European Journal of Applied Sciences – Vol. 13, No. 02
Publication Date: April 25, 2025
DOI:10.14738/aivp.1302.18590.
Yukawa, T., Sato, H., Takeda, Y., & Sasaki, J. (2025). Mechanical Design Criteria of a Six-D.o.F Retractor Equipped with an Interlock Mechanism for Locking and Releasing All Joints. European Journal of Applied Sciences, Vol - 13(02). 309-319.

Mechanical Design Criteria of a Six-D.o.F Retractor Equipped with an Interlock Mechanism for Locking and Releasing All Joints

Toshihiro Yukawa
Dept. of Mech. Eng., Faculty of Eng., Iwate University, Japan

Hiroki Sato
Dept. of Mech. Eng., Faculty of Eng., Iwate University, Japan

Youichi Takeda
Division of Technical Support, Iwate University, Japan

Jun Sasaki
Iwate Medical University, Japan

ABSTRACT

In this paper, we describe a new type of assist fixator (arm), which is a surgical instrument developed as an abdominal retractor during surgery. The developed fixator as the instrument can increase the efficiency of retraction function during surgery. As for the conventional retractor, the amount of rotation of the knob required for fixing and loosening was large, the number of the knob was many, and it took time to operate. To overcome these problems, we propose an assistance mechanism in which a six-D.o.F has high controllability at the end-effector. The whole mechanism of the assist arm consists of a serial four-link with three joints, and each joint is composed of a universal gear mechanism. The assist arm can maintain the posture and hold a part of a person's body on the operation table.

Keywords: Fixator, Retractor, Assist Arm, Surgical Arm, Fixation, Six-D.o.F, Ball Joint, Universal Joint, Differential Gear, Friction, Brake.

INTRODUCTION

We develop a retractor with six-D.o.F as a surgical abdominal retractor. The study requires high operability so that a surgeon can operate the lever with one hand alone, especially for the structural design of a lever for operating a fixing device holding the tissue opening. Each joint with a differential gear mechanism can be driven through gear trains and shafts simultaneously by the operator's manual operation using the lever handle. A universal joint installed in each joint in the retractor can transmit the power of the knob to fix and release each joint in any posture. The differential gear mechanism synthesizes the motions of two or more gears into one motion and outputs the motion. A mechanism combining three bevel gears is for the differential gear mechanism. By installing the joint in three stages, all the rotation of the shafts can transmit to each joint through a universal joint, and all joints can be rigid and released simultaneously. Thus, the advantage in operability of the retractor developed here is that fixation and release of all joints can perform simultaneously using a knob installed on any position of the reactor.

HISTORICAL BACKGROUND

For the current state of fixation devices in surgical settings, Sheffield Ring Fixator is designed to provide maximum support for the bone, with a frame suitable for dealing with simple and complex trauma cases and providing the full range of requirements of a Limb Reconstruction System. Tensioned Kirschner wires provide stable fixation in metaphyseal bone. It is the property responsible for their successful use in metaphyseal and articular fractures [1]. A StrongArm Holder and positioner is an instrument that can hold and not move during the surgical procedure. The standard single arm holder and positioner come complete with a quick disconnect tip and heavy-duty rail clamp. It can be used with the table-mounted retractor system in some surgeries or some adult small incision procedures. It can also hold laparoscopic instruments such as fan retractors. The arm is with 360° rotation in the plane [2]. For the second fixation devices in surgical settings, fixators intended for tibia reduction enable open reduction and internal fixation (ORIF) by tibial nail fixation, and knee ligaments can be repaired and reconstructed [3].

