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Biomechanical characteristics of rib fracture fixation systems

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ABSTRACT

Background: The primary aim of this study was to determine and compare the biomechanical properties of a fractured or intact rib after implant fixation on an embalmed thorax.
Methods: Five systems were fixated on the bilateral fractured or intact (randomly allocated) 6th to 10th rib of five post-mortem embalmed human specimens. Each rib underwent a four-point bending test to determine the bending structural stiffness (Newton per m^2), load to failure (Newton), failure mode, and the relative difference in bending structural stiffness and load to failure as compared to a non-fixated intact rib.
Findings: As compared to a non-fixated intact rib, the relative difference in stiffness of a fixated intact rib ranged from −0.14 (standard deviation [SD], 0.10) to 0.53 (SD 0.35) and for a fixated fractured rib from −0.88 (SD 0.08) to 0.17 (SD 0.50). The most common failure mode was a new fracture at the most anterior drill hole for the plate and screw systems and a new fracture within the anterior portion of the implant for the clamping systems.
Interpretation: The current fixation systems differ in their design, mode of action, and biomechanical properties. Differences in biomechanical properties such as stiffness and load to failure especially apply to fractured ribs. Insight in the differences between the systems might guide more specific implant selection and increase the surgeon's awareness for localizing hardware complaints or failure.

1. Introduction

Ribs are intimately associated with respiration. Thoracic pain following rib fractures can result in ineffective breathing mechanics and poor secretion clearance. This subsequently precipitates the development of pneumonia or respiratory insufficiency (Talbot et al., 2017). Rib fractures are the most common bony injury following blunt thoracic trauma and traditionally have been managed nonoperatively (de Moya et al., 2017; Schulz-Drost et al., 2016). Surgical stabilization of rib fractures (SSRF) has increased exponentially over the last decades following beneficial results in patients with a flail chest with regard to pneumonia rate, hospital, and intensive care unit length of stay (HLOS and ICU LOS) (Cataneo et al., 2015; Leinicke et al., 2013). Moreover, SSRF appears to be cost-effective (Swart et al., 2017). Currently, several consensus guidelines recommend SSRF in patients with a flail chest (Choi et al., 2021a; Kasotakis et al., 2017; Pieracci et al., 2017). Outcomes after SSRF have been studied for a variety of techniques, including wire cerclages, struts, clips, or plate and screw fixation (Fitzpatrick et al., 2010). Concurrent to the increase in SSRF, there has been an increase in the number of available fixation systems. The occurrence

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of hardware failure and revision surgery after SSRF is low (3–4% and 3%, respectively), but subjective implant irritation has been shown to be the main reason in patients undergoing implant removal (Choi et al., 2021b; Peek et al., 2020; Sarani et al., 2019). It is hypothesized that biomechanical properties of plate and screw systems such as a higher stiffness might be linked to hardware failure (*e.g.,* screw pull-out) or persistent thoracic discomfort (*e.g.,* attenuated sensitivity or residual pain) (Bottlang et al., 2010a; Lardinois et al., 2001). As this has never been assessed objectively, it remains uncertain to what extent this is because of the initial trauma to the chest wall and associated structures or to the operative procedure and implants.

To date, no study has yet compared the biomechanical properties of the available rib fixation systems. The primary aim of this study was to determine and compare the biomechanical properties (*i.e.,* stiffness, load to failure, and mode of failure) of a fractured or intact rib after implant fixation.

2. Methods

2.1. Study design

A human anatomical specimen study was conducted using five embalmed (AnubiFix (Theeuwes et al., 2017)) *post mortem* human subjects. The *post mortem* human specimens had a mean age of 76 years (standard deviation [SD] 22) and two (40%) were female. All donors were part of the national donor program and had given written consent to tissue donation for educational and scientific purposes before passing away. Under these conditions and Dutch law, no approval of the medical research ethics committee was required. In accordance with European privacy regulations, the medical history of the donors was not available. Specimens were excluded if on visual examination thoracic abnormalities such as scars, congenital deformities or signs of previous thoracic procedures that might compromise rib fixation were observed. For each thorax, the bilateral 6th to 10th rib was selected for fixation because of their functional and morphological similarities, while the 5th rib was used as a baseline reference of a non-fixated intact rib. The following rib fixation systems were used: MatrixRIB™ (DePuy Synthes, West Chester, PA, USA), RibLoc® U+ (Acute Innovations, Hillsboro, OR, USA), RibFixBlu™ (Zimmer Biomet, Jacksonville, FL, USA), STRACOS™ (MedXpert GmbH, Eschbach, Germany), and NiTi Rib (Cosmos Medical International, Luxembourg City, Luxembourg). The fixation systems were randomly allocated to the specimens' 6th to 10th rib, while ensuring that every implant was at least allocated twice to the same specimen with a similar distribution of intact and fractured ribs across the systems.

