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ORIGINAL ARTICLE

Evaluation of a new optical measuring system for experiments on fractured human mandibles

A biomechanical feasibility study in maxillofacial surgery

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Abstract
Objectives Biomechanical loading on human mandibles was performed and a new optical measurement device was introduced for the quantification of interfragmentary movement in fractured mandibles stabilized with different osteosynthesis systems.
Materials and methods Comparison tests were performed with monocortical non-locking double plates and bicortical single locking plate. For the experiments on a specialized test bench, 18 ex vivo fractured human cadaveric mandibles were tested. Interfragmentary motion was detected in all three spatial dimensions using the optical measurement device PONTOS®. The movement was investigated over increasing incisal force and one summarized parameter was investigated.
Results For the maximal tested load of 300 N m, the resultant interfragmentary movements in the two investigated groups were 2.96±1.85° for the fixation with two conventional miniplates (six hole, profile 1.0 mm) and 4.53±2.49° for single bicortically fixed locking plates (four hole, profile 1.5 mm). For both plate systems, we used the 2.0 mm screw system.
Conclusions The test bench in combination with the new optical device PONTOS® can test the primary stability of osteosynthesis. We offer a solution to the problem of rate of twist of the mandible as well as typical rotational problem in recent measurements. Further, the method can be used for development of new osteosynthesis products.
Clinical relevance Pseudoarthrosis formation is a common problem based on unsatisfying fixation of the fracture gap. The here presented combination of mechanical tests and numerical simulations can provide support for an improved treatment of fractured mandibles.

Keywords Mandible · Osteosynthesis · Finite element analysis · Experimental testing · 3D optical measurement · Biomechanics

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Introduction

Open reduction and internal fixation of mandibular fractures with miniplates is considered to be the gold standard treatment [1–4]. But the weaker microplates are also used in the treatment of simple fractures [5]. Sometimes, in more complex cases such as mandibular reconstruction or mandibulotomy repair, a non-union with pseudoarthrosis formation occurs. We think this is caused by excessive interfragmentary movement and is correlated to the type of osteosynthesis chosen and the achieved rigidity [6]. In order to avoid pseudoarthrosis formation, maximal mechanical support of the fracture gap from the osteosynthesis system is desired.

An appropriate level of interfragmentary motion is desirable to aid good healing [7]. Kenwright and Goodship reported that 0.2–1 mm interfragmentary motion allows satisfactory secondary bone healing, and Wolf suggested that optimal axial movement is 0.4 mm [8, 9]. The stiffness of the osteosynthesis system has major impact on the interfragmentary motion during loading and is therefore of high importance for the mechanical stability at the fracture site and thus for subsequent healing. However, it is difficult to assess and evaluate the interfragmentary movement. In the past, strain measurement gauges and photometric methods have been used [10–12], but a certain degree of inaccuracy is associated with these procedures. For that task, we have used an optical measurement device (PONTOS®; Gesellschaft für Optische Messtechnik, Braunschweig, Germany) to capture the three-dimensional movement of the mandibles' surface during mechanical loading. This system is currently widely used in engineering. Döbele et al. are the first to describe biomechanical tests with this new optical measurement device [13] for applications in trauma surgery (interfragmentary movement in tibial diaphyseal fractures) and showed an accuracy of up to 0.003 mm. However, as will be demonstrated, the system is also suitable for biomechanical analysis in the field of cranio-maxillofacial surgery. The aim of this study is therefore to demonstrate the use of the PONTOS optical measuring system for investigating interfragmentary motion in mandibular fractures.

Methods

Instrumentation

For the mechanical loading of the fractured and osteosynthetically treated bones, a specially developed test bench—called Mandibulator—was used. This device is suited to perform experimental tests on artificial bone models as well as in this study on cadaver mandibles. A picture of the device is shown in Fig. 1. In a modified way, a similar test bench has been used in several research projects [14, 15] in previous studies at our university.

In the utilized configuration, the Mandibulator applies incisal biting forces. The temporomandibular joints are modeled through bearings made of concavely lathed spherical boxes to represent the anatomical shape of the fossae. Biting forces are applied by stiff ropes which are pulled by electromechanical cylinders under displacement control to apply the required forces on the mandibles. Muscular forces are also modeled via ropes which are fixed onto the framework of the Mandibulator above the mounted mandibles. This means that the muscular forces are the result of the applied biting force and not vice versa. This has been defined since many publications give references on biting forces [11, 16–19], but only few provide values for muscular forces [15, 20–22]. Here, all muscular forces are integrated in one noose of the rope at each side of the mandible located at the mandibular angle, which allows to mimic the main muscular groups (masseter, temporalis, and medial pterygoid) [16, 23]. The load measurements are conducted by stress sensors attached to the ropes that are controlled by specifically developed software and transmitted to the computer which allows an evaluation and documentation of the forces at any time. Even though three different biting forces can be applied to the tested bones at any time, we restricted ourselves to incisal biting force in this study.

