Original Article

Mechanical advantages of a truss-structure-based fracture fixation system

-A Novel Fracture Fixation Device "PinFix"-

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Running title: Truss-structure-based fracture fixation

ABSTRACT

We developed a small, light ball-joint device called PinFix that can instantly convert a simple percutaneous cross pin fracture fixation into a rigid external fracture fixation based on truss structure. The purpose of this study was to compare the mechanical load and breaking strength of this truss-structure-based fixation to that of the conventionally used external cantilever structure based fixation. We performed three types of mechanical loading tests, axial, bending, and torsion on an artificial fractured bone treated with either a three-dimensional PinFix fixation, two-dimensional PinFix fixation, or a conventional external fixation. The three- and two- dimensional PinFix fixations showed significantly more stiffness compared with the conventional fixation on all three loading tests. Finite element analysis was performed next to calculate the stress distribution of the parts in PinFix and in the conventional fixator. The applied stress to the rod and connectors of PinFix was much less than that of the conventional external fixator. These results reflected the physical characteristic of truss structure in which applied load is converted to pure tension or compression forces along the members of the PinFix.

In conclusion, PinFix is a simple fracture fixation system that has a truss-structure with a high rigidity.

Keywords: truss-structure, fracture fixation system, PinFix

INTRODUCTION

Providing sufficient stability, preservation of circulation, and avoidance of infection at the fracture site are the three most important requirements for promoting fracture healing(1),(2),(3). In order to provide an optimal healing environment, various fracture fixation techniques have been developed such as transcutaneous Kirschner wire (K-wire) fixation, external fixation, plating, and intramedullary nailing(3),(4),(5). Each method has advantages and disadvantages. In terms of circulation preservation and infection avoidance, transcutaneous Kirschner wire (K-wire) fixation and external fixation have theoretical advantages over the plating and intramedullary nailing due to their minimum harm to soft tissues as well as fracture fragments(6),(7). In addition, these procedures are usually performed following closed reduction. Conversely, plating and intramedullary nailing tend to be more harmful to fracture site, however they can generally allow more precise reduction, provide better stability, and allow patients more freedom of daily activity during fracture healing(8),(9),(10).

Percutaneous K-wire fixation is a cost effective procedure that does not require any special devices for implementation. It is also technically less demanding, and is highly versatile in terms of range of application(11). However, fixation provided by K-wires alone is less secure and carries significantly higher risk of loss of reduction than other techniques even when applied to fractures in the upper extremities(12). External fixation can generally provide much higher stability at the fracture site compared to K-wire fixation(13),(14),(15). Connections between the external fixation device and its screws are located outside of the body. Because of much longer lever arms compared to those of internal fixation devices, huge moment of force develops around them. Therefore, all the components have to be rigidly fixed so that the fixator system can keep its shape. This makes the external fixator a heavy, cumbersome, and less versatile device. As a result, most external fixators are designed for a specific site or a specific type of fracture and are supplied with special jigs for assembly. External fixator devices use a cantilever structure and they are only supported on one side with screws that project horizontally in space16). These factors make the external fixation devices more expensive and more technically demanding compared to K-wire fixation.

In architecture, bridges are designed and constructed using the cantilever methods. To ameliorate the moment around the connections and to make them more robust against cyclic drifts, the use of diagonal support frames and sway braces is highly recommended17). The X-bracing system is one of the easiest methods to transfer lateral loads in buildings18). Cross-bracing systems, with or without friction dampers, are believed to be fundamental for the seismic response19). Therefore, cantilevered bridges in architecture are seldom completed as true cantilevers but are instead completed as truss bridges17). A truss is a structure comprising one or more triangular units constructed with straight members whose ends are connected at joints, referred to as nodes20) and external forces act only at the nodes and result in forces on the members which are either tensile or compressive, resulting in exclusion of moment21),22).

We have developed a novel ball-joint device named the PinFix that instantly converts a simple crossed K-wire fixation into a robust external fixation by constructing a truss structure.

The purpose of this study was to compare the mechanical load and breaking strength of the fracture fixation of PinFix to those of the conventional cantilever external fixator using an artificial bone model and finite element analysis.

