Patient-specific modular system for bone deformities: experimental and numerical investigation of mechanical properties

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Abstract:

This study introduces a new concept for osteosynthesis plate for veterinary application. The new design is made of two plates linked together with a double-clip. Validation of the concept is based on evaluation of its mechanical behavior compared to a classical monobloc plate as reference, using experiments and simulations. Experiments follow the ASTM F382 standard and simulations are carried out with representative finite element models. A numerical design-of-experiments has allowed the exploration of geometrical variations to maintain suitable mechanical characteristics while minimizing the size of the system. The results show promising trends in its mechanical properties for the intended application. This study introduces a new osteosynthesis system that allows combining three patient-specific devices used for angular limb deformities into a single modular system, improving accessibility. The objective of this work is to evaluate the mechanical performance of this new system following the ASTM F382, combining experimental and numerical approaches and to compared it with a monobloc reference plate. Two prototypes appear to be viable. Nevertheless, a fully integrated assembly within the plate wasn't possible, because it strongly affected the mechanical properties. The numerical model provided quick and reliable information on the stiffness and failure prediction for design optimization.

Keywords: limb deformities; osteosynthesis assembled plate; numerical and experimental methods; mechanical testing; veterinary surgery.

1. Introduction

Correction of angular limb deformities (ALDs) in veterinary surgery requires accurate surgical techniques for optimal recovery (Armond et al., 2022; Worth et al., 2019). Methods for this type of correction have greatly advanced with improvements in medical imaging. Two-dimensional analyses (Paley, 2002) use radiography, while three-dimensional virtual surgical planning (VSP) relies on computer-tomography images and is often combined with patient-specific instruments (PSIs), such as surgical guides for accurate osteotomy, reduction, and plate fixation. VSP and PSIs are widely used in human surgery and have recently been introduced for veterinary applications (Panichi et al., 2024; Scheuermann & Kim, 2024). Indeed, PSIs present several advantages over standard instruments, such as ~~These methods~~ significantly improve~~s~~ing surgery accuracy, ~~reduce~~ reducing operation duration, and ~~accelerate~~ accelerating patient recovery (Carwardine et al., 2021; Worth et al., 2019). However, their high cost~~, mainly due to significant design preparation and manufacturing processes,~~ limits their use in clinical practice (Teo et al., 2021). Indeed, the need to design three separate patient-specific devices (one surgical guide and two plates) results in significant design preparation and manufacturing process.

~~-~~To enhance PSIs accessibility, we propose a novel, patient-specific modular bone-plate solution that enables the full integration of the surgical guide and fixation plate into a single device, instead of using three ~~separate~~ different devices (guides and two plates). It can be used for osteotomy, reduction, and fixation. Therefore, i~~I~~t optimizes the manufacturing process, reduces cost and delivery time, and facilitates surgical operation. ~~Modular bone plates already exist (Biedermann, 2021; Destainville & Richart, 2019; Long et al., 2009; Mirghasemi & Gabaran, 2015); however, these systems only enable plate length adjustment and none of them offer patient-specific surgical guides nor provide multiple functions.~~ The proposed system (Figure 1) is composed of two patient-specific plates serving as ~~cutting~~ osteotomy guides and an additional part composed of two clips used for the reduction and the fixation surgical step. Several modular standard bone plates concepts have already been proposed in the literature (Biedermann, 2021; Destainville & Richart, 2019; Long et al., 2009; Mirghasemi & Gabaran, 2015). However, their tenon–mortise–based assembly design ~~was~~is not suitable for ~~our system~~serving as osteotomy guide, as it relies on the insertion of one component into another. Preserving the functionality

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of the osteotomy guide was a key requirement, which necessitated that the plates remain in planar contact with each other. Therefore, we used an additional part (clips) that surrounded the plates, which also. Moreover, it ensures accurate positioning during the reduction andIt optimizes the manufacturing process, reduces cost and delivery time, and facilitates surgical operation. The use of a clip offers several advantages. First, it facilitates assembly design and manufacturing. Second, it preserves the planes of the extreme plates, providing support for the cutting guides and ensuring accurate positioning during the reduction. As the modular plates must remain in place, a compact, minimally invasive assembly design is required to reduce discomfort and tissue lesions.