PONTOS optical measurement system

PONTOS is a dynamic optical measuring system produced and distributed by GOM Gesellschaft für Optische Messtechnik (GOM, Braunschweig, Germany). It allows accurate three-dimensional measurements with a resolution of $2{,}448 \times 2{,}048$ pixels and speed up to 15 Hz (Table 1). As previously mentioned, it has also been used for the measurement of interfragmentary movement in fractured tibias [13]. The PONTOS system works by tracking passive optical markers applied to the surface that is investigated, while the number of recognized markers is in theory unlimited. PONTOS sensor is mounted on a fixed tripod and positioned in front of the object being measured (Fig. 2). The self-controlled system records images for one or more loading stages uses flexible triggering techniques. However, the points of support of the actors are in principle arbitrarily customizable.

It is capable of registering the motion of marker points over time in three-dimensional space. This approach is superior to other measurement methods with strain gauges since no devices have to be applied directly to the bone which could interact with its surface and thereby falsify the results. Furthermore, no glue is needed, which could also be critical on the irregular bone surface. This method is also superior to the procedure of using two photo cameras and measuring the position of specified points in the resulting pictures, both in accuracy and ease of handling. PONTOS5M offers a software solution for optical, dynamic, three-dimensional analysis and measurement. This enables the precise calculation of position, motion, and deformation out of the surface movement of investigated structures and components. It delivers the dynamic, accurate, and synchronized position of a practically unlimited number of markers—these are, in the case of this study, small stickers that are directly attached to the bone surface. Without influencing the structures to be measured by directly touching them, displacements and deformations are captured rapidly and accurately. To acquire the image, the PONTOS sensor is mounted

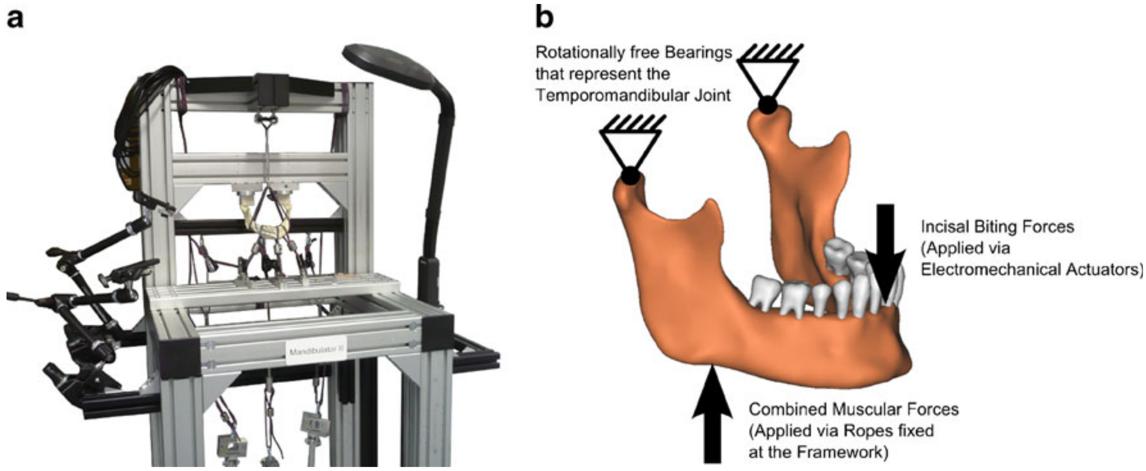

Fig. 1 **a** The Mandibulator—a test bench for the ex vivo experimental testing of the human mandible under predefined loads. **b** Principal sketch of bearings and the mechanical loading

on a tripod and positioned freehanded in front of the object to be measured. For image processing, 3D coordinates, 3D displacements, and 3D deformations are calculated automatically for all markers using photogrammetric evaluation procedures. Results such as 3D coordinates, and absolute or relative movement are displayed in reports or exported in standard file formats. The PONTOS system furthermore records analog signals to trigger the image capturing and to document the loading situation by capturing the signal gripped by strain measurement gauges attached at the ropes that represent summarized muscle forces and biting forces, respectively.

