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# Pre- and Post-operative Assessment of Bone with Osteogenesis Imperfecta using Finite Element Analysis: A Review

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**ABSTRACT**

Applications of finite element analysis (FEA) to demonstrate the pre- and post-operative conditions of the brittle bone-related disease known as osteogenesis imperfecta (OI) has been widely used in the past and at present. The method used to reconstruct the bone model that resemble the OI bone geometry plays an important aspect to accurately represent the bone condition to provide more alternative ways to evaluate surgical intervention options. Other factors such as material properties and boundary conditions also reflect the results of the analysis. Therefore, the aim of this review paper is to analyse the approaches of previous studies in terms of model geometry construction, selection of materials properties and boundary conditions to enable a deeper understanding and evaluation of bone fractures in OI patients. The biomechanical design of the intramedullary (IM) rods used in post-operative surgery and the interface between IM rods and bone fragments are also discussed in this review paper.

## 1. Introduction

Osteogenesis imperfecta (OI) is a rare disease that affects the bones and causes frequent fractures throughout the patient's life. According to Ralston & Gaston, 2020 [1], David Sillence introduced the classification of OI types known as Type I, Type II, Type III, and Type IV based on clinical and radiological presentation. The newer form of OI is categorized as Types V, VI, and VII. Tauer *et al.,* 2019 [2] stated that the later types of OI are not associated with type I collagen mutation, instead, it is classified according to genetic tests that relate to OI phenotype or genotype which are more complex to identify its classification. Statistically reported by Phonela *et al.,* 2020 [3] and Shafie *et al*., 2020 [4], this disease can affect 1 in 20,000 births worldwide and in Malaysia, OI is listed as the top three rare diseases that affected 1 in 4,000 communities.

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To date, there is no specific treatment to cure OI. All the treatment proposed by the physicians are to help patients maximize their movement in daily life and reduce the occurrence of fractures. The treatments can be divided into non-surgical and surgical procedures. Non-surgical procedures involve physical therapy, medication, including drugs, rehabilitation, and splinting which aims to maintain and improve muscle and bone strength. For many years, bisphosphonates (BP) and Vitamin D have been one of the treatments used to increase bone density over the years. It is reported that the amount of BP control used in treatment, especially in children with OI shows a consistent increase in bone density [2]. This is supported by a statistical study conducted by Chen *et al.*, 2022 in a Chinese cohort population, showing that BP treatment appears to respond to bone density in the early adolescent group over a period of 10-15 years [5]. Some studies reported that the amount of insufficient Vitamin D in pediatrics with OI is as high as 80% which is very worrying [6,7]. This is because, in the early phases, children need sufficient levels of Vitamin D to help metabolism and bone development as they function as calcium-phosphorus metabolism, especially for the formation of bone mineral matrix in bone.

The surgical procedure involves bone surgery with intramedullary (IM) rod used to stabilize the fractured bone. The IM nail is used to support an acute fracture, minimizes recurrent fractures, and re-aligns the bowing bones. The application of the rod used to support deformed bones was first introduced by Harold Sofield and Edward Millar through the multiple osteotomies called shish kebab technique as described by Fassier, 2021 [8]. In the open osteotomy method, the deformed bone is cut into several fragments and aligned together along the diaphysis of the bone. The rod is used to support and correct the deformities of the bone fragment. Figure 1 illustrates the shish kebab technique. Since then, multiple osteotomies using IM rods had become the main technique used in OI cases.

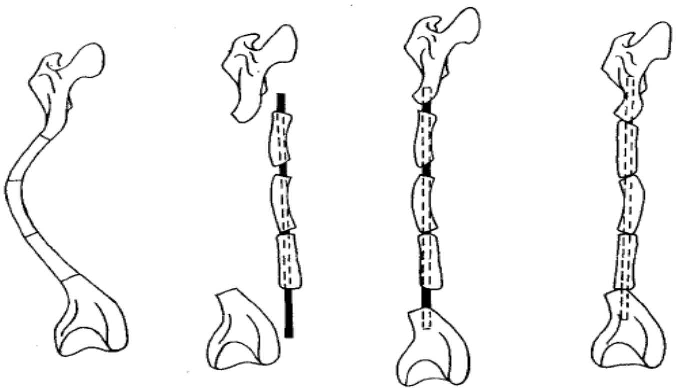

**Fig. 1.** Osteotomy method

With the new implementation of the telescopic rod, and the new minimally invasive surgical approach known as the percutaneous technique, which is less complicated, allows less skin incision and offers less surgery time is more preferrable in today's surgery. An example of telescopic rod Fassier–Duval (FD) through a percutaneous technique is shown in Figure 2. Fassier, 2021 [8] describes a percutaneous technique by inserting a guidewire into the greater trochanter through gluteus muscle to the distal end of the bone. Partial osteotomy is required to straighten the fractured bone. When it reaches the distal end, the guide wire is withdrawn, and the rod is inserted. The male component will first be inserted and screwed toward the end of the distal epiphysis. The female component is inserted into the male component and screwed into the greater trochanter.

