

## ■ BIOMECHANICS

# Effect of material selection on tibial post stresses in posterior-stabilized knee prosthesis

A COMPARISON AMONG CONVENTIONAL, CROSS-LINKED, AND VITAMIN E-STABILIZED POLYETHYLENE



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## Aims

The material and design of knee components can have a considerable effect on the contact characteristics of the tibial post. This study aimed to analyze the stress distribution on the tibial post when using different grades of polyethylene for the tibial inserts. In addition, the contact properties of fixed-bearing and mobile-bearing inserts were evaluated.

## Methods

Three different grades of polyethylene were compared in this study; conventional ultra high molecular weight polyethylene (UHMWPE), highly cross-linked polyethylene (HXLPE), and vitamin E-stabilized polyethylene (VEPE). In addition, tibial baseplates with a fixed-bearing and a mobile-bearing insert were evaluated to understand differences in the contact properties. The inserts were implanted in neutral alignment and with a 10° internal malrotation. The contact stress, von Mises stress, and equivalent plastic strain (PEEQ) on the tibial posts were extracted for comparison.

## Results

The stress and strain on the tibial post for the three polyethylenes greatly increased when the insert was placed in malrotation, showing a 38% to 56% increase in von Mises stress and a 335% to 434% increase in PEEQ. The VEPE insert had the lowest PEEQ among the three materials. The mobile-bearing design exhibited a lower increase in stress and strain around the tibial posts than the fixed-bearing design.

## Conclusion

Using VEPE for the tibial component potentially eliminates the risk of material permanent deformation. The mobile-bearing insert can help to avoid a dramatic increase in plastic strain around the tibial post in cases of malrotation. The mobility allows the pressure to be distributed on the tibial post and demonstrated lower stresses with all three polyethylenes simulated.

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**Keywords:** Polyethylene, Highly cross-linked, Vitamin E-stabilized, Malposition, Stress-strain distribution

## Article focus

- Posterior-stabilized (PS) knees are the most common knee arthroplasties used in patients with severe osteoarthritis.
- The stress and plastic strain on tibial liners composed of highly cross-linked polyethylene (HXLPE) and vitamin-E stabilized polyethylene (VEPE) used in PS knees has not been studied previously.

- The study investigated different materials and designs of the tibial insert using a validated finite element model to understand the effect on stress around the tibial post.

## Key messages

- The choice of material and design features of the tibial insert can have a

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considerable effect on the stress distribution around the tibial post.

- When placed in malrotation, all models showed high compression stress at the edge of the tibial post and the greatest tensile stress was found near the base of the post.
- The choice of material has less of an impact on contact properties in the mobile-bearing design, because the mobility of the tibial insert reduces the severity of edge loading and greatly reduces stress and the plastic strain around the tibial post.

### Strengths and limitations

- This study is the first to analyze the effect of material selection on tibial post stresses in fixed-bearing and mobile-bearing PS knee prostheses.
- Tensile stress and plastic strain around the tibial post were compared for different polyethylene materials to understand the risk of post fracture.
- Soft tissue forces, such as the quadriceps contraction force, were not simulated. Post-cam engagement was simulated in a worst-case condition when suffering an anteroposterior (AP) shear force at a deep flexion angle with and without malrotation.

### Introduction

Posterior-stabilized (PS) knee prostheses have been widely used in total knee arthroplasty (TKA) with satisfactory functional performance<sup>1</sup> and clinical outcomes.<sup>2,3</sup> The post-cam mechanism used in PS knees is designed to provide anteroposterior (AP) stability to the knee joint to prevent posterior subluxation of the tibia in flexion.<sup>4</sup> In addition to the high contact compressive stress on the articular surface of the post-cam mechanism, high tensile stress can be generated at the anteroinferior portion of the post when the anterior tibial post impinges upon the femoral component, which can then become a compressive stress when the cam engages the posterior post at high flexion angles.<sup>5,6</sup> Such oscillating loading patterns around the same region would undoubtedly increase the incidence of post failure. Related complications, such as material wear and fatigue fracture of the tibial post, have been reported in retrieval studies.<sup>7-13</sup> The incidence of these complications varies depending on the material and design features of the prosthesis.