With minimally invasive techniques which have increased in popularity in recent years, they explained that one such minimally invasive technique is the use of percutaneous pedicle screw fixation, which is paramount for promoting rigid and stable constructs and fusion in the context of trauma, tumors, deformity and degenerative disease [4]. C. Lee et al. explained that the treatment of distal femur fractures with modern pre-contoured locked plating is complex and challenging commonly held principles to reduce malalignment include obtaining and maintaining a reduction throughout the procedure and ensuring proper plate application, adjunctive techniques to assist in the application of these principles include the use of a well-placed bump, the use of an external fixator for provisional stabilization, the use of uni cortical plates, and the use of crossing K-wires [5]. As for a minimally invasive technique such as the approach where direct anterior approach (DAA) for total hip arthroplasty (THA), two assistants are necessary, authors have developed a retractor holding device called Spider Arm to replace an assistant on the contra-lateral side. In the experiment, the function of the proposed arm in THA through a direct anterior approach was reconfirmed. The results showed no statistical significance between the two groups in all parameters. No clinical complications occurred. With Spider arm, the DAA-THA was done by two surgeons without deterioration of the surgery time and blood loss. The accuracy of cup position and leg length discrepancy was not affected. Thus, the proposed arm can bring to reduce the operator's tasks in DAA-THA [6]. In recent years, many researchers have developed surgical instruments and robotic surgery. As a simple surgical instrument, a needle holder is one of the surgical instruments used by surgeons to hold a surgical suture, and it is similar to a hemostat for closing wounds during suturing in surgery. As a robot with a needle holder, the DEX robot has been designed to cut and dissect for precise and safe minimal invasive surgery while reducing surgeon discomfort and fatigue [7]. In open abdominal surgery, supporting staff had to hold the opening in the skin or internal organ of a patient undergoing surgery for a long time. An appropriate retractor maintains the shape of the relevant body part while maintaining its posture during surgery. For previously proposed retractors or surgical instruments, some developed devices were driven by gas pressure and needed additional peripheral devices [8]. T. Watanabe et al. have presented a force-visually-observable silicone retractor, which is an extension of a previously developed system that had the same functions of retracting, suction, and force sensing. These features provided not only high usability by reducing the number of tool changes but also a safe choice of retracting by visualized force information. Suction was done by attaching the retractor to a suction pipe. The retractor has a deformable sensing component with a hole filled with a liquid [9].

We have developed a new type of flexible retractor and an assist arm with surgical instruments developed as substitutes for an abdominal retractor during surgery. The instruments can increase the efficiency of retraction function during surgery. As for a conventional flexible retractor, the amount of rotation of the knob required for fixing and loosening was large, and it took time to operate. To overcome this problem, we installed a motor for the former retractor and performed torque control. For the latter instrument, their developed assistance mechanism has a six-D.o.F as high controllability at the tip of the mechanism, and the whole mechanism of the assist arm consists of a serial three-link with three joints whose each joint is composed of a differential gear mechanism [10]. Also, we have developed a retractor with a mechanism for holding its posture using spherical joints and inner-outer cables. We have analyzed the deformation and stress of the hollow sphere joints and determined the relationship between wall thickness and the amount of deformation. Dimples were introduced to the ball to improve the holding force by friction in the joint. As a result, the holding force at each joint has improved [11]. However, in our conventional development, when moving the tip of the retractor between two points, there was a disadvantage where the trajectory of the tip and each joint trajectory were not determined independently, which led to the controllability and usability of the retractor being low.

SIX-D.O.F RETRACTOR EQUIPPED WITH INTERLOCKING LOCK-RELEASE MECHANISM AT ALL JOINTS

Mechanism of the Six-D.o.F Retractor

Here, we explain a design of a device that can fix all joints by moving only one knob. It took time to fix the arm for the conventional retractors with a multi-degree-of-freedom mechanism for fixation, which has several brake knobs. To move the tip of the arm freely, we designed it with six degrees of freedom, and the arm had four links. As design criteria for the retractor, the surgeon's area was considered the area of the general tissue opening. The movement range of the end of the retractor is set within a rectangle of 200 mm, considering the length of each link. We design a permissible operating angle in each joint within $\pi/6$ rad due to its constraints on load, movable range, and mechanical structure since the range in open abdominal chest surgery is enough to operate. Each joint has two degrees of freedom because of a feature of the differential gear mechanism. Since the retractor has three joints, the total degree of freedom of the tip becomes six degrees of freedom. Therefore, the end of the retractor is rigid at an arbitrary position and posture. Each joint is fixed when the brake component consisting of the brake part and the inside surface of the joint unit is rigid. The brake component continues to push inside the joint surface in case anyone does not take the handle of the brake lever.

Figure 1 shows the overall view of the proposed retractor. Figure 2 shows an enlarged view of the joints. Each joint (Joint n (n = 1, 2, 3)) consists of two identical units (Unit A, Unit B) with a universal joint. These two identical units are composed by combining one unit with the other unit rotated by 90°. A thin central shaft runs through the inside of each link (Link n (n = 1 to 4)) that connects each joint. Each central shaft installed in each link connects by a universal joint installed in each joint. Therefore, all the central shafts in each link and the universal joints are linked and rotated together. A lever is attached to the bottom of unit A, which rotates around the central axis of the link and extends vertically from the central axis of the link. Using this lever, the operator operates the lock/release mechanism.

