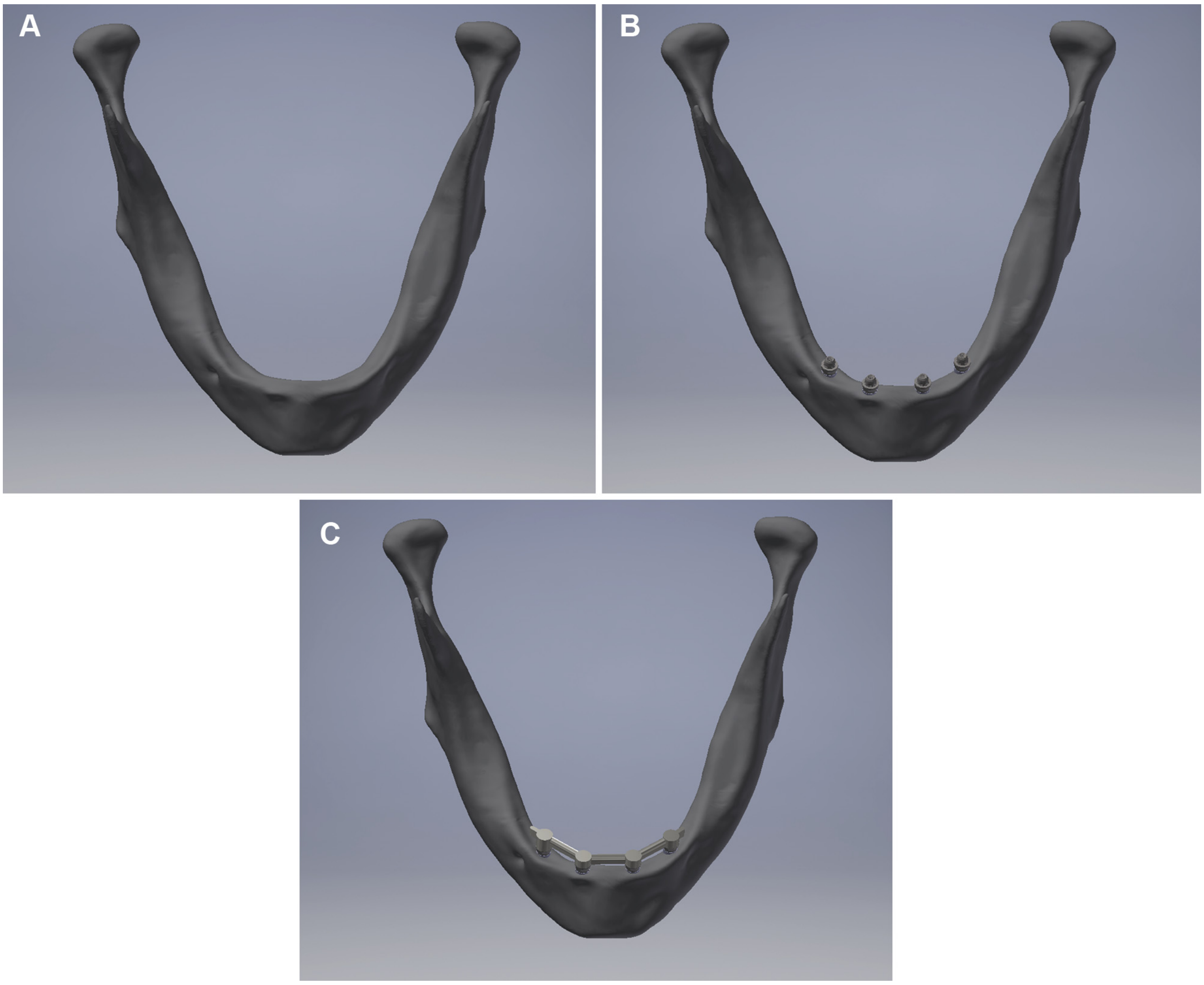

FIGURE 2. Three-dimensional models without dental implants (model A) (*A*), with 4 unsplinted interforaminal implants (model B) (*B*), and with 4 splinted implants (model C) (*C*).

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defined and located as follows (Fig 4): ROI 1, region between the anterior implants at the cranial–mandibular crest border (symphyseal area); ROI 2, region posterior to the lateral implants in the mental foraminal area; and ROI 3, region at the incisura mandibulae in the condylar neck of the mandible.

Table 1. NUMBERS OF TETRAHEDRONS AND NODULI OF 3 MODELS

Model	Noduli	Elements
A	233,532	140,820
B	814,207	529,136
C	818,925	532,064

Note: Model A is an edentulous mandible without implants; model B, edentulous with 4 unsplinted interforaminal implants; and model C, edentulous with 4 splinted interforaminal implants.

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Table 2. ELASTIC MODULUS AND POISSON RATIO OF STUDY MATERIALS[20,23]

Material	Elastic Modulus (*E*), MPa	Poisson Ratio
Cortical bone	13,700	0.33
Cancellous bone	1,370	0.3
Titanium alloy (Ti-6Al-4V)	110,000	0.35

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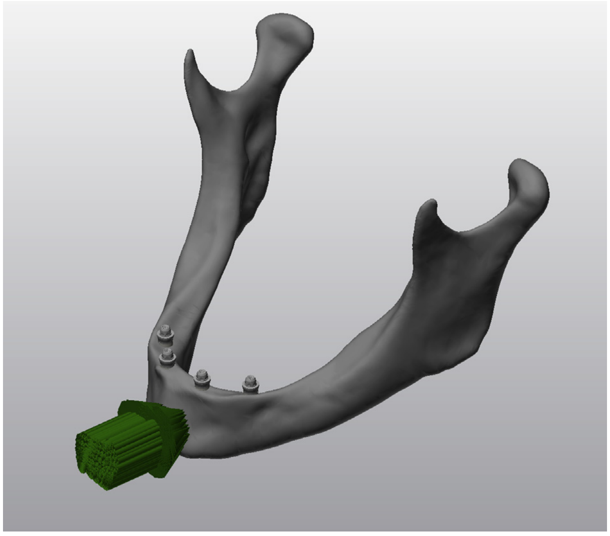

FIGURE 3. Simulation of frontal symphyseal trauma (2,000 N).

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In the defined ROIs, the effective stress was measured at predefined control points in the superficial cortical mandibular areas. The location and number of measured control points for ROIs 1, 2, and 3 were identical for models A, B, and C. The control points corresponded to the noduli of the measured tetrahedrons and presented defined von Mises stress values.

STATISTICAL ANALYSIS

Parameters (von Mises stress values) of ROIs 1, 2, and 3 and models A, B, and C were tabulated as mean ± standard deviation. For the comparison of normally distributed continuous variables within each region, repeated analysis of variance or—in the case of non-normality (verification with the Kolmogorov-Smirnov test with Lilliefors correction)—Friedman rank analysis of variance was used. For post hoc comparisons, Bonferroni-adjusted paired *t* tests or Conover post hoc tests were used. The type I error was set at 5% (2-sided) without adjustment for multiple testing except for the post hoc comparisons, and $P < .05$ was considered statistically significant. Intraindividual (intramodel) comparisons (ROI 1 vs ROI 2 vs ROI 3) for each model (A, B, and C), as well as interindividual (intermodel) comparisons (ROI 1, 2, or 3 for model A vs ROI 1, 2, or 3 for model B vs ROI 1, 2, or 3 for model C), were performed. For statistical analysis, the statistical computing software R (version 3.5.2; R Foundation for Statistical Computing, Vienna, Austria; http://www.R-project.org) was used.

Results

FEA STRESS VALUES: ROIs

Figure 5 shows the stress values evaluated at ROIs 1, 2, and 3 for models A, B, and C subjected to frontal application of 2 MPa of traumatic stress. Detailed data for all models and ROIs (ROIs 1, 2, and 3) expressed as mean and standard deviation values are presented in Table 3.

INTRAMODEL ROI STRESS VALUES

Figure 6 presents the intramodel evaluation and shows the highest stress values at ROI 3 at the condylar neck for each of the 3 FE models (mean von Mises stress values of 539, 281, and 277 MPa). For each

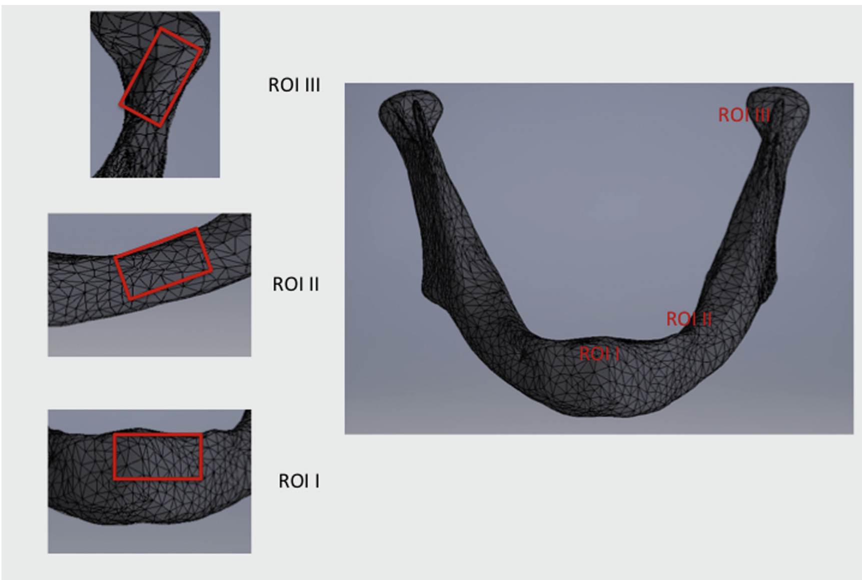

FIGURE 4. Regions of interest (ROIs) (*rectangles*): anterior mandible (ROI 1), mental foraminal area (ROI 2), and condylar neck (ROI 3).

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model (models A, B, and C), the stress values measured at the condylar neck (ROI 3) differed significantly ($P < .001$) from those measured in the symphyseal area (ROI 1) and mental foraminal area (ROI 2) (Table 3).