2.2. Fixation of the ribs

The specimens were placed on an operating table in a lateral decubitus position. The lateral aspect of the 5th to 10th rib was exposed through a longitudinal incision at the level of the anterior axillary line (Bottlang et al., 2013; Taylor et al., 2013). After dissection and retraction of the muscles and subcutaneous tissue, the ribs were exposed. Each rib was randomly allocated to be fractured or not, irrespective of side and rib number. These designated ribs were fractured at approximately 50% of the rib's length, measured anteriorly from the costochondral junction to posteriorly at the transverse process of the associated thoracic vertebra, using a tape measure (centimeters). A transverse simple rib fracture was made in half of ribs 6 to 10 ($n = 25$), using an oscillating bone saw with a 1 mm cut thickness. All intact and fractured ribs 6 to 10 were fixated ($n = 50$) at the same anterolateral level. The fixated intact ribs were used to mimic a consolidated rib fracture.

Per fixation system, the rib fixations were performed by board-certified Trauma and Acute Care Surgeons who had performed at least 25 surgical procedures with the specific implant. The fixated ribs (n = 50) and non-fixated ribs ($n = 10$) were resected with the oscillating bone saw at the costochondral junction and costovertebral joint. All ribs were subsequently cleaned from soft tissue and periosteum.

2.3. Biomechanical test set-up

All resected ribs underwent a four-point bending test on a Lloyd LR5K universal materials testing machine (AMETEK, Berwyn, IL, USA; Fig. 1). All tests were performed at room temperature, except for the thermoreactive NiTi Rib system for which the set-up was complemented with a thermostat and hot air blower at 37 °C. Implants were tested after fixation on an intact rib and on a fractured rib. In general, implants are not removed after rib fixation, thus construct testing of the implant on an intact rib was chosen to mimic a fixated consolidated rib fracture in the long-term.

2.4. Quasi-static testing

First, the ribs were subjected to a single cycle four-point bending at a crosshead speed of 0.25 mm/s and a center span (a) distance of 20 mm and loading span (h) distance of 60 mm (Fig. 1C). With the load-displacement curves, the bending stiffness was determined (K; N/mm) by calculating the linear elastic section of the curve. Subsequently, the bending structural stiffness (EI; Nm^2) was calculated where E is the elasticity modulus (N/m^2) and I the second moment of inertia (m^4). The EI is the effective bending stiffness of a construct normalized to the dimensional aspects of the test rig (Gere and Timoshenko, 1999). In addition, the maximum load to failure (F_{max}; N) was determined from the load-displacement curve (Gere and Timoshenko, 1999). Supplemental Digital Content 1, SDC, 1 provides a more in-depth overview of the applied equations and methodology. The test was continued until construct failure. Failure was defined as the occurrence of a new rib fracture or hardware failure including dislocation or breaking of the implant associated with a rapid deformation in the load-displacement curve.

For each fixation system, the EI of a fixated fractured or intact rib as compared to the EI of a non-fixated intact rib can be determined by the relative difference in EI (SDC 1). This allows for comparison of the biomechanical properties between the fixation systems across different specimens. For a fractured rib, for example, a relative difference in EI of "0" indicates that the construct of the implant on the fractured rib has a stiffness similar to that of a non-fixated intact rib. A positive value indicates that the stiffness of the implant and fixated rib exceeds that of a non-fixated intact rib, where a value of "1" represents an increase of 100% (or twice the stiffness). A negative value means that the fixated rib is less stiff than the non-fixated intact rib, where a value of "-1" represents a decrease of 100%. A similar approach was used to determine the average relative difference in F_{max} (SDC 1).

2.5. Cyclic testing

Per system, one fixated intact rib was subjected to a cyclic four-point bending test. The center and loading span distance were equal to the quasi-static test. This test was performed at a minimum load of 3 N and maximum load of 30 N to mimic internal and external intercostal forces (Marasco et al., 2010). The load cycled at a crosshead speed of 1 mm/s until failure or until 18 h when the test was stopped.

