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Biomechanical properties of bicortical and monocortical plate fixation for rib fractures in the adolescent human rib fracture model

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Purpose: The technical advancement of surgical stabilization of ribs often prevents the surgeons from fixation, despite the procedures documented improved outcomes. The aim of this study was to evaluate a less invasive approach involving a simplified monocortical rib fixation technique. *Methods*: Eighteen frozen human ribs obtained intraoperatively from young individuals aged 13–18 were employed for this study. First, the ribs were fractured under three-point bending, with their intrathoracic side put under tensile stress. Following this, the ChM 4.0 rib fixation system was utilized. The specimens were categorized into two groups: bicortical fixation ($n = 9$) and monocortical fixation ($n = 9$). Subsequently, bicortical and monocortical fixation groups underwent dynamic testing over 400 000 cycles under combined sinusoidal tensile bending and torsional loading (2–5 N at 3 Hz). In the final stage, all samples were subjected to a destructive load to failure. *Results*: Our analysis revealed that the fixation method did not demonstrate statistically significant differences in terms of preliminary bending stiffness ($p = 0.379$). Similarly, undergoing a course of 400 000 cycles involving combined tensile and torsional loading did not constitute a statistically significant factor affecting the monocortical and the bicortical fixation groups ($p = 0.894$). In the monocortical fixation group, all specimens failed due to screws pulled out from the bone. In contrast, all specimens in the bicortical fixation group exhibited failure attributed to fractures occurring just behind the plate. Nonetheless, the fixation method was not a significant factor affecting bending strength ($p = 0.863$). *Conclusions*: The monocortial fixation could be a reasonable option among younger populations with comparable stability of fixation.

Key words: *monocortical fixation, rib fractures, osteosynthesis*

1. Introduction

Thoracic trauma and concomitant rib fractures frequently arise as consequences of motor vehicle accidents [19]. The number of traffic collisions constantly increases, with blunt chest trauma constituting the second most frequent type [20]. Thoracic trauma contributes significantly to morbidity and mortality rates, where roughly 8–10% of drivers die due to chest wall trauma [22]. The severity of fractures may vary from simple to multilevel, including flail chest. Management of multiple fractures, especially with the flail component, has progressively focused on the injury of underlying tissues [9], [19]. The majority of patients with flail chests, require intensive pain management and mechanical ventilation to support the fractured segment[10]. Over the last decades, numerous implants have been developed to improve outcomes of surgical fixation of ribs, encompassing locking plates, intramedullary wires, struts and absorbable plates [1], [21]. Robust data support the benefits of surgical rib stabili-

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zation over symptomatic treatment [9], [13], [18], [19], [26]. Operative fixation of multisegmental rib fractures can significantly improve pulmonary function [9], [18], [19], [26]. The surgery prevents common complications, such as prolonged intubation often leading to pneumonia and sepsis [24], [30]. The pivotal argument in favor of operative rib stabilization is the noteworthy 38 to 72% reduction in mortality rates [1], [12], [30]. Unfortunately, the surgery is still executed in the minority of cases, in which the patient could benefit from [3], [10], [30], [31]. A contributing factor to the limited popularity of this procedure is the requirement for technical advancement of rib fixation, according to current recommendations [11], [34]. The conventional approach, performed with a locking plate system, utilizes three screws placed in a bicortical manner on each side of the fracture [11], [34]. Although single-lung intubation is not mandatory for surgical fixation of the ribs, it enhances surgical exposure and minimizes the risk of lung parenchyma injury while drilling through both cortices [11]. Moreover, improper screw selection may result in protrusion of the screw tip, causing pleural irritation or even pneumothorax [3], [11], [34].

The majority of existing literature examines the mechanical properties of various rib fracture fixation constructs [4], [5], [11], [23]. However, none of those studies involve the analysis of rib material obtained from living individuals under the age of 20 subjected to combined tensile-torsional cyclic loading. Authors study their fixation constructs in vitro utilizing cadaveric ribs acquired from elderly donors [5], [23]. Nevertheless, clinically essential parameters such as bone stock, bone purchase, and the initial stiffness could introduce bias to the results [14], [15], [19], [29], [32], [33].

This study aimed to compare, for the first time, the biomechanical properties between bicortical and monocortical locking plate fixation in the human rib fracture model acquired from young living subjects. We hypothesize that the monocortical or bicortical screw placement does not jeopardize the overall stability of the reduced fracture site.