For the edentulous mandible without implants (model A; Fig 5A), the lowest stress pattern was seen in the mental foraminal area (ROI 2, 43.24 ± 16.03 MPa; Table 3). In contrast, the lowest stress values for the unsplinted implant model (model B, 91.28 ± 26.90 MPa) and the splinted implant model (model C, 72.98 ± 22.35 MPa) were noted in the symphyseal region (ROI 1; Figs 5B, C; Table 3). The intramodel stress values evaluated and compared between the symphyseal area and mental foraminal area (ROI 1 vs ROI 2) differed significantly ($P = .003$) for the implant-less model (model A) but did not differ for the 2 models with endosteal dental implants (unsplinted model [model B] and splinted model [model C]; $P > .999$ and $P = .410$, respectively; Table 3).

INTERMODEL ROI STRESS VALUES

Figure 7 shows the stress values expressed as box plots of ROIs 1, 2, and 3 for the intermodel comparison of ROIs. For the symphyseal ROI (ROI 1; Fig 7A), the model with unsplinted interforaminal implants (model B; mean ± standard deviation, 91.28 ± 26.90 MPa) showed a significantly higher stress value than the edentulous mandible without implants (model A, 71.22 ± 19.79 MPa; $P < .001$) and the model with 4 splinted interforaminal implants (model C, 72.98 ± 22.35 MPa). The stress value of the edentulous mandible without implants (model A) was similar to that of the edentulous mandible with 4 splinted

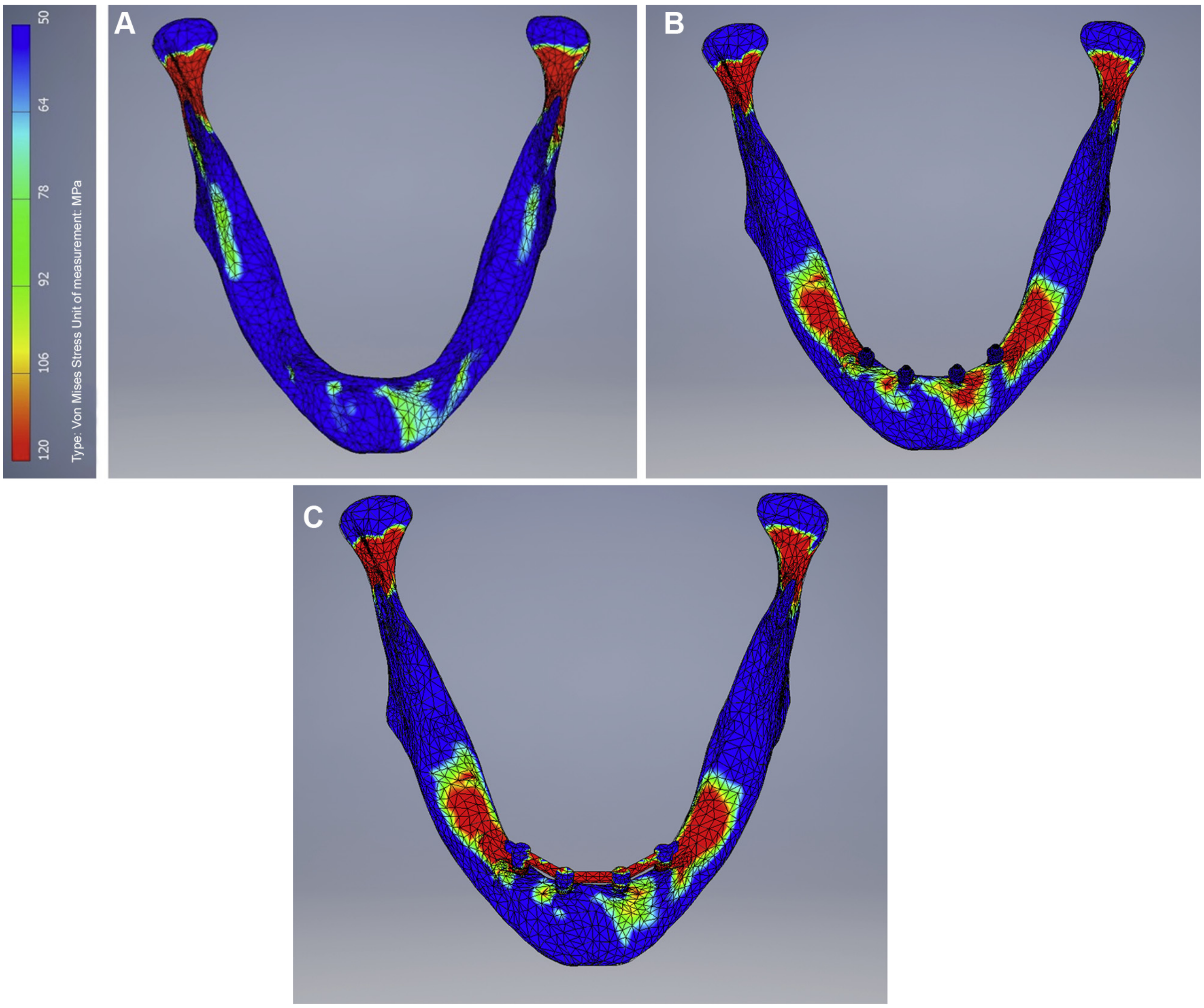

FIGURE 5. Stress values at regions of interest 1, 2, and 3 for model A (*A*), model B (*B*), and *C*, model C (*C*).

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Table 3. DETAILED DATA FOR ALL MODELS AND ROIS

	Mean ± SD (MPa)	*P* Value
ROI 1		<.001
Model A	71.22 ± 19.79	
Model B	91.28 ± 26.90	
Model C	72.98 ± 22.35	
ROI 2		<.001
Model A	43.24 ± 16.03	
Model B	95.60 ± 36.17	
Model C	94.50 ± 35.21	
ROI 3		<.001
Model A	539.00 ± 312.07	
Model B	281.64 ± 151.60	
Model C	277.02 ± 150.36	
Interindividual comparison (for each ROI)		
Model A vs model B		
ROI 1		<.001
ROI 2		<.001
ROI 3		<.001
Model A vs model C		
ROI 1		.580
ROI 2		<.001
ROI 3		<.001
Model B vs model C		
ROI 1		<.001
ROI 2		.950
ROI 3		.587
Intraindividual comparison (for each model)		
ROI 1 vs ROI 2		
Model A		.003
Model B		>.999
Model C		.410
ROI 1 vs ROI 3		
Model A		<.001
Model B		<.001
Model C		<.001
ROI 2 vs ROI 3		
Model A		<.001
Model B		<.001
Model C		<.001

Abbreviations: ROI, region of interest; SD, standard deviation.

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interforaminal implants (model C), without any significant difference ($P = .687$; Fig 7A, Table 3).

Figure 7B shows von Mises stress values evaluated in ROI 2. In ROI 2, the unsplinted implant model (model B) and splinted implant model (model C) showed significantly higher stress values ($P < .001$) than the edentulous mandible without implants (model A, 43.24 ± 16.03 MPa; Table 3). The stress values analyzed did not differ between the unsplinted implant model (model B, 95.60 ± 36.17 MPa) and splinted implant model (model C, 94.50 ± 35.21 MPa) for ROI 2 ($P = .950$; Fig 7B, Table 3).

Detailed von Mises stress values (box plots) with intermodel comparisons of ROI 3 are shown in Figure 7C. The stress values evaluated at ROI 3 (condylar neck) were significantly lower in the unsplinted model (model B) and the splinted implant model (model C) compared with the model without implants (model A). However, the stress values in ROI 3 did not differ between the unsplinted and splinted implant models (model B vs model C, $P = .687$; Fig 7C).

Discussion

Today, the use of dental implants represents a standard treatment method in the implant-prosthetic rehabilitation of the edentulous mandible.[8-16] In addition, several epidemiologic investigations have shown that an increasing number of elderly implant patients live increasingly active lives and take part in numerous sporting and leisure-time activities.[34,35] The mandible is the bone with the highest likelihood of injury in the event of a facial trauma.[1-3] With the increasing use of dental implants, it therefore must be assumed that an increasing number of elderly patients with implant-based rehabilitation of an edentulous mandible may be faced with such traumatic situations.[3-5]

Overall, the topic of dental implants in the case of facial trauma has been covered by very few investigations, and studies in the literature and available data are very limited, with the exception of some isolated reports on fractures induced by implant insertion.[17,18] As the available studies investigating the impact of frontal trauma on implant restorations have used FEA, the validity and applicability of this methodology also appear to be justified for our study.[19,20,33]

In this context, the initial hypothesis of this experimental study—that is, splinting of 4 interforaminal implants would show a positive effect on the stress pattern and consequently on the fracture risk—could only be confirmed for certain ROIs investigated. Overall, this FEA found that frontal trauma in both the atrophic edentulous mandible without any implants and the edentulous mandible with splinted or unsplinted implants invariably showed the highest stress values in the region of the condylar neck. These results are in accordance with the experimental FEA findings of Santos et al[33] and Ayali and Bilginaylar,[20] who also were able to show that with a frontal trauma, the highest stress values are seen in the condylar neck. The finding of the highest stress values in the condylar neck may be attributed to the mechanical response, related to bone strength and mechanical properties, such as thickness, density, and stiffness, which are