2.6. Statistical analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS) version 25.0 (SPSS, Chicago, IL). Normality of continuous variables was tested with the Shapiro-Wilk test. Descriptive analysis was performed to report data for each fixation system. Continuous data are reported as mean and standard deviation, categorical data as numbers and frequencies. For continuous data, statistical significance of differences between fixation systems were assessed using the one-way

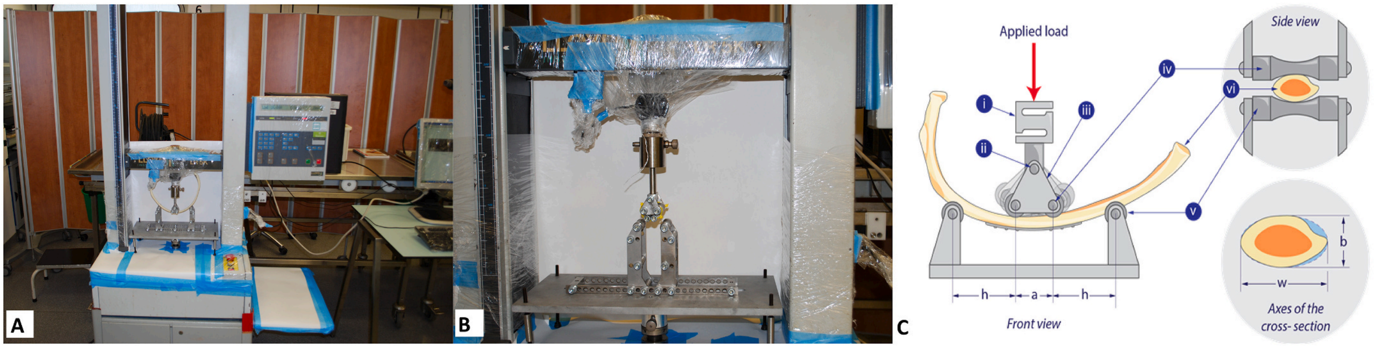


Fig. 1. Biomechanical four-point bending test set-up (A), close-up (B).

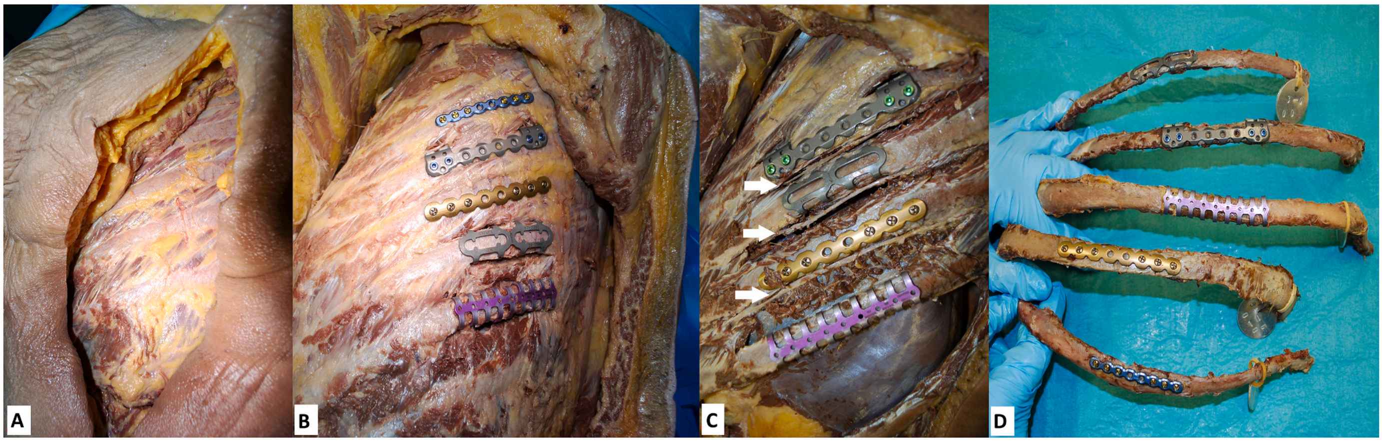


Fig. 2. Embalmed thoraces showing the rib fixation approach (A), implant fixation (B), intercostal nerve dissection (C; arrows), and rib resection (D). Fig. 2B, from top of the picture to bottom: RibFixBlu™, RibLoc® U+, MatrixRIB™, NiTiRib, and STRACOS™; Fig. 2C: RibLoc® U+, NiTiRib, MatrixRIB™, and STRACOS™; Fig. 2D: NiTiRib, RibLoc® U+, STRACOS™, MatrixRIB™, and RibFixBlu™.

analysis of variance (ANOVA) and student's *t*-tests for differences between two systems (with (un)equal variance according to the Levene's test). For categorical data, χ^2 or Fisher's exact test was used as applicable. A *p*-value lower than 0.05 was considered statistically significant and all tests were two-sided.