2. Materials and methods

2.1. Specimens

All specimens were collected intraoperatively from 18 females undergoing the anterior approach spine surgery. The patient's age ranged from 13 to 18 and the BMI of 19.58 (SD 1.45) at the time of surgery. Basic demographics of the subjects have been presented in Table 1. Informed consent was acquired from all donors. The exclusion criteria were as follows: a BMI below 5 percentile, the presence of systemic diseases or any drug administration that could affect bone metabolism. The material in the form of rib fragments was taken according to the methodology described by Suk et al. [28]. For patients treated through the anterior approach, a single rib was removed, to facilitate surgical access. Additional ribs were also resected in the course of rib hump correction. Most of the resected rib fragments were grounded and utilized for the anterior fusion, while the surplus segments unused in fusion comprised the samples for testing. In total, eighteen frozen human ribs level IX–X from the lateral and posterior locations were employed. The bone material was stored in a double plastic container at –20 °C until the testing day. According to several studies, such conditions do not alter mechanical parameters [16], [25]. After thawing for 12 hours, all soft tissue was removed and each rib was cut into a total arc length of 160 mm. In accordance with the methodology described by Mischler et al. [23], the ventral ends of the ribs were embedded with epoxy resin into polymethylmethacrylate (PMMA) custom-made PMMA cylinder-radius 30 mm. The dorsal ends were embedded with epoxy resin into a plastic ball radius of 40 mm. Following that procedure, a weak spot was generated utilizing an oscillating saw equipped with a 0.5 mm thick blade.

Table 1 Basic demographics of the subjects

Patient No.	Age	Weight	Height	BMI
1	18	45	158	18.026
2	14	50	167	17.928
3	13	45	155	18.730
4	14	56	164	20.821
5	16	57	170	19.723
6	16	59	166	21.411
7	14	48	167	17.211
8	16	55	164	20.449
9	15	52	167	18.645
10	16	51	163	19.195
11	17	57	164	21.193
12	13	55	171	18.809
13	15	43	154	18.131
14	16	52	166	18.871
15	18	60	163	22.583
16	16	54	165	19.835
17	16	55	167	19.721
18	17	59	167	21.155

In all instances, an eight-hole 77 mm ChM 4.0 ChLP straight reconstruction plate made of titanium alloy was employed (Fig. 1) [35]. A certified orthopedic surgeon – lead author performed the plating of the ribs following the ChM manufacturer's guidelines. To standardize the beam while contouring the plate and achieving uniform rib length, a custom mold made of plaster was prepared. The thickness of the cortex was assessed with the caliper, during fixation of rib fragments. The average thickness ranged from 0.6 mm to 0.8 mm. The specimens were consequently instrumented using a ChM's drill guide with a ChM's drill bit (1.8 mm). Finally, three titanium alloy 2.4 mm locking screws (6 mm of total length) were placed on each side monocortically and 2.4 mm locking screws (8 mm of total length) were placed on each side bicortically, depending on the assigned group (Fig. 2). Two holes near the fracture site were left empty. The insertion torque applied to each screw on each plate was standardized to values recommended by the ChM manufacturer – 1 Nm for the ChM 4.0 ChLP plate and 2.4 mm locking screw [35]. A calibrated torque-limiting screwdriver (MicroClick MC 5, Proxxon Industrial) were used. The resolution of this device was determined by the scale ring with 0.1 Nm graduation. The manufacturer certified that the accuracy was +/–6%. Once the limiting torque was set, no further adjustments were made. All screws were tightened under the same conditions by the lead author.

Fig. 1. The ChM 4.0 ChLP straight reconstruction plate

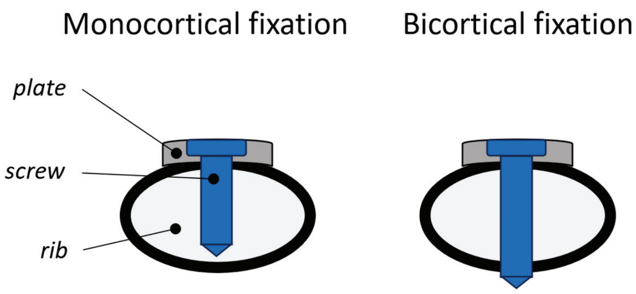

Fig. 2. Fixation diagram

2.2. Measuring setup

Each rib was fractured on a three-point bending universal servohydraulic testing machine (ZWICK Z100/TL3S Zwick GmbH & Co. KG, Ulm, Germany) (Fig. 3). Both the initial and the final biomechanical testing were performed using the same universal servohydraulic testing machine (ZWICK Z100/TL3S Zwick GmbH & Co. KG, Ulm, Germany). The resulting bending strength was reported in Nm. The resolution and accuracy of distance measurement were 1 μm and 2 μm accordingly. A built-in sensor of the testing machine was used for distance. The force was measured by a 5 kN load cell (Xforce HP, Zwick GmbH & Co. KG, Ulm, Germany). The resolution and accuracy of the force measurements were 0.01 N and 1% of the nominal load (accuracy class 0.5). The standard calibration procedure with a custom-made beam made of aluminum was executed prior to each test. Please note that 1 N corresponds to a gravity force acting on a mass of approximately 0.102 kg on Earth.