MATERIALS AND METHODS

Mechanical loading tests

The PinFix is a plastic ball-joint weighing 2.9 g that can connect pins (ø1.6–2.4 mm) with rods (ø3 mm) at any desired angle to form a truss-structure-based fracture fixation. As shown in ***Figure 1***, the pins are inserted in a crisscross fashion across the fracture site. This is a universal system that can construct either two- or three-dimensional fixations in any configuration.

A 30 radius sawbones with a cancellous inner core and a foam cortical shell (26 cm long, 5.5-mm canal diameter; Model #1027, Pacific Research Laboratories, Inc., Vashon, WA, USA) was prepared for axial and bending load testing. The proximal radial shaft of each specimen was potted with a metallic adapter, leaving approximately 10 cm of the radius exposed. For the axial and bending load testing, an oscillating saw was used to create a transverse osteotomy 3 mm proximal to the styloid process. A 3-mm fracture gap was created by making a second transverse osteotomy 3 mm proximal to the initial cut and this section of bone was removed to simulate the complete lack of cortical contact seen in severely comminuted unstable, extra-articular distal radius fractures. The fracture models were divided randomly into the following groups: three-dimensional PinFix fixation (Group A, n=5, ***Figure 2a***), two-dimensional PinFix fixation (Group B, n=5, ***Figure 2b***), and the conventional external fixation (Hoffman II mini External Fixator Stryker, Mahwah, NJ; Group C, n=5, ***Figure 2c***). In the PinFix groups, 2.4-mm Kirschner wires were used for fixation. In the group C, 3-mm dedicated threaded pins were used for fixation.

The fracture models were placed on the loading platform of a universal testing machine (Autograph AG-1, Shimazu, Kyoto, Japan). Each specimen was loaded at a rate of 1 N/s to a maximum load of 3-mm displacement for both axial (***Figure*** 3a) and bending loads (***Figure*** **3b**), with 2-mm/min cross head speed. To generate optimal loading, a three-dimensional plastic gripping adaptor was put on the distal end of the sawbone radius during axial loading and on the volar side of the distal fragment during bending load. Displacements of 1, 2 and 3 mm were compared in the 3 groups, and the load-displacement curve was plotted for each axial and bending load.

In the torsion loading, the machine had to grip both ends of the bones, but the radius bone could not be gripped firmly because of the shape. Instead, the femur sawbones were used. Fifteen femurs (Model #1130, Pacific Research Laboratories, Inc. Vashon, WA, USA) were prepared for torsion load testing. Both sides of the femur were cut at 10 cm from the fracture site and fixed using a metallic clamp of a testing machine (Low Capacity Torsion Testing Systems, Instron Japan, Kanagawa, Japan). The fracture fixation method using each fixator was tested in the same manner as the axial and bending loading. Torsion loading was applied as shown in Figure 3c. Each specimen was loaded at a rate of 1 N/s to a maximum load of 25 N with a 2-cm moment arm in torsion. Rotations of 10 and 20 degrees were compared in the 3 groups, and the load-displacement curve was plotted.

Finite element analysis

Cylindrical simulated bone that is consisted of cancellous and cortical bone was created on the computer (SolidWorks Simulation, Dassault Systemes SolidWorks Corp. Waltham, MA, USA). The material properties of cortical and cancellous bone were determined based on the previous report23). The cylinder was divided into two parts to simulate the fracture. In order to fix the fracture, the cantilever-frame-fixation (C.F.F) (***Figure 4a***) or the truss-frame- fixation (T.F.F) (***Figure 4b***) was performed. The lower end of the cylinder was set to the cornerstone and the other end received the load. The structures of C.F.F were constructed with the rods, the connectors and the pins. All of them were made by Ti-6Al-4V. In contrast, the T.F.F were constructed with the rods, connectors and pins. The materials of each part were Ti-6Al-4V, PPSU and SUS304 respectively.

The material properties in each construct are shown in ***Table 1***.

Axial, bending, and torsion loading were applied. ***Figure 5a*** and ***5b*** show the each direction of the load to C.F.F and T.F.F. Axial load stress testing (100 N), bending load stress testing (100 N) and torsional load stress testing (2 N・m) were performed. The stress of each pin, connector and pin-crossing-part in T.F.F. was recorded.