For biomechanical tests, Döbele et al. checked the precision mechanical device technology of the PONTOS system. The tests showed even an accuracy of 0.005 mm [13]. Furthermore, PONTOS software offers numerous functionalities for a customized data acquisition, evaluation, and results visualization.

Study design

For first testing purposes to evaluate the usability of the PONTOS system for this specific task, experiments with artificial bone models (Sawbone, Sawbones Inc., Malmö, Sweden) were double osteotomized and incisally loaded with a consecutive series with 0 N, 25 N, 75 N, and again 0 N. In order to evaluate the accuracy of the presented method of optical measurement with the PONTOS system (6DoF sensors), we compared these results to the previously used photometric methods (Image J©). The pictures used for this approach were taken with a Nikon Coolpix 6000 (13.5 megapixels; 4× optical zoom). Since the photometric measurements are performed manually on the computer screen, the human factor as a source of error cannot be avoided. For a quantification of intra-observer variability, one experienced test person performed 20 measurements of one defined distance between two markers at the same photo.

Within the study, 18 human mandibles (fixation Thiel embalming method [24]; age 78.1±8.4 years; seven male, 11 female), partially dentate, were tested. These jaws come from donated bodies and were taken in accordance with the committee of ethics (Klinikum rechts der Isar, Technische Universität München). Corresponding to the doctrine of S.O. R.G. [25], we saw an interesting comparison in testing primary stability between a monocortical double plate conventional system 1.0 mm profile and a bicortical single locking plate system 1.5 mm profile. The test specimens were divided into three groups of six cadaveric mandibles: two groups were

Table 1 PONTOS technical data system configurations 5M

System configurations	5M
Camera resolution	2,448×2,048 pixels
Other cameras	Optional
Frame rate	Up to 15 Hz
Measurement volume	0.1×0.08 up to 2×2 m
Accuracy	0.01 to 0.05 mm
Number of measurement markers	Unlimited
Sensor dimensions	1,300×200×140 mm^3

Fig. 2 Optical measurement system: PONTOS

osteotomized in a standard way at the right side in the canine region to simulate a fracture while the third group remained without fracture. In group 1, the fracture gap was treated with two miniplates (Medartis, Basel, Switzerland) and fixed to the bone with monocortical screws. For group 2, only one locking plate (Medartis) per fracture was placed, but fixation was performed with the longer bicortical screws. Plates were screwed only from one person using a torque key [Model Torque Vario® 2851 (0.8–2.0 Nm); Wiha GmbH, Schonach, Germany]. Cadaveric mandibles we used were adult, non-atrophic but more and less dentate. All mandibles were CT-scanned to exclude bigger cavities. Performing the measurements of interfragmentary motion with different forces, we used the combination of our Mandibulator and the PONTOS measuring system (Fig. 3 and Table 2).

Quantification of interfragmentary movement

The evaluation of interfragmentary motion is a difficult task. Since there is not one specific directly visible movement, a combined representative of the overall movement of the fractured parts relative to each other has to be defined in order to provide the possibility of a comparison of different measurements. From investigating the displacement of the passive markers on the bone surface in space, it is possible to calculate rigid body motions of the different parts. Thus, all six possible degrees of freedom—three translation and three rotations—are accessible within the PONTOS software. Shetty et al. [26] presented a formula to compute a composite rotational angle Θ out of the three separate axial rotations Θ_1, Θ_2, and Θ_3:

$$\Theta = \sqrt{\Theta_1^2 + \Theta_2^2 + \Theta_3^2}$$

This formula according to Shetty et al. is the Euclidean norm of the singular relative movements along the coordinate axes. Therefore, it is invariant towards any coordinate system specification, which is demanded in this task since a consistent definition of a coordinate system is impossible due to the distinct anthropomorphic variability in the group of the tested mandibles, which leads to variations in the spatial orientations of the bones in the test assembly.

Results

For evaluation purpose, the marker distances taken from the PONTOS system are compared to photometric measurements previously used for similar studies like described above. The photometrically measured distance was in mean 429.27 pixels with a standard deviation of 2.12 pixels which leads to a coefficient of variation of 0.49%. This value seems notably low at first glance, but taking into account that the overall interfragmentary movement is little compared to the distance between the adhesive markers, hence this variation has a non-negligible effect on the assessment of the relative movement of the different parts in respect to each other.

Figure 4 shows the typical hourglass-shaped pattern of investigated points for photometric measurement, which was already used in the study of Karoglan et al. [10]. These distances can also be captured and evaluated by the PONTOS system. For testing purposes, a load series with 0 N, 25 N, 75 N, and again 0 N were applied on a double osteotomized artificial bone (Sawbone) (Fig. 5). If a linear relationship between applied load and deformation is assumed, correlations between the load collective and the measured distances may provide a quantification of accuracy of the used method, i.e., low correlation indicates no agreement between loads and measured displacements. The Wilcoxon–Mann–Whitney U test showed a p value of 3.57% (<5%).