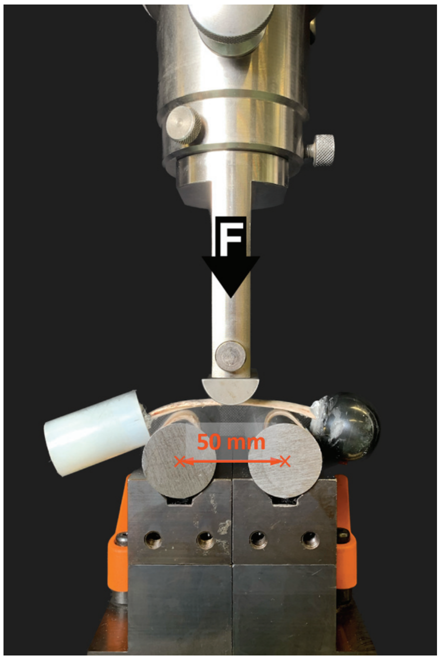

Fig. 3. The three-point bending setup

The initial stiffness of each construct post-instrumentation was assessed non-destructively through axial compression (Fig. 4). Additionally, the initial stiffness of 4 specimens was assessed pre-instrumentation. Subsequently, the specimens were mounted to the custom cyclic loading device. The machine combined tensile and torsional loading by applying cyclic force from 2 N to 5 N at a rate of 3 Hz, with a total of 400 000 cycles according to the methodology described by Mischler et al. [23]. This machine simulated the physiological bucket handle motions of the ribs during respiration [2], [23]. Construct subsidence was controlled and adjusted every 50 000 cycles (Fig. 5). An intravenous system was used to deliver the Ringer solution to prevent the specimen from drying. At the final stage, the constructs underwent load-to-failure testing using an axial compression machine (ZWICK Z100/TL3S Zwick GmbH & Co. KG, Ulm, Germany).

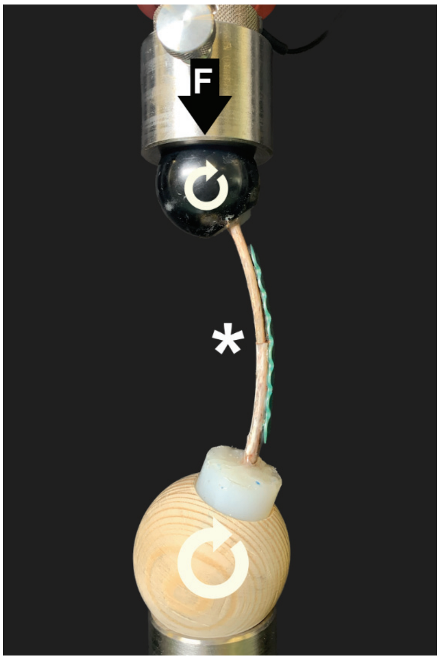

Fig. 4. An axial compression machine (ZWICK Z100/TL3S Zwick GmbH & Co. KG, Ulm, Germany) and rib fragments-ChM 4.0 ChLP monocortical fixation

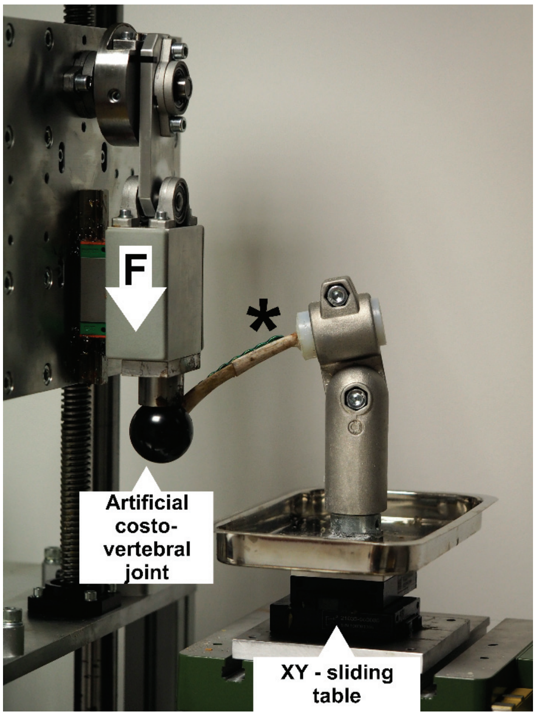

Fig. 5. Specimen mounted to a custom-made machine with *x-y* sliding table for combined tensile and torsional loading

