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To,

The coordinator,

NAAC, Bengaluru.

Subject: Book/chapters published, and the papers published in the conference proceedings.

Reference: 3.3.3 - Number of books and chapters in edited volumes/books published and papers published in national/ international conference proceedings per teacher during year 2021-22.

Dear Sir/Madam,

The details of the books and chapters in edited volumes/books published and papers published in national/ international conference proceedings per teacher during year 2021-22 are attached herewith this letter.

J.S.P.M. Narhe Technical Campus Narhe, Pune-41.

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Enclosure-

1. Sample paper/book

Finite Element Analysis of Knee Joint with Special Emphasis on Patellar Implant

M. A. Kumbhalkar, D. T. Rangari, R. D. Pawar, R. A. Phadtare, K. R. Raut, and A. N. Nagre

Abstract Patella is supporting part of knee and also guide for quadriceps or patellar tendon. Patellar implant is used for proper functioning of patella after injury. For implant, it is required to cut injured portion of host patella and keep remaining part minimum up to 12–14 mm and overstuffing of 2 mm to prevent patellar fractures. The patellar implant makers provide only 8-mm-thick implant to maintain original patellar thickness which is difficult to achieve especially in patients with host bone thickness less than 20 mm. Hence, there is need to analyze for reduction in thickness of patellar implant from 8 to 6 mm for perfect engagement with adequate residual bone. The critical force analysis on host patella with tendon is carried out for quadriceps force, patellofemoral force, and patellar tendon force using analytical and finite element method. Two cases are considered for the force and stress analysis of patella, and the comparison of various implant thicknesses is discussed.

Keywords Patella · Knee joint · Finite element analysis · Patellar implant (button) · Patellofemoral force

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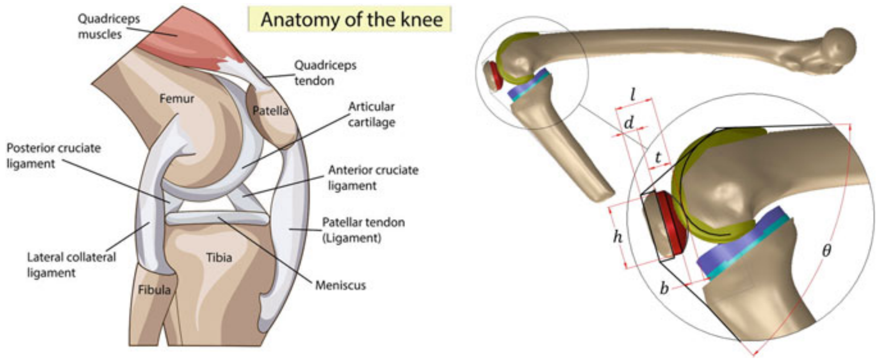


Fig. 1 Anatomy of knee and biomechanical model of knee joint with patellar implant [1]

1 Introduction

The rotary motion of knee joint is based on the successful movement between femur-tibia and patella. The tendons attached at femur and tibia cover and compress patella toward femur while rotary motion of knee joint. Due to compressive force or frictional force between femur and patella, the patella may damage and therefore it is required to provide implant over it. Figure 1 shows biomechanical model of knee joint with patella implant.

For the possible movement of knee joint, it is necessary to maintain patellar thickness after knee arthroplasty [1]. The host patella thickness is required to maintain up to 12–14 mm during knee arthroplasty for the patellar thickness less than 20 mm, and standard implant of 8 mm is used to recover original patellar thickness [1–3]. Sometimes intraoperative patellar thickness increases due to 8 mm standard patella implant for the person having original patellar thickness less than 20 mm. If the original thickness of patella is not maintained by applying patellar implant, then the knee cannot bend at that extent and pain will occur during walking, climbing, or running. Hence, for perfect meeting of original patella thickness after operation, it is required to use patella implant having thickness less than 8 mm. This research aim is to check effect on patellar implant by reducing its thickness from 8 mm to 6 mm at various flexion angles.

2 Mathematical Formulation and Force Analysis

As per the experimental study done in various literature papers, it is observed that the tendons attached with tibia and femur will stretch while motion due to which a compressive force is acted on patella. The magnitude of forces and direction acting on leg vary with the knee flexion angle and weight. Two lateral forces i.e., patellar tendon force and quadriceps force are acting on patella which acts patellofemoral reactive force toward contact point of patella and femur. Patellar tendon force acting between the patella and tibia, patella quadriceps force acting between patella and femur, and patella femoral force acting on patella as a compressive because of the forward moment are locked due to the quadriceps and ligament. A free body diagram for forces acting on patella is shown in Fig. 2.