Although ultra high molecular weight polyethylene (UHMWPE) has been successfully used as an orthopaedic bearing material for several decades,<sup>14</sup> wear of contemporary polyethylenes is still inevitable due to the considerable loads placed on the knee. Wear-particle-induced osteolysis remains a concern, affecting the longevity of joint arthroplasties.<sup>15</sup> Highly cross-linked polyethylene (HXLPE) was developed by high-dose irradiation of UHMWPE followed by thermal treatment to reduce the content of free radicals. This material has been

demonstrated to improve the wear resistance in total hip prostheses,<sup>13,16-18</sup> but safety concerns remain regarding its use as a tibial insert.<sup>8,19-22</sup> The loss in toughness as a result of crosslinking and the presence of residual free radicals can lead to material oxidation,<sup>23</sup> which can decrease the resistance to fatigue crack propagation.<sup>24</sup> Short-term clinical results<sup>25-27</sup> have shown no statistical significance in clinical outcomes between HXLPE and conventional UHMWPE tibial inserts, and some surgeons have expressed doubts regarding its cost efficiency<sup>26</sup> and concerns about its long-term safety when used as a knee bearing.<sup>7,25-28</sup> In addition, fracture of the tibial post<sup>7,29</sup> and patellar peg<sup>9</sup> in HXLPE knee components has been occasionally reported, raising doubts about its safety for use in non-wear-based articular surfaces.<sup>7,21,25,28</sup> Recently, vitamin E-stabilized polyethylene (VEPE) was introduced to neutralize residual free radicals without reducing the mechanical properties.<sup>30</sup> This new material has demonstrated considerable improvements in oxidative resistance and wear rates.<sup>31,32</sup> However, more long-term clinical follow-up studies are needed to understand whether the tougher VEPE material can reduce the incidence of fracture of tibial inserts, particularly at the tibial post.

In addition to the insert material, the mobility of tibial inserts on the metallic baseplate can also affect the long-term performance of TKAs. The insert in contemporary PS knees can be categorized as being either a fixed-bearing or mobile-bearing. Therefore, the primary aim of this study is to compare the contact characteristics on the tibial post in both fixed-bearing and mobile-bearing inserts made from UHMWPE, HXLPE, and VEPE using finite element analysis (FEA). Also considered was how implant malrotation can affect the contact characteristics on the tibial insert. This study used FEA to obtain information on 3D stresses and plastic strains on the tibial post. The results of this study may be useful to clinicians when choosing an implant to suit individual patient needs.

### Methods

**Material property.** Three commercially available polyethylene materials were compared in this study: conventional UHMWPE (GUR 1020, 0 kGy); remelted HXLPE (GUR 1020, 75 kGy); and VEPE (0.1% vitamin E-blended 75 kGy HXLPE). The raw data from the stress-strain curves for these materials were obtained from the authors' prior experimental study.<sup>33</sup> All three materials demonstrated elastoplastic characteristics with a linear elastic region and nonlinear plastic region (Figure 1). The lower mechanical strength of HXLPE can clearly be seen in Figure 1.<sup>33</sup> The stress-strain raw data were imported as a material input for the FEA. The linear elastic region was categorized as the interval between the initial point and yielding stress point. For the plastic region, 42 intervals were assigned to ensure more reliable stress-strain values for the nonlinear region.

**Knee component FEM models.** The PS knee used in this study was modelled from a Uknee I prosthesis, size 3

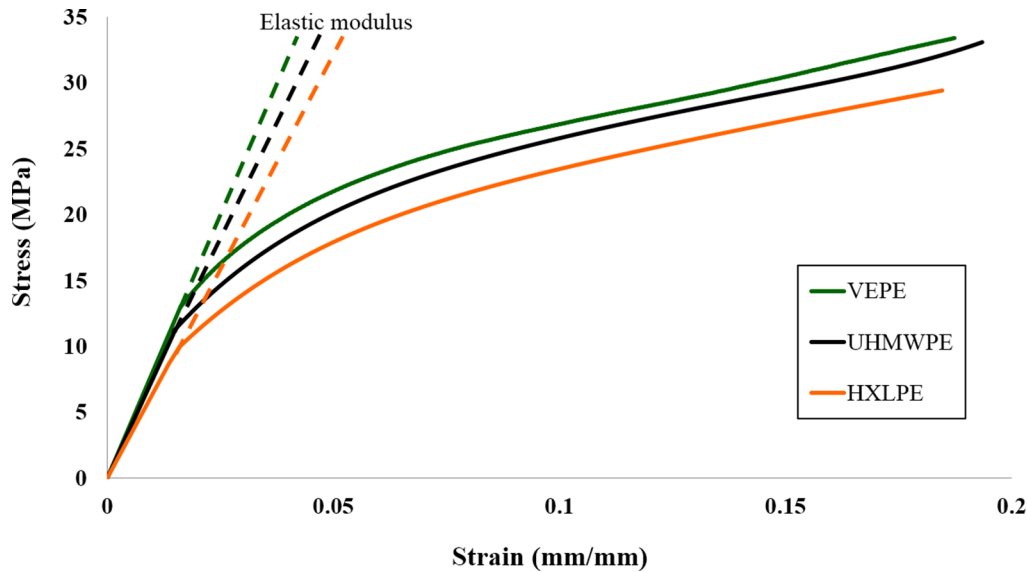


Fig. 1

Typical elastoplastic stress-strain curves of ultra high molecular weight polyethylene (UHMWPE), highly cross-linked polyethylene (HXLPE), and vitamin E-stabilized polyethylene (VEPE).