Statistical analysis

All values from the mechanical testing are expressed as mean ± standard deviation. Data were compared between 3 groups using a one-way analysis of variance (Excel 2010 statistics). The level of significance for all tests was set at $P < 0.05$.

RESULTS

Mechanical loading tests

Axial loading:

The load-displacement curve of the axial load is shown in Figure 6a. The load of 1 mm displacement of each group (A, B, C) in the axial loading was 102.3±24.1, 56.2±18.2 N, and 14.9±3.7 N. That of 2 mm displacement was 209.4±37.2 N, 120.5±16.5 N, and 30.3±3.9 N, and 3 mm displacement was 310.9±48.8 N, 181.3±41.0 N and 44.8±5.6 N, respectively.

Comparisons between Group A and C, and that between Group B and C, at 1 mm, at 2 mm, and at 3mm displacements showed significant differences with p-values of p=0.0001 and p=0.0134 at 1mm, p=0.0001 and p=0.0111 at 2mm, and p=0.0001 and p=0.0093 at 3mm, respectively.

Bending loading

The load-displacement curve of the bending load is shown in Figure 6b. The load of 1 mm displacement of each group (A, B, C) in the bending loading was 21.80±13.89N, 17.45±5.38N, and 12.57±0.20N. That of 2 mm displacement was 55.09±22.23N, 43.93±9.10N, and 24.81±0.26N, and 3 mm displacement was 98.94±17.81N, 68.59±13.00N and 33.57±0.18N, respectively.

Comparisons between Group A and C, and that between Group B and C at 1 mm and 2 mm displacements did not show significant differences (p=0.2022, p=0.4667, respectively). In contrast, a significant difference were found at 3 mm displacement with p values of p=0.0001 and p=0.0061, respectively.

Torsion loading:

The load-angle curve of torsion load is shown in Figure 6c. The torque of 10 degree rotation of each group (A, B, C) in the torsion loading was 37.2±4.0N・m, 22.5±1.7 N・m, and 16.4±1.4N・m. That of 20 degree rotation was 58.6±4.8Nm, 33.0±1.1 N・m, and 24.7±2.7 N・m, respectively.

Comparisons between Group A and C, and that between Group B and at 10 degree , 20 degree,rotations demonstrated significant differences with p-values of p<0.0000 and p=0.0012 at 10 degree, p=0.0001 and p=0.0111at 20 degree, espectively. The three-dimensional PinFix fixation was the strongest in torsion loading.

Finite element analysis

As appreciated from table 1 and 2, FEA showed remarkable differences in stress distribution pattern between C.F.F and T.F.F. in all the three loading conditions. In axial loading, stress in the rod was 436.0 N/mm^2 in C.F.F, while that in T.F.F, was 2.9 N/mm^2, and stress at the distal and proximal joint-blocks of C.F.F were 823.8 N/mm2 and 848.4 N/mm2, while those at the distal and proximal connections of T.F.F. were 4.4 N/mm^2 and 4.4 N/mm^2 , respectively. In bending loading, stress of the rod was 419.6_N/mm^2 in C.F.F, while that in T.F.F was 59.0 N/mm^2, and stress at the distal and proximal connectors of C.F.F were 90.5 N/mm^2 and 1061.0 N/mm^2, while those at the distal and proximal connectors of T.F.F. were 40.4 N/mm^2 and 35.3

N/mm^2, respectively. In torsion loading, stress of the rod was 152.2 N/mm^2 in C.F.F, while that in T.F.F was 37.8 N/mm^2, and stress at the distal and proximal joint-blocks of C.F.F were 119.6 N/mm^2 and 109.0 N/mm^2, while those at the distal and proximal connecters of C.F.F, were 57.8 N/mm^2 and 57.9 N/mm^2, respectively. Statistical analysis clearly demonstrated significant differences between C.F.F. and T.F.F. in all the three loading conditions. On the other hand, in C.F.F., relatively high stress concentration takes place along the crossing pins inside the bone with values of 51.0 N/mm^2 in axial loading, 731.1 N/mm^2 in bending loading, and 597.3 N/mm^2 in torsion loading, respectively. It appears that higher stress concentration takes place in rods and joint blocks in C.F.F, while that happens in crossing pins inside the bone in T.F.F. These results indicate that applied load is converted to pure compression or tension load along the pins in the PinFix, thereby significantly reduces stress in members outside the bones.