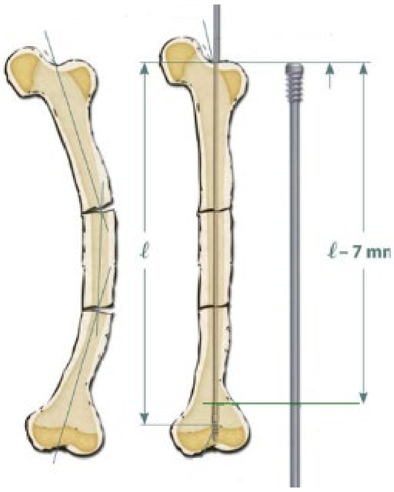

**Fig. 2.** Percutaneous technique using FD rod

Over the years, finite element analysis (FEA) has been used to assess the fracture risk of OI bone. Since fractures occur throughout the patient's life, it is most likely that there are no signs or no early signs of a fracture under physical activity that involves the patient's mobility. Prediction of the fracture occurrence can provide early awareness to the patients and the caretakers. The application of finite elements helps to provide a reliable analysis method to create an unforeseen situation to predict the fracture risk. The wide range of variables and parameters accessible in the tool allows researchers to simulate conditional situations to analyze the biomechanical behavior of bones due to the repeated fracture. Therefore, this analysis provides data and details about the condition or situation that caused the fracture and at the same time can offer patients the highest possible support for them in their mobility in daily life activities. Celin *et al.*, 2020 [10] relate that function and quality of life related to fracture severity are interrelated. Few past studies published focus on fracture analysis in OI bone offered interesting outcomes that benefit both the surgeons and patients [11-17]. An interdisciplinary medical approach through surgical intervention is required to minimize fractures and improve mobility. This usually takes place at an early phase in the child's growth stage. Above all, it is a repeat procedure because of repeated fractures. IM rods help to align the bones, but complication post-surgery needs to be closely monitored.

Overall, this review aims to access the existing finite element tools used to identify fractures in OI bone pre-operative and post-operative surgery. This review consists of four sections: (1) the FEA of fracture risk on OI-affected bone for pre-operative assessment, (2) follow-up on the fracture strength of IM rods post-surgery, (3) the biomechanical design and challenges of IM rods in current surgical intervention procedures and (4) recommendation for future work to provide a better use of simulation result to create a better lifestyle for the patient with OI.

## 2. Finite Element Analysis Preoperative Assessment

Early studies of fracture risk assessment in OI bone in finite element are by Fan *et al.*, 2004 [11] and Fritz *et al.*, 2009 [12]. This study was carried out in Abaqus software where both authors used the standard femur (SF) bone model available from the internet, but the distinctive difference is the reconstruction of the SF into the OI bone model. Fan *et al.*, 2004 [11] deformed the bone model to resemble the frontal angulation bowing of OI bone using matrix laboratory (MATLAB). On the other hand, Frit *et al.*, 2009 [12] constructed a patient-specific finite element model by matching the X-ray image of OI pediatric patient to the SF bone model in the coronal plane using the nodal coordination method. The length of the SF was adjusted according to match with the patient OI bone. For comparison, Fan *et al*., 2004 [11] produced three OI bone models representing three bone amplitude severities of 10 mm, 20 mm, and 30 mm where in the real case the severity does not reflect the actual bow angle. Meanwhile, Frit *et al*., 2009 [12] produces one OI bone model with the exact bowing angulation through matching technique. Another difference is that the former study used the same physiological load and location for the deformed model without including muscle force while the latter study included muscle force in their model and applied hip moment and forces at the femoral head and knee moments and forces at the center of the condyle's femur. Fan *et al*., 2004 [11] targeted 10% of the gait cycle covered only stance phase and concluded that as the deformity of bowing increases the stress and strain also increases. Fritz *et al*., 2009 [12] covered all seven phases of the gait cycle where von Mises stresses were analyzed against fracture strength of 115 MPa to indicate the fracture risk of the femur. They set Young's modulus of the femur bone as 19 GPa and Poisson's ratio of 0.3. The bone model was assumed to be isotropic. The finding showed no risk of fracture in OI patients in a normal gait cycle. But the highest fracture was recorded during the mid-stance and loading response of the gait cycle.

Caouette *et al*., 2014 [13] simulate the tibia bone models using Radioss software to predict the fracture risk in tibial bowing. The tibia mesh was adjusted to resemble the OI tibia patient radiography images. A variation of ten bowing angles was developed to assess the tibial bowing effect on fracture risk. The force was given during two-legged hopping, internal and external twisting of the tibia, and a direct force on the tibia in the horizontal direction in lateral, medial, anterior, and posterior directions. The tibia plateau was kept constrained and joint reaction force was applied at the distal end of the tibia. The findings of this study show that the risk of fracture in tibial bowing is related to vertical loads but not for lateral loads. In a follow-up study, Caouette *et al*., 2016 [14] used a patient-specific kriged mesh method to alter the tibia bone model to fit with the OI tibia bone. In this technique, four control points at the endosteal border per slice were used as reconstruction error to indicate the accuracy of the deformed bone, and eight points on the tibial plateau and three points of the distal tibia shaft used as references mark to recreate the OI tibia bone model. Figure 3 explained the reconstruction image developed from healthy tibia mesh and deform into OI tibia bone. CT scan images were used as reference the kriging technique with the respective location is referred to transform the model. In both studies the bone assumed to be isotropic with elastic modulus of 19 GPa. The result suggested that cortical thickness is indeed one of the factors affecting the fracture risk in OI.