2.3. Statistical analysis

Statistical analyses were performed using Mathematica 12 software (Wolfram Research, Inc., Oxfordshire, United Kingdom). Data was reported as mean ± standard deviation, statistical significance was set to $p < 0.05$.

Mann–Whitney *U*-test was used hereby to evaluate whether the insertion method affected the maximum force registered during the single cycle to failure testing post-cyclic loading. To determine the effect of cyclic loading (pre versus post test), the insertion method (mono versus bicortical) and its combination on the bending stiffness, two-way ANOVA was used considering repeated observations. For additional validation, power analysis of the test was performed to determine the probability of committing type II error. The assumed acceptable power of the test was ($\beta < 0.2$) [6]. The normality of residuals was assessed through the Shapiro–Wilk test.

2.4. Ethics

This study was approved by the Human Research Ethical Committee No 105/22. The patient's consent was obtained each time before the surgery.

3. Results

3.1. Comparison of pre and post-cycling loading stiffness

Bone stiffness prior to fixation was 14.124 N/mm (SD 2.36) ($N = 4$). The mean initial bending stiffness was 18.58 N/mm (SD 6.61) ($N = 9$) for the monocortical fixation group and 16.09 N/mm (SD 4.12) ($N = 9$) for the bicortical fixation group (Fig. 6). Statistical examination with the ANOVA demonstrated that the fixation method was not a statistically significant factor affecting bending stiffness ($p = 0.379$, $\beta = 0.196$). Interestingly, the ANOVA test revealed that the bending stiffness after cyclic loading was also not a statistically significant factor ($p = 0.906$, $\beta = 0.194$). Combination of both groups with pre- and post-cycling loading also demonstrated (ANOVA) no statistically significant differences ($p = 0.894$, $\beta = 0.194$) (Fig. 6). We did not observe any construction failures post-cycling in either group.

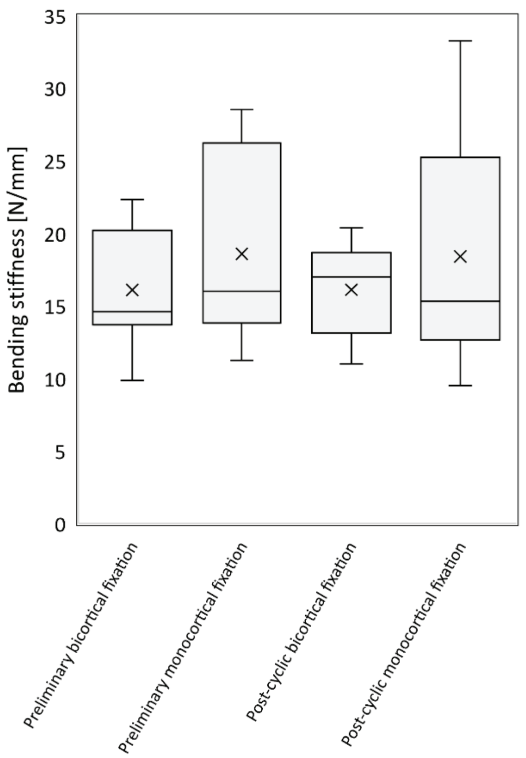

Fig. 6. Box and whisker plots with preliminary and post-cycling loading stiffness in analyzed groups

3.2. Mechanism of failure

The mean load to failure was 82.82 N (SD22.23) ($N = 9$) for the monocortical fixation group and 77.94 N (SD22.82) ($N = 9$) for the bicortical fixation group. Load-displacement curves for two representative mono- and bicortical constructs are presented in Fig. 7. Statistical examination with the Mann–Whitney *U*-test demonstrated that the fixation method was not a statistically significant factor affecting bending strength ($p = 0.863$) Fig. 8). All monocortical fixation group specimens (failed due to screws pulled out from the bone (Fig. 9A). In contrast, all specimens in the bicortical fixation group failed due to fractures occurring just behind the distal screw hole (Fig. 9B).