3. Results

Table 1 presents the characteristics of the implanted fixation systems. For a non-fixated intact rib five, the mean F_{max} was 87.97 N (SD 63.84) and the structural bending stiffness 1.07 Nm^2 (SD 0.87).

3.1. Biomechanical outcomes

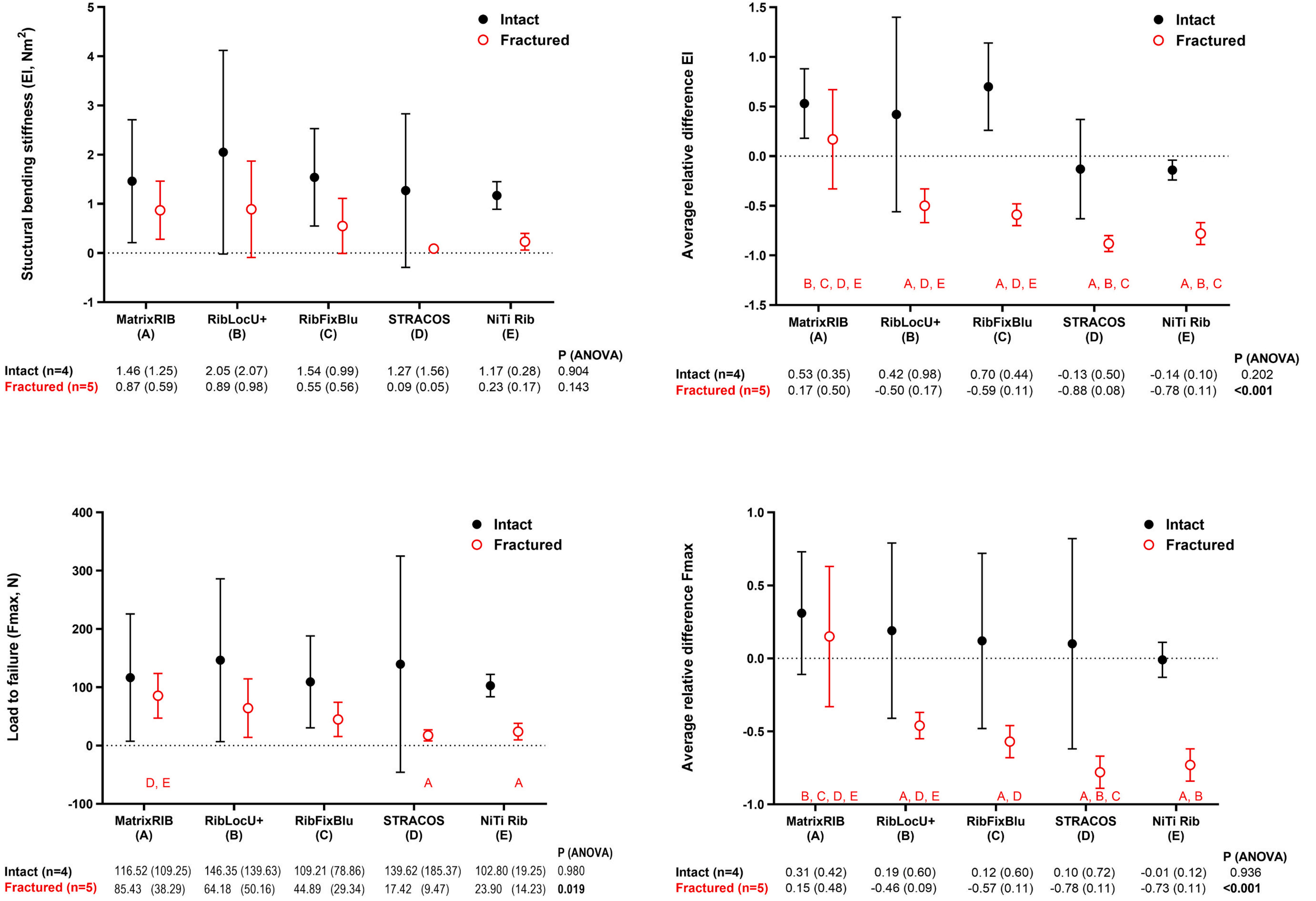
In total, 44 ribs underwent quasi-static testing, and five ribs cyclic testing, because one rib (RibFixBlu™ system) was excluded from testing due to the occurrence of a new iatrogenic fracture during resection. For the fixated fractured ribs, the average relative difference in EI, F_{max}, and the relative difference in F_{max} varied significantly between the fixation systems (Fig. 3B-D). The average relative difference in EI of a fixated fractured rib ranged from −0.88 (SD 0.08) for the STRACOS™ system to +0.17 (SD 0.50) for the MatrixRIB™ system ($p < 0.001$). The average relative difference in EI of a fractured rib fixated with the MatrixRIB™ system was significantly higher than the other systems and the clamping systems differed significantly from the plate and screw systems (Fig. 3B). The average relative difference in F_{max} ranged from −0.78 (SD 0.11) for the STRACOS™ system to +0.31 (SD 0.42) for the MatrixRIB™ system ($p < 0.001$). The average relative difference in F_{max} of the MatrixRIB™ system was significantly higher than all other systems (Fig. 3D).