DISCUSSION

The truss-frames are composed of triangles that are the simplest geometric figure that will not deform once the lengths of the sides are fixed. In comparison, a four-sided figure such as a cantilever-frame will change shape in response to external forces. Therefore, both the angles and the lengths must be firmly fixed to retain its shape.

Finite element analysis clearly showed high stress concentrations at the angles of the cantilever frame. In contrast, in the case of truss frame, the mechanical stress spread along the pins crossing the fracture site therefore less stress concentration occurs at the joints or along the rods. Therefore, the structure can be constructed using relatively small and weak connecting materials. Because of this, we were able to make PinFix with plastic of as light as 3 grams each. Despite the lightweight material used, all mechanical load testing clearly demonstrated that the PinFix truss fixation can better withstand mechanical stresses in all directions than can conventional external fixator systems.

In truss structure, it is noteworthy that predicted axial force is significantly smaller as compared to bending or torsion force. This result could be explained by the law of the lever24). In the case of axial load analysis, the axis of the applied load is almost collinear with the longitudinal axis of the bone. Therefore, the lever arm is practically zero. In contrast, in the case of bending and torsional load testing, the axis of load is distant from the action point. Much larger lever arm in these testing results in much higher mechanical stress at the action point.

On the other hand, FEA showed relatively high stress concentration along the pins around the cross part despite the fact that the two pins are not connected each other within the bone in PinFix. This reflects the physical characteristics of truss in which applied deforming force is converted into pure compression or tension stress along the parts. This type of structure is widely used in a variety of truss constructions such as Brown truss bridges25),26).

The mechanical loading test clearly showed the greater stiffness of the truss-frame, both of three and two-dimensional PinFix, than that of the cantilever-frame. In addition, three dimentional PinFix was obviously stiffer than two-dimensional PinFix. This indicates that a more robust structure can be constructed by combining the simple truss structures. In fact, according to Pouangare27), a complex three-dimensional truss, alias 'the space-truss', can give constructions with extremely high strength.

In our mechanical study, the sawbones were used. The main advantage28) of using sawbones is that it has been well validated in comparisons with cadaver specimens and is considerably better represented in the hand and upper extremity biomechanics research. In fact, a variety of problems with cadaver specimens have been pointed out, including high cost, tenuous availability, handling and storage challenges, and a remarkable degree of inter specimen variability that reportedly exceeds 100% of the mean in some metrics.

Historically, crisscross pin fixation has been widely used in fracture managemen13). It is a less invasive fracture fixation technique that can be performed at any medical facility that utilizes simple fracture treatment devices such as image intensifiers, drills, and Kirschner wires. In addition, the technique is also widely used during surgery to temporarily maintain reduction until internal fixation with plates is completed. The caveat is that it is much less reliable compared to other fracture techniques and almost always requires additional supports such as cast immobilization29). However, once the PinFix is attached to these Kirschner wires, it instantaneously turn into a stronger supporting device comparing to other fixation systems.

PinFix is not the only external fixator using the truss structure. The CPX system developed by Mirza et al. is a uniplane external fixation system that supports multiple small 1.6 mm cross-pins30). Using a cadaveric fracture model, Strauss et al. compared the CPX system with volar locking plate fixation and concluded that there was no significant difference between the two fixation techniques. Their results also proved the mechanical advantages of a truss system. The problem of CPX is that it is a site-specific fracture fixation system. It can only be applied to a limited number of fracture types of the distal radius such as AO type B2 or B331). In contrast, the PinFix can be used in various types and at various sites of fracture without requiring any special devices. Indeed, distal radius fracture might be a good indication for the PinFix, and it can also be used for forearm, elbow and humerus fractures.

This study has several limitations. The sample size is small, and we used only sawbones and simulated bones were used. However, this study clearly demonstrated the usefulness of introducing basics of structural engineering to the designing of fracture fixation devices.

In conclusion, by taking the mechanical advantages of truss structures into consideration, we successfully developed a simple fracture fixation device, the PinFix, which can convert a simple cross pin fixation into an extremely robust external fixation system by inducing drastic changes in load distribution.