The patellofemoral force is acting on patella at various knee flexion angles at different conditions of human movement. The full body weight of human is acting on knee joint at straight condition which is fixed at end of tibia, but while walking, climbing, or running, the moment acts at joint which distributes body weight into different forces. The free body diagram of patellofemoral joint with force distribution and joint flexion moment is shown in Fig. 3 [4, 5]. As patella changes its own position according to flexion angle, forces acting on patella change according to the flexion angle. The main three forces acting on patella, i.e., quadriceps force, patella tendon force, and patellofemoral forces are derived by considering various angular movements at joint.

Also other two elements are plotted as free body diagrams, i.e., for patellar tendon and for quadriceps tendon where the forces, angles, and the different lengths are shown. For force analysis on patella, specific geometric form is not considered but the specific thickness of patella is considered during finite element analysis. Fekete et al. [4] considered dimensionless parameters to simplify the results of relationship between patella and tendon and are given in Table 1.

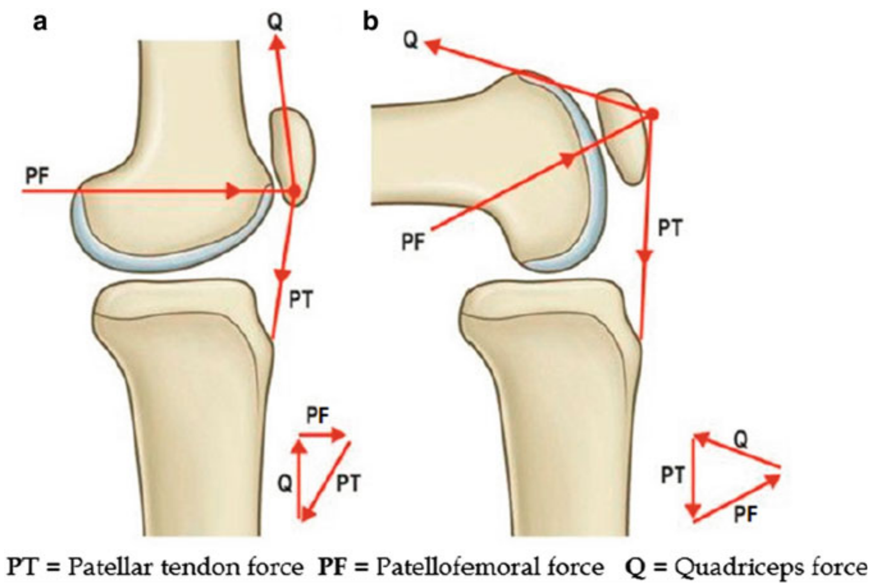


Fig. 2 Forces acting on patella [13]

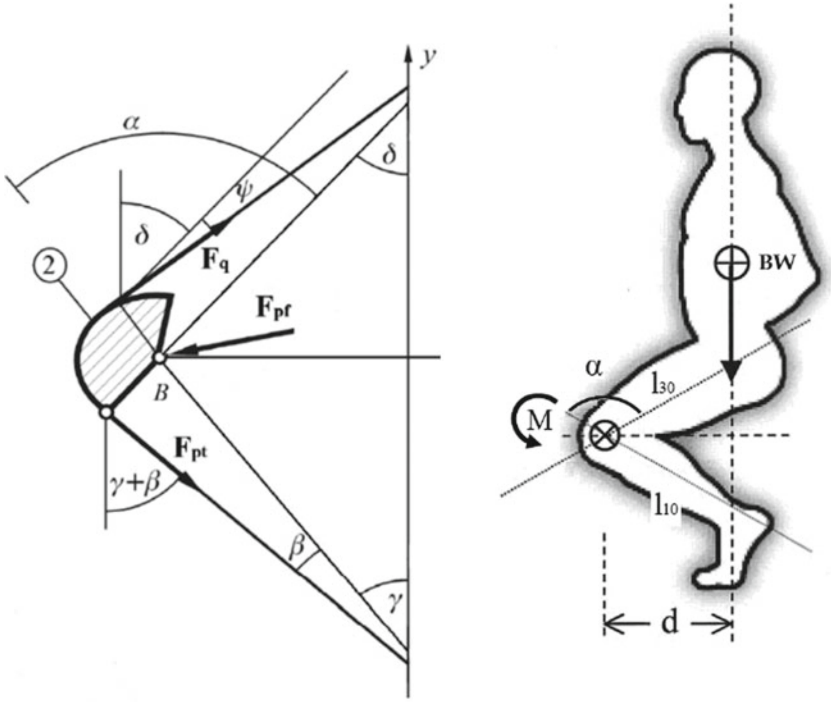


Fig. 3 Free body diagram of patellofemoral joint and joint flexion moment by Fekete et al. [4] and Mason et al. [5]