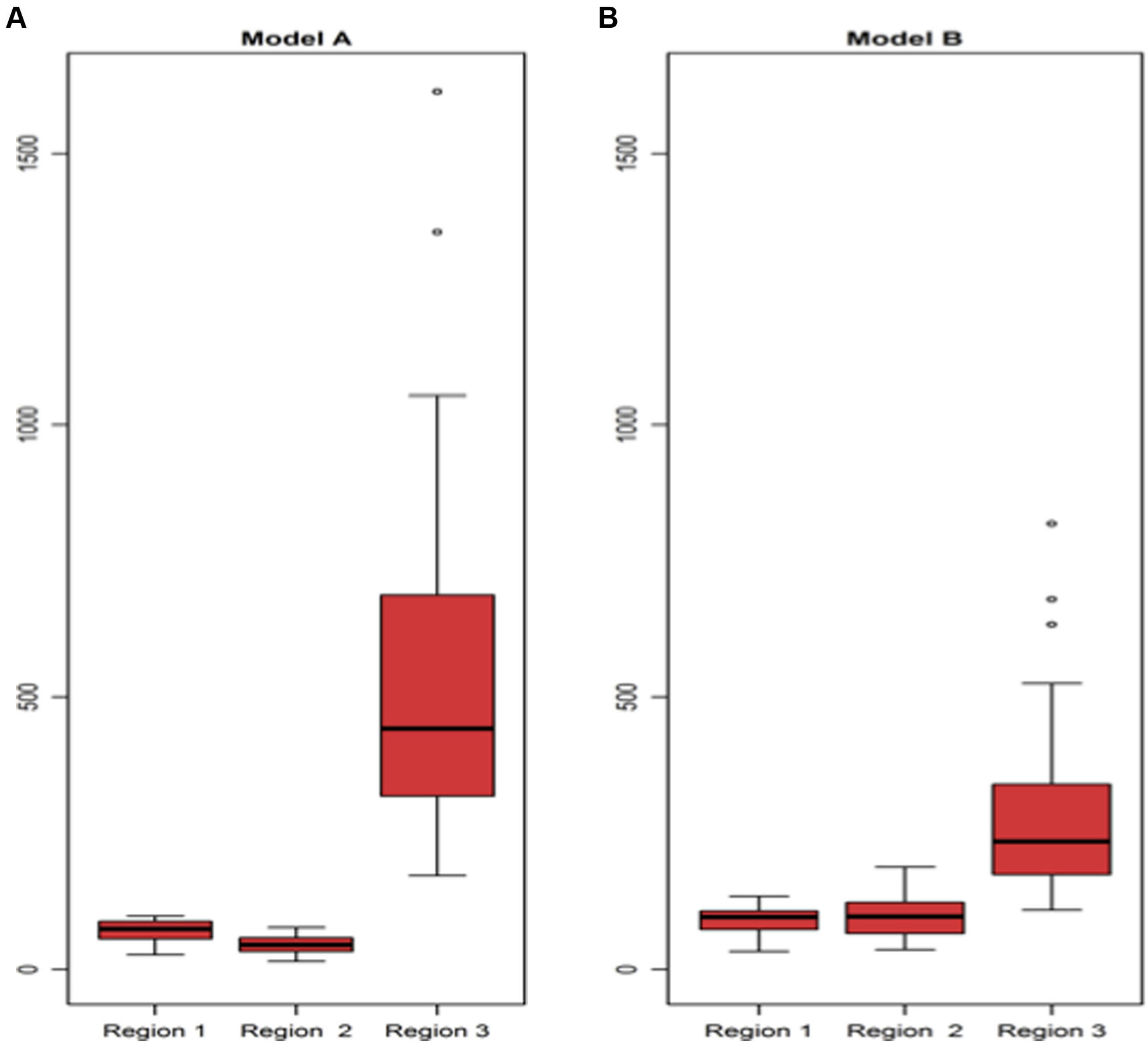

FIGURE 6. Evaluation of stress values of regions of interest 1, 2, and 3 for model A (*A*), model B (*B*), and model C (*C*). *Box bottom* indicates lower quartile (Q1), *box top* indicates upper quartile (Q3), *box length* indicates interquartile range (IQR), *box middle* indicates median (Q2), *whiskers* indicates variability outside lower and upper quartile based on 1.5 × IQR, and *circles* indicates values outside the range defined by *whiskers*. **(Fig 6 continued on next page.)**

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variable along the length of the mandible.[31-33,36] According to the statements of Schwartz-Dabney and Dechow,[36] the bone is narrower in the condylar neck, so this region shows less bone strength and is more at risk of fracture. However, as a striking feature, the highest stress values in all models were seen in the condylar neck, whereas the cortical stress values in the condylar neck were significantly reduced in both mandibular models with implants versus those in the model with an edentulous mandible without implants. It may be assumed that in the event of a frontal trauma in the atrophic implant-restored mandible, the force stress in the area of the symphysis and in the mental foraminal area close to the bone structure surrounding the implants will be absorbed and thus exert only a reduced effect in the region of the condylar neck.[37-39] An implant-prosthetic reconstruction using 4 interforaminal implants, regardless of whether splinted or unsplinted, may account for a stress reduction in the condylar neck and, thus, appears to be beneficial for a reduced fracture risk in the area of the condylar neck. Consequently, the initial hypothesis that implant-anchored rehabilitation would have a beneficial effect regarding the stress values and would be associated with a beneficial fracture risk for the condylar neck region could be confirmed.

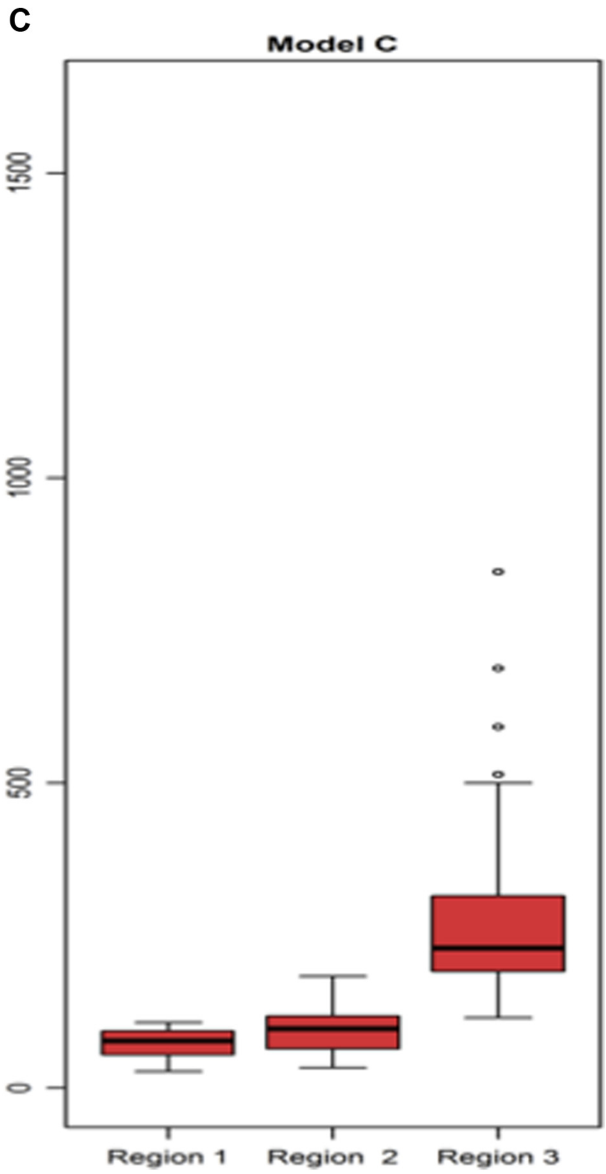

FIGURE 6 (cont'd).

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However, in obvious contrast to the initial hypothesis, an increased stress situation in the mental foraminal area was seen with both implant models. The fact that increased stress values in the mental foraminal area were seen as a consequence of a symphyseal stress force has already been described in the trauma study of Santos et al.[33] In addition, several clinical and experimental studies have shown that the region of the mental foramen may be considered a weak point with frequent fracture events.[3-5,23,40,41] With an anterior implant insertion, the interaction among acceleration, mass inertia of the implants, and deformational changes of the jawbone will provide for increased cortical stress conditions with an added fracture risk in the region of the mental foramen.[25,33,34]

An interesting finding in our investigation was the variable behavior of the stress values in the region of the symphysis evaluated by FEA between the models with 4 splinted and unsplinted interforaminal implants. Under simulation of a frontal trauma, it was noted that with unsplinted implants, increased stress levels—and thus an increased fracture risk—in the region of the symphysis could be seen compared with an implant-free edentulous mandible or a mandible with splinted implants. The fact that, in situations with an applied frontal trauma, increased symphyseal stress levels in the bone region and in the region of the implants may be seen has already been described by Kan et al[19] and Ayali and Bilginaylar[20] in separate FEA studies and could be confirmed in our investigation. The results of our experimental investigation also confirm previous clinical results showing that dental implants will weaken the bone structure and induce fracture areas with a higher risk potential when traumatic forces are applied.[17,18,42]

In contrast, the results of our study additionally show that splinting of the 4 interforaminal implants will provide for a virtual readjustment of the cortical stress values in the region of the symphysis to those seen with an atrophic implant-free jawbone and thus provide for more beneficial load conditions. For the symphyseal region, the assumption that splinting will provide for more beneficial symphyseal stress values than in the unsplinted setting could be confirmed. This finding might be attributed to the fact that in the model with 4 splinted implants, the stress values evaluated were transferred to the splinting bar and/or framework devices and were not located in the cortical bone area as in the unsplinted model. Thus, splinting of 4 interforaminal implants may be considered synonymous with external fixation providing for a beneficial effect on bone stress values and fracture risk.[21,22,43] It is a well-known fact that external pin fixation represents a conventional method for the stabilization of fracture segments and has been used in specific situations in traumatology.[21,22,43] Thus, without any such initial intention, a prosthesis bar or the supporting framework of a fixed full-arch prosthesis will provide appropriate external splinting and serve as a therapeutic approach for a potential fracture.[15,16,22] Therefore, it can be considered of clinical relevance that splinting as such will serve as an appropriate treatment approach and obviously appears to provide for a reduction in the fracture risk in the area of the symphysis.[21,22,43]

In summary and within the limitation of the study, the findings showed that interforaminal implants reduce the stress levels and the fracture risk in the region of the condylar neck and increase them in the mental foraminal area. Absorption of stress in the area of the implants is considered responsible for and consequently also associated with increased stress