**Fig. 3.** MRI Image of the tibia and Finite element model tibia

Tan *et al.*, 2019 [15] develop the tibia bone model to observe the influence of cancellous bone in modeling the OI bone in the Voxelcon. Two tibia bone models were developed based on the CT images of an OI patient where the first one was the solid OI tibia bone, and the other model was separated into cortical and cancellous bone. The bone models assumed to be isotropic and linearly elastic. Both models were given artificial load in the tibiofemoral joint and activities of daily load consisted of standing, walking, and running. The results show that the neglect of cancellous bone in the OI bone model does not make a significant difference in the given boundary conditions.

The most recent studies to assess the fracture in OI bone are by Ramírez-Vela *et al.*, 2021 [16] and Wanna *et al.*, 2022 [17]. The similarity between these studies is the setting of the loading condition on the bone model. They both set the constraints at the medial and lateral condyle of the femur and vertical force was applied at the femoral head. Figure 4 and 5 showed where the constraints were set at the medial and lateral condyle of the femur and force was applied at the femoral head. Ramírez-Vela *et al.*, 2021 [16] created a three-dimensional femur model based on CT scan images of OI patients. They evaluated the respond between femur bone model toward three types of fractures of transverse, oblique, and comminute in normal walking gait. Their finding indicated that comminute fracture causes the highest level of stress in the central zone of the diaphysis in the femur. Wanna *et al.*, 2022 [17] predicted the fracture load in femoral bone with ten variations of bowing severity under various types of loading consisting of medial-lateral impact, compression-tension, and internal-external torsion. The material properties of the bones are set as isotopic behavior. Using the same formula calculation from Fritz *et al.*, 2009 to predict the fracture risk, the result showed that fracture load increases in medial-lateral impact and external torsion as the bowing of femur bone increases. In internal torsion, the fracture load decreases as the severity of bone bowing increases implying the maximum load that the femur can bear before fracture. Table 1 lists all the past studies in relation to the pre-operative assessment in OI.