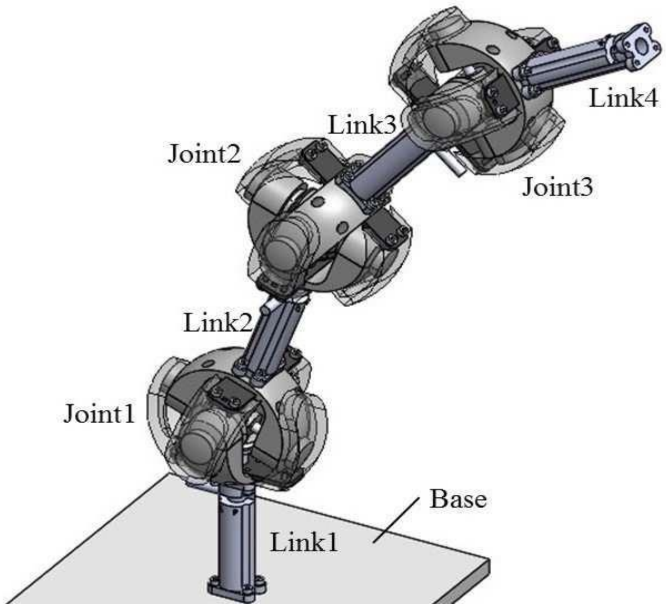


Figure 1: The proposed Six-D.O.F retractor.

Figure 3 shows the structure of the lock-release mechanism for each joint. When the central shaft (Figure 3 (a)) rotates using a lever, the rotation is transmitted by a miter gear (Figure 3 (b)) to two trapezoidal screws (Figure 3 (c)) arranged perpendicular to the central shaft and facing each other inside the two units (unit A and unit B). In the brake component (Figure 3 (d)), the inserted trapezoidal thread is fitted with an internal thread. With the male thread, the trapezoidal screw rotates, two brake components move to the outside along the axial direction of the female thread and come into contact with the inside surface (guide) of the two units (Figure 3 (f)) and pressed against the inside surface. The frictional force occurs, and the joints are rigid by employing the pressure applied to the contact surface of the brake components with the inside surface. Since the two units have the same structure, the brake material inside one unit A or B is pushed out and pressed against the inside surface of the other unit B or A similarly. For the direction of rotation of the screws, one of the trapezoidal threads on the units is a reverse-thread screw for the other thread on the other side. The universal joint has the characteristic that it does not affect the transmission of rotation even if the relative position or angle between two axes is changed. As the left and right gears rotate in the same direction, the entire joint bends around the axis of the left and right gears, whereas as these rotate in the opposite direction, only the bottom gear rotates, as shown in Figure 3. As a means of fixing the rotation of each joint, a couple of brake parts, which are attached to the left and right inside the units by a slide mechanism using the trapezoidal screw thread moves the braking surfaces, which attach to the adjacent links and become rigid situation by friction due to pressing force after the brake parts contact the surface inside units.

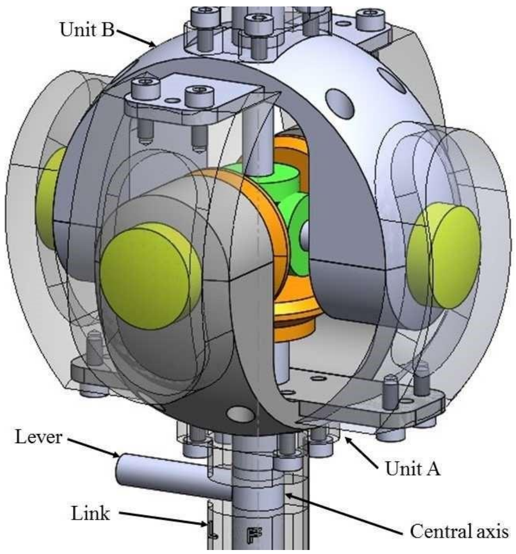


Figure 2: The enlarged view of the joint.