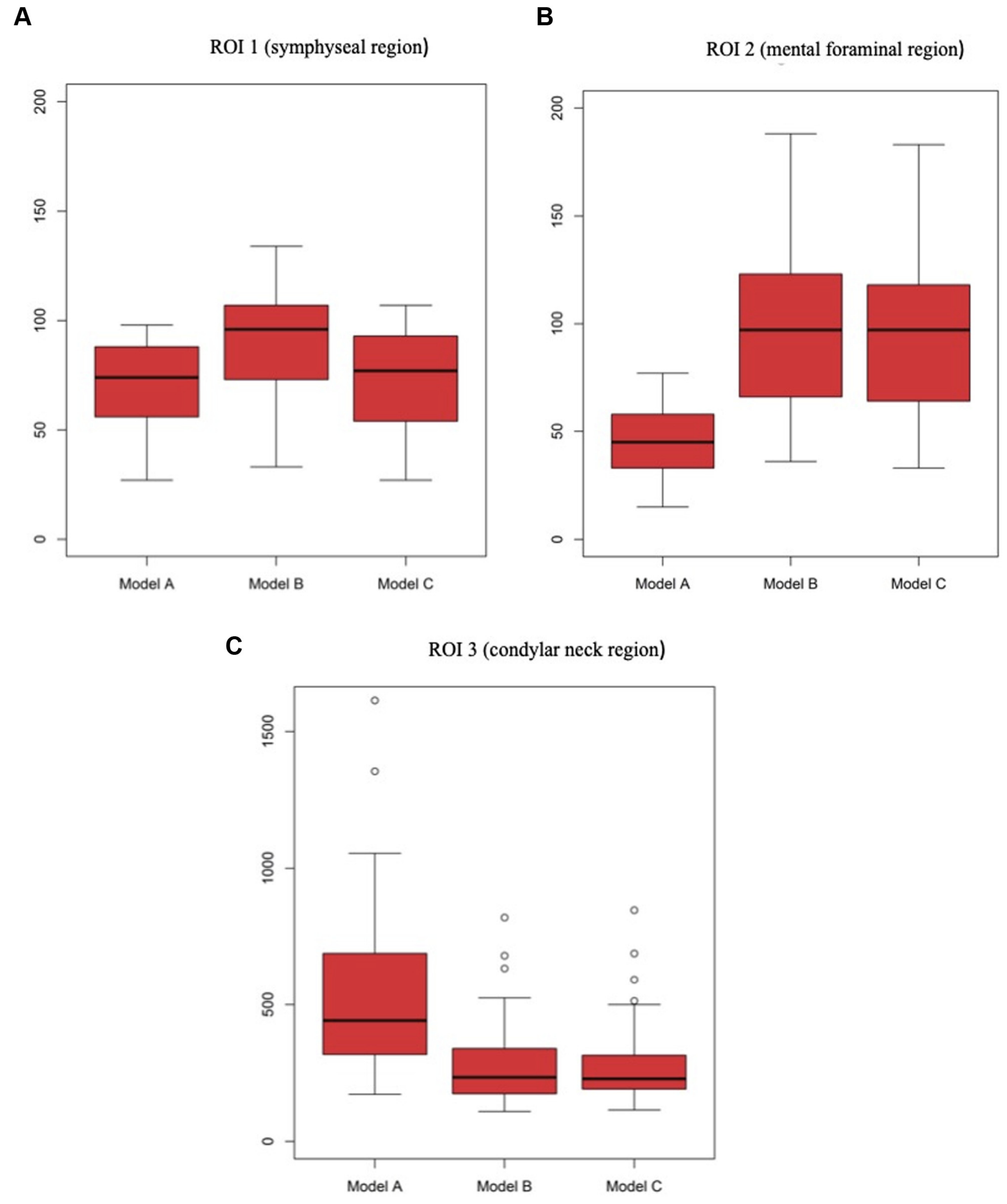

FIGURE 7. Intermodel comparison of stress values of region of interest (ROI) 1 (*A*), ROI 2 (*B*), and ROI 3 (*C*). *Box bottom* indicates lower quartile (Q1), *box top* indicates upper quartile (Q3), *box length* indicates interquartile range (IQR), *box middle* indicates median (Q2), *whiskers* indicates variability outside lower and upper quartile based on 1.5 × IQR, and *circles* indicates values outside the range defined by *whiskers*.

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values in the mandibular corpus.[23,41] In addition, we noted that 4 unsplinted interforaminal implants will increase the cortical stress values in the region of the symphysis and may increase the fracture risk, whereas implant splinting provides a beneficial and protective effect on the stress situation.

Considering the limitations of the study, it must be pointed out that this study had an experimental design and represented only changes in the objects being evaluated. In addition, because the risk of mandibular fracture is predominately influenced by the varying degrees of mandibular atrophy and mandibular bony quality,[1-3,44,45] a detailed quantitative statement as to the extent to which implant placement and consequently implant splinting might protect or negatively affect several regions cannot be determined. However, the experimental findings showing changes in the fracture patterns and relocation of potential injuries to sites allowing better surgical access and/or facilitated treatment procedures suggest specific advantages for both clinicians and patients.[43-48] Reducing the risk of condylar neck fractures by implant splinting is of clinical significance considering that such fractures may frequently require higher efforts for surgical interventions and affect the recovery rate and postoperative care compared with fractures in the mandibular body and/or foramen area.[46,49,50] Hence, in the context of our findings, the clinical relevance assumed may refer to the preferential use of implant splinting in patients showing an increased risk of falls because of prevailing diseases or high physiological activity.[5,6,33]

Although FEA in the mandible under traumatic conditions has recently been shown as a reliable and accurate noninvasive method for studying biomechanical behavior in the literature and although the anterior mandible, as the site of implant placement in our study, shows a more homogeneous structure, the results of this FEA should nevertheless be interpreted with appropriate caution.[36-39]

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6. Publikation II

Edentulous mandible with four splinted interforaminal implants exposed to three different situations of trauma:

A preliminary three-dimensional finite element analysis

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ORIGINAL ARTICLE

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Edentulous mandible with four splinted interforaminal implants exposed to three different situations of trauma: A preliminary three-dimensional finite element analysis

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Abstract

Background/Aim: An increasing number of elderly patients with implant-prosthodontic rehabilitation of the edentulous mandible frequently show increased life activity, and consequently, a greater number of aged patients is at risk for maxillofacial trauma. The aim of this 3-dimensional (3D) finite element analysis (FEA) was to evaluate the biomechanical effects of the edentulous mandible (EM) with and without four splinted interforaminal implants exposed to three different trauma applications including assessment of different mandibular fracture risk areas.

Materials and Methods: In a 3D-FEA study design, EM with and without four splinted interforaminal implants were exposed to the application of 1000 N at the symphyseal, parasymphyseal, and mandibular angle region. On four pre-defined superficial cortical mandibular areas (symphysis region, mental foramen region, angle of mandible, and mandibular neck) representing regions of interest (ROI), the von Mises stresses were measured for the three trauma applications. For all ROIs, stress values were evaluated and compared for the different force application sites as well as between EM models with and without interforaminal implants.

Results: For EM with and without four splinted interformaninal implants, all traumatic loads generated the highest stress levels at the mandibular neck region. However, in the EM with four splinted interforaminal implants, an anterior symphyseal force application generated significantly (P < .01) increased stress values in the parasymphyseal (mental foramen) region than in EM without implants. For force applications at the parasymphaseal region (mental foramen) and at the angle of the mandible elevated, von Mises stress values were noted directly at the application sites without difference between edentulous mandibles with and without four interforaminal implants.

Conclusion: In an edentulous mandible model with four splinted interforaminal implants, the condylar neck and the mental foramen represent the predilectional risk areas for mandibular fracture for both anterior symphyseal and lateral parasymphyseal force application.

KEYWORDS
finite element analysis, four splinted interforaminal implants, stress value, trauma application

1 | INTRODUCTION

The use of dental implants has become a well-accepted treatment modality for oral rehabilitation of edentulous mandibles.[1–4] Although the use of two interforaminal implants has been postulated as a standard treatment procedure for stabilization of an implant-retained overdenture, the placement of four interforaminal implants used for fixed prostheses has been shown to provide more denture stability, denture retention, and patient satisfaction.[1,2,4–7] In addition, the use of four connected interforaminal implants for fixed mandibular prostheses as the widely accepted "all-on-4" concept has received increased attention within the wide range of different implant-prosthodontic rehabilitation modalities.[6–11]

The target group of patients for implant-prosthetic rehabilitation of edentulous jaws primarily includes the elderly population.[1,2,6–8] This elderly population has been shown to be physically highly active, and it may therefore be assumed that this active and agile group of elderly patients may be increasingly exposed to the risk of physical trauma.[12,13]

Considering that the use of dental implants will continue to increase due to significant clinical implant-prosthodontic advancements, maxillofacial surgeons will also encounter an increased rate of maxillofacial trauma in patients with dental implants.[14–16] As shown in several epidemiologic studies, mandibular fractures represent one of the most common facial injuries and they are predominately related to falls, motor vehicle accidents, violent crime, injuries, sports, and work accidents.[12,17–19] However, only scarce information is available on the evaluation of trauma in patients with dental implants.[20,21] Kan et al[20] and Ayali and Bilginayler[21] investigated unsplinted implants exposed to traumatic situations using finite element analysis. According to their findings, a more beneficial stress modulation was found for implants placed in the lateral incisor region than for those in canine regions when frontal trauma occurred.[20,21]

As only a few studies on trauma exposure in the edentulous jaw have been published, they are primarily experimental studies that are used for evaluation.[20–24] Finite Element Analysis (FEA) has become widely accepted as it features a non-invasive tool that provides valuable results for estimating different parameters of the complex biomechanical behavior of the mandible.[22–24] De Santos et al[23] used FEA to evaluate the edentulous mandible without dental implants and with application of frontal and/or lateral forces, and they found the main stress values were in the mandibular neck region and in all regions of force application.