Table 1
Implant-specific characteristics of each fixation system.

Fixation system	Device type	Device length (mm)	Screws required (anterior-posterior)	Type of screw
MatrixRIB™	Plate	80	3–3	Bicortical
RibLoc® U+	Plate	75	2–2	Bicortical
RibFixBlu™	Plate	60	3–3	Bicortical
STRACOS™	Clip	70	None	Not applicable
NiTi Rib	Clip	60	None	Not applicable

For the fixated intact ribs, the biomechanical outcomes were similar between all fixation systems (Fig. 3A-D). During cyclic testing, the rib fixated with the RibFixBlu™ system fractured at the drill hole of the most anterior screw. The other systems completed the 18 h of cyclic testing without failure.

Multiple modes of failure were identified for the different fixation systems. For the MatrixRIB™ system ($n = 9$), the most common failure mode was the occurrence of a new fracture at the most anterior drill hole ($n = 7$, 78%), while the other two fixated ribs failed through plate dislocation at the initial fracture site (Supplemental Fig. 1). The occurrence of a new fracture at the most anterior drill hole or end of the plate was also the most common failure mode for the RibFixBlu™ system ($n = 5$, 63%) and RibLoc® U+ system ($n = 8$, 89%). The other fixated ribs failed because of plate deformation for the RibLoc® U+ system in the middle ($n = 1$, 11%) and caused by anterior screw dislodgement for the RibFixBlu™ system ($n = 3$, 37%). For the NiTi Rib ($n = 9$) system, the



	MatrixRIB (A)	RibLocU+ (B)	RibFixBlu (C)	STRACOS (D)	NiTi Rib (E)	P (ANOVA)
Intact (n=4)	1.46 (1.25)	2.05 (2.07)	1.54 (0.99)	1.27 (1.56)	1.17 (0.28)	0.904
Fractured (n=5)	0.87 (0.59)	0.89 (0.98)	0.55 (0.56)	0.09 (0.05)	0.23 (0.17)	0.143

	MatrixRIB (A)	RibLocU+ (B)	RibFixBlu (C)	STRACOS (D)	NiTi Rib (E)	P (ANOVA)
Intact (n=4)	0.53 (0.35)	0.42 (0.98)	0.70 (0.44)	-0.13 (0.50)	-0.14 (0.10)	0.202
Fractured (n=5)	0.17 (0.50)	-0.50 (0.17)	-0.59 (0.11)	-0.88 (0.08)	-0.78 (0.11)	**<0.001**

	MatrixRIB (A)	RibLocU+ (B)	RibFixBlu (C)	STRACOS (D)	NiTi Rib (E)	P (ANOVA)
Intact (n=4)	116.52 (109.25)	146.35 (139.63)	109.21 (78.86)	139.62 (185.37)	102.80 (19.25)	0.980
Fractured (n=5)	85.43 (38.29)	64.18 (50.16)	44.89 (29.34)	17.42 (9.47)	23.90 (14.23)	**0.019**

	MatrixRIB (A)	RibLocU+ (B)	RibFixBlu (C)	STRACOS (D)	NiTi Rib (E)	P (ANOVA)
Intact (n=4)	0.31 (0.42)	0.19 (0.60)	0.12 (0.60)	0.10 (0.72)	-0.01 (0.12)	0.936
Fractured (n=5)	0.15 (0.48)	-0.46 (0.09)	-0.57 (0.11)	-0.78 (0.11)	-0.73 (0.11)	**<0.001**

Fig. 3. The structural bending stiffness (EI; A), average relative difference in EI (B), load to failure (F_{max}; C), and average relative difference in F_{max} (D) for each fixation system on an intact or fractured rib. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Each figure presents a biomechanical outcome for an implant on an intact (black) or fractured rib (red).