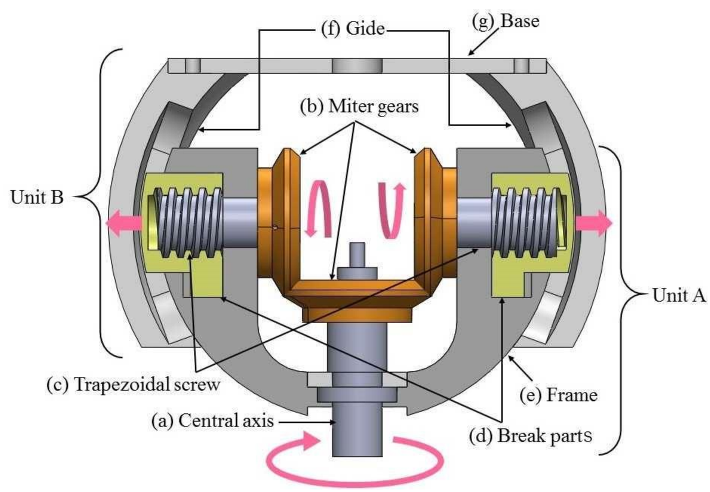


Figure 3: The details of the joint locking mechanism.

Figure 4 shows the positional relationship between the gears and the universal joint inside the joint. As a couple of rotation axes of the universal joint and the axes of the four couples of trapezoidal screws per each joint are always on the same plane, the lock-release mechanism functions in the same way at all joints regardless of the position of the retractor. The range of motion of a joint corresponds to the maximum flexion angle of a universal joint. The allowable operating angle of each universal joint has a limitation within ±π/6 rad structurally. It is necessary to select gears of different sizes for Unit A and Unit B to prevent interference between the miter gears inside of the joint when a joint rotates. Even if the size of the miter gears is different, the amount of variation in the movement of the brake component concerning one of the rotations of the central shaft does not change. In terms of the mechanical feature of operating the lock-release mechanism by rotating the central axis inside the link, the structure of the retractor developed this time is the same as the mechanism of the retractor that incorporated a differential gear joint developed previously.

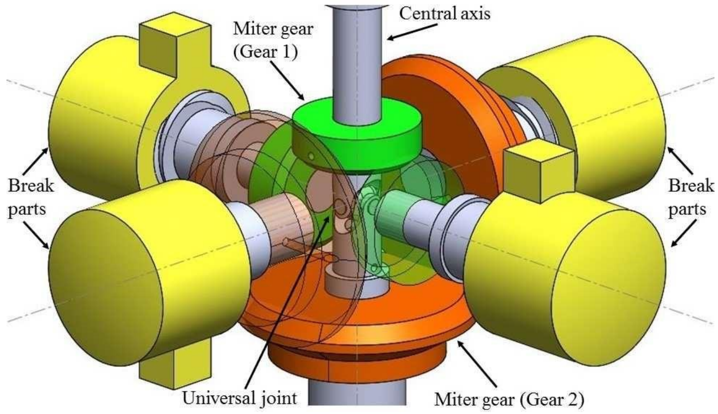


Figure 4: The placement of universal joint and miter gears.

However, as the up-to-date retractor has the advantage in situations where no joints rotate around the axes along each link, the lock-release mechanism does not affect the angular displacement of any joints. In other words, all joints can be locked and released simultaneously by operating the lever installed on any joint, even if the lever is installed in any link, to make the retractor function highly more operative.

Selection Criteria for Miter Gears and Universal Joints

We determine the selection conditions for two types of large and small miter gears and a universal joint based on the relationship between the positions of the parts inside the joint when the joint is rotating. As shown in Figure 5, the pitch circle diameter, tip circle diameter, assembly distance, total length, tip distance, and face width of each gear are defined as C_n, D_n, E_n, F_n, G_n, and J_n, respectively (n = 1, 2, all units are [mm]). The smaller miter gear is named Gear 1, and the larger miter gear is named Gear 2. Various dimensions are defined by the parameters, as shown in Table 1.

Design Conditions for Miter Gears and Universal Joints:

As for a unit consisting of a miter gear and a universal joint, the X-axis is defined as the line parallel to the central axis of the straight line, and the Z-axis is defined as the line parallel to the axis of the small miter gear Gear 1 (Figure 6 (a)). The maximum-minimum range of motion of the joint in the Z-X plane is defined as the range within $\pm\theta$ [rad], where θ is smaller than the angle of the tip angle of the gear.