In addition, there are only a small number of reports of mandibular fractures induced by, during or after implant placement procedures.[25–27] According to the findings of Torsiglieri et al[25] and Steiner et al[26] in an atrophic setting, dental implant placement may weaken the bony structures. In atrophic mandibles, fractures also tend to occur as a result of reduced vascularity and decreased blood flow. However, there is still a lack of information on how osseointegrated dental implants may influence the stress modulation of an edentulous mandible in the presence of traumatic forces.[23] To date, no study has evaluated the effect of splinted four interforaminal implants as used for fixed prostheses exposed to trauma applied to the symphysis, corpus, or angle of the mandible.

Therefore, the aim of this three-dimensional finite element analysis (3D FEA) study was to evaluate the biomechanical effects of an edentulous mandible treated with four splinted interforaminal implants exposed to three different types of trauma (symphyseal, corpus, and the angle of the mandible). It was initially hypothesized that increased cortical stress values representing a higher mandibular fracture risk will occur in the condylar neck as well as in the regions corresponding to the force application. In addition, it was assumed that four splinted interforaminal implants may increase the symphyseal stress values in a frontal trauma situation as a result of an implant-induced bone weakening.

2 | MATERIAL AND METHODS

Scanned computed tomography (CT) images of a 68-year-old male patient with a completely edentulous mandible (ProMax, Planmeca) served as the morphological basis for the FEM mandible models. The CT data selection was based on the patient's medical record status representing age-appropriate health and bone status without any morphological and mineralization variabilities. The generated raw image data with a pixel resolution of 651 × 651, 96 kV and increment slices of 0.2 mm in thickness were then exported to a computer in DICOM format. The anatomical data of cortical and cancellous mandibular structures were acquired by semi-automatic segmentation of CT layer using Amira software® (Visage Imaging). After cross-linking point clouds (Delauney triangulation) to three-dimensional polygon meshes, morphologically identical models of the cancellous and cortical mandible were generated (Figure 1).[28–30]

The resulting rough polymesh models were transformed to the reverse-engineering software Geomagic Wrap (Geomagic Studio) to generate a smooth computer-aided design (CAD) model of the mandible.[31]

Established CAD tools in Inventor™ software (Autodesk GmbH) was chosen for the virtual design of all constructable elements, such as suprastructure, abutments, and implants.[28–30] Dental implants and corresponding abutments were modeled on imported Camlog® CAD Data. The dimensions of 13 mm in length and 3.8 mm in diameter were selected for the implant models. Based on the detailed proportions of Screw-Line Promote + Dental Implants (tapered) (Camlog® Winsheim), the models included detailed assessments of the external thread and internal housing. The dimension of 1 mm in height and 3.8 mm in diameter was selected for the corresponding abutments, based on imported CT data.

Subsequently, four implant models were positioned in the interforaminal region of the model of the edentulous mandible. The two anterior implants were placed vertically in the lateral incisor region with an inter-implant distance of 13 mm. Both posterior implants were positioned parallel to the anterior implants in the region of the first premolar with a mesial distance of 5 mm to the mental foramen.[32] The distance of the posterior implants from the anterior ones had a constant dimension of 12.5 mm.[32] In relation to the neck of the implants selected including a machined collar of 0.4 mm, the implants were placed in a slight supracrestal position (0.4 mm) according to the manufacturer's instructions (Camlog® Winsheim). In addition, implants were placed in a horizontal direction representing adequate surrounding cortical and cancellous bone. The implants had a distance ranging from 0 mm (cervical regions) to 3.5 mm (apical regions) to the inner cortical wall.

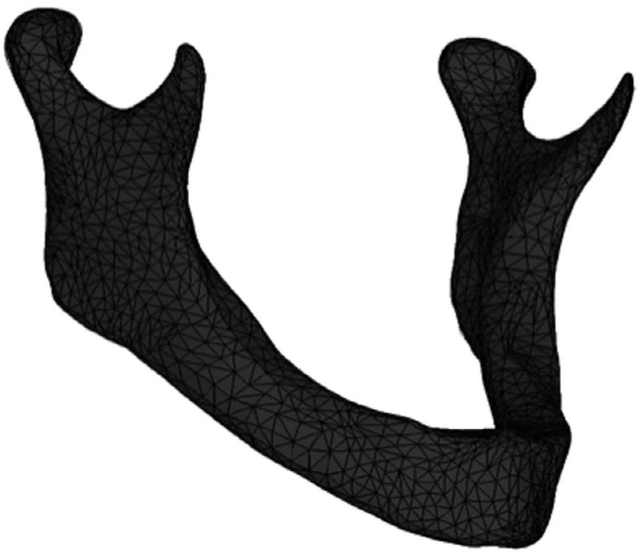

FIGURE 1 The three-dimensional polygon meshes of the model of an edentulous mandible

Subsequently, abutment models and a model of a suprastructure corresponding to a splinted fixed titanium framework similar to a bar or a fixed implant-prosthodontic reconstruction were added to the model with four incorporated interforaminal implants.

The combination of all resulting solid models was processed in Inventor™ software® (Autodesk GmbH) using Boolean operators (addition and subtraction).[28–30] The study design then consisted of two different models: model-A was an edentulous mandible without dental implants (EM; Figure 2A), while model-B represented the combination of the edentulous mandible with 4 splinted interforaminal implants (4-I-EM, Figure 2B).

The resulting models A and B were entered into the FEM Simulation section of Inventor™ software® and then three-dimensionally (3D) cross-linked to build corresponding FEM models.[28–30] The FEA method represents a mathematical technique that allows for the reduction of complex geometries into a finite number of elements (voxels), each with a simple geometry. The elements used for cross-linking in the FEM models were parabolic tetrahedrons with four nodes at each corner and one node in the center of each edge.[21,28–30] The numbers of generated tetrahedrons and nodes of both models were as follows: model-A: noduli: 233 532; tetrahedra 140 820; model-B: noduli 818 925; tetrahedra: 532 064.

The material properties of the materials that were simulated corresponded to standard values described in the literature.[22] The implants, abutments, and suprastructure as well as the cortical and cancellous bone were characterized as isotopic and elastic structures, respectively.[22] These were assigned values for the Young modulus (cortical bone: 13.70 GPa, cancellous bone: 1.370 GPa, Titanium alloy (Ti-6Al-4V): 110.0 GPa; Poisson ratio:cortical bone: 0.33; cancellous bone: 0.3, Titanium alloy (Ti-6Al-4V): 0.34).[21,28,29,33,34] For the implants, the abutments as well as the suprastructure were designed with the material properties corresponding to titanium alloy (Ti-6Al-4V), as reported in previous FEA and clinical studies.[20,21,34]

In three different simulations for each model, a traumatic load of 1000 N was applied in a perpendicular direction to the cortical bone surface of the symphysis, the parasymphyseal region (mental foraminal region) and the lateral body (mandibular angle) region (Figure 3).[19,20,32] The mandible was constrained in

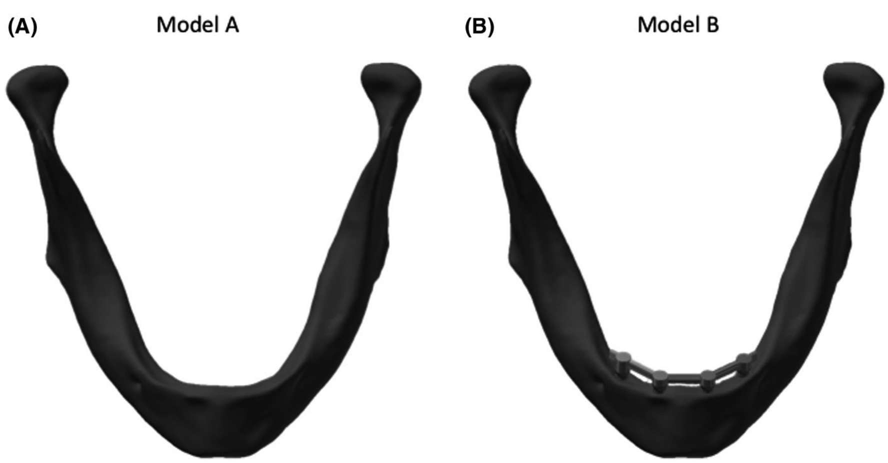

FIGURE 2 3-D edentulous mandible model without (A) dental implants (model-A) and 3-D edentulous mandible model with (B) four splinted interforaminal implants (model-B)

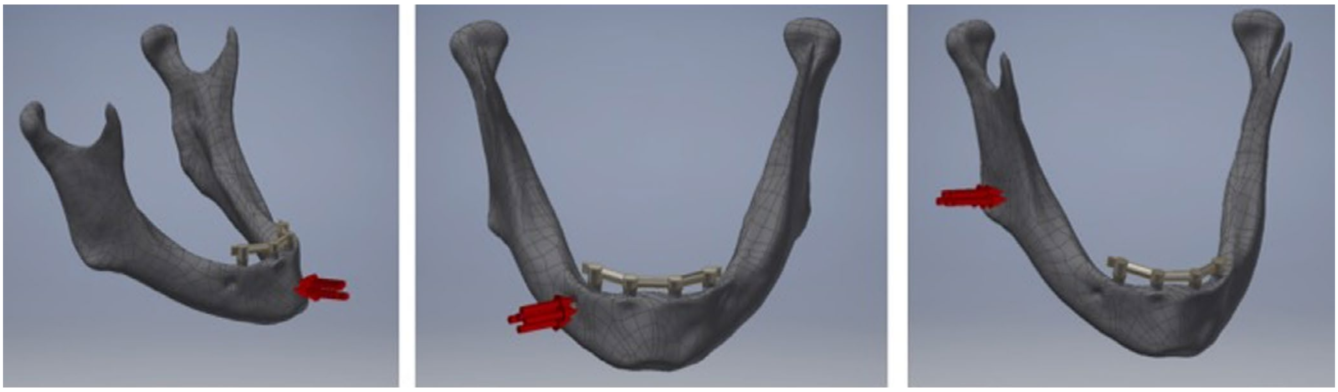

FIGURE 3 Simulation of (A) frontal symphyseal, (B) parasymphyseal, and (C) mandibular angle trauma by application of a force of 1000 N