The colored letters below each dot represent the fixation system (A to E) with which that system has significantly different outcomes: a red letter signifies the system with which the fixation system has different outcomes from when fixated on a fractured rib; a black letter when fixated on an intact rib. For example, a red A under the red dot D for Fmax indicates a significant difference in Fmax between system A and D when fixated on a fractured rib.

Data are presented as mean ± standard deviation. Bold values represent *p*-values below 0.05.

most common failure modes were a new fracture within the anterior portion of the implant (*n* = 4, 44%) and plate deformation at the initial fracture site (n = 4, 44%; Supplemental Fig. 2). In one rib (11%), the initial fracture end dislodged out of the NiTi Rib implant. The failure modes of the STRACOS™ system (n = 9) were the occurrence of a new fracture within the anterior portion of the implant (n = 3, 33%), a new fracture at the implant's ends (n = 3, 33%), and plate deformation at the initial fracture (n = 3, 33%).

4. Discussion

This biomechanical study evaluated the biomechanical properties of five currently available rib fixation systems. The available implants differed in their specific characteristics (*e.g.,* plate and screw or clamping system, the implant's length) and their biomechanical properties. For the plate and screw systems, the most common mode of failure was a new fracture at the most anterior drill hole or anterior end of the plate. This breaking point at the anterior end was also seen for the clamping systems in which a new fracture occurred most often within the anterior portion of the implant with contact to the rib. The average relative difference in stiffness (EI) of the implants on a fractured or intact rib differed strongly between the fixation systems. The constructs' stiffness, as compared to that of a non-fixated intact rib, ranged from −14% to +70% when fixated on an intact rib and from −88% to +17% on a fractured rib.

Unexpectedly, the negative average relative difference in stiffness of the fixated fractured ribs for all implants except one implies that a non-fixated intact rib is likely stiffer than the construct of an implant on an acutely fractured rib. Previously, studies have confirmed this for both unicortical and bicortical plate fixation, but interestingly these studies used the fixation system which, in the current study, had a higher stiffness than a non-fixated intact rib (Bottlang et al., 2010a; Choke et al., 2019). This might be explained by the current study's four-point bending test *versus* their two-point bending test, and use of bending structural stiffness (Nm^2), corrected for the test rig's and rib's dimensional aspects instead of using stiffness (N/mm) alone. A low stiffness can be advantageous because relatively, elastic implants minimize peak stresses which is especially beneficial in fixation of osteoporotic bone (Bottlang et al., 2010b; Lill et al., 2003). Moreover, implants for SSRF are not designed to withstand high loads such as those in, for example, the lower extremity, necessitating high rigidity, but are required to principally restore chest wall integrity without restricting respiratory kinematics (Bottlang et al., 2010b). On the other hand, a high stiffness of the construct might impede with respiratory mechanics in the acute setting, and a too rigid fixation might cause cortical porosity below the implant, delayed union or nonunion, or new fractures at the end of the implant (Bottlang et al., 2010b; Choi et al., 2021b; de Jong et al., 2018; Labitzke, 1981).

The main reason for implant removal are subjective complaints of chest tightness and irritation, which might be the consequence of the high stiffness of an implant on a consolidated rib, restricting chest wall movement (Peek et al., 2020). Chest tightness has been reported in up to 16% of patients with rib fractures in the long-term, irrespective of treatment modality (SSRF or nonoperative management) (Prins et al., 2021). As expected, in the current study, intact ribs fixated with a plate had a positive relative difference in stiffness, indicating a higher rigidity than a non-fixated intact rib. This leads to the novel hypothesis whether this increased stiffness of the fixated consolidated rib as compared to the non-fixated rib is associated with these mentioned subjective thoracic complaints. In previous literature, implant removal after SSRF has been performed for subjective complaints of chest tightness, but these patients did not have consequent restricted pulmonary function at the time of removal (Lardinois et al., 2001; Reber et al., 1993). This implies that the role of the implant in chest tightness might be less important than the effect of amongst others post-traumatic scar tissue formation. Such aspects require further evaluation in *in vivo* or larger pre-clinical studies.