These innovations require mechanical evaluation, particularly because plate geometry strongly influences mechanical behavior, and the mechanical properties of modular standard bone plates have been sparsely discussed in the literature The geometry of the plate influences its mechanical properties(Revol et al., 2024; Subasi et al., 2021). Moreover, Compared to a monobloc plate, assembled bone plates reduce mechanical properties, such as bending stiffness and strength (Subasi et al., 2021). iIn the immediate postoperative period, the implant must withstand the full mechanical load, as the bone has not yet begun to heal. This is especially critical in veterinary applications, where restricting post-surgery animal activity is challenging—leading to potential premature fatigue failure (Brunner & Simpson, 1980). Consequently, investigating their mechanical behavior and evaluating fatigue strength is essential to ensure the overall reliability of such systems (Menghini et al., 2023). Finally, aAs theour modular bone plates must remain in place, a compact, minimally invasive assembly design is required to reduce discomfort and tissue lesions.

Although assembled bone plate concepts have been proposed, none have yet reached commercialization, and the mechanical properties of osteosynthesis plate assemblies have only been sparsely discussed (Revol et al., 2024; Subasi et al., 2021). Tenon-mortise assemblies, mainly used for assembly plates in literature (Subasi et al., 2021), were not suitable for our system, as they require the insertion of one part into the other. A key system requirement was ensuring the function of the osteotomy guide, which necessitated that the plates remain in planar contact with each other. Therefore, we used an additional part (clips) that surrounded the plates.none have yet reached commercialization, and the mechanical properties of osteosynthesis plate assemblies have only been sparsely discussed (Revol et al., 2024; Subasi et al., 2021). FE analysis has been widely used in orthopedic biomechanical analysis and for testing new designs or materials (Subasi et al., 2021; Tarniţă et al., 2010; Zhou et al., 2017), because they avoid the need for multiple experimental tests.. To evaluate our proposed solution, FE models will be essential for optimizing the design of our modular system design, in order to limit its invasiveness. It is useful for optimizing the device design and predicting its behavior under different loading conditions. In the context of patient-specific devices, the use of a numerical model becomes even more valuable to avoid the need for multiple experimental tests.

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~~The study presents a mechanical evaluation of the proposed modular system prototype that follows the methodology introduced in our previous study (Revol et al., 2024).~~ In this context, the objectives of the present study are (i) to evaluate the mechanical properties of our modular system under static and cyclic loading in order to assess its mechanical feasibility, and (ii) to build and validate an easily implementable linear static FE model representative of static experiments, for comparative design optimization. ~~The study objectives is evaluation of the mechanical characteristics of the modular system~~The target evaluations are limited to the intrinsic mechanical behavio~~u~~r of the modular system compared to a reference monobloc bone-plate to focus exclusively on the influence of the assembly system (clips), while excluding other factors in this initial evaluation; for that, ~~it is~~we will not ~~necessary to~~ consider screw–bone or plate–bone interaction. Given that this study represents a feasibility assessment of the proposed concept, the number of prototypes was limited. ~~(using both numerical and experimental methods) and verification of its ability to be used for bone reconstruction.~~ Moreover, ~~due to the complexity of physiological loading conditions,~~ the study follows the widely accepted standard ASTM F382-24, which is concentrated on bending testing. ~~Effectively~~Indeed, although bending loading does not fully replicate physiological loading, it represents a conservative surrogate loading case for worst-case implant performance. Under in vivo conditions, a bone plate is not subjected to pure compressive or torsional loading because it is fixed to the bone. Consequently, the simulation of such loading conditions requires fixation to bone. In our case, bending most accurately represents the loading conditions encountered by the plate.

2. Material and methods

2.1 Reference plate and prototype

The mechanical properties of the modular system prototype were always compared to a monobloc reference plate. A simplified, straight-line geometry was used to represent both the reference plates and the system under study. This simplification permitted facilitation of plate fabrication in the laboratory. Both reference plates and prototypes (Figure 2) were machined using a HASS OM2 with 316L stainless steel. The plate dimensions (10 × 150 × 3.5 mm^3 with a 3.5 mm hole diameter) ~~corresponded~~ corresponds to commercially available osteosynthesis plates typically used for large dogs (of approximately 30 kg).

The prototype comprised two half plates (10 × 75 × 3.5 mm^3) joined together by clips screwed in the half-plates. ~~Tenon-mortise assemblies, mainly used for assembly plates in literature (Subasi et al., 2021),~~

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were not suitable for our system, as they require the insertion of one part into the other. A key system requirement was ensuring the function of the osteotomy guide, which necessitated that the plates remain in planar contact with each other. Therefore, we used an additional part (clips) that surrounded the plates.