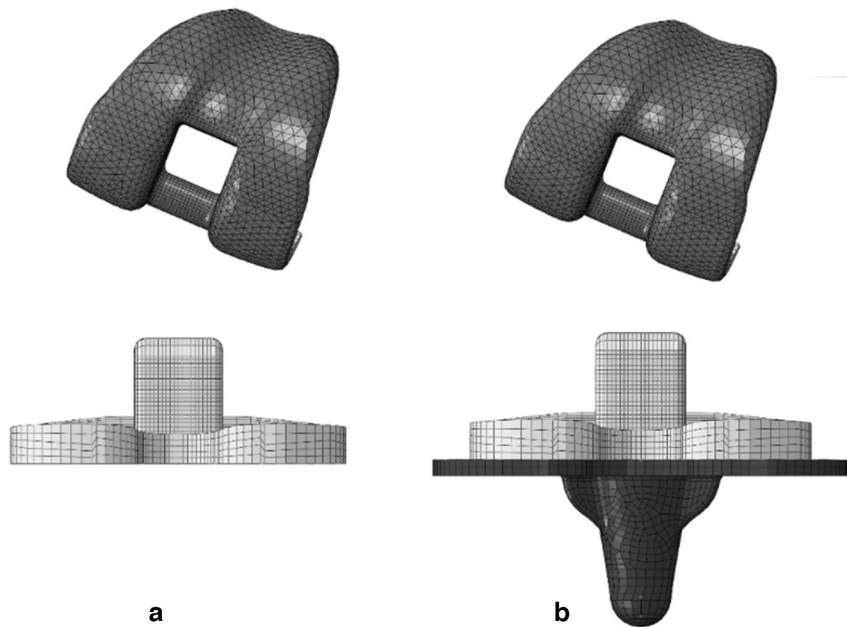


Fig. 2

Finite element models of a) fixed-bearing and b) mobile-bearing knee prostheses.

(United Orthopaedic Corp., New Taipei City, Taiwan) using 3D reverse engineering. The fixed-bearing and mobile-bearing designs have an identical conformity on the tibiofemoral articular surfaces, and the contact surface between the tibial post and femoral cam on the transverse plane is flat-on-flat for both models. The corners of the post were filleted with a radius of 2.5 mm. The geometrical data of the fixed-bearing model (Figure 2a) and mobile-bearing model (Figure 2b) were imported into

ABAQUS 2018 (SIMULIA, Dassault Systèmes, Versailles, France) for meshing and analysis.

The metallic femoral and tibial metal-backed components were assumed to be rigid bodies,<sup>5,6</sup> because the elastic modulus of metal (220 GPa) is substantially larger than that of polyethylenes.<sup>33</sup> The femoral component contained 1,240 quadrilateral elements and 3,331 triangular elements. Quadrilateral elements were used at the femoral cam to smoothen the contact surface, while the

### Convergence test

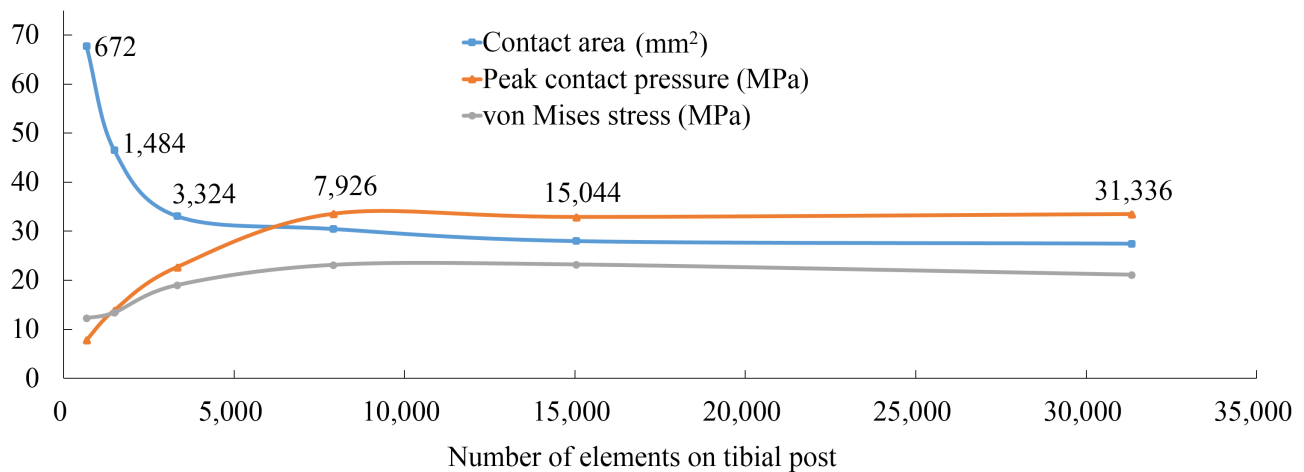


Fig. 3

Convergence test of the contact area, peak contact pressure, and von Mises stress on the tibial post.