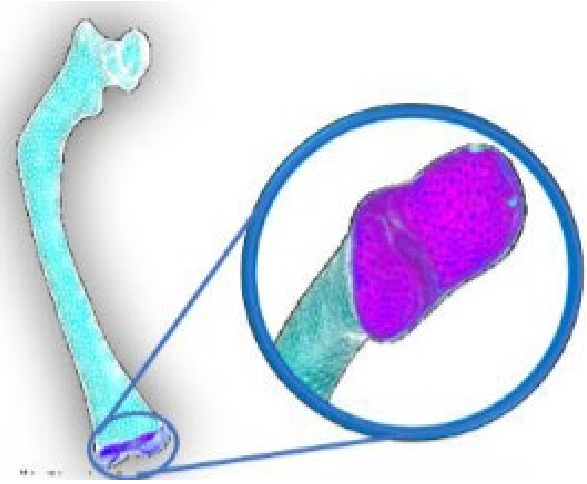

**Fig. 4.** Constraint on the medial and lateral condyle of the femur

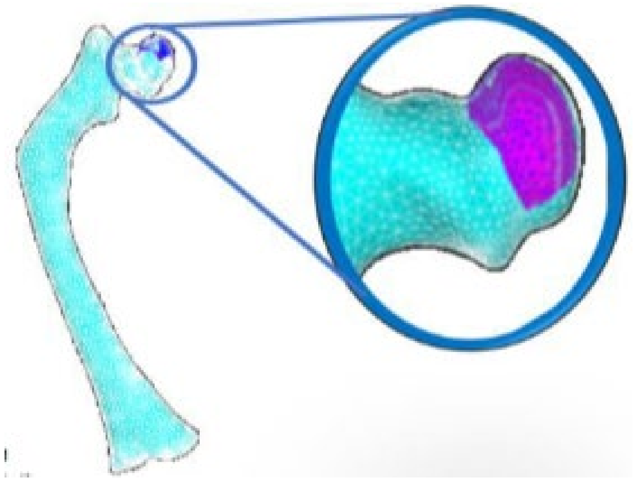

**Fig. 5.** Force applied at the femoral head

**Table 1**
Finite element studies on pre-operative assessment

| Author (Year) | Aim | Anatomic site | Source of image/model | Methods | Software | Concluding remarks |
|---|---|---|---|---|---|---|
| Fan *et al.*, 2004 [11] | To observe the stress/strain relationship in 10% of the gait cycle. | Femur | Standard femur (SF) model | • Four different severities created known as normal, light, mild, and severe | Abaqus | • As the deformity of bowing bone increases, the stress/strain on the OI bone model also increases. |
| Fritz *et al.*, 2009 [12] | Prediction of fracture risk assessment in OI. | Femur | Standard femur (SF) model | • Joint force reaction, hip moment, and knee moment in midstance position.<br>• von Mises stresses were analyzed against fracture strength of 115 MPa in the gait cycle. | Abaqus | • No risk of fracture in the normal gait cycle. |
| Caouette *et al.*, 2014 [13] | Prediction of fracture risk associated with tibia deformity. | Tibia | CT scan images | • FE tibia model with ten different angles of deformities.<br>• Force in two-legged hopping, internal and external twisting of the tibia, and a direct force on the tibia in the horizontal direction in lateral, medial, anterior, and posterior directions. | Radioss | • Increase fracture risk with increased angles of deformities for vertical impact.<br>• No changes were observed in lateral impact and twisting. |
| Caouette *et al.*, 2016 [14] | To develop a method with patient-specific geometry reconstruction based on the patient radiograph. | Tibia | CT scan image<br>Tibia template mesh | • Tibia template mesh deformed to fit with OI data.<br>• Different cortical thickness from patient data. | Radioss | • Cortical thickness affects the fracture risk in the tibia bone. |
| Tan *et al.*, 2019 [15] | To develop FE models of the tibia with OI based on patient-specific CT images. | Tibia | CT scan images | • Single solid model of the tibia bone.<br>• Cancellous and cortical tibia bone model.<br>• Artificial load on sagittal coronal plane.<br>• Loading from activity of daily living of 1.07×BW in standing, 2.83×BW in walking and 7.83×BW in running. | Voxelcon | • No significant effect of cancellous bone in OI bone model. |
| Ramírez-Vela *et al.,* 2021 [16] | To develop FE model to assess fracture in transverse, oblique, and comminute. | Femur | CT scan images | • Load applied in the normal walking cycle. | Ansys | • Comminute fracture causes the highest level of stress compared to the other two fractures. |
| Wanna *et al.*, 2022 [17] | Finite Element Prediction on Fracture Load of Femur with Osteogenesis Imperfecta under Various Loading Conditions | Femur | Standard femur (SF) model | • Ten different bowing angles were recreated.<br>• Load applied in the femoral head in medial-lateral impact, compression-tension, internal and external rotation. | Ansys | • Fracture load increases in medial-lateral impact and external torsion as the bowing of femur bone increases.<br>• Fracture load decreases as the severity of bowing angles increases in internal rotation. |

Overall, in the aspect of bone model representation, each study used different methods to reconstruct the bone model to mimic OI bone. These different approaches create different variations of OI bone geometry to present different degrees of bone severity. Therefore, this can offer a different perspective of the bone variation model to describe possible unexpected conditions to predict the occurrence of fractures related to this disease. For this reason, transferring CT scan image slices into the software should be carefully detailed. As per findings by Caouette *et al.*, 2016 [14] reported that cortical thickness affects fracture risk prediction. Therefore, the loss or lack of images of cortical bone slices will ultimately affect the results. On the other hand, cancellous bone does not have any significant impact on the result as per investigation by Tan *et al.*, 2019.

Apart from the representation of the bone model, another element that cannot be ignored is the material properties of the bone. OI bones are assumed to be isotropic bone material properties in finite elements. In general, bone was described as anisotropic material properties due to its response when forces were applied in different directions although some past studies declared bone as orthotropic material [18-20]. Individuals with OI have lower bone mineral density. Because of this, OI bone when subjected to an indentation test at the microstructural level, both cortical and cancellous bone displayed a woven appearance and sometimes a lamellar pattern as described by Ren *et al.*, 2014 [21]. This is supported from previous studies by an ultrastructural study which indicated that OI bone appeared to have a loose disoriented fibrous texture [22,23]. This abnormal appearance of OI at the microstructural level explained why OI bone was assigned as an isotropic bone material. Therefore, OI bone was set as isotropic material properties in most of the previous FEA studies. A study by Kazembakhshi & Luo., 2014 [24] attempted to observe the differences in finite element healthy femur bone model when assigned to different material properties and proposed that indeed there are differences in the prediction of stress-strain when the bones assigned into different material properties.

## 3. Finite Element Analysis Of Post-Operative Assessment

Intramedullary (IM) rods are used to support bowed bones, but postoperative complications are precautions that should be given extra attention. Finite element models of OI-treated bone with IM rods are equally important to evaluate to investigate the postoperative strain and stress fracture response. Table 2 summarizes the recent finite element studies on post-operative assessment [25-30].