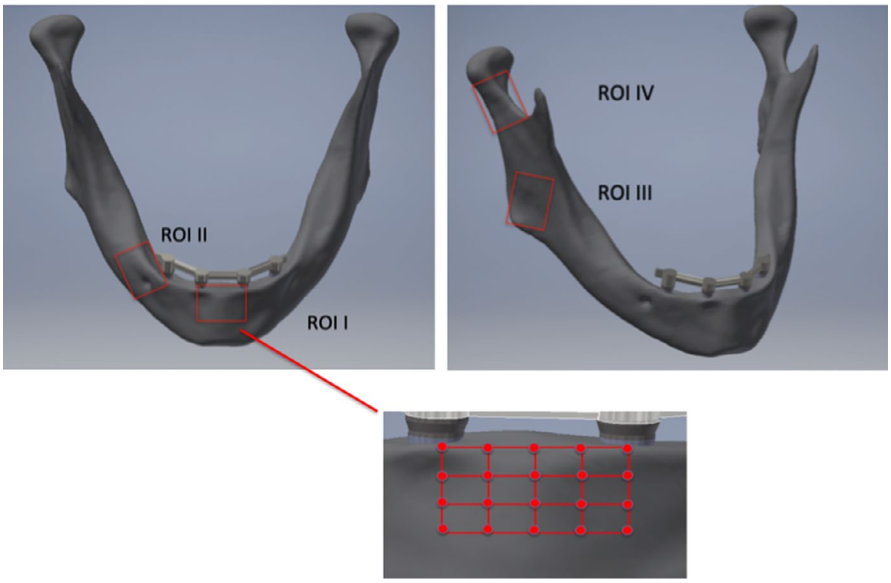

FIGURE 4 The regions of interest evaluated for von Mises stress values. (ROI 1 = anterior mandible; ROI 2 = mental foramen region; ROI 3 = angle of the mandible region; ROI 4 = condylar neck region; homogenous allocation of the 20 pre-defined measurement points identical for all ROIs)

the proximal portion of the condyles to prevent free movement in the *x*-, *y*-, and *z*-axes during traumatic loading for simulating the presence of masticatory muscles during trauma.[35–37] The contact conditions between the single model units of implants, abutments, and suprastructure were defined as constrained. The bone tissue/implant interfaces were assumed to be fully bonded (ie, implants with 100% osseointegration).[34] For both models, the force load and application as well as the boundary and contact conditions were identical.

The traumatic cortical stress was evaluated in detail for four defined specific areas which were selected on the basis of important regions involved in traumatic fractures in the recent literature.[21,23] The evaluated sites, including mandibular body, mental foramen area, and mandibular angle area as well as condylar neck, were defined as regions of interest (ROI) and were located as follows (Figure 4):

- ROI 1: region between the anterior implants (next to alveolar crest).
- ROI 2: region posterior to the lateral implants, in the mental foramen area.
- ROI 3: mandibular angle area.
- ROI 4: region at the condylar neck area.

All four ROI showed a homogeneous area dimension of 10 × 5 mm, and the effective stress measurements in ROIs were calculated at 20 homogeneously distributed pre-defined points of measurement at specific superficial cortical mandibular areas. The inter-point distances, the allocation, and the number of measured control points were identical for every region of interest in both models (Figure 4). Therefore, an exactly identical stress evaluation of all trauma simulations in both models could be obtained. The traumatic stress results were evaluated at these predilectional sites according to von Mises equivalent stress distribution.

Parameters (von Mises stress values) of ROI 1, ROI 2, ROI 3, and ROI 4 for model-A (without implants) and model-B (with four splinted interforaminal implants) have been tabulated as means ± standard deviation and, additionally, boxplots with log-transformed y-axes are presented. Interindividual (intermodel) comparisons of stress values between ROI 1, ROI 2, ROI 3, and ROI 4 between model-A (EM) and model-B (4-I-EM) as well as interindividual (intermodel) comparisons of ROI 1/2/3/4 for model-B (4-I-EM) were performed. For the intraindividual comparison of normally distributed continuous variables, repeated analysis of variance or—in the case of non-normality (verification using the Kolmogorov-Smirnov test with Lilliefors correction)—Friedman rank analysis of variance was used. For the interindividual comparison of normally distributed continuous variables, the independent two-sample t test or—in the case of non-normality—the exact Mann-Whitney-*U* test was used.

The type I error rate was set to 5% (two-sided) without any adjustment. Therefore, the results of the inferential statistics are descriptive only. For statistical analysis, the statistical computing software R Version 3.6.1 (R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org) was used.

3 | RESULTS

Figure 5 shows the individual finite element stress values (von Mises stress) evaluated for model-A (without implants) and for model-B (with four splinted interforaminal implants) when subjected to frontal symphyseal (Figure 5A,B), lateral parasymphyseal (mental foramen region) (Figure 5C,D), and lateral angle of the mandible (Figure 5E,F) application of 1000 N of traumatic stress. Detailed data for all models (EM, 4-I-EM) and regions of interest (ROI 1, ROI 2, ROI 3, ROI 4) expressed as means and standard deviations are presented in Table 1.

Figure 6 shows the cortical stress values for ROI 1, ROI 2, ROI 3, and ROI 4 for the edentulous mandible without (EM) and with four splinted interforaminal implants (4-I-EM) exposed to the three different types of traumatic force application. Regardless of the type of force application, the highest stress values (von Mises stress) were invariably found at the ROI 4 at the mandibular neck for model-A (mean: 265.1 MPa; 186.1 MPa; 127.2 MPa) and model-B (172.4 MPa; 153.3 MPa; 119.9 MPa), respectively. For each model, the stress values measured at the mandibular neck (ROI 4) differed significantly ($P < .001$) from those measured at the symphysis (ROI 1), the supramental (ROI 2), and the mandibular angle regions (ROI 3) (Table 1).

With a symphyseal force application (Figure 6A), the von Mises stress evaluated did not differ for the frontal symphyseal area (ROI 1) between model-A and model-B ($P = .748$) (Figure 6A). However, for the 4-I-EM model a frontal symphseal force application led to an significant increase ($P < .001$) of the stress values in the mental foraminal region (ROI 2) but reduced the stress level in the mandibular angle (ROI 3) and mandibular neck region significantly (ROI 4) (Table 1; Figure 6A) ($P = .002$; $P = .025$).

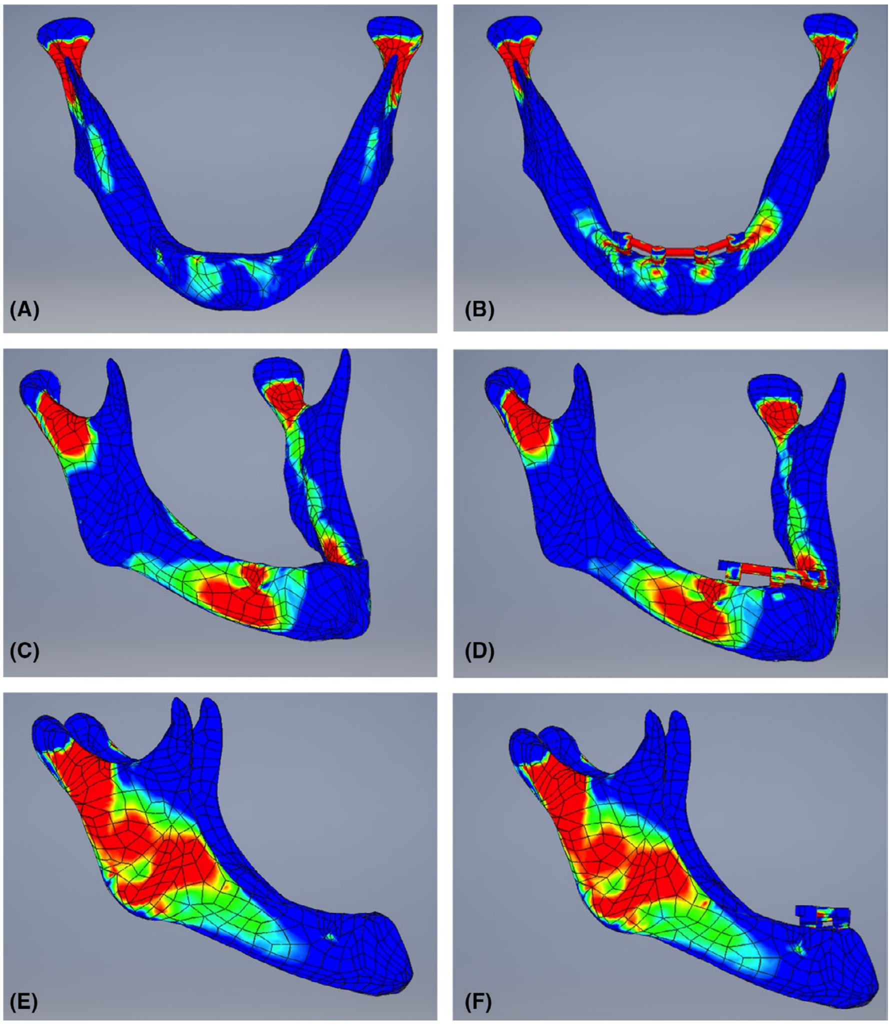

FIGURE 5 The Finite element stress values (von Mises stress) for EM model-A (A) and 4-I-EM model-B (B) exposed to symphyseal trauma. The Finite element stress values for EM model-A (C) and 4-I-EM model-B (D) exposed to parasymphyseal trauma. The Finite element stress values for EM model-A (E) and 4-I-EM model-B (F) exposed to angle of the mandibule trauma

TABLE 1 Stress values for the four regions of interest (ROI) in relation to three different force applications and between edentulous mandible with and without four splinted interforamional implants

	Four interforaminal implants	Without implants	
	Stress value (MPa)	Stress value (MPa)	P value
Symphyseal force			
ROI 1	37.8 ± 11.5	38.9 ± 9.9	.748
ROI 2	51.7 ± 24.5	17.1 ± 8.3	**.001**
ROI 3	12.1 ± 3.4	16.5 ± 2.9	**.002**
ROI 4	172.4 ± 88.7	265.1 ± 153.1	**.025**
Parasymphyseal force			
ROI 1	21.5 ± 14.4	19.2 ± 15.9	.560
ROI 2	66.6 ± 28.4	57.5 ± 32.4	.301
ROI 3	20.8 ± 4.5	21.6 ± 5.8	.610
ROI 4	153.3 ± 95.2	186.1 ± 119.1	.342
Angle of the mandible			
ROI 1	18.2 ± 6.0	20.9 ± 4.9	.135
ROI 2	23.9 ± 9.8	20.8 ± 8.0	.271
ROI 3	77.9 ± 13.7	77.6 ± 13.4	.931
ROI 4	119.9 ± 50.9	127.2 ± 58.8	.718

Lateral traumatic force application at the mental (parasymphyseal) region (Figure 3C; Figure 5D; Figure 6B) and at mandibular angulus region (Figure 3D; Figure 5F; Figure 6C) did not produce any differences in stress values for ROI 1(*P* = .560), ROI 2 (*P* = .301), ROI 3 (*P* = .610), and ROI 4 (*P* = .342) between the mandible without (EM model-A) and with interforaminal implants (4-I-EM model-B) (Figure 6).