insert was modelled with a hexahedral mesh and assigned nonlinear material behaviour in accordance with a previously validated knee model.<sup>5,6</sup> Geometrical and material nonlinearities were used for analysis. On the tibial insert, the elastoplastic stress-strain curves of UHMWPE, HXLPE, and VEPE were loaded into the models with a Poisson's ratio of 0.45.<sup>5,6</sup> Convergence testing was performed on the tibial post to ensure that the contact area, peak contact pressure, and von Mises stress did not change appreciably with mesh refinement (Figure 3). After mesh refinement, the tibial post contained 7,926 hexahedral elements (C3D8). The post-cam contact behaviour was defined as finite sliding with hard contact. The friction coefficient between the metallic and the polyethylene interfaces was assumed as 0.04.<sup>34</sup>

**Loading conditions and measurement.** Tibiofemoral malrotation is commonly seen in TKA and can increase the stress on the tibial post. In this study, neutral alignment and malrotation of the tibiofemoral joint were simulated. Neutral alignment is defined as having no axial tibiofemoral rotation, whereas malrotation was simulated by placing the tibial insert with a 10° internal rotation relative to the femoral component as a worst-case condition.<sup>5</sup> Both the fixed-bearing and mobile-bearing models were simulated in neutral alignment and malrotation, and the centre point at the base of the tibial insert was set as the axial rotation centre. The base of the tibial component was not allowed for movement in the fixed-bearing model, while the mobile-bearing model only permitted axial rotation. The femoral component was allowed to move in the AP direction only. The centre of the posterior condylar radius of the femoral component was set as the centre of rotation for knee flexion. The contact surface between the tibial post and femoral cam in PS knee prostheses is designed to prevent posterior subluxation of the tibia during high flexion. As such, the post-cam mechanism in this

study was simulated to engage at a knee flexion angle of 120°,<sup>35,36</sup> at which point the posterior surface of the tibial post was subjected to an anterior engagement force of 500 N from the femoral cam.<sup>5,37</sup> This loading condition was used in a previous study analyzing the influence of post-cam design on the stress distribution in PS knees.<sup>6</sup>

The contact pressure, von Mises stress, and equivalent plastic strain (PEEQ) on the tibial post were recorded to compare the contact characteristics between the UHMWPE, HXLPE, and VEPE materials. These parameters were also compared between fixed-bearing and mobile-bearing tibial inserts when placed in a neutral position or axial malrotation.

### Results

**Effect of material selection.** When placed in neutral rotation, the maximum contact pressure on the fixed-bearing tibial posts on the UHMWPE, HXLPE, and VEPE inserts was 25.2 MPa, 23.8 MPa, and 26.4 MPa, respectively (Figure 4a). The maximum von Mises stress on the UHMWPE, HXLPE, and VEPE posts was 19.3 MPa, 17.8 MPa, and 21.1 MPa, respectively (Figure 4b). The PEEQ of UHMWPE, HXLPE, and VEPE posts was 2.3%, 3.0%, and 1.7%, respectively. The PEEQ on the UHMWPE and VEPE posts was 26% and 44% lower than the HXLPE post (Figure 4c).

**Effect of design feature.** Table I details the contact characteristics of the fixed-bearing and mobile-bearing designs when placed in neutral alignment and malrotation. Considering the VEPE insert, the von Mises stress on the tibial post in the fixed-bearing model increased by over 50% when the model changed from neutral alignment to malrotation (21.1 MPa and 32.0 MPa, respectively). However, the mobile-bearing model experienced a less than 10% increase in stress when placed in malrotation

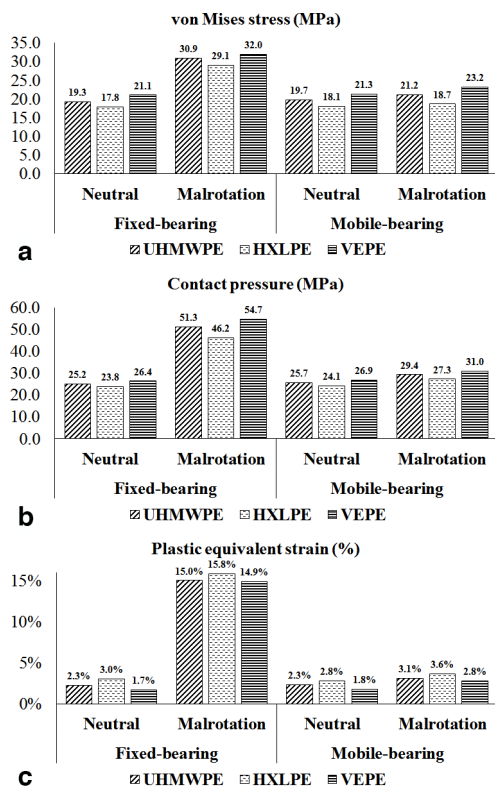


Fig. 4

Graphs of a) contact pressure, b) von Mises stress, and c) equivalent plastic strain (PEEQ) of ultra high molecular weight polyethylene (UHMWPE), highly cross-linked polyethylene (HXLPE), and vitamin E-stabilized polyethylene (VEPE) posts in fixed-bearing and mobile-bearing knee prostheses under neutral and malrotation contact.