**Table 2**
Finite element studies on post-operational assessment

| Author (Year) | Objectives | Anatomic site | Source of image/model | Methods | Software | Concluding remarks |
|---|---|---|---|---|---|---|
| Perez *et al.*, 2008 [25] | To compare the FE model of the femur bone and IM rods of stainless steel and titanium alloy | Femur | Femur model downloaded from the Internet. | • Static analysis.<br>• 15N load was applied on top of the femoral head in the y-direction and 10.61N applied in the x and y-direction. | Marc software | • Stainless steel increases the gap closure and nail slippage. |
| Mehboob *et al.*, 2013 [26] | To investigate the healing performance of composite intramedullary rods (IM rods) used for tibial diaphyseal fractures. | Tibia | Remodel in finite element | • Variation in fracture angle of 0°, 15°, 25°, and 35°.<br>• Variation in fracture gap of 1,2,3,6 and 10mm | Abaqus | • Modulus of the IM rod affects the tibial fracture healing according to the fracture angles and size. |
| Tucker *et al.*, 2019 [27] | Investigation of IM nail biomechanics for proximal femur fractures | Femur | Virtual femur model | • Static load of full body weight during heel strike in the gait cycle.<br>• Variation of fracture types: pertrochanteric, intertrochanteric, and subtrochanteric in planar fracture.<br>• 2000N force load at the femoral head from a 13° abduction angle and 8°posteriorly.<br>• Nail diameter with variations from 10-13mm and lengths of 43.4cm and 26.9cm | Abaqus | • Larger nail diameter can reduce the axial and shear interfragmentary motions. |
| Cui *et al.*, 2020 [28] | To provide a biomechanical detail between existing intramedullary nails and novel intramedullary nails. | Femur | CT Scan images | • Standing and walking conditions.<br>• Distal end of the femoral set as a constraint.<br>• Load of 700N was applied between the femoral head and acetabulum. | Geomagic Studio 2012 | • Novel intramedullary nails reduce stress shielding and promote stress transmission. |
| Pérez *et al.*, 2021 [29] | To access bone fixation using rods with three different lengths. | Femur | Remodel in finite element | • Based on four-point bending testing. | Febio | • IM nails can only support up to 25% of their original length before failure. |
| Wang *et al.*, 2021 [30] | To observe the biomechanical behaviors of IM rods on different materials of Titanium alloy, Stainless Steel (SS), PEEK, and two FG materials. | Femur | CT scan images | • One leg stance in the gait cycle.<br>• Joint reaction force of 2872N and muscle force of 1237N applied at the femoral head and greater trochanter.<br>• The distal end of the femur is fixed in all directions. | Abaqus | • PEEK and two FG materials provide better biomechanical material properties. |

Perez *et al*., 2008 [25] computed a finite element model of the femur with a mid-diaphysis fracture in Marc software to investigate the influence of different materials properties affect rod stability. Two type material properties of IM rods, stainless steel and titanium alloy were used to compare gap closure and nail slippage. The rods were inserted into the canal of the femur bone model simultaneously. They were tested under static analysis where the weight-bearing is the vertical force acting on the top of the femoral head and the knee acting as a constraint. Both rods and bone were assumed to behave isotopically with Young's modulus of 110 GPa for titanium and 200 GPa for stainless steel. The results show that titanium alloy provides better stability than stainless in terms of gap closure and nail slippage, thus this material is a better choice for surgical implant selection. On the other hand, Mehboob *et al*., 2013 [26] investigated the healing performance of composite IM rod through a mechano-regulation algorithm. In the simple cylindrical tibia bone model with the fracture site at the center and hollow pipe model represent the IM rod were designed in Abaqus software. The rod was inserted into the cylinder tibia model with no structural contact between these two models. Their findings claimed that the modulus of the IM rod affects the tibial fracture healing according to the fracture angles and size. Tucker *et al*., 2019 [27] investigated the importance of implant parameters such as IM nail diameter, length, and materials associated with different fracture types. The nail diameter was designed with variations of 10-13 mm and lengths of 43.4 cm and 26.9 cm based on clinical data. Figure 6(a) and Figure 6(b) presented the difference between both rods. The simulation was performed under a single static load of full body weight during a heel strike in the gait cycle in different fracture types: pertrochanteric, intertrochanteric, and subtrochanteric in planar fracture. The study proposed that a larger nail diameter can reduce the axial and shear interfragmentary motions and adjusting nail length does not seem to have a big significant difference in fracture. Cui *et al*., 2020 [28] compare the existing intramedullary nail and a novel intramedullary nail on the healing of femoral shaft fracture in Geomagic Studio 2012. The traditional rod has two slotted nails at both ends of the rod and the novel rod has additional nails slotted in the middle of the rod with more curvy design of the rod. The rods were inserted into the femur bone model and tested in standing and walking conditions. The novel rod provides better stability at fracture site and improves the gap of the implant and the fracture bone. Plus, it reduces stress shielding and promotes stress transmission.