Table 1 Dimensionless parameter [4]

Description	Formulas
Dimensionless, intersected tibia length function	$\lambda_1 = {}^{l_1}/_{l_{10}}$
Dimensionless, intersected femur length function	$\lambda_3 = {}^{l_3}/_{l_{30}}$
Dimensionless length patella tendon	$\lambda_p = {}^{l_p}/_{l_{10}}$
Dimensionless thickness of shin	$\lambda_t = {}^{l_t}/_{l_{10}}$
Dimensionless thickness of thigh	$\lambda_f = {}^{l_f}/_{l_{30}}$

2.1 Patellar Tendon Force

From Fig. 3, free body diagram of tibia and femur gets separated to find its force distribution. Figure 4 illustrates the forces acting on tibia due to patellar tendon and body weight. The lengths denoted in free body diagram as length of tibia (l_{10}), length between line of action of tibia and body weight (l_1), length of patellar tendon (l_p), length from axis of tibia, and tibia tuberosity (l_t). Taking the moment at point *B*, by fixing the point *B*.

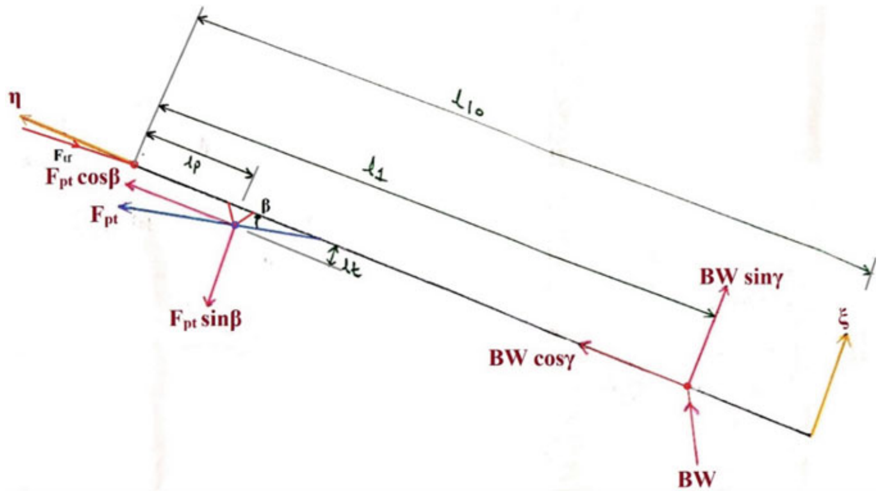


Fig. 4 Forces acting on tibia and patellar tendon

$$
\begin{aligned}
&\sum \mathrm{MB} = 0\\
&0 = -l_{\mathrm{p}} \cdot f_{\mathrm{pt}} \cdot \sin\beta - l_{\mathrm{t}} \cdot f_{\mathrm{pt}} \cdot \cos\beta + l_1 \mathrm{BW} \cdot \sin\gamma\\
&l_1 \mathrm{BW} \cdot \sin\gamma = l_{\mathrm{p}} \cdot f_{\mathrm{pt}} \cdot \sin\beta + l_{\mathrm{t}} \cdot f_{\mathrm{pt}} \cdot \cos\beta\\
&l_1 \mathrm{BW} \cdot \sin\gamma = f_{\mathrm{pt}}\left(l_{\mathrm{p}} \cdot \sin\beta + l_{\mathrm{t}} \cdot \cos\beta\right)\\
&f_{\mathrm{pt}} = \mathrm{BW} \cdot \frac{l_{\mathrm{p}} \cdot \sin\gamma}{l_{\mathrm{p}} \cdot \sin\beta + l_{\mathrm{t}} \cdot \cos\beta}
\end{aligned}
\tag{1}
$$