Four configurations of the prototype were studied (Figure 3). The selection of these configurations was based on an analysis of geometrical parameters carried out using the design-of-experiments methodology based on FE simulations. The P1 prototype possessed the largest clip dimension, likely resulting in greater stiffness. This design aimed to minimize deviations in stiffness with respect to the reference plate and reduce stress concentrations. The P2, P3, and P4 prototypes used dimension-reduced clips: each successive prototype P(i) had a 25% reduction in height and width compared to the previous one P(i-1).

2.2 Bending tests

Four-point bending tests were performed on the reference plate and the prototypes in accordance with the ASTM F382-24 (2024) standard. This testing method is used to experimentally characterize osteosynthesis plates. The distance h between support rollers and loading rollers was set to 35 mm, and the distance a between loading rollers was set to 50 mm. Identical conditions were applied to both numerical simulations and experimental testing (Figure 4).

2.3 Numerical simulations

The finite element (FE) model (Figure 4), based on a linear isotropic material model for the 316L, was executed with the SolidWorks Simulation program (v.2024). The material properties (Young's modulus, yield strength, and Poisson's ratio) were calibrated using tensile tests conducted on three tensile specimens machined from 316L plate, the same used for manufacturing the experimental test plates. Non-penetrating contact conditions were implemented to model the interactions between the different parts of the modular prototype with a friction coefficient of 0.6 based on (Fellah et al., 2013). Assembly screws were modeled with the "bolt connector" of SolidWorks with a 0.5 Nm torque preload.

The symmetry condition was used in the plan $(\vec{x}, \vec{z})$ to reduce the size of the numerical problem. A load of 100 N was chosen to ensure that the system remained within the linear range. To maintain symmetry, a 50 N load was applied, distributed across two lines. The maximal displacement at the middle of the plate was extracted. A convergence study on the displacement results was conducted to assess the final mesh size. The localization of Von Mises stress concentration areas was also examined to identify potential failure zones.

Two simulations were carried out. The first one was based on the nominal geometry (named nominal) without dimensional deviation due to fabrication. The second one used a modified model (named real) that integrated average values measured on the manufactured plates as observed in the prototype configuration, including the plate thickness (3.43 mm) and the gap between plates (0.2 mm).

2.4 Experimental bending testing

2.4.1 Experimental setup

The reference plates and the prototypes were experimentally tested under quasi-static and cyclic loading conditions with an electrodynamic testing machine (ElectroPuls E1000) (Figure 4). Both static and cyclic tests followed the ASTM F382-24 standard, using the same roller distances as those implemented in the FE models. A guide ensured repeatable positioning of the samples to prevent slipping during the cyclic tests. An optical sensor (Opto NCDT-1420) was positioned at the middle of each sample to record themaximal deflection.

2.4.2 Quasi-static bending tests

Quasi-static tests were then conducted on a total of 14 specimens. This set was made of 6 reference plates and two prototypes of each of the four configurations. The testing procedure included five preloading cycles, ranging from -8 to -80 N (elastic domain) at 0.05 Hz. After the preloading stage, the test was run by controlling the displacement with a ramp rate of -1 mm/s from 0 to -10 mm. The displacement and the load were recorded at 40 Hz to extract the experimental bending properties. Before the quasi-static bending tests, reproducibility was assessed by performing ten times non-destructive tests on one plate using the same setup. After each test, the plate was removed from the setup.

2.4.3 Cyclic bending tests

Cyclic tests were conducted on both the reference plate (n = 2) and the prototypes (n = 2 for P1, n = 1 for P2, P3, and P4). The method used a sinusoidal load with an R_ratio of 0.1 (R_ratio = F_{min}/F_{max}) and a frequency of 5 Hz. Two Fmax loads were tested (200 and 270 N), representing ±15% of the reference proof load, following the ASTM F382. To observe the influence of geometry on fatigue failure, the load was increased (from 200 to 270 N) to test the remaining configurations, and new samples were used for these tests. Each test was conducted for 1 million cycles or until failure; if failure occurred, the number of cycles was recorded.

2.5 Evaluation of bending properties from numerical simulations and experimental tests

The numerical bending stiffness was computed as the applied load divided by the maximum extracted displacement in the z dimension. In the experiments, bending stiffness *K* was defined as the slope of the load–displacement curve within its linear region. An iterative, repeatable method was employed to define the curve segment for linear regression. Starting with limits between 0.5 and 0.55 mm, the R^2 value was computed using Python. The upper limit was incremented in steps of 0.05 mm until R^2 fell below 0.999. The final displacement range was defined between 10% and 70% of this upper limit. Bending structural stiffness (N.m^2/mm) was calculated using Equation 1 (with *h* and *a* values as defined in Figure 4); it characterized the intrinsic properties that were unaffected by the setup.