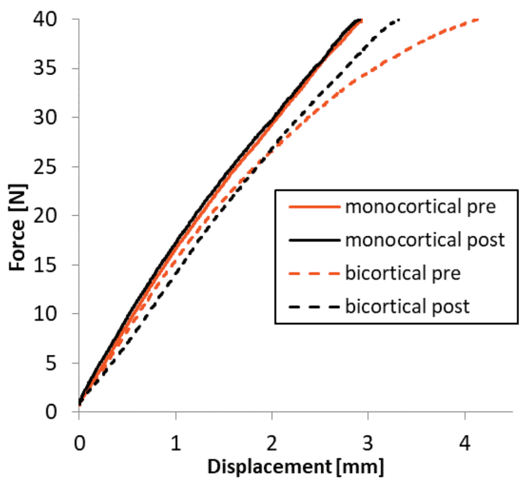

Fig. 7. Load-displacement curve

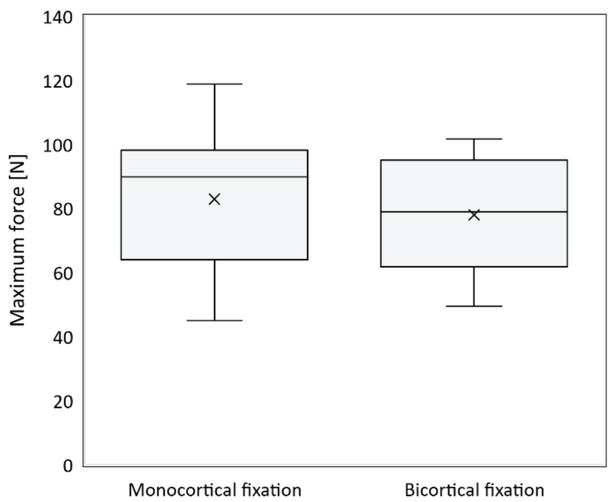

Fig. 8. Box and whisker plots with maximum load-to-failure in analyzed groups

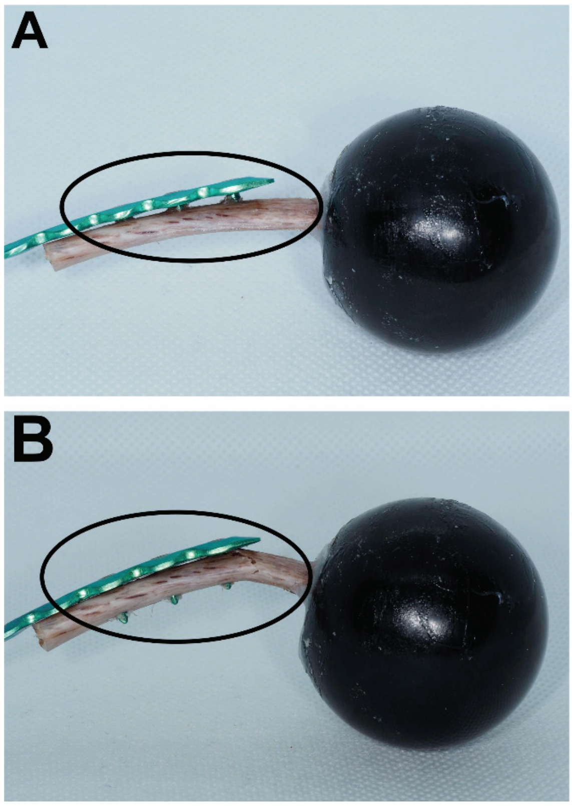

Fig. 9. A) Dismantled monocortical fixation with the screws pulled out of bone, B) Dismantled bicortical fixation with the fracture behind the plate

4. Discussion

The technical and anesthesiological advancement of rib fracture fixation often limits the surgeons from osteosynthesis [3], [10], [11]. Compression plating utilizing bicortical screws was a standard technique supported by literature [10], [21]. However, the introduction of low-profile locking plate systems facilitated less invasive surgical approaches as the locked construct's strength is independent of bone compression [7], [11], [27]. Therefore, the healing process remains nearly undisturbed while the periosteum stays intact [10]. Furthermore, the occurrence of locking screw loosening and migration is rare when thorough surgical techniques are employed [10], [11].