Rearranging Eq. (1)

$$
\frac{f_{\mathrm{pt}}}{\mathrm{BW}} = \frac{l_{\mathrm{p}} \cdot \sin\gamma}{l_{\mathrm{p}} \cdot \sin\beta + l_{\mathrm{t}} \cdot \cos\beta} \tag{2}
$$

$$
\frac{f_{\mathrm{pt}}}{\mathrm{BW}} = \frac{\lambda_1 \cdot \sin\gamma}{\lambda_{\mathrm{p}} \cdot \sin\beta + \lambda_t \cdot \cos\beta} \tag{3}
$$

2.2 Quadriceps Force

Figure 5 illustrates the forces acting on femur due to quadriceps tendon and body weight. The parameters denoted in free body diagram are length of femur (l_{30}), length between line of action of tibia and body weight (l_3), angle between the axis of femur and quadriceps force (ψ), and angle between the axis of femur and line of action of body weight (δ). Taking moment at point B, by fixing the point B.

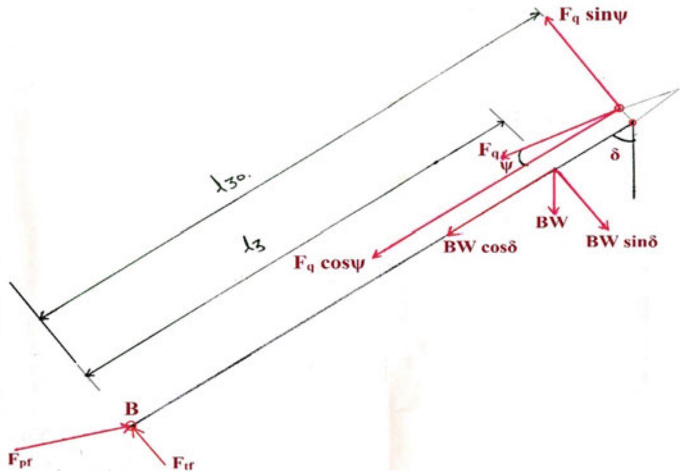


Fig. 5 Forces acting on femur

$$
\begin{aligned}
&\sum \mathrm{Mb} = 0 \\
&0 = l_{\mathrm{f}} \cdot f_{\mathrm{q}} \cdot \cos\psi + l_{30} f_{\mathrm{q}} \cdot \sin\psi - l_3 \mathrm{BW} \cdot \sin\delta \\
&\delta = \alpha - \gamma \\
&\psi = 0 \text{ Assumption} \\
&l_3 \mathrm{BW} \cdot \sin\delta = l_{\mathrm{f}} \cdot f_{\mathrm{q}} \cdot \cos\psi + l_{30} f_{\mathrm{q}} \cdot \sin\psi \\
&\mathrm{BW} = \frac{f_{\mathrm{q}}(l_{\mathrm{f}} \cdot \cos\psi + l_{30} \cdot \sin\psi)}{l_3 \cdot \sin\delta} \\
&\frac{f_{\mathrm{q}}}{\mathrm{BW}} = \frac{l_3 \cdot \sin\delta}{l_f \cdot \cos\psi + l_{30} \cdot \sin\psi} \\
&\frac{f_{\mathrm{q}}}{\mathrm{BW}} = \frac{\lambda_3 \sin(\alpha - \gamma)}{\lambda_{\mathrm{f}}}
\end{aligned}
\tag{4}
$$

2.3 *Patellofemoral Force* ($\mathbf{F}_{pf}$)

It is reaction force acting on femur through patella and ligament forces that is quadriceps and tendon forces which is obtained from F_{q} and F_{pt} forces by parallelogram theorem of resultant forces.

By using equilibrium equation,

$$\sum fy = 0$$

$$\sum fx = 0$$
$$0 = f_q \sin\delta - f_{pt}\sin(\gamma+\beta) + F_{pfx}$$
$$F_{pfx} = -f_q \sin\delta - f_{pt}\sin(\gamma+\beta)$$
$$0 = f_q \cos\delta - f_{pt}\cos(\gamma-\beta) + F_{pfy}$$
$$F_{pfy} = -F_q \cos\delta + F_{pt}\cos(\gamma+\beta)$$