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$$Bending\ structural\ stiffness = \frac{(2h + 3a)Kh^2}{12} \quad (1)$$

Finally, the bending strength (Nm) indicated the point of yielding and was computed (Equation 2) using the 0.2% offset method ($q = 0.002 \times a$) of the ASTM F382-24 standard.

$$Bending\ strength = \frac{P*h}{2} \quad (2)$$

Bending fatigue strength properties were assessed using the cyclic-testing method, with the maximum cyclic load established in relation to the proof load *P*.

3. Results

3.1 Numerical model calibration

The material properties of the 316L used for the simulations were Young's modulus equal to 185 GPa, yield strength to 308 MPa, and Poisson's ratio to 0.33. The element size was set to a value in the range of 0.3–0.8 mm, representing 40,041 tetrahedral elements for the reference plate and between 43,426 and 46,249 for the prototypes (cf. supplementary materials for details). The simulations took 10 ± 3 min without convergence issues, and the bending-stiffness error remained below 0.2%.

3.2 Quasi-static properties

The numerical bending stiffness for P1 shows a 5% deviation from the reference plate (Table 1). A linear decrease in stiffness ($R^2 = 0.995$) was observed for P2, P3, and P4 as the assembly system became progressively more compact.

Experimental bending-stiffness results were comparable. Numerical results estimated the experimental bending stiffness with a maximum of 13% deviation (Figure 5). As the Young's modulus was calibrated, the variation could be attributed to unavoidable geometrical dispersions linked to the manufacturing process. Although the number of tested plates was limited, the reproducibility test showed a difference of less than 1% between each measurement, quantifying the repeatability of the experiments.

All plate types displayed plastic deformation; however, no failure occurred before test completion (Figure 6). The variation of the bending strength between the different plates was different from those observed for the bending stiffness: P1 and P2 maintained similar strength to the reference plate (between 4.4 to 5.1 Nm), while P3 and P4 presented significant reduction. Despite lower stiffness, P1 and P2 could sustain similar loads before plastic deformation; following the method advised in the ASTM F382, P2 displayed a 4% decrease compared to P1.

3.3 Fatigue strength

At 200 N (Figure 7), only the reference plate and the P1 prototype were tested, and both withstood the load, thereby validating the prototype. At 270 N, all specimens failed before reaching 1 million cycles. P1 and P2 exhibited bending strengths of approximately 45% of the reference plate, while P3 and P4 showed lower cyclic strengths of approximately 10% and 3%, respectively.

3.4 Failure location and stress concentration

The numerical model of the prototype shows a stress concentration around the screws on the plates and on the outer edges of the clip (Figure 8). During the static tests, deformation was also observed in these areas (Figure 9a). In the fatigue tests, failure occurred along the outer edges of the clip (Figure 9b), matching with stress concentration zone obtained with the numerical model.

4. Discussion

This study investigated the mechanical ~~performance~~ feasibility of a new modular system for the correction of ALDs.~~ ~~ The main objective was to compare the intrinsic mechanical properties of this solution with standard monobloc plates, rather than replicating the complexity of physiological loads encountered in vivo. ~~The main objective was limited to a standard mechanical assessment against a monobloc bone plate, rather than replicating the complexity of physiological loads encountered in vivo. The study is a standard mechanical assessment, since the testing setup does not replicate the complexity of physiological loads that occur in reality. Although~~ Therefore, biological environment involves multiple loading modes, including torsion and compression, only bending tests were conducted because bending represents the primary load applied to the plate (H.-R. Lee et al., 2022). Bending tests were conducted in accordance with the ASTM F382-24 standard (ASTM F382-24, 2024) to assess the mechanical properties of the system using both experimental and numerical approaches. Owing to the variability in testing setups and plate designs reported in the literature (Schorler et al., 2017), a reference plate was used to ensure consistent performance evaluation.

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The static results obtained from simplified reference bone plates were similar to those of the study using commercial 316L stainless-steel bone plates with comparable dimensions (DeTora & Kraus, 2008), confirming the consistency of our results.