Unfractured group as reference

When fractured and osteosynthetically treated human bones are mechanically loaded, movement does not only occur in the fracture gap. The bone itself is non-rigid and undergoes a certain deformation due to the loading. In order to estimate this internal deformation of the human mandibles in our experimental setting with incisal biting forces, one group

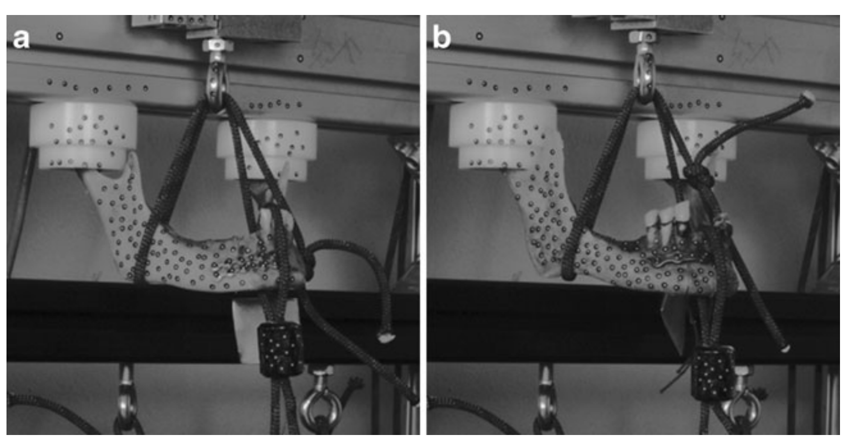

Fig. 3 Tested bone specimen fixed with different osteosynthesis systems

Table 2 Fixation methods of the two test groups

Group		No. of plates	No. Screws	System	Anchorage	Plate thickness
1		1	4 x 2.0 locking screws	2.0.Trilock® - locking system	Bicortical	1.5 mm
2		2	12 x 2.0 non locking screws	2.0.Conventional miniplate-system	Monocortical	1.0 mm

of six specimens was left non-fractured and then tested in the Mandibulator. After the tests, the randomly placed markers whose positions were detected by the optical acquisition system are divided into several groups according to their initial locations (see Fig. 6). In the graph (Fig. 6b), mean values of the six tested mandibles are depicted in bold lines while the respective maximal values over all specimens and all sections are represented through thin lines. The displacement of the sectors relative to each other never exceeds a value of 0.65°. Hence, deformations even up to the highest relevant loading of 300 N of the bone are small. As we will show later, the relative deformations in the fracture gap are much higher. Therefore, the assumption to treat the fractured bone parts as rigid bodies that do not undergo large deformations is justified. For capturing rigid body motion, PONTOS offers the so-called 6DoF sensors that provide three translations and three rotations.

Osteosynthesis comparison

With the use of the summation formula according to Shetty et al. described above, it becomes possible to condense only one overall representative of the relevant interfragmentary movement or “instability factor” out of the three investigated relative rotations of the two bone parts to each other. In Fig. 7a and b, the experimental results of the two test series with fractured mandibles stabilized with different osteosynthesis systems are depicted and statistically evaluated.

The test row with six mandibles fixed with miniplates (Medartis) is visualized in Fig. 7a. There the movement representative according to Shetty is plotted for all tests of this group over the incisal biting force (N). Furthermore, median plus range and mean value of the group are depicted. One of the tested specimens displayed a sudden increase at a loading of about 120 N. Another one showed a high slope compared to the rest of the test group at the beginning of the measurement but at approximately 60 N the slope was again similar to the group’s average. Besides these two outliers, the test group is relatively homogeneous, especially taking into consideration that test specimen are human bones with a natural scatter in morphology and material stiffness.

The second test row with six mandibles fixed with one locking plate (Medartis) is shown in Fig. 7b. Here again, there is one experiment with a sudden increase of interfragmentary movement in the region of 60 to 90 N but a similar slope compared to the rest of the test groups outside this area. Again, the rest of this set is relatively homogeneous (Table 3).

Even though the test group of cadaver mandibles has been chosen relatively homogeneous, there are scatterings in material behavior as well as different anatomical shapes. We think that this is probably the reason for the existence of these outliers described above.