Resultant of two concurrent forces (Law of Parallelogram)

$$\frac{f_{pt}}{\mathrm{BW}} = \frac{\sqrt{f_{pfx}^2 + f_{pfy}^2}}{\mathrm{BW}} = \frac{\sqrt{f_q^2 + f_{pt}^2 - 2f_q f_{pt}\cos(\beta+\delta+\gamma)}}{\mathrm{BW}}$$
$$\frac{f_{pt}}{\mathrm{BW}} = \frac{\sqrt{f_q^2 + f_{pt}^2 - 2f_q \cdot f_{pt}\cos(\beta+\delta+\gamma)}}{\mathrm{BW}} \tag{5}$$

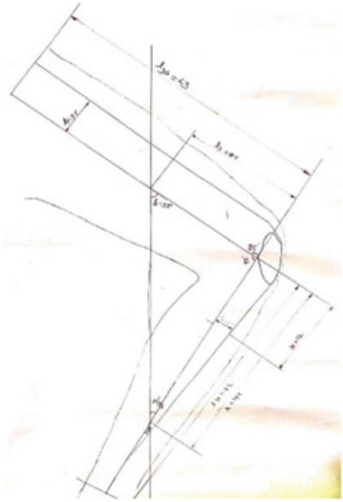
2.4 Case Study

Two cases having different body weight and height are considered to find patellar tendon force, quadriceps force, and patellofemoral force as per the formulae derived in Sects. 2.1, 2.2, and 2.3 for various flexion angles. The manual drawings of both cases having weight 74 kg and 61 kg and height 5.9 ft. and 5.5 ft., respectively, are drawn to plot various lengths and angle for calculation of forces. As the tibia and femur length vary with respect to height and weight, these two different cases are considered for force calculation. The manual drawings of two cases are shown in Fig. 6, and all parameters like length, angle, and dimensionless values are shown in Table 2.

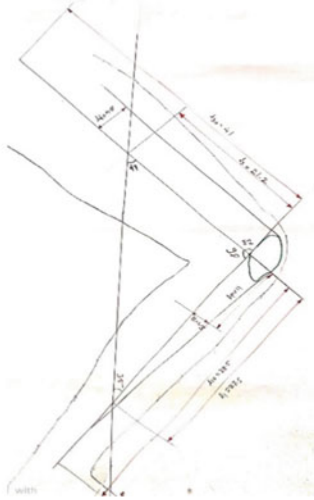
The mathematical formulation represents forces acted on knee joint at quasi-static condition, and it is exposed to high magnitude of compression force during walking, climbing, and running condition [6, 7]. As per literature [8–10], the force acting on knee joint during walking is 1.3 times body weight, during climbing stair is 3.3 times body weight, and during knee bends is 7.8 times body weight. The compression force and area of articular contact increase with knee flexion and are max between 60° and 90° [11, 12].

3 Finite Element Analysis of Patella

In this paper, finite element analysis technique is used for stress analysis of knee joint with special emphasis on patellar implant with varying thickness from 6 to 8 mm. For finite element analysis of patella, a critical CAD model of knee joint



(a) CASE-I: Person having weight 73 kg and height 5.9 feet



(b) CASE-I: Person having weight 61 kg and height 5.5 feet

Fig. 6 Manual drawing of two different case study for force calculation

Table 2 Parameters of two different cases

Sr. No.	Parameter	CASE-I	CASE-II
1.	BW	73 kg	61 kg
2.	L_1	29.5 cm	27.5 cm
3.	L_3	18.5 cm	21.2 cm
4.	L_f	5.5 cm	4.5 cm
5.	L_p	12 cm	11 cm
6.	L_t	2.7 cm	2.3 cm
7.	L_{10}	42 cm	38.5 cm
8.	L_{30}	43 cm	41 cm
9.	λ_3	0.4302	0.517
10.	λ_1	0.7023	0.714
11.	λ_p	0.2857	0.285
12.	λ_t	0.0642	0.059
13.	λ_f	0.1279	0.109
14.	γ	30 º	35º
15.	δ	55º	47º
16.	A	85º	82º
17.	B	10º	8º

with patella and tendon is prepared in solid modeling software CATIA and its stp file is imported in FEA tool, ANSYS. At first, the analytical patellofemoral force is verified with ANSYS result by applying boundary condition as patella tendon force and quadriceps force at the end of tendon and is fixed and at femur end. This reaction force is exactly matched by analytical and finite element method, and the results are shown in Table 3. All three forces are also calculated for different conditions such as walking, climbing, and running as per the ratio discussed in 2.4, and patellofemoral force is verified in ANSYS at different knee flexion angles.