Our study demonstrated that the P1 prototype ~~represents~~ seems to be a functional system, as its static mechanical properties are equivalent to those of the reference plate. The fatigue strength of P1 at 200 N was equivalent to that of the reference plate for one million cycle. These results indicate that the modular system could be a viable alternative for ALD correction. At 270 N, resistance was significantly reduced. This load was intentionally selected to simulate an unfavorable configuration and identify the weaknesses of our design. Cyclic tests were conducted up to 1 million cycles or until failure, as recommended by the standard. The optimal fatigue strength required for healing long bones is uncertain and depends on numerous factors such as age, location, and types of fractures (ASTM F382-24, 2024; Hammel et al., 2006; Johnston & Tobias, 2018). Comparison with physiological load is not possible due to the boundary conditions of the testing setup. d However, to achieve this performance, the volume of the modular system must be greater than that of the plates, which can be restrictive, particularly with certain breeds of dogs like greyhounds, which have thin skin on their front paws.

Our comparative study based on four different geometries demonstrated that reducing prototype volume while achieving suitable mechanical performance is possible. However, the P2 prototype presents a slightly smaller configuration in terms of clip length and width with mechanical performance relatively similar to the reference plate. Despite its reduced stiffness, P2 prototype ~~exhibited~~ suggests comparable bending strength compared to the reference plate. In fatigue performance, it withstood a number of cycles comparable to the P1 prototype under a 270 N load, suggesting that it could represent a viable option in specific clinical scenarios. However, as the clip dimensions decreased with the P3 and P4 prototypes, the mechanical performance of the system progressively diverged from those of the reference plate. Although these configurations offer advantages in terms of compact geometry, they also seem to lead to a significant degradation in both static and fatigue mechanical properties. Owing to these changes, the P3 and P4 prototypes may be better suited for specific clinical cases where mechanical loads are relatively low—such as animals with reduced body weight, low activity, or older age. In these situations, the reduced performance in terms of strength could be tolerable, as the applied mechanical stresses would be lower. However, the clip dimension reduction also leads to a significant decrease in the system stiffness. Insufficient stiffness could compromise the device's ability to keep the bone fragments properly aligned during the reconstruction process, which is essential to avoid creating new deformations. In this context, it would be preferable to use a system capable of maintaining sufficient stiffness to ensure correct alignment of the bone fragments throughout the bone healing process.

Our study also demonstrated good correlation between the results obtained with the numerical models and those obtained through experimental testing, both in terms of bending stiffness and failure location.

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The reliability of the FE models was validated, enabling additional investigations for different configurations without the need for further experiments. Using a simple and fast model, we demonstrated that it is possible to optimize the design, identify failure areas, and subsequently test different loading conditions.

Even though this study reports interesting results for the proposed modular system, several limitations must be noted.

The ~~third~~first limitation is the limited number of tested prototypes, owing to the constraints in plate-fabrication time and cyclic-testing duration~~; this excluded~~ , preventing any statistical analysis. However, the variability in the results was very low, increasing the confidence in our study.

Second, the evaluation was limited to the four-point bending test because bending is the main load experienced by bone plates *in vivo* (ASTM F382-24, 2024), and it is commonly used to test plates in the literature (Blake et al., 2011; Lee & Song, 2019; MacArthur et al., 2020; Verset, 2013). However, this loading case does not represent the actual *in vivo* conditions of osteosynthesis plates (Zhang et al., 2022; Johnston & Tobias, 2018), where compression and torsion loadings are also important and must be considered in the overall evaluation of the prototype.

~~First~~~~Second~~Third, biomedical environmental constraints have not been considered during this first stage of our study. Only the loading conditions specified in the ASTM standard have been used to compare our results with those in the literature. To approach biomedical conditions, the next step would be to test the modular prototype screwed into a support such as a synthetic bone, as is common during in vitro studies (Blake et al., 2011; Cabassu et al., 2011). ~~However, our approach aimed to isolate the mechanical effects of a modular system.~~

~~Second~~Thirdly~~, the evaluation was limited to the four-point bending test because bending is the main load experienced by bone plates *in vivo* (ASTM F382-24, 2024), and it is commonly used to test plates in the literature (Blake et al., 2011; Lee & Song, 2019; MacArthur et al., 2020; Verset, 2013). However, this loading case does not represent the actual *in vivo* conditions of osteosynthesis plates (Zhang et al., 2022; Johnston & Tobias, 2018), where compression and torsion loadings are also important and must be considered in the overall evaluation of the prototype.~~

~~The third limitation is the limited number of tested prototypes, owing to the constraints in plate-fabrication time and cyclic-testing duration; this excluded any statistical analysis. However, the variability in the results was very low, increasing the confidence in our study.~~

~~Finally~~In addition, the developed numerical model is limited to a linear model for the material. Nonlinear modeling of the material could provide additional information, particularly regarding post-yield prediction (Subasi et al., 2021) and the inclusion of plasticity or contact nonlinearities could allow more realistic ~~predictions~~forcastings.