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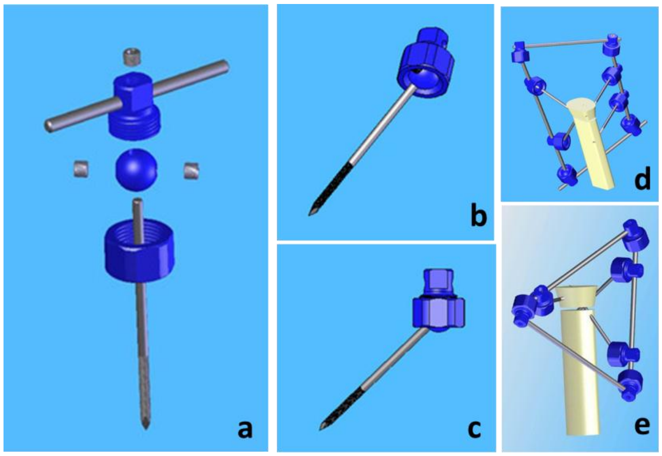

Figure 1(a, b, c, d, e)
The PinFix is a plastic ball-joint weighing 2.9 g that can connect pins (ø1.6–2.4 mm) with rods (ø3 mm) at any desired angle to form a truss-structure-based fracture fixation. '*a*' is the view from above. '*b*' is the view from side. '*c*' is the view from below.
The pins are inserted across the fracture site in a crisscross fashion. This is a universal system that can construct either two- or three-dimensional fixations in any configuration. The assembly is infinite(*d* and *e*)

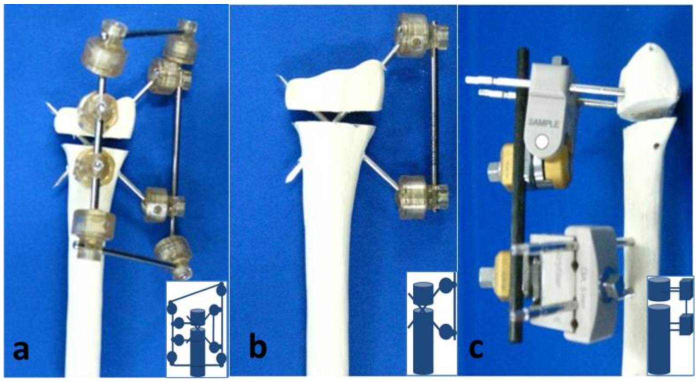

Figure 2(a,b,c).
The fracture models in mechanical loading tests
The fracture models were divided randomly into the following groups: three-dimensional PinFix fixation (Group A, n=5, ***Figure 2a***), two-dimensional PinFix fixation (Group B, n=5, ***Figure 2b***), and the conventional three-dimensional external fixation (Hoffman II mini External Fixator Stryker, Mahwah, NJ; Group C, n=5, ***Figure 2c***).

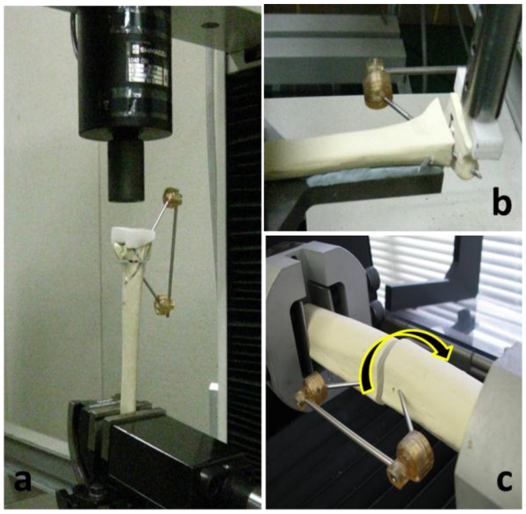

Figure 3(a,b,c).
Axial, bending and torsion loading in mechanical loading tests
Each specimen was loaded at a rate of 1 N/s to a maximum load of 3-mm displacement for both axial (***Figure 3a***) and bending load (***Figure 3b***), with 2-mm/min cross head speed.
Torsion loading was applied as shown in ***Figure 3c***.
Each specimen was loaded at a rate of 1 N/s to a maximum load of 25 N with a 2-cm moment arm in torsion.