(21.3 MPa and 23.2 MPa). Similarly, the PEEQ on the tibial post increased by 560% to 770% when the insert changed from neutral alignment to malrotation, but only increased by 29% to 58% in the mobile-bearing model (Figure 4c).

## Discussion

This study is the first to evaluate and compare the contact characteristics of different contemporary orthopaedic polyethylenes when used in the tibial insert of PS knees. The results found that the type of polyethylene and mobility of the tibial insert have a considerable impact on the stress/strain distribution on the tibial post. High stresses were found on the tibial posts in all cases, but the stresses were particularly high in the fixed-bearing designs when placed in malrotation. In the mobile-bearing knees, the inherent ability of the tibial insert to move in response to forces placed upon it was found to reduce the stress on the tibial post, in comparison to the fixed-bearing design.

HXLPE is widely used in total hip prostheses owing to its superior wear resistance compared to conventional UHMWPE.<sup>13,16,17,38</sup> However, there are concerns around the risk of catastrophic fracture of the tibial post<sup>28</sup> owing to the oxidative degradation and reduced fracture toughness of

**Table 1.** Contact area, contact pressure, von Mises stress, and equivalent plastic strain of ultra high molecular weight polyethylene, highly cross-linked polyethylene, and vitamin E-stabilized polyethylene posts in fixed-bearing and mobile-bearing knee prostheses under neutral and malrotation contact.

P. type	Contact area, mm <sup>2</sup>	Contact pressure, MPa				von Mises stress, MPa				Plastic equivalent strain, %						
		Fixed-bearing		Mobile-bearing		Fixed-bearing		Mobile-bearing		Fixed-bearing		Mobile-bearing				
		Neutral	Malrotation	Neutral	Malrotation	Neutral	Malrotation	Neutral	Malrotation	Neutral	Malrotation	Neutral	Malrotation			
UHMWPE	26.3	14.3	26.3	27.9	25.2	51.3	25.7	29.4	19.3	30.9	19.7	21.2	2.3	15.0	2.3	3.1
HXLPE	28.0	14.4	28.0	30.3	23.8	46.2	24.1	27.3	17.8	29.1	18.1	18.7	3.0	15.8	2.8	3.6
VEPE	26.3	14.3	26.3	27.1	26.4	54.7	26.9	31.0	21.1	32.0	21.3	23.2	1.7	14.9	1.8	2.8

HXLPE, highly cross-linked polyethylene; P., polyethylene; UHMWPE, ultra high molecular weight polyethylene; VEPE, vitamin E-stabilized polyethylene.