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~~To address these limitations, conducting complementary biomechanical studies under realistic boundary conditions (like screwing the prototype into synthetic bone, for example) and testing loading other than bending (such as torsion and compression) are necessary to further evaluate the performance of the proposed modular system for the correction of limb deformities.~~

5. Conclusions

This study provides ~~-~~valuable preliminary ~~experimental and numerical results to~~ for evaluating the mechanical feasibility of using ~~the~~~~evaluate~~ the new modular system for the correction of limb deformities. To meet clinical needs, finding a balance between reducing the volume of the prototype and ensuring adequate mechanical performance is important. Further mechanical and biomechanical tests should be conducted to further evaluate ~~to confirm~~ the ~~viability~~ feasibility and reliability of the results for veterinary orthopedic applications.

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Declaration of interest statement

The authors declare no conflicts of interest related to this study.

Author contributions: CRediT

L.Revol: Writing-original draft, Methodology, Investigation, Formal analysis, Conceptualization. **A. Gilbin:** Methodology, Writing – review & editing, Validation, Supervision, Conceptualization, Investigation. **A. Levillain:** Methodology, Writing – review & editing, Validation, Supervision, Conceptualization. **B. Billottet:** Methodology, Writing – review & editing, Validation, Supervision, Conceptualization. **Y. Lafon:** Methodology, Writing – review & editing, Validation, Supervision, Conceptualization. **T. Barrière:** Methodology, Writing – review & editing, Validation, Supervision, Conceptualization. **N. Boudeau:** Methodology, Writing – review & editing, Validation, Supervision, Conceptualization.

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Table 1: *Numerical and experimental quasi-static bending properties of the reference plate and prototypes. Reported values represent the observed minimum and maximum ranges.*

Plate types	Numerical Bending stiffness *(N/mm)*	Experimental Bending stiffness *(N/mm)*	Experimental Bending structural stiffness *(Nm²)*	Experimental Bending strength (*Nm*)
Ref. plate	185–194	175–183	5.4–5.6	4.4–4.9
P1	153–184	166–173	5.1–5.3	5.2–5.2
P2	140–158	131–141	4.0–4.4	5.0–5.1
P3	124–138	120–135	3.7–4.2	4.3–4.5
P4	106–118	104–107	3.2–3.3	3.6–3.7

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Figure 1. Modular system: Step 1: Positioning of the patient-specific plate on both sides of the deformation; Step 2: Osteotomy of the deformed bone; Step 3: Reduction with the dual-clip assembly system; Step 4: Fixation during bone healing. The figure on the right shows the assembly system with one clip.

Figure 2. (a) Reference plate and (b) prototype comprising two half plates joined by clips.

Figure 3. Four configurations of the prototypes with successive reduction in height and width (P1: green, P2: blue, P3: orange, and P4: red).

Figure 4. Numerical model (left) used for simulation under the same boundary conditions (roller distances) as the experimental setup (right).

Figure 5. Difference between numerical (nominal: black edge colors; real: red edge colors) and experimental (triangle) bending stiffness for the reference plate (gray) and the prototypes (P1: green, P2: blue, P3: orange, and P4: red).

Figure 6. Quasi-static bending load–displacement curves (for the reference plate (gray) and the prototypes (P1: green, P2: blue, P3: orange, and P4: red).

Figure 7. Number of cycles to failure at 200 N and 270 N for the reference plate (gray) and the prototypes (P1: green, P2: blue, P3: orange, and P4: red). The percentages represent the difference between the achieved number of cycles and 1 million cycles.

Figure 8. von Mises Sstress distribution obtained from the simulation performed on prototype P1. Localization of maximum stress concentration areas are indicated by red rectangles on the plates (left) and on the clip (right) and plates.

Figure 9. Two distinct specimens of prototype P1 after testing: (a) deformation on clip under static testing and (b) fractures -on clip under cyclic test. Red rectangles indicate fracture location..

Commenté [AL18]: Il y a 3 figures et 2 prototypes. Est-ce que la figure b représente le même proto ou 2 différents ? Il faut clarifier

Commenté [AL19]: Peut-être ajouter les flèches pour montrer la fracture ?