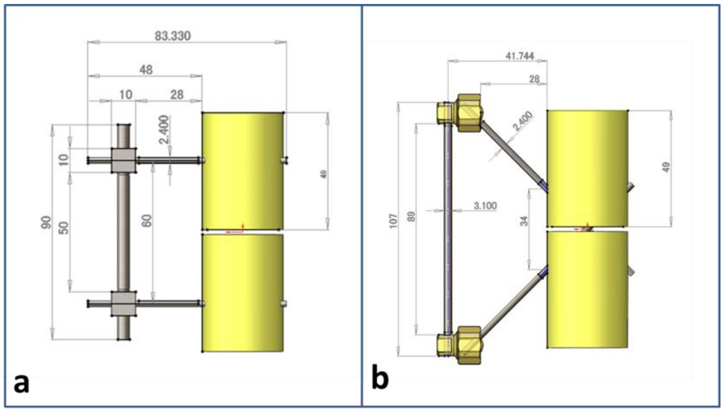

Figure 4(a,b). Cantilever-frame-fixation (C.F.F.) and Truss-frame-fixation (T.F.F.). Cylinder was divided into two parts to simulate the fracture. In order to fix the fracture, the cantilever-frame-fixation (C.F.F) (***Figure 4a***) or the truss-frame- fixation (T.F.F) (***Figure 4b***) was performed.

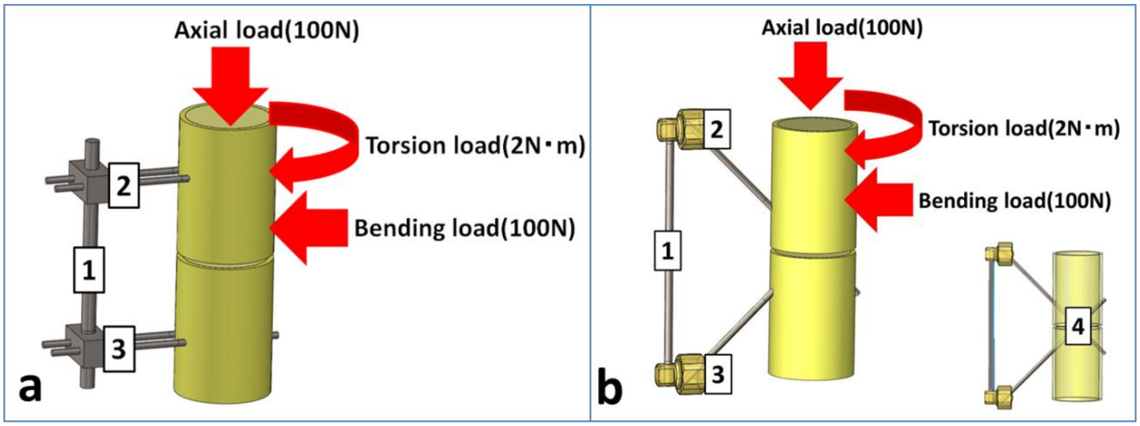

Figure 5(a,b). Direction of the load

Figure 5a and ***5b*** show the direction of the load to C.F.F and T.F.F. Axial load stress testing (100 N), bending load stress testing (100 N) and torsional load stress testing (2 Nm) were performed.

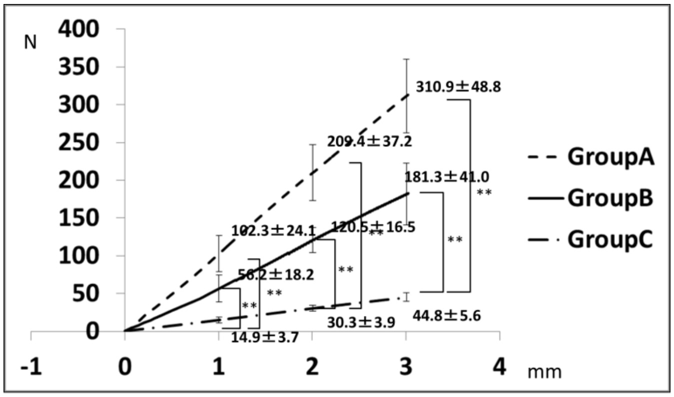

Figure 6. The load-displacement curve of the Axial load.
Comparisons of each two different fixations of Group A and Group C, and that of Group B and Group C, at 1 mm displacement demonstrated significant differences (p=0.0001, p=0.0134, respectively), at 2 mm displacement (p=0.0001, p=0.0111) and at 3 mm displacement (p=0.0001, p=0.0093).