Figure 7 shows the stress values for three different types of force application explicitly for EM with four interforaminal implants (4-I-EM) relative to each other and in context with all ROIs evaluated. Excluding the mandibular neck with its invariably highest stress values without any significant difference between the three different types of force application performed, direct force application was correlated with high stress values only for the parasymphyseal and the mandibular angle region.

For ROI 2 (parasymphyseal region) and for ROI 3 (mandibular angle region), with both being located at a distance to the splinted interforaminal implants, direct force application resulted in high cortical stress levels at the application area.

In contrast, direct force application at the symphyseal region showed significantly higher stress values in the adjacent mental foramen region than in the symphyseal region. For frontal (symphyseal) trauma application, the risk of mandibular fracture is transferred from the direct force application site to the adjacent parasymphyseal mental foramen region (Figure 7).

Detailed differences of the stress values evaluated for ROI 1, ROI 2, ROI 3, and ROI 4 exposed to symphyseal, parasymphyseal, and angle of the mandible force application are presented in Figure 8. The stress values for ROI 1 (Figure 8A) and ROI 3 (Figure 8C) differed significantly (*P* = .001) between the three force applications. For ROI 2 (Figure 8B) and ROI 4 (Figure 8D), the force application did not reveal significant differences in the stress values evaluated (*P* = .133; *P* = .86, respectively).

4 | DISCUSSION

Fixed implant-prosthetic restorations supported on four interforaminal implants represent an established and well-proven treatment modality for the rehabilitation of mandibular edentulism.[6–11]. Epidemiological investigations have shown that an increasing number of elderly patients with implant-supported rehabilitation of edentulism lead an increasingly active life taking part in numerous sporting and leisure time activities.[12–14] Thus, it can be concluded that the primary target group for implant-prosthetic rehabilitation will be exposed to an increased risk of trauma in the future.[6,7,13,14,38]

An injury sustained by a fall on the face represents a frontal trauma that may result in maxillo-mandibular fractures.[14–19] While falls on the face may be caused by general medical neurologic or cerebrovascular disorders, a frontal or facial collision or impact may also be the result of an accident during physical or sporting activities. In obvious contrast, a lateral impact of force will mostly be associated with physical violence.[16–19]

In a 3D-FEA study, three different impact sites of force (symphyseal, mandibular body, and mandibular angle) and their effects on the fracture risk of the edentulous mandible were evaluated. Apart from the invariably highest stress values in the mandibular neck, increased stress levels were always seen at the sites of the respective application of force. Consequently, it was concluded that apart from the mandibular neck, an increased fracture risk must also be assigned to the site of the direct force application.[23] In addition, several case reports have also shown that the edentulous mandible will be especially weakened by the insertion of implants and that fractures may develop in the region of the implants.[25–27]

The initial hypothesis that increased cortical stress levels will be found in the edentulous mandible with four splinted interforaminal implants in the region of the mandibular neck and at the sites of the direct impact of force could only partly be confirmed by the results obtained.[20–23] The results for the present FEA confirmed that with different applications of force (symphyseal, mandibular body, mandibular angle), the highest stress levels—and consequently the highest fracture risk—could again be seen in the region of the mandibular neck.[23,36,37] Thus, the results of de Santos et al[23] for the edentulous mandible without any implants, and the results of Bilingylar and Ayali[21] for implant-treated edentulous mandibular models could be confirmed. According to Schwartz-Dabney and Dechow,[39] the bone is narrower in the mandibular neck so this region has less bone strength and a greater tendency to fracture and this can be assumed as a potential explanation.[17,18,23,39]

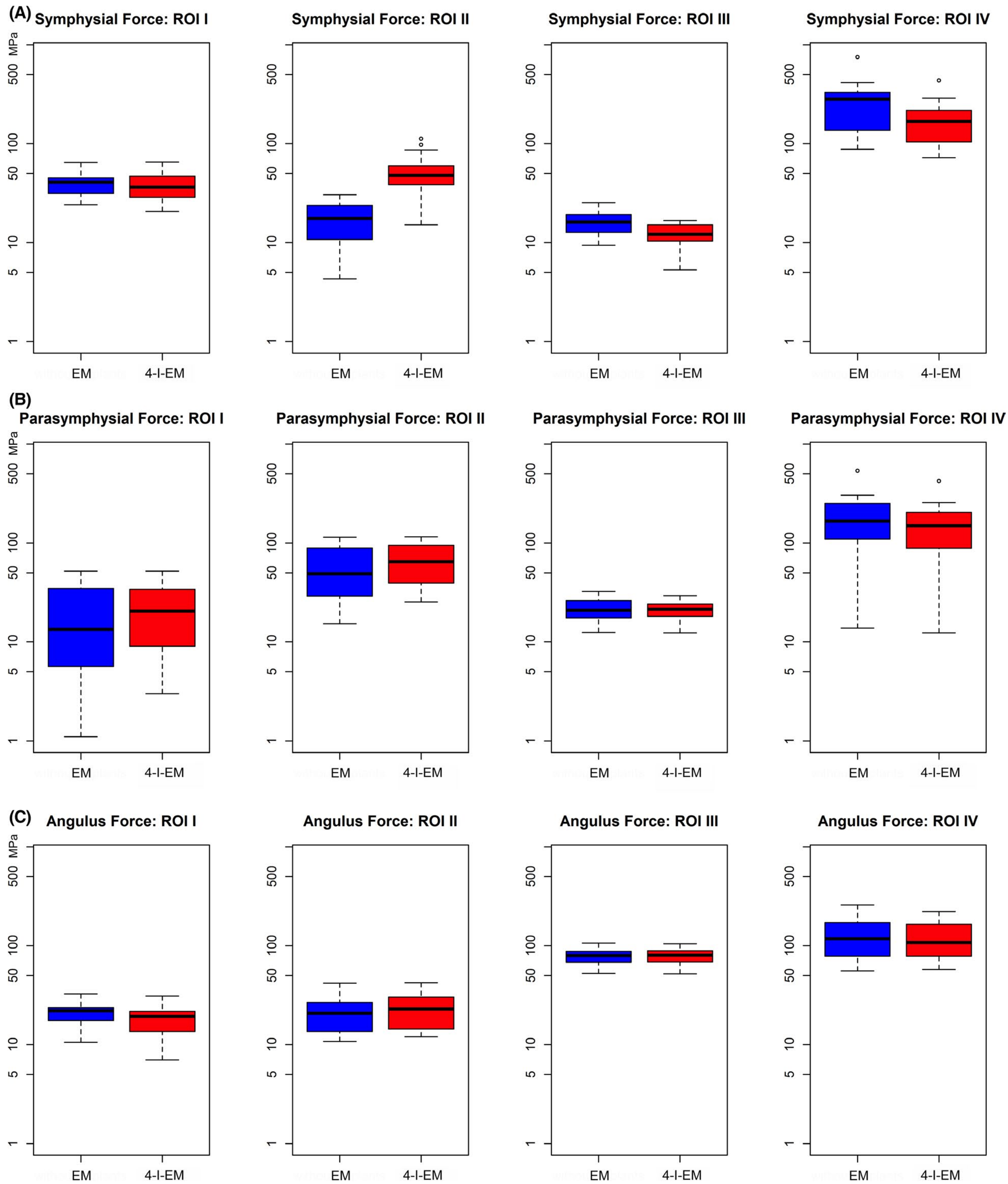

FIGURE 6 Intermodel comparisons of stress values for ROI 1, ROI 2, ROI 3 and ROI 4 for model-A (EM) and model-B (4-I-EM) with symphyseal (A), parasymphyseal (B), and angle of the mandibule (C) trauma application

In obvious contrast, the assumptions that the sites of direct force application would also show increased cortical stress levels and an increased fracture risk could not be confirmed for all regions of the mandible with four interforaminal implants.[23,35,36,39] Strikingly, no increased stress levels at the site of force application could be seen with a frontal force application on the edentulous mandible with interforaminal implants as compared to edentulous mandibles without any implants.[23] In the event of a frontal force application, the impacting kinetic forces will be absorbed in the region of the interforaminal blocking and transmitted to the neighboring regions.[40–42] Therefore, no increased cortical stress levels at the site of direct force application will develop, but much rather the increased stress levels as well as the fracture risk will be transferred to the adjacent region of the mental foramen.[41,43,44] It can be assumed that the external implant