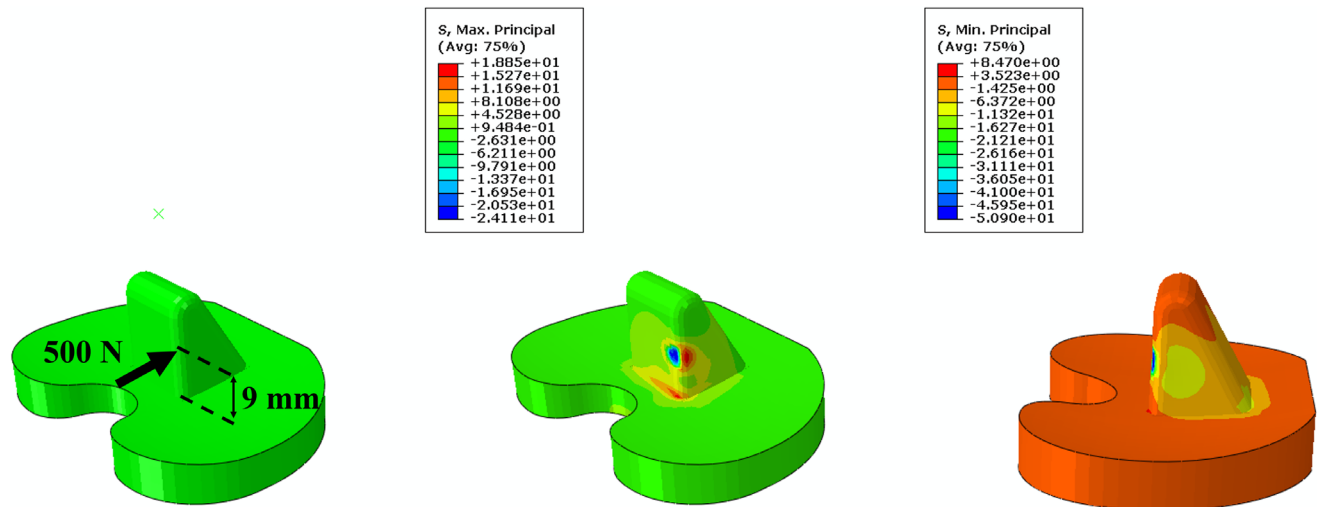


Fig. 5

The maximum tensile stress was observed at the base of the tibial post and maximum compressive stress at the anteroinferior portion of the tibial post during post-cam engagement.

HXLPE.<sup>39</sup> The heating process associated with production of HXLPE is intended to reduce the content of residual free radicals after high-dose irradiation, but the heating process has also been shown to reduce the mechanical resistance.<sup>40</sup> Thus, VEPE was introduced to neutralize residual free radicals without reducing the mechanical properties. Vitamin E acts as an antioxidant and helps to maintain material longevity by preventing oxidation.<sup>41</sup> However, short-term clinical follow-up studies<sup>42</sup> revealed no statistically significant advantage of VEPE over HXLPE, but long-term clinical results are needed to evaluate the patients' condition over the lifetime of the material. This current study analyzed the contact properties on tibial posts composed of three polyethylene materials commonly used in orthopaedic implants (UHMWPE, HXLPE, and VEPE). This study also compared fixed-bearing and mobile-bearing tibial inserts to understand whether different materials could improve the post-cam contact mechanics in cases of surgical malposition.

Failure of the polyethylene tibial insert component is one of the dominant failure modes in knee arthroplasties, as insert is subjected to considerable compressive, tensile, and deviatoric loading.<sup>43</sup> Arnout et al<sup>44</sup> reported on the contact pressure and contact area on the posterior face of the post using pressure-sensitive Tekscan sensors. However, placement of the sensors could affect the stress fields on the surface of the component, and a pressure sensor can only measure the contact pressure on the articular surface. The maximum principal stress (tensile stress) and von Mises stress, a measurement of material distortion often used to predict subsurface delamination wear,<sup>43</sup> cannot be measured by pressure sensors, but can be calculated by FEA.<sup>45</sup> Regarding the mechanical properties, previous related studies<sup>5,6,46</sup> tended to model the polymeric component with only elastic properties, but it is known that orthopaedic polymers behave as elastoplastic

materials with both linear elastic and nonlinear plastic portions.<sup>14,39</sup> This current study introduces a nonlinear elastoplastic model derived from experimental data to accurately describe the compressive loading behaviours of conventional UHMWPE, HXLPE, and VEPE.<sup>33</sup> To our knowledge, this is the first study comparing the contact properties of various common polyethylenes when used in fixed-bearing and mobile-bearing tibial inserts.

The stress-strain curves of polyethylene were input as material properties into the finite element models to evaluate the plastic deformation behaviour. As the resulting stress on the models after loading was below the material yield point, the von Mises stress could be used to predict damage on the bearing surface. When the stress exceeded the yield point, the materials underwent plastic deformation, and thus an irreversible strain deformation appeared on the tibial post. The level of material distortion and permanent plastic deformation is difficult to measure using in vitro methods, but can be easily calculated using FEA. Bartel et al<sup>43</sup> demonstrated that the locations of maximum stress and strain (approximately 1 mm beneath the surface) in a finite element model of a tibial insert were consistent with those observed in retrieved components. The findings of this current study are consistent with those of Bartel et al,<sup>43</sup> who reported that the contact centre experienced compressive stress and that the maximum von Mises stress always occurred between 1 mm and 2 mm below the contact surface. This subsurface stress is considered to contribute to the formation and growth of internal defects, which may be used to predict polyethylene delamination wear.<sup>47,48</sup> In the current study, high von Mises stresses not only occurred on the contact surface of the tibial post but were also observed at the base of the tibial post. The maximum von Mises stress at the base of the tibial post in the UHMWPE, HXLPE, and VEPE models was 12.2 MPa, 11.1

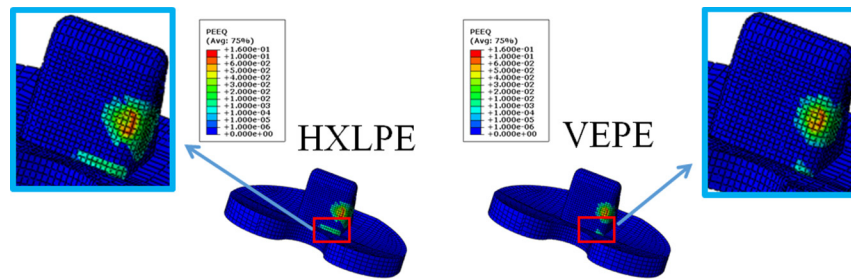


Fig. 6

Plastic deformation at the posterior surface and the base of the tibial post. Vitamin E-stabilized polyethylene (VEPE) had a smaller equivalent plastic strain (PEEQ) around the post than highly cross-linked polyethylene (HXLPE).