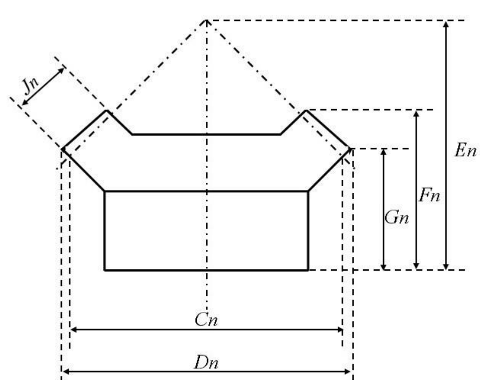
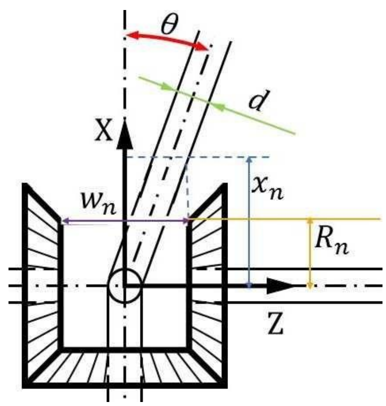


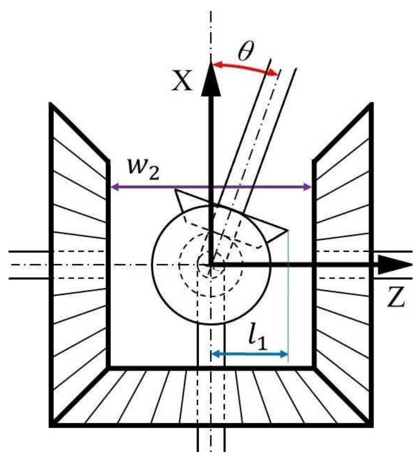
Figure 5: Dimensions of miter gears.

Table 1: Various dimensions of gears.

Miter gear	Gear 1 [mm]	Gear 2 [mm]
Pitch circle diameter	C_1	C_2
Outside circle diameter	D_1	D_2
Mounting distance	E_1	E_2
Total length	F_1	F_2
Crown to back length	G_1	G_2
Face width	J_1	J_2



(a) Differential gear train consisting of Gear 1s.



(b) Differential gear train consisting of Gear 2s.

Figure 6: The interference analysis.

Let d be the diameter of the central shaft, w_n be the minimum width between two opposing miter gears, x_n be the X coordinate of the intersection between the perpendicular line drawn from the point $z = w_n/2$ on the Z axis and the central axis bent clockwise by an angle θ from the X axis, and R_n be the radius of the gear at $z = w_n/2$ (n = 1, 2, all units are [mm]).

The condition for the universal joint and the gear not to interfere with each other is defined as follows:

$$x_n > R_n \tag{1}$$

w_n is expressed as

$$w_n = 2\,(E_n - F_n) \tag{2}$$

using E_n and F_n. Using w_n, d, and θ, x_n becomes

$$x_n = \frac{w_n cos\theta - d}{2\sin\theta} = \frac{2(E_n - F_n)cos\theta - d}{2\sin\theta} \tag{3}$$

Using D_n, F_n, G_n, and J_n, R_n is expressed as follows:

$$R_n = \frac{D_n}{2} - \sqrt{J_n^2 + (F_n - G_n)^2} \tag{4}$$

Then, the selection conditions for the miter gear and universal joint that constitute one unit are as follows:

$$\frac{2(E_n - F_n)cos\theta - d}{2\sin\theta} > \frac{D_n}{2} - \sqrt{J_n^2 + (F_n - G_n)^2} \tag{5}$$

Gear Size Requirements:
In the case when Unit A and Unit B are combined, the Z axis is defined along the axis of the trapezoidal screw connected to Gear 2, and the X axis is as the axis which is parallel to the central axis (Figure 6 (b)).

When the joint rotates clockwise by θ on the Z-X plane, the maximum distance that the teeth of Gear 1 pass in the Z-axis direction is as $l1$ [mm], and the shortest distance between the two opposing Gear 2s is as $w2$ [mm].