This study might aid decision-making on which implant to choose. A lower stiffness (clamping system) might be preferred in the long-term after fracture consolidation or for acute solitary simple rib fractures. In more comminuted or non-united rib fractures, a higher stiffness (plate and screws system) might be beneficial to sufficiently stabilize the fracture ends (Bottlang et al., 2010b). While this study provides relevant biomechanical data for the specific configurations of rib fixation systems, many injury and implant related factors were not investigated. For example, segmental rib fractures might require a larger plate instead of two standard plates or clamps because this might increase the fixated rib's stiffness (Fokin et al., 2020). In addition, the implant's length and the amount and location(s) of surface contact between the implant and bone might affect the biomechanical properties of a specific construct. Posteriorly located rib fractures have relatively worse outcomes in terms of deformity and secondary displacement, even when a concomitant lateral fracture in a flail segment is reduced and fixated (Marasco et al., 2014). Due to their proximity to the vertebral column and difficult surgical approach due to osseous, muscular and ligamentous attachments, posterior fractures might be less likely to be fixated with a plate and screw system. Using a smaller implant with clips instead of bilateral screw requirement might be a feasible alternative for these posterior rib fractures. Other implant-specific characteristics such as combining plate and screw and clamping systems, the (minimal) invasiveness of the surgical approach, operation time, and cost-effectiveness should be compared in future clinical studies.

This study observed large differences in stiffness between the constructs but it remains unclear what range is optimal to prevent hardware failure but also be associated with the least subjective complaints for the patient. A previous study has shown similar stability for unicortical and bicortical screw fixation, advocating unicortical screw use to minimize occurrence of these hypothesized complications (Choke et al., 2019). Another explanation for the chest tightness complaints could be maladaptive callus formation between fixated ribs, which has been seen in 16–23% of patients following SSRF (Campbell et al., 2021; Marasco et al., 2010).

Insight into the fixation system's mode of failure is of clinical relevance. Hardware failure after SSRF is rare (4%) with mechanical failure (60%) as the most common cause (Choi et al., 2021b). Literature on the prevalence and effect of additional thoracic trauma after SSRF is limited. The average relative difference in load to failure was lower for fixated fractured ribs and similar or up to 30% higher for fixated intact ribs. On chest CT for additional thoracic trauma, one should be suspicious of possible new rib fractures at the most anterior drill hole or anterior end of the implant for plate and screw systems and for fractures within the implant or implant deformation at the initial fracture site in case of the clamping systems. The amount of pressure on each rib from surrounding muscles is thought to be up to 30 N during 80% of maximum respiratory effort (Marasco et al., 2010; Ratnovsky et al., 2003). On an intact rib, the F_{max} of all systems was >100 N before failure. On a fractured rib, the clamping systems' F_{max} (<25 N) might have problems. Nevertheless, these systems did not fail on cyclic testing when undergoing loads up to 30 N. Of note, as the systems were only tested once during cyclic testing, these results should be interpreted with caution. Future research could add value by measuring for example fracture gap movements to gain insight in differences between consolidating or non-united ribs.

This study has several limitations. First, due to European privacy regulations, the only available baseline characteristics were gender and age. Other patient characteristics such as a diminished bone mineral density (BMD) are associated with a higher rate of rib fractures after thoracic trauma (Prins et al., 2020). Ribs six to ten were used for fixation due to their relative similarities morphologically, but rib level, which has been shown to impact fracture load and stiffness for ribs four to eight, was not accounted for (Liebsch et al., 2021). The difference in age across the specimen and possible association with BMD or cortical and trabecular bone thickness might have negatively impacted biomechanical properties (Liebsch et al., 2021). In addition, the dissimilarities in age might have led to more heterogeneous data. However, as every system was tested in every specimen, the impact was similar and unlikely to have caused differential bias across the fixation systems. Also, the large SD of the F_{max} of the 5th rib indicates this variability in bone quality of the different specimens. This discrepancy was partially corrected for by evenly allocating the systems to each specimen, using the structural bending stiffness and the average relative difference in EI and F_{max} in relation to a non-fixated intact 5th rib. Also, no chest radiography or (quantitative) computed tomography were available. Subsequently, pre-existent pathologies might have been present, compromising implant fixation and outcomes. Also, the use of embalmed specimens might have affected the biomechanical outcomes. Embalmed cortical bone has been associated with different mechanical properties as compared to fresh-frozen bone (Unger et al., 2010). By using only embalmed specimens for all fixation systems this impact was reduced, but the observed outcomes should not simply be extrapolated to living bone as the biomechanical properties of the tissues are not comparable. A future study should incorporate fresh-frozen bone of specimens which have underwent a diagnostic work-up including radiography as well as insight into demographics such as BMD to minimize a possible bias due to relevant biological differences across the specimens' ribs.