For comparison between the two tested groups, the median of each set is depicted in Fig. 8. It could be shown that the miniplate configuration with two plates fix the fracture more rigidly than the locking plate system with one plate although bicortical screw fixation was employed there. In the statistical evaluation according to a Wilcoxon–Mann–Whitney test (*U* test), *P* was found to be under 0.067 in the region of interest. The relatively low level of significance might be a result of the small power of the test consisting of relatively small test groups due to the expensive and time-consuming preparation of the test specimen.

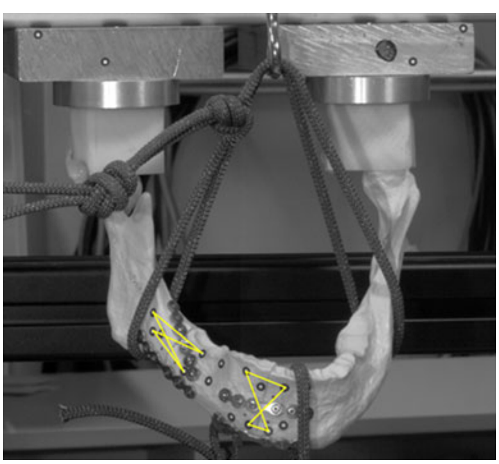

Fig. 4 Test for comparison to photometric measurement

Discussion

We think the easy handling of the PONTOS system and its accuracy is superior to strain measurement gauges and

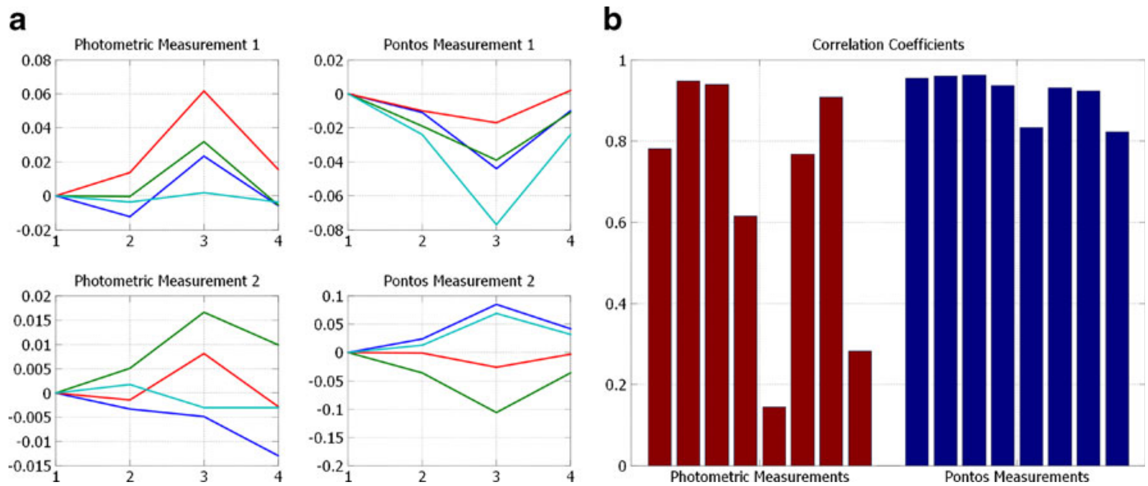

Fig. 5 **a** According respective accuracy, we compared results of PONTOS (6DoF sensors) with conservative photometric methods. **b** Correlation coefficients between optical measurements and applied loads

photometric methods. The software allows easy post experiment analysis of data. To detect the composition of motion in an osteotomized gap, PONTOS system can track all movements three-dimensionally on the complex-shaped body of the human mandible. This is one relevant condition to discover the mechanical failure of osteosynthesis plates and to optimize their shape to the clinical needs.

The design of the test bench is well harmonized with the PONTOS system, so measures can be conducted rapidly and easily. According to the producer of the optical system, it is qualified to measure deformations of loaded structures. With the aid of numerical simulations, the internal movement can be evaluated out of this data. More than ever, modern research in biomechanics demands a better understanding of load composition and micro-motion within the fracture gap. Therefore, this approach is an essential step towards a more sophisticated technique to further the investigation of those tasks. Compared to other systems for measuring interfragmentary motion, the facile mechanical handling is a real benefit both in time and effort, and therefore superior to strain measurement gauges like those that have been used in [27] or photometric methods [10]. Another advantage of PONTOS in biomechanics is to generate a multitude of results over time that can all be evaluated in post-processing of this data. Furthermore, the auxiliary visualization of the results on the computer enables a simple and intuitive analysis of the components' behavior.