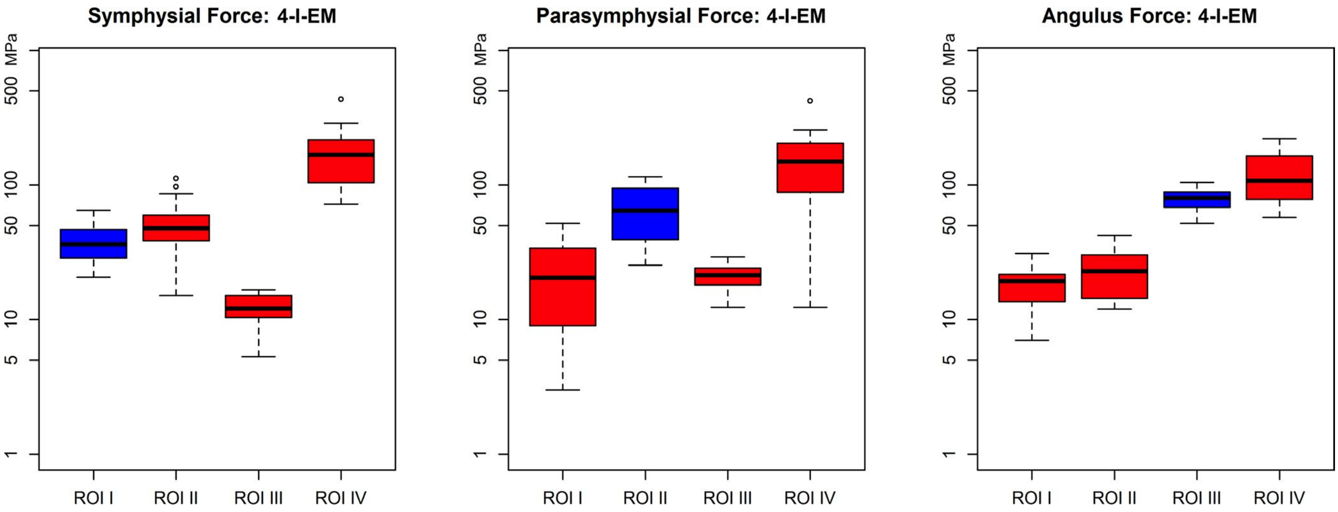

FIGURE 7 The stress values for three different types of force application explicitly for EM with four interforaminal implants (4-I-EM) in context with all ROIs evaluated

splinting, representing an external fixation, will function as a force transducer and that the external stabilization will counteract the initial weakening of the mandible by the implants.[45–47] In addition, it could be noted that with a frontal trauma, the stress values in the region of the mandibular neck will be reduced compared to the models without implants. The kinetic energy of the trauma will be absorbed by the implant splinting and transmitted into the mandibular neck to a reduced extent.[21,23,48] Therefore, the stress level reduction found in the area of the mandibular neck may also indicate a reduction of the fracture risk for the mandibular neck.[48]

It was interesting to note that at sites without external splinting, a direct force impact will still be associated with increased stress levels and an increased risk of fracture.[23,47] Anterior implant splinting appears to have no effect on the force impact in the region of the mandibular body or the mandibular angle on account of the remote location of the external stabilization. Thus, the initial hypothesis that the site of direct force application will also represent the site of the increased fracture risk has been confirmed again and the characteristics of an edentulous mandible without implants may thus also be used for edentulous mandibles with four interforaminal implants.[23,43,48] In accordance with previous findings of de Santos et al,[23] the results showed that a direct force application in the region of the mental foramen and in the region of the mandibular angle will invariably induce increased stress levels in the edentulous mandible with or without implants and be associated with an increased fracture risk in these regions.[42–44]

As a striking feature, the area of particular risk in the case of a frontal application of force is shifted away from the symphyseal region toward the region of the mental foramen.[44] With this obvious shift, the virtually identical site—namely the region of the mental foramen—could be identified as the site with increased stress levels and as the region of risk with both frontal symphyseal and lateral parasymphyseal force application.[23,43,44] Thus, regardless of the site of the force application, it is especially the region of the mental foramen—in addition to the mandibular neck—that must be considered as a predominant risk area and as predilectional site of fracture.[44,48]

Changes of fracture pattern and relocation of potential injuries to sites allowing for better surgical access and/or facilitated treatment procedures suggest specific advantages for both clinicians and patients.[48–50] Reducing the risk for condylar neck fracture with symphyseal frontal trauma application by splinted four interforaminal implants is also of clinical significance considering that condylar neck fractures will frequently require greater efforts for surgical interventions, recovery, and postoperative care.[20–23,47,51,52]

Considering the limitations of the study, it must be pointed out that the present study had an experimental design that represented only changes in the objects being evaluated.[20,41,42] As the risk for mandibular fracture is predominantly also influenced by the varying degree of mandibular atrophy and mandibular bone quality, a detailed quantitative statement as to what extent implant placement and, consequently, implant splinting may protect or negatively affect several regions cannot be made.[53,54]

In summary, the findings showed that in the case of frontal trauma, four splinted interforaminal implants as being used clinically in the "All-on-4" concept will reduce the stress levels and the fracture risk in the area of the anterior implants and the mandibular neck and may increase the same in the region of the mental foramen.[23,47] Stress absorption of the impacting forces in the implant region and, consequently, also increased stress values in the mandibular corpus are considered as responsible factors. It could be seen that a direct lateral force impact in the area of the mandibular body and the mandibular angle was not affected by the splinted interforaminal implants. In such a case, the stress levels and the fracture risk remain restricted to the site of the force application.

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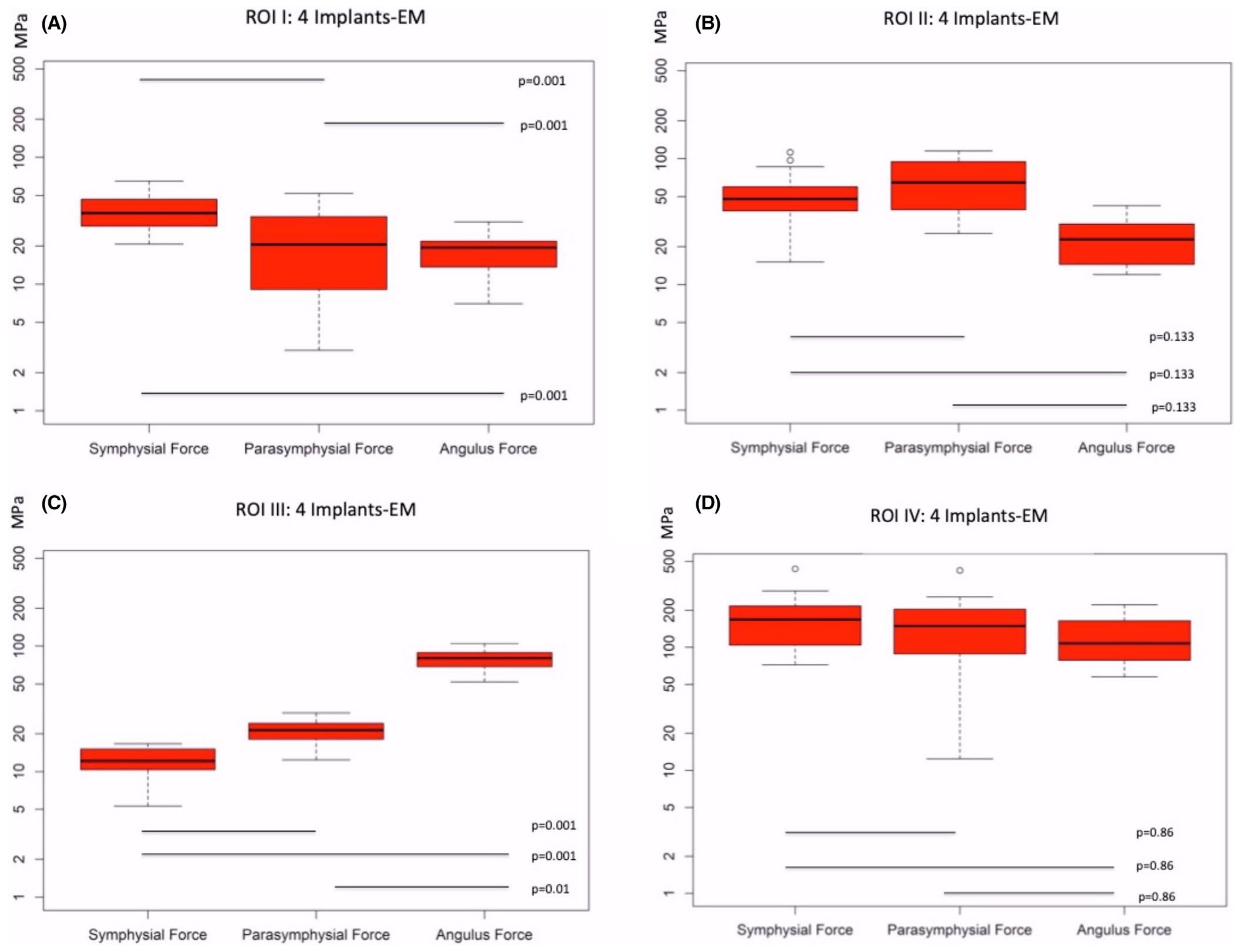

FIGURE 8 Comparison of stress values evaluated at ROI 1 (A), at ROI 2 (B), at ROI 3 (C), and at ROI 4 (D) for symphyseal, parasymphyseal, and angle of the mandible force application

CONFLICT OF INTEREST

The authors confirm that they have no conflict of interest.

AUTHOR CONTRIBUTIONS

Stefan Krennmair involved in study design/conception, material preparation, data analysis, draft preparation, and statistic analysis. Stefan Hunger involved in methodology, investigation, and statistic analysis. Lukas Postl performed draft preparation, review, and discussion. Philipp Winterhalder involved in data analysis, methodology, and investigation. Svenia Holberg involved in investigation and data acquisition. Michael Malek involved in draft preparation, discussion, and review. Christof Holberg involved in review, supervision, and discussion. Ingrid Rudzki performed review and discussion.

ETHICAL APPROVAL

The study design of FEA Simulation does not require ethical approval. This article does not contain any studies with human participants or animals performed by any of the authors.

DATA AVAILABILITY STATEMENT

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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