Second, ribs and fixated implants were only tested in a quasi-static loading mode through a four-point bending test whereas in real life, ribs are subjected to dynamic forces distributed over the entire rib's length as well in other directions (*e.g.*, antero-posterior and rotational). Also, the exact stiffness and force to failure for the implants and ribs is likely different due to secondary stabilization from adjacent ribs and surrounding muscles and ligaments *in vivo* (Bottlang et al., 2010b). This test set-up does more closely approximate physiological loads than a three-point bending test. It also allows for testing fractured ribs as the two upper loading rollers provide a dynamic pressure over the rib instead of a single roller providing pressure on the fracture line itself. Acknowledging the differences between the individual fixation systems, future research should evaluate the effect of fixating fractured ribs on the biomechanics of the entire thorax, using for example a previously published model by Myers et al. (Myers et al., 2020). This allows testing all ribs amenable for fixation, including ribs four and five which are most often fractured as well as ribs six and seven (Liebsch et al., 2019). The large standard deviations of the biomechanical outcomes also indicate the need for larger sample sizes and a more uniform testing method. In addition, biomechanical testing was limited to fixated lateral simple transverse fractures and did not assess other fracture types or anatomical locations. While transverse or simple fractures are common, a large part of patients has other fracture types such as wedge, complex, or a combination (Clarke et al., 2019; Prins et al., 2020). These fracture types can be fixated, but might impact the construct's biomechanical properties differently. Furthermore, additional (*e.g.* longitudinal) fracture lines occurred while fracturing the designated ribs. This might have impacted the construct's biomechanical characteristics or might be mistakenly considered a result of the implant fixation.

Third, due to fixating different systems on one hemi thorax, specific procedural variances such as exposure and approach could not be evaluated. During an actual surgical intervention, it is likely that crucial fixation aspects such as rib thickness measurements would have been performed more accurately to provide optimal adaptation to the anatomical circumstances. For the NiTi Rib system, the required body temperature might not have been reached in the test setting, possibly impacting the biomechanical characteristics. Also, not all screw, plate, and clamp sizes were available for all systems. These suboptimal fixation conditions might have affected the implant's biomechanical properties or resulted in the screw protrusion through the inner rib cortex as seen with several systems. On the other hand, it might have resulted in incorrect assumptions on (sub)optimal implant positioning and outcomes. This includes unforeseen findings such as the negative relative difference in stiffness of the fixated fractured ribs for all implants and the fixated intact ribs for the clamping systems. Furthermore, the sample sizes per fixation system were too low to, for example, provide a classification system for the best implant in a patient with specific (fracture) characteristics. Also, for the MatrixRIB™ system, only universal non-pre-contoured implants were available. Despite these limitations, to our knowledge, this is the first study to collectively evaluate current fixation systems and provide a starting point for future preclinical research.

5. Conclusion

In conclusion, the current fixation systems differ in their design, mode of action, and biomechanical properties. Differences in biomechanical properties such as stiffness and load to failure especially apply to fractured ribs. Furthermore, insight into the failure modes of these implants does not only aid in early discovery of new fractures after SSRF with or without new trauma, but also helps in the development of improved implants in the future. Insight in the differences between the systems might guide more specific implant selection, choosing an implant based on rib fracture type and location, in addition to the preferred aim of fixation; flexible (clamping system) or more rigid (plate and screws system). Future prospective clinical studies are required to assess the effect of these differences on intra-operative characteristics and short- and long-term outcomes in patients who undergo SSRF.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

EMM Van Lieshout reports a relationship with Netherlands Organisation for Health Research and Development that includes: funding grants. MME Wijffels reports a relationship with Netherlands Organisation for Health Research and Development that includes: funding grants. EMM Van Lieshout reports a relationship with DePuy Synthes that includes: funding grants. MME Wijffels reports a relationship with DePuy Synthes that includes: funding grants. EMM Van Lieshout reports a relationship with Coolsingel Foundation that includes: funding grants. MME Wijffels reports a relationship with Coolsingel Foundation that includes: funding grants. EMM Van Lieshout reports a relationship with Osteosynthesis and Trauma Care Foundation that includes: funding grants. MME Wijffels reports a relationship with Osteosynthesis and Trauma Care Foundation that includes: funding grants.

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