Moreover, we solved the problem of rate of twist of the mandible [28, 29] as well as the typical rotational problem occurring in recent measurements [10, 15]. That was the problem of how to detect the three possible interfragmentary

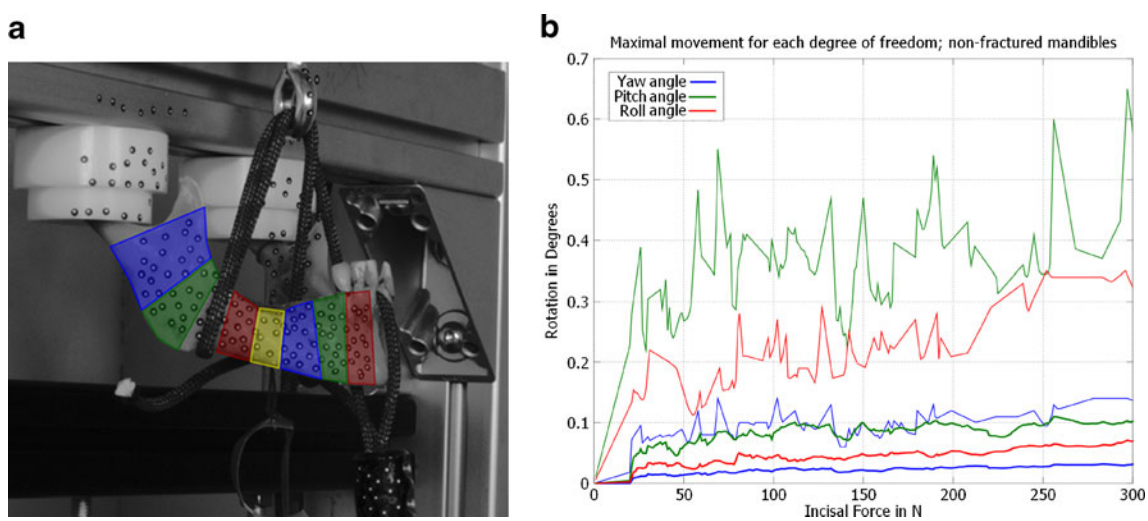

Fig. 6 **a** Division of mandible into several sections. **b** Maximal deformations displayed over incisal force

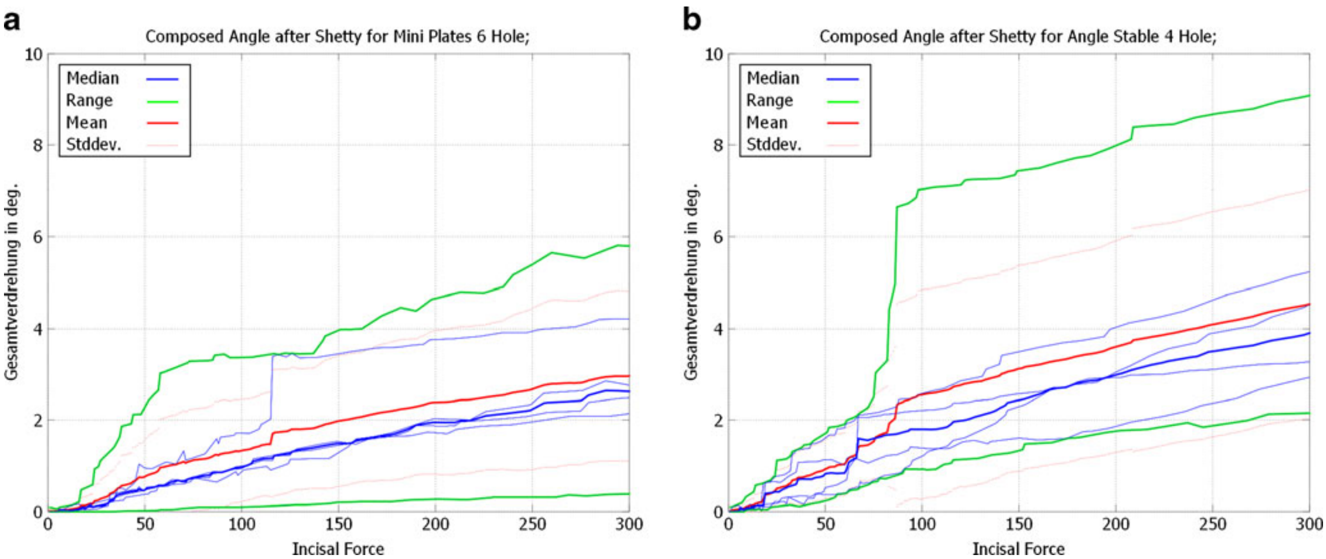

Fig. 7 **a** Miniplates (Medartis). **b** Angle stable plates (Medartis)

rotations properly and in a reproducible manner. This especially would be very difficult by using conventional measurement techniques like photographic approaches or the use of conventional strain gauges or extensometers.