The condition for Gear 1 and Gear 2 not to interfere with each other even if the joint rotates becomes

$$l_1 = \frac{w_2}{2} \tag{6}$$

Using angles θ, D_1, E_1, and G_1, l_1 is expressed as

$$l_1 = (E_1 - G_1)sin\theta + \frac{D_1}{2}cos\theta \tag{7}$$

After deriving w_2 using equation (2) and substituting l_1 and w_2 into equation (6), the condition for the gears not to interfere with each other is expressed as

$$(E_1 - G_1)sin\theta + \frac{D_1}{2}cos\theta < (E_2 - F_2) \tag{8}$$

Therefore, the parameters of the miter gears and universal joints constituted to each unit can be selected based on formulas (5) and (8).

Experimental Evaluations

As shown in Table 2, we evaluated mechanical interference in combinations of large and small miter gears in six patterns, from pattern (1) to pattern (6). Parameters other than those in Table 1 are Boss

Table 2: Various dimensions of gears and combinations of the gears in six patterns.

Gear pattern of engagement	mall gear (Pinion)	Pitch circle diameter C_1	Outside circle diameter D_1	Mounting distance E_1	Total length F_1	Crown to back length G_1	Boss length (H_1)	Hole length (I_1)	Face width (J_1)	Clamping surface diameter N_1	External size (O_1)
	Large gear (Gear)	Pitch circle diameter C_2	Outside circle diameter D_2	Mounting distance E_2	Total length F_2	Crown to back length G_2	Boss length (H_2)	Hole length (I_2)	Face width (J_2)	Clamping surface diameter N_2	External size (O_2)
(1)	Gear 1	30.0	32.12	30.0	21.24	16.06	13.0	19.0	8.0	15.4	34.0
	Gear 2	50.0	52.83	40.0	24.33	16.41	10.0	20.0	12.0	26.1	60.0
(2)	Gear 1	25.0	26.41	23.0	14.70	11.21	8.0	13.0	5.3	15.0	30.0
	Gear 2	50.0	51.33	40.0	23.34	16.41	11.0	21.0	10.5	32.3	58.0
(3)	Gear 1	31.3	33.02	28.0	17.88	13.26	9.3	16.0	7.0	18.7	37.5
	Gear 2	62.5	66.04	50.0	30.41	20.52	12.5	26.0	15.0	34.6	75.0
(4)	Gear 1	25.0	26.41	23.0	14.70	11.21	8.0	13.0	5.3	15.0	30.0
	Gear 2	45.0	47.12	38.0	22.83	16.56	12.3	21.0	9.3	29.6	51.3
(5)	Gear 1	30.0	32.12	21.0	11.00	7.06	3.0	9.0	6.0	19.0	36.0
	Gear 2	50.0	51.33	40.0	23.34	16.41	11.0	21.0	10.5	32.3	58.0
(6)	Gear 1	16.0	17.10	16.0	11.00	8.56	5.0	10.0	3.7	-	22.0
	Gear 2	30.0	31.41	26.0	15.89	11.71	8.9	14.5	6.2	-	34.2

Table 3: The contact states between the universal joint and gears.

Gear pattern of engagement	mall gear (Pinion)	$w_1/2$	x_1	R_1	Non-contact /Contact
	Large gear (Gear)	$w_2/2$	x_2	R_2	
(1)	Gear 1	8.76	9.17	9.96	Contact
	Gear 2	15.67	21.14	17.40	Non-contact
(2)	Gear 1	8.30	8.38	9.22	Contact
	Gear 2	16.66	22.86	17.78	Non-contact
(3)	Gear 1	10.12	11.53	11.25	Non-contact
	Gear 2	19.59	27.93	21.74	Non-contact
(4)	Gear 1	8.30	8.38	9.22	Contact
	Gear 2	15.17	20.28	16.69	Non-contact
(5)	Gear 1	10.00	11.32	11.53	Contact
	Gear 2	16.66	22.86	17.78	Non-contact
(6)	Gear 1	5.00	4.97	5.77	Contact
	Gear 2	10.11	19.01	11.13	Non-contact

Table 4: The mechanical contact state between the small and large gears.