(a) (b)

**Fig. 6.** Nail with distal fixation screw (a) short, 13mm diameter (b) long, 10mm diameter

Recent research by Pérez *et al.*, 2021 [29] to observe maximum stress and deformation of the rod fixation in the bone based on four-point bending by varying the length of the rod in the Febio software. Three variation of rod lengths were tested as illustrated in Figure 7. The authors set the modulus of stainless-steel rod as 200 GPa and titanium alloy as 110 GPa and Poison ratio of 0.3 and the rods material are assumed to behave isotopic. The results suggested that the rod can support up to 25% of its original length before failure. A finite element study by Wang *et al.*, 2021 [30] to observe the biomechanical behaviors of the rods of different materials consisting of Titanium alloy, Stainless Steel (SS), polyetheretherketone (PEEK), and two Function- graded (FG) materials in Abaqus. The IM rod was modeled after the manufacture of the Zimmer Nature Nail rod and virtually inserted into femur bone model. All the IM rods were subjected to one leg stance during the gait cycle on the femur. The analysis suggests that PEEK and two FG materials provide better biomechanical material properties than the other two materials where they reduce stress shielding and could be an alternative design for the future.

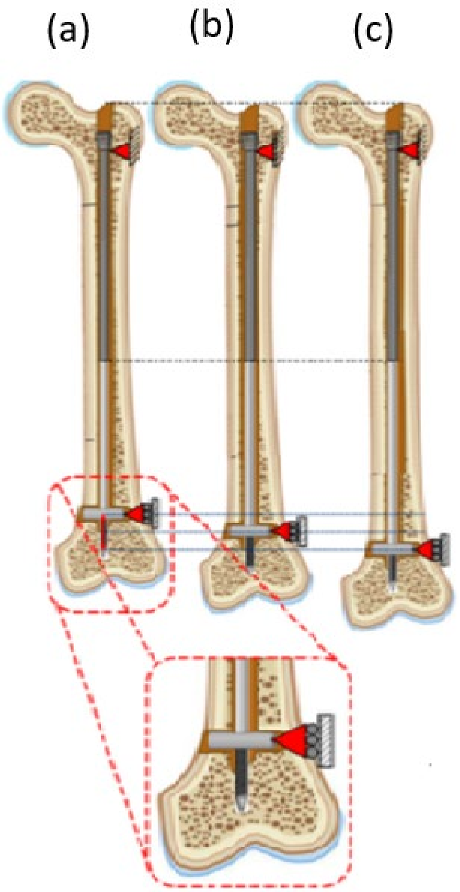

**Fig. 7.** Three-length condition of the rod (a) The original length (b) Extended one-third from the original length (c) Extended two-thirds from the original length

## 4. Biomechanics of Intramedullary Nailing: Design and Its Challenges

The biomechanical design of the IM rod has evolved over the past several years to improve the patient mobility. The biomechanical analysis behind IM rod design is a critical criterion to consider in providing the most suitable rod for cases such as osteogenesis imperfecta. Non-telescopic rods such as Rush pins used in the early phases of surgical procedures are still in demand today. The rush pin can be used either as a single rush pin or a dual rush pin. Rush pin comes with various diameters and lengths depending on the manufacturer. Perez *et a*l., 2008 [25] mentioned that in an ideal case, the rod diameter is 40% of the canal diameter. Rush pin is a long straight pin with a hook at the tip of the pin is to avoid rotation and to obtain stability of the rod. The ability of the Rush pin to minimise the stress riser effect and provide a longer period of bone fixation before revision surgery is the reason for its choice as stated by Cho *et al.*, 2020 [31]. The concept behind the rush pin insertion is based on a three-point fixation which can produce compression at the fracture site to prevent axial displacement. Consequently, the tip of the nail can penetrate the cortex bone and cause damage to the soft tissue near the joint. The material of the rod can either be stainless steel or titanium. The elastic mechanical behavior of the stainless steel restricts the movement of the rod and the need for secondary bending along the medullary canal. On the contrary, Prajapati *et al.*, 2019 [32] claimed that stainless steel material is stiffer and stronger with less elastic properties than titanium. This material property determines the resistance to sagittal and coronal bending and the torsional stability of the rod. The strong and rigid stainless steel can support and fix the bone, but the less flexible part of it seems to be a liability in the bone-implant interface. On the other hand, the simplicity of the rush pin required less cost and less recovery time.