However, when analyzing the results, it is necessary to take into consideration that they were taken from cadaver (ex vivo) bones and not from fresh living bones. Obviously, ex vivo bones are stiffer and more brittle and lead to a lower deformation [30].

Conclusion

The PONTOS system allows to measure motion in three dimensions which enables to reach superior results when looking at the complex shape of the mandible. This is important for the investigation if pseudoarthrosis formation is related to the mechanical properties of the osteosynthesis system. The design of the test bench is well harmonized with the GOM system, and measurements can be conducted quickly and easily. With the aid of numerical simulations, internal movement of the fracture can also be estimated. With these methods, we are not restricted to the directly visible surfaces. Thus, this allows us a better understanding of load composition and micro-motion within the fracture gap and not only at the outer parts. Furthermore, evaluation and widening of test possibilities, particularly with regard to clinical questions, should be performed in the future. The outcome of these measurements can be used for validation of finite element simulations and subsequently be used for the development of improved designs of osteosynthesis.

Table 3 Resulting displacements for different incisal loads (degrees of summarized angle, according to Shetty et al.)

Group	100 N	200 N	300 N
Miniplates	1.33±1.12	2.38±1.57	2.96±1.85
Locking screws	2.55±2.28	3.60±2.30	4.53±2.49

Values given as mean±SD

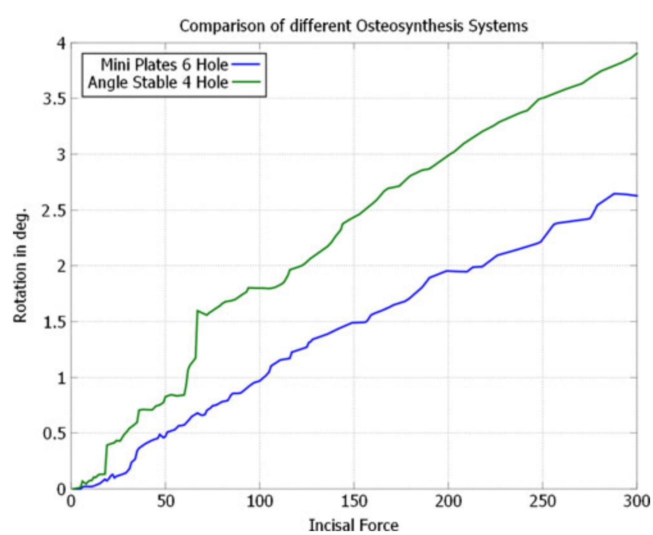

Fig. 8 Comparison of the two different osteosynthesis systems

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Conflict of interest On behalf of all authors of this manuscript, we certify that there is no actual or potential conflict of interest in relation of this article. Additionally, we declare that there exists no financial or personal relationship with other people or organizations that could inappropriately influence this work.