MPa, and 13.5 MPa (Table I), respectively, when placed in malrotation. The post-cam contact surface experienced compressive stress, whereas the maximum tensile stress was observed at the base of the tibial post because of the cantilever effect. During engagement when the knee was flexed to 120°, the femoral cam contacted the posterior surface of the tibial post at a height of approximately 9 mm from the base of tibial post (Figure 5). The tensile stress on the UHMWPE, HXLPE, and VEPE posts was 18.9 MPa, 18.3 MPa, and 19.3 MPa, respectively, when placed in malrotation. However, the stress around the same region of the tibial base can change to compressive stress if the tibial post suffers anterior impingement.<sup>6</sup> Such stress fluctuations around the same area, even at low values not exceeding the yielding stress, could cause material fatigue, which may lead to fracture of the tibial post.

Implant malalignment is considered a major source of excessive stress and strain on orthopaedic implants.<sup>7,11,29,49,50</sup> Jung et al<sup>29</sup> postulated that post fractures are often the result of component malpositioning, which can lead to flexion instability and also cause the femoral component to become impinged on the tibial post in extension. Despite the lack of long-term clinical data on the prevalence of tibial post fracture in VEPE inserts, the results presented in this study are consistent with available data from retrieval studies. VEPE could reduce component plastic deformation compared with HXLPE, especially in cases of malrotation between the femoral component and tibial insert. If not properly aligned, the AP impact force between the femoral component and tibial insert can lead to a cantilever effect at the base of the tibial insert and increase the risk of post fracture. When tibiofemoral rotation occurs, the contact force could lead to a bending moment and transversal torsion on the tibial post. In this study, a higher PEEQ was observed at the base of the tibial post in the fixed-bearing design, which was 0.21%, 0.48%, and 0.08% for the UHMWPE, HXLPE, and VEPE tibia inserts, respectively, when placed in malrotation. The VEPE material underwent considerably less plastic deformation at the base of the post than the HXLPE post (Figure 6). This also fits well with other findings<sup>31</sup> in which in vitro mechanical testing simulating clinically relevant conditions demonstrated

an improved fatigue strength over VEPE posts. There are concerns regarding using HXLPE in PS knee prostheses because of the high stress on the component during deep flexion angles, placing the tibial post at risk of permanent plastic deformation. Similarly, in cases of malrotation, the high contact force on the post may induce irreversible plastic deformation, particularly at the posterior edge of the tibial post and base of the post in fixed-bearing knees.

In addition to the material type, the design of the locking mechanism between the tibial insert and the metal-backed component could also influence knee performance. A retrieval study showed a statistical significance between the fixed-bearing Attune and press fit condylar (PFC) implants with regard to backside surface damage, which indicated the extent of damage was related to the implant design rather than the material.<sup>12</sup> The theoretical advantages of fixed-bearing or mobile-bearing designs are still controversial, although reduced wear and improved implant performance have been reported with mobile-bearing knees,<sup>51</sup> especially when malrotation occurs between the femoral component and tibial insert. In this current study, under the neutral contact condition, both the fixed-bearing (Figure 7a) and the mobile-bearing (Figure 7c) models showed strap-shaped contact contours on the posterior surface of the post. Under the malrotation contact condition, the fixed-bearing model showed a clear stress concentration at the posterior corner of the tibial post (Figure 7b), whereas the mobile-bearing model retained a strap-shaped contour (Figure 7d). These findings echo the theoretical advantages of mobile-bearing inserts, which are designed to lower stress concentrations on the post and produce less plastic deformation under malrotation. However, there are concerns related to greater backside wear in mobile-bearing knees because of the larger interface contact between the tibial insert and metallic baseplate.<sup>52,53</sup> Cone fracture<sup>54</sup> underneath the tibial insert is another failure mode seen in mobile designs but rarely found in fixed-bearing knees. Further investigation is required to understand whether novel biomaterials could reduce implant wear in TKA<sup>55</sup> or reduce the incidence of component breakage.