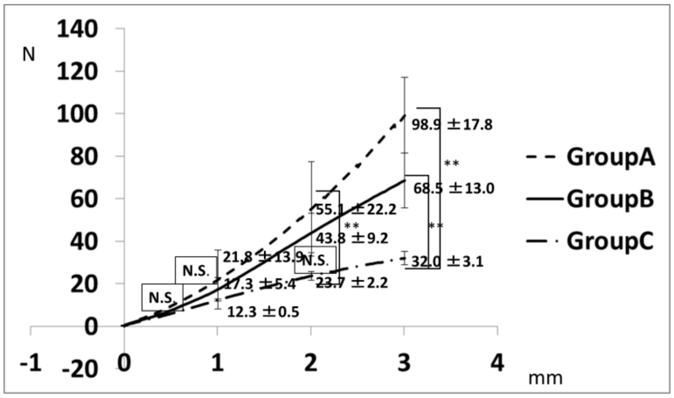

Figure 7. The load-displacement curve of bending load.
Comparisons of each two different fixations of Group A and Group C, and of Group B and Group C, at 1 mm displacement showed no significant differences (p=0.2022, p=0.4667, respectively). Although there were not significant differences between PinFix and conventional fixators at 1 and 2 mm displacement, a significant difference was found at 3 mm displacement between Group A and Group C (p=0.0001),Group B and Group C (p=0.0061).

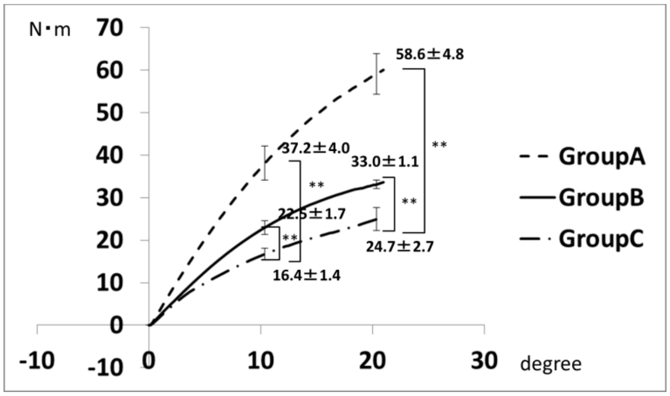

Figure 8. The load-angle curve of torsion load.
Comparisons of each two different fixations of Group A and Group C, and of Group B and Group C, at 10 degrees rotation demonstrated significant differences (p=0.0000, p=0.0012), at 20 degrees rotation (p=0.0001, p=0.0111) and at 3 mm displacement (p=0.0000, p=0.0013). The three-dimensional PinFix fixation was strongest in torsion loading.

fixation method	parts	Material	modulus of elasticity (N/mm^2)	Poisson's ratio	mass density (kg/m^3)	tensile strength (N/mm^2)	yield strength (N/mm^2)
truss-frame-fixation (PinFix)	Pin-Fix connector	PPSU	2350	0.3	1290	70	-
	φ2.4mmK-wire	SUS304	190000	0.29	8000	517.017	206.807
	φ3.1mm rod	Ti-6Al-4V	110000	0.3	4430	860	760
cantilever-frame-fixation (External Fixator)	joint block	Ti-6Al-4V	110000	0.3	4430	860	760
	φ2.4mm Pin						
	φ5mm rod						
-	bone	human bone (cortical)	17200	0.3	1640	106	-
-	bone	human bone (cancellous)	350	0.3	1020	7	-

Table1. Material properties of each part in a finite element analysis

		Maximum stress (N/mm^2)					
		axial		bending		torsion	
		C.F.F	*T.F.F*	*C.F.F*	*T.F.F*	*C.F.F*	*T.F.F*
1	rod	436.0	2.9	419.6	59.0	152.2	37.8
2	distal connector	823.8	4.4	90.5	40.4	119.6	57.8
3	proximal connector	848.4	4.4	1061.0	35.3	109.0	57.9
4	pin-crossing-part		51.0		731.1		597.3

Table2. Load applied to each portion