References

1. Champy M, Lodde JP, Schmitt R, Jaeger JH, Muster D (1978) Mandibular osteosynthesis by miniature screwed plates via a buccal approach. J Maxillofac Surg 6(1):14–21
2. Champy M, Wilk A, Schnebelen JM (1975) Die Behandlung der Mandibularfrakturen mittels Osteosynthese ohne intermaxillare Ruhigstellung nach der Technik von F.X. Michelet. Zahn Mund Kieferheilkd Zentralbl 63(4):339–341
3. Gerlach KL, Pape HD (1980) Prinzip und Indikation der Miniplattenosteosynthese. Deutsche zahnarztliche Zeitschrift 35(2):346–348
4. Gerlach KL, Schwarz A (2003) Belastungsmessungen nach der Miniplattenosteosynthese von Unterkieferwinkelfrakturen. Mund Kiefer Gesichtschir 7(4):241–245
5. Burm JS, Hansen JE (2009) The use of microplates for internal fixation of mandibular fractures. Plast Reconstruct Surg 125 (5):1485–1492
6. Claes L, Augat P, Suger G, Wilke HJ (1997) Influence of size and stability of the osteotomy gap on the success of fracture healing. J Orthop Res 15(4):577–584
7. Piffko J, Homann C, Schuon R, Joos U, Meyer U (2003) Experimentelle Untersuchung zur biomechanischen Stabliltat unterscheiedlicher Unterkieferosteosynthesen. Mund Kiefer Gesichtschir 7(1):1–6
8. Goodship AE, Kenwright J (1985) The influence of induced micromovement upon the healing of experimental tibial fractures. J Bone Joint Surg 67(4):650–655
9. Wolf S, Janousek A, Pfeil J, Veith W, Haas F, Duda G, Claes L (1998) The effects of external mechanical stimulation on the healing of diaphyseal osteotomies fixed by flexible external fixation. Clin Biomech (Bristol, Avon) 13(4–5):359–364
10. Karoglan M, Schutz K, Schieferstein H, Horch HH, Neff A (2006) Development of a static and dynamic simulator for osteosyntheses of the mandible. Technol Health Care 14(4–5):449–455
11. Meyer C, Kahn JL, Lambert A, Boutemy P, Wilk A (2000) Development of a static simulator of the mandible. J Craniomaxillofac Surg 28(5):278–286
12. Rudman RA, Rosenthal SC, Shen C, Ruskin JD, Ifju PG (1997) Photoelastic analysis of miniplate osteosynthesis for mandibular angle fractures. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 84(2):129–136
13. Dobele S, Horn C, Eichhorn S, Buchholtz A, Lenich A, Burgkart R, Nussler AK, Lucke M, Andermatt D, Koch R et al (2010) The dynamic locking screw (DLS) can increase interfragmentary motion on the near cortex of locked plating constructs by reducing the axial stiffness. Langenbecks Arch Surg 395(4):421–428
14. Neff A, Muhlberger G, Karoglan M, Kolk A, Mittelmeier W, Scheruhn D, Horch HH, Kock S, Schieferstein H (2004) Stabilitat der Osteosynthese bei Gelenkwalzenfrakturen in Klinik und biomechanischer Simulation. Mund Kiefer Gesichtschir 8(2):63–74
15. Schieferstein H (2003) Experimentelle Analyse des menschlichen Kausystems. Technische Universität, München
16. Koolstra JH, van Eijden TM (1992) Application and validation of a three-dimensional mathematical model of the human masticatory system in vivo. J Biomech 25(2):175–187
17. Koolstra JH, van Eijden TM, Weijs WA, Naeije M (1988) A three-dimensional mathematical model of the human masticatory system predicting maximum possible bite forces. J Biomech 21(7):563–576
18. Pruim GJ, de Jongh HJ, ten Bosch JJ (1980) Forces acting on the mandible during bilateral static bite at different bite force levels. J Biomech 13(9):755–763
19. Waltimo A, Kononen M (1993) A novel bite force recorder and maximal isometric bite force values for healthy young adults. Scand J Dent Res 101(3):171–175
20. Baragar FA, Osborn JW (1984) A model relating patterns of human jaw movement to biomechanical constraints. J Biomech 17(10):757–767
21. Nickel JC, Iwasaki LR, Walker RD, McLachlan KR, McCall WD Jr (2003) Human masticatory muscle forces during static biting. J Dent Res 82(3):212–217
22. Osborn JW, Baragar FA (1985) Predicted pattern of human muscle activity during clenching derived from a computer assisted model: symmetric vertical bite forces. J Biomech 18(8):599–612
23. Koolstra JH (2002) Dynamics of the human masticatory system. Crit Rev Oral Biol Med 13(4):366–376
24. Hölzle F, Franz EP, Lehmbrock J, Weihe S, Teistra C, Deppe H, Wolff KD (2009) Thiel embalming technique: a valuable method for teaching oral surgery and implantology. Clin Implant Dent Relat Res
25. Franz Härle MC, Terry BC (2009) Atlas of craniomaxillofacial osteosynthesis: microplates, miniplates, and screws, 2nd edn. Thieme, Stuttgart
26. Shetty V, McBrearty D, Fourney M, Caputo AA (1995) Fracture line stability as a function of the internal fixation system: an in vitro comparison using a mandibular angle fracture model. J Oral Maxillofac Surg 53(7):791–801, discussion 801-792
27. Joos U, Piffko J, Meyer U (2001) Neue Aspekte in der Versorgung von Unterkieferfrakturen. Mund Kiefer Gesichtschir 5(1):2–16
28. De Marco TJ, Paine S (1974) Mandibular dimensional change. J Prosthet Dent 31(5):482–485
29. Fischman B (1990) The rotational aspect of mandibular flexure. J Prosthet Dent 64(4):483–485
30. Steinhauser E, Diehl P, Hadaller M, Schauwecker J, Busch R, Gradinger R, Mittelmeier W (2006) Biomechanical investigation of the effect of high hydrostatic pressure treatment on the mechanical properties of human bone. J Biomed Mater Res 76(1):130–135