There are some limitations to this study that should be mentioned. Firstly, a worst-case condition for post-cam

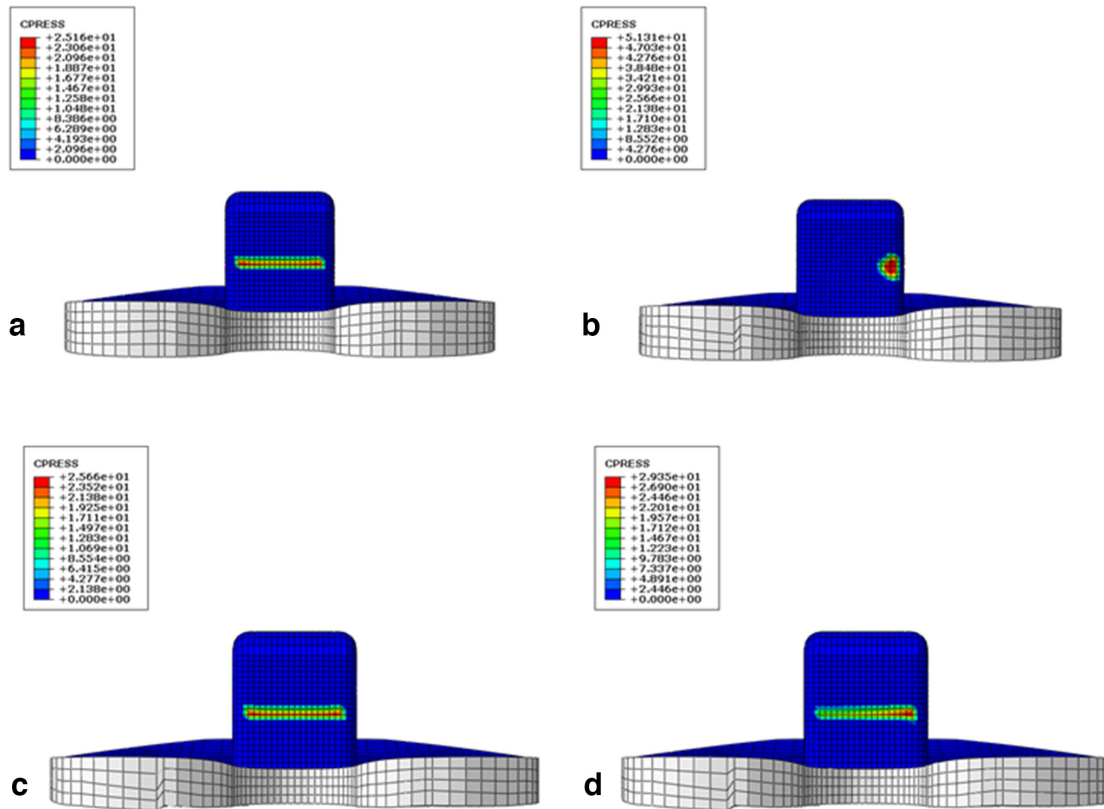


Fig. 7

Contact pattern of the post-cam contact surface in a) neutral contact of fixed-bearing, b) malrotation contact of fixed-bearing, c) neutral contact of mobile-bearing, and d) malrotation of mobile-bearing. Note: CPRESS indicates compression pressure.

engagement was simulated in this study at a flexion angle of  $120^\circ$ , and the tibial post was subjected to an anterior engagement force of 500 N by the femoral cam. However, the inherent soft tissue forces around the knee joint were not simulated. Secondly, only one design shape for the post-cam mechanism was analyzed for both the mobile-bearing and fixed-bearing models. Future studies may consider modifying the corner surrounding the tibial post to stress concentrations generated during engagement with the femoral cam. In addition, this study only considered a symmetric tibial plateau, but contemporary knees can use either a symmetrical or anatomical design, and the shape can play an important role in knee positioning and kinematics. Therefore, the results of this study represent the specific designs simulated and may not accurately reflect the properties of other knee prostheses. Finally, the presence of soft tissues such as the quadriceps, patellar tendon, and cruciate ligament could affect the actual values of tibiofemoral and patellofemoral contact stress, but these were not incorporated into the models in this study. A simplified model was used to eliminate the bias of complex loading conditions and concentrate on determining whether cross-linking or vitamin E stabilization could affect the stress on the post and its plastic behaviour. Aside from the above limitations, this

current study provides valuable information to clinicians when considering PS TKA implants.

In conclusion, the choice of material and design features of knee prostheses can have a considerable effect on the risk of permanent deformation of the tibial post. In comparison to HXLPE, using VEPE for the tibial insert can reduce plastics strains during post-cam engagement. The choice of material has a much less noticeable effect on mobile-bearing knees, which offer the advantage of reduced edge loading. When placed in malrotation, the stress on the tibial post in the mobile-bearing knees was 38% to 56% less than in the fixed-bearing model, and the mobile-bearing design was able to reduce the plastic strain by 335% to 434% at the corner of the tibial post. The results presented in this study provide orthopaedic surgeons with useful information when selecting a suitable material and design for PS knee arthroplasty.

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