A study by Choke et al. [5] focused on the cadaveric investigation of bicortical and monocortical Synthes MatrixRIB fixation system. Interestingly, the authors proved no statistically significant differences between post-cycling loading stiffness for both analyzed groups ($p = 0.872$). However, the study was limited to axial compressive cycling-loading, without testing the torsional force that occurs in physiological breathing [5], [23]. In contrast, in our study, we utilized combined tensile and torsional loading for a duration representative of over 2 weeks of fracture healing [2], [23]. Similarly, we did not observe higher bending stiffness among the bicortical fixation group ($p = 0.894$). Choke et al. [5] also did not observe significant differences in load to failure between monocortical and bicortical fixation ($p = 0.549$). However, only 2 out of 10 specimens failed due to screw pull out, whereas in our study all monocortical specimens failed as result of pull out from the bone. Moreover Choke et al. [5] reported that all analyzed bicortical fixations failed by plate bending and refracture at the fracture line. This was not the case in our study, whereas all bicortical fixations failed just behind the distal screw hole. Mischler et al. [23] analyzed the modified rib's fixation technique with only two bicortical screws per fragment. The authors also did not observe a significant influence of the number of screws in relation to post cycling bending stiffness and maxium force ($p = 0.64$ and $p > 0.13$, respectively). Similarly to our results, the failure mode of this type of fixation was consistent, featuring bone fracture at the most distal screw hole [23]. However, compared to monocortical fixation, a simple reduction of inserted screws cannot prevent common complications associated with bicortical screw stabilization, such as lung parenchyma injury [11]. Contrary to Mischler et al. [23] we did not register a significant increase in bending stiffness after the course of cyclic loading due to settling and non-linear force-displacement behavior. However, this property holds minimal relevance in non-weight-bearing bones, as stress loading during respiration is not axially directed as in axial load to failure tests. Regarding the discussion above, both studies conducted by Mischler et al. and Choke et al. were conducted on identical plates – MatrixRiB Synthes [5], [23], [34]. It is worth emphasizing that the final mode of failure during a similar axial loading test was quite different. Taking bone variability and inevitable differences between loading parameters into account, any direct comparisons between these *in vitro* studies should be treated with caution.

The current standard for rib fracture fixation is the placement of a minimum of three bicortical locking screws per fragment [34]. This recommendation refers to all age groups [34]. Monocortical fixation which is less technically demanding procedure could lead to fixation failure due to screw pull-out in osteoporotic bone [34]. Therefore, literature regarding monocortical fixation or fixation with less screws is limited [5], [23].

Post-mortem studies are characterized by some general limitations [5], [23]. Concerns regarding bone quality and its mechanical parameters during the tests arise from the limited number and senior age of cadaveric specimens [17], [32], [33]. A study by Takahashi et al. [29] that analyzed age's impact on the ribs' BMD values, documented a 25% drop at the age of 60 compared to peak values at the ages from 15 to 25. Wang et al. [32] pointed out that altered parameters of rib cortical bone are influenced not only by BMD, but also by microarchitecture and the ratio between mineral and organic substances. Currey et al. [8] reported considerable variations in rib cortical bone parameters, associated with age. The post-mortem analysis of 18 donors (aged 2–42), proved that ribs from the younger population exhibit lower Young's modulus and bending stiffness. Simultaneously, they displayed increased deflection and greater energy absorption prior to fracture.

Our study performed on ribs obtained from young living subjects suggests that monocortical fixation with three screws per fragment offers similar stability to bicortical fixation. Our method of monocortical fixation offers the advantage of simplifying screw measurements compared to thorough measurements required in bicortical fixation [11], [34]. Furthermore, the monocortical fixation technique could be a salvage option, while a contralateral pulmonary contusion limits the tolerance to single-lung ventilation [20].

Limitations

This study presents several limitations. First, our analysis concerns material obtained only from living individuals under the age of 20. Analyzed rib fragments are rather homogenous in terms of regular cortical thickness and cortical bone density. Second, our investigation was confined to a single-rib testing model. Moreover, the axial load to failure test is not an anatomical loading mode. *In vivo*, fracture lines could be far beyond standardized transverse fractures of tested samples. Furthermore, we used only one type of rib plate fixation system. Therefore, those *in vitro* results should be treated with caution.

5. Conclusions

For the first time, our study compared the biomechanical performance of bicortical versus monocortical fixation in axial and tensile-torsional tests, utilizing ribs acquired from adolescent living subjects. Our study's results indicate that monocortical plate fixation could deliver comparable construct strength in younger populations while simultaneously simplifying the technical advancement of surgical procedures.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author **[J.G].**

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