Review by Fassier, 2021 [8] stated that the development of telescopic rods began with the Bailey Dubow (BD) rod. BD rod was first implemented by Robert Bailey in 1963 to address the shortcoming of non-telescopic rods. T-male part and the female part where each of the rods is anchored to the proximal and distal epiphysis of the long bones. A t-shaped male part is placed along the femoral bone and the female part passes through the male part to reach the greater trochanter. As the bone grows, the t–male part is elongated according to the length of bone according to previous study. The complexity of the surgical approach is often associated with joint pain post-operation that can cause loss of knee flexion. To insert the rod, an arthrotomy is required and it is particularly complicated if long bone fractures are involved since two arthrotomies are needed at the joints. This seems inefficient and complex. Fassier Duval (FD) rod is the newest generation of telescopic rod and is widely used in today's surgery. It consisted of the male rod attached to the distal epiphysis and the female nail attached at the proximal end of the epiphysis. The threaded part of female and male nails helps to fix the fracture in the femoral shaft. Figures 8, 9, and 10, below show examples of the evolution of the IM rod taken from past clinical review [44-46]. The FD rod offers a minimally invasive procedure approach which can be performed through a percutaneous approach, therefore less surgical time is required, reduce blood loss, fewer surgical scars, and low postoperative complications. This is proven in a study carried out Persiania *et al.*, 2019 [33] to access the advantages of percutaneous approaches over the open osteotomies method using FD rod in the tibial bowing. The result shown that percutaneous approaches allowed fast recovery post-operative surgery therefore improve the fracture management in OI. Spahn *et al.*, 2019 [34] and Yang *et al.*, 2023 [35] also support this through their findings that the telescopic rod required less surgical revision with four more years of survival and less rod complications. However, the use of FD rod is quite costly, and the migration of rod is still unavoidable with high rate of 69% to 100% as reviewed by Fassier, 2021 [8]. This is addressed by Behera *et al.*, 2020 [36] in a clinical case study of a 10-year-old patient who used a FD look alike rod. While the rod helps to improve mobility of the patient, but the migration still occurs where male part of the rod got dislodged. Badr *et al.*, 2022 [37] also stressed this concern in which he stated that distal threaded male part of the rod indeed quite challenging for the children as they tend to have smaller bone epiphysis and thus over the time can cause migration at the distal part of the bone. The placement of the rod in the bone plays a significant role in determining the rod survival as described by Holmes *et al.,* 2020 [38]. The longer the rod stay in the middle of distal epiphysis of the bone the longer the survival rate. Previous studies by Popkov *et al.*, 2020 [39] and Mingazov *et al.*, 2019 [40] reported that using a combined telescopic rod technique together with an external fixator in children with OI helped to overcome rotation, instability, and rod migration after surgery. Contrary to this, A. Popkov *et al.*, 2019 [41] advised that external fixators are not suitable for use in children due to the attachment of the external frame to the weak bone material. There is an invention that had been applied to provide better support for bone fixation in OI patients with the corkscrew telescopic rod as case study by Sarikaya *et al.*, 2019 [42]. The corkscrew telescopic rod was specially designed to provide sufficient stability and prevent migration of the rod as well as to avoid the insertion through the joint. Their case study claimed a corkscrew telescopic rod indeed can overcome the rod migration issue faced by BD and FD rods, however, the tip of the screw could penetrate the cortex if not careful when inserting the rod. Erdal *et al.,* 2021 [43] reported case studies where a corkscrew telescopic rod achieved complete union and no migration was reported.