Gear pattern of engagement	l_1	Clamping surface diameter N_1	Noncontact/Contact
	l_2	Clamping surface diameter N_2	
(1)	20.88	20.0	Contact
(2)	17.33	19.0	Non-contact
(3)	21.67	24.0	Non-contact
(4)	17.33	17.0	Contact

(5)	20.88	19.0	Contact
(6)	10.58	11.5	Non-contact

length H_n, Hole length I_n, Clamping surface diameter N_n, and External size O_n, which are listed in Table 2. (n = 1, 2, all units are [mm]). Table 2 shows various dimensions of miter gears and combinations of the large and small gears in six patterns from pattern 1 to pattern 6. Table 3 shows the contact and non-contact states between the universal joint connecting the central shafts and the miter gear trains in six patterns, from pattern 1 to pattern 6. Parameters w_n, x_n, and R_n in Table 3 can be obtained from formulas (2), (3), and (4). (n = 1, 2, all units are [mm]). Among patterns 1 to 6, there is no physical interference between the universal joint and the small or the large gear in only pattern 3. Table 4 shows the mechanical contact state between the small and large gears when the joint rotates. I_n can be derived from equation (7), and N_n is listed in Table 3. The table shows there is no mechanical contact between the pinion and the gear, which are the combinations of the gears in patterns 2 and 3 when the joint rotates.

CONCLUSIONS

In this paper, we have developed a retractor with a linkage mechanism for holding the opening in the skin or internal organ of the patient undergoing surgery for a long time. The proposed fixation device has a six-D.o.F serial link and joints. Based on previously developed six-D.o.F retractors with joints consisting of differential gear and ball joints, we have constituted a design criterion of a sixD.o.F retractor equipped with interlock mechanisms for locking and releasing all joints with miter gears and universal joints. According to the new design criterion of the six-D.o.F retractor equipped with a simultaneous fixation mechanism for all joints to reduce the operating force of the fixation knob for ease of use and evaluated to select several functional parts. The developed fixing method was improved, as a couple of the brake components mounted in each joint enhanced the holding force by friction inside the joint, and the proposed brake mechanism can be rigid to each joint simultaneously. An articulated mechanism installed in the proposed retractor could move a restricted working space horizontally and vertically on an operating table. Thus, the proposed retractor has increased the efficiency of surgery.

References

[1]. M. Saleh, Orthofix Ltd., The Ring Fixator System, Part C: The Sheffield Ring Fixator-Limb Reconstruction and Complex Trauma, Operative Technique, https://abscdn.orthofix.it/resources/PM_12C_E0.pdf

[2]. MediFlex Incorporated, Single Arm StrongArm® Series, Ref#: 73000-TM, http://mediflex.com/products/strongarm%E2%84%A2-systems

[3]. Tibial Nailing, Open Reduction and Internal Fixation (ORIF), Application of uni- or multiplane external fixator, Knee ligament repairs and or reconstruction, INNOVATIONS in Orthopedic Instruments, InnomedEurope LLC, https://fischermedical.dk/wp-content/uploads/Innomed_Trauma_Oct2016-1.pdf

[4]. Ralph J. Mobbs, Kevin Phan, History of Retractor Technologies for Percutaneous Pedicle Screw Fixation Systems, Orthopaedic Surgery 2016, Vol. 8, (1):4-10.

[5]. Christopher Lee, Dane Brodke, Ajay Gurbani, Surgical Techniques - Surgical Tips and Tricks for Distal Femur Plating, American Academy of Orthopaedic Surgeons, Sept. 15, 2021, Vol 29, No 18, pp. 770-779.

[6]. Hirotake Yo, Hirotsugu Ohashi, Ryo Sugama, Tessyu Ikawa, Development of a Retractor Holding Device to Reduce the Manpower in Total Hip Arthroplasty through Direct Anterior Approach, Open Journal of Orthopedics, 2016, 6, 23-28.

[7]. DEX, *Agile Robot*, http://www.dexteritesurgical.com.

[8]. Mitaka Kohki Co., Ltd., *Medical Equipment/instrument*, http://www.mitakakohki.co.jp/english/medical/.

[9]. Watanabe, T., Koyama, T., Yoneyama, T. and Nakada, M., *A Force-Visualized Silicone Retractor Attachable to Surgical Suction Pipes*, Journals Sensors, Vol. 17, Issue 4, 17(4), p. 773, 2017.

[10]. Yukawa, T., *Electrification of a Retractor Consisting of Flexible Structure and Development of Six-D.o.F Surgical Assist Arm with Unactuated Joints*, SCIREA Journal of Mechanical Engineering, 2023, Vol. 4, Issue 1, p.1-20.

[11]. Yukawa, T., Sasaki, J., *Evaluation of Holding Force on Six-D.o.F Surgical Assist Arm with Sphere Joints and Inner-Outer Cables*, Int. J. of Automation Technology, 2018, Vol.12 No.3, p. 405-412.