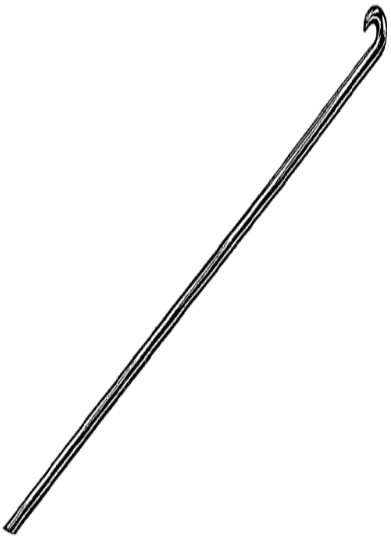

**Fig. 8.** Rush pin

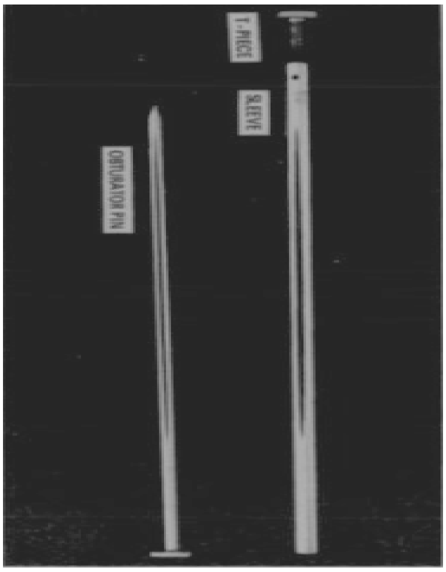

**Fig. 9.** Bailey Dubow

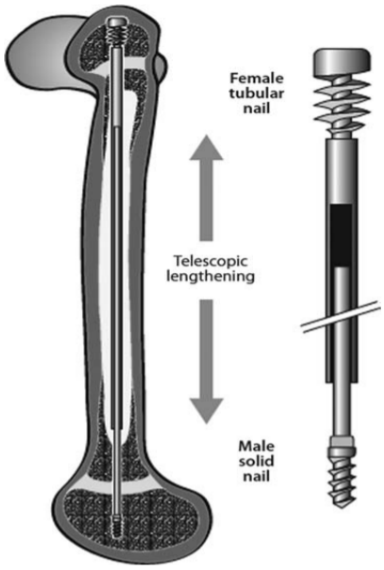

**Fig. 10.** Fussier Duval

Rod complications like non-union or delayed union, malunion, and rod loosening are common issue face in fracture fixation in OI reported. Implant placement is important, and this can be challenging as insertion of the implant play a crucial role to avoid iatrogenic damage. Surgical technique and the suitable instrument and implant must be taken extra care of as patients always display secondary injury of abnormal bone anatomy following the former injury. Esposito and Plotkin, 2008 [47] indicated that the rod might give better fixation, but the downside is it lacks sufficient rigidity and torsional resistance that allow union. Also, the decision to use a telescopic or non-telescopic rod is a risk that cannot be ignored. Usually, the application of telescopic rods seems to favour children, however, there are situation where non-telescopic rods are considered more appropriate. In young children who have a narrow intramedullary canal, severe malfunction, and major comorbidities it is advisable to use a non-telescopic rod suggested by Persiani *et al.*, 2019 [48]. Likewise in adult patients, there is not necessary to use a telescopic rod because of the mature skeleton, therefore surgeon's judgment to choose the appropriate rod plays a vital role here. In a retrospective study by Goiano *et al.*, 2023 [49], 71.4% showed that telescopic rod functionally elongated as the bone growing in children under 14 years old. Nonetheless Bacaksiz & Akan, 2023 [50] reported that post-operative complication between telescopic and non-telescopic rod still high.

This is because the simplicity design of the non-telescopic rod required repetitive surgery as the bone growth, on the other hand the technically complicated telescopic rod design cause rod complication such as migration into abductor muscle. In a comparison study using Rush rod and FD rod by De Jager *et al*., 2021 [51], showed that no recurrent surgery needed in 3.6 years using FD rod while a high rate of 58% patient used Rush pin required follow-up surgery.

Recurrent fractures, especially in children, require telescopic rods to avoid frequent surgery and telescopic rods are useful in the long term as they can extend together as the bone grows and prevent new deformities. Sterian & Ulici, 2020 [52] described that most of the time rod migration happen before bone healing especially for the femoral part of the rod and the need for rod revision can be considered during this period. In contrast during the revision surgery, removal of the telescopic rod might be challenging given its design feature where its anchoring system is larger than the middle rod and thus could damage the epiphyses. Some suggested that children above five years old should be treated with a telescopic rod considering the high implication and probability of revision surgery [53,54]. The fragility and weak bone material in OI, plate and screw should be avoided at all costs as proposed by Jovanovic *et al*., 2022 [55]. Plate and screw cause stress shielding and lead to bony resorption with the risk of fracture on the plate and some cases link to the formation of a hypertrophic callus as revealed by previous studies [47,56]. Cho *et al*., 2015 [57] reported a case of using a plate and screw in osteotomies of OI bone and when the plate and screw were removed after the union, noticeable there are some fractures on the bone plate interface. The hip joint should be able to rotate internally when a plate and screw were used for fixation. Although it helps to fix and heal the fracture site especially in rotational stress in joint area, but it also increases the stress concentration especially at the tip of the plate and might cause subsequent peri-implant fracture. Therefore, the authors emphasize the need for removal of plate and screw after the healing cure.

## 4. Prospect for Future Research

Preoperative surgery through FEA gives us a better understanding of the biomechanics of OI bone which can benefit the affected population. This information can serve as an early sign of bone fracture with respect to their daily activities. To access in depth the early signs of fracture, several perspectives can be projected for future research.

One of them is the impact of single and double deformities on bone fracture mechanics in long bones. Patients with OI experienced the highest fracture rates in their first two decades of their life, and the percentage of patients with double deformities increased from 31.3% to 43.1%, requiring simultaneous rodding surgery in a clinical study involving 588 patients from Linked Clinical Research Centers [58]. Weight-bearing can be an additional part of causing a fracture as the patient grows and can move on their own. For this reason, investigations of the relationship between weight-bearing and simple mobility, such as walking on the double deformities, can significantly add new data and additional information about the fracture mechanisms in the lower extremities. Since this is a brittle bone disease that ultimately affects the patient for a lifetime, repeated fractures are common. However, apart from the nature of the disease and the bone growth, it is also caused by implant loosening or implant failure that can cause recurrent fractures. The average need for surgery for recurrent fractures can be reduced to provide a better quality of life for patients is one of the potential aspects to look forward to in future studies. Analysis of postoperative surgery can be performed to investigate the bone-rod interface to improve the quality of life for the OI patients. This also can be extended to explore the stress-strain interaction between the bone rod interfaces. When the rod is inserted to support the fracture bone, there is a discontinuity of the bone along the rod as the bone fragments align together. The stress elongation along the rod to support the discontinuity of the bone fragments may explain the strength of the rod prior to first post-operative mobility. Additionally, the stability of the rod to hold the bone fragments along the diaphysis after multiple osteotomies can be demonstrated through FEA to identify the deformation of the rod which indicates the sign of implant failure. The stress-strain respond during the initial phase when bones are lined up after deformities could provide some information about the stability of the implant inside the bone. In general, patients need revision surgery due to loosening or migration of the rod, for this reason, stress shielding can be viewed as one of the factors why this condition often occurs. The load transfer between the bones and rod greatly impacted the stability and balance of the lower body part, therefore this information on stress shielding can contribute to guide the right selection of implant to reduce implant migration to minimize revision surgery.

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