The research aim is to replace standard available patellar implant of 8 mm thickness to minimum 6 mm thickness for the host patella size of less than 20 mm thickness. Hence, the stress analysis is carried out on host patella first and checks stresses induced at point of contact of patella and femur. Then, the stress analysis is carried out on patella with implant for different thicknesses. For stress analysis, direct patellofemoral force is applied on upper surface of patella and femur is fixed at end. The patellar implant with varying thickness is shown in Fig. 7, stress analysis result on contact point of patella and femur is shown in Fig. 8, and stresses on patella are

Table 3 Force acting on patella for two different cases and at different flexion angles using analytical and finite element method

Condition	Case	Case-I			Case-II		
	Flexion angle	65°	85°	110°	65°	85°	110°
Static	F_{pt}	2427.42	2289.7	4460.6	2894.90	2539.36	3976.63
	F_q	1714.39	2026.1	3022.5	2207.16	2109.85	3021.42
	F_{pf}	2390.31	3186.9	6358.2	3015.2	3301.48	5545.8
	F_{pf} (FEA)	2390.3	3186.9	6358.3	3015.2	3301.5	5545.8
Walking	F_{pt}	3186	2983.7	5850.5	3763.3	3301.1	5169.5
	F_q	2242.9	2652.8	3958.5	2869.3	2742.8	3927.8
	F_{pf}	3134.8	4161.6	8335.1	3919.5	4291.8	7209.5
	F_{pf} (FEA)	3134.9	4161.7	8335	3919.7	4291.9	7209.5
Climbing	F_{pt}	8087.6	7574.1	14851.3	9553.2	8379.9	13122.9
	F_q	5693.6	6733.9	10048.5	7283.6	6962.5	9970.60
	F_{pf}	7957.65	10564	21158.2	9950.3	10894.9	18301.1
	F_{pf} (FEA)	7957.8	10564	21158	9950.2	10895	18301
Running	F_{pt}	19116.2	17902.4	35103.2	22580.2	19807	31017.71
	F_q	13457.6	15916.8	23750.9	17215.8	16456.8	23567.12
	F_{pf}	18808.9	24970.2	50010.5	23518.7	25751.5	43257.32
	F_{pf} (FEA)	18,809	24,970	50,010	23,519	25,752	43,257

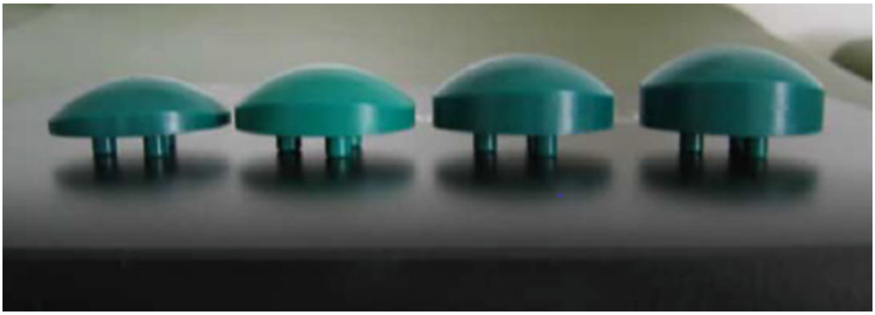


Fig. 7 Patellar implant (button) with varying thickness [3]

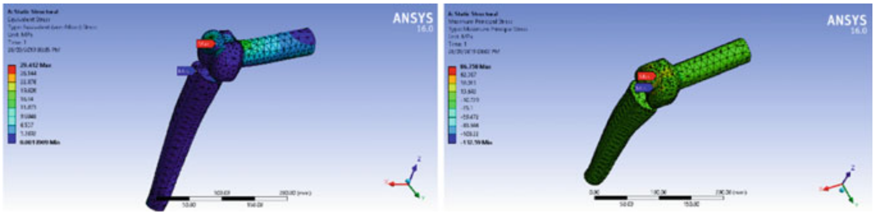


Fig. 8 Equivalent stress and maximum principal stress acting on contact of patella and femur at knee joint

shown in Fig. 9.

Stress analysis on host patella with patellar implant is also carried out using finite element analysis. The host patella is cut from interior side and keeps 12 mm thickness of posterior part of patella where 8 mm implant is fitted. The maximum principal stress and equivalent stress on patellar implant are shown in Fig. 10, and the results are given in Table 4 for flexion angle of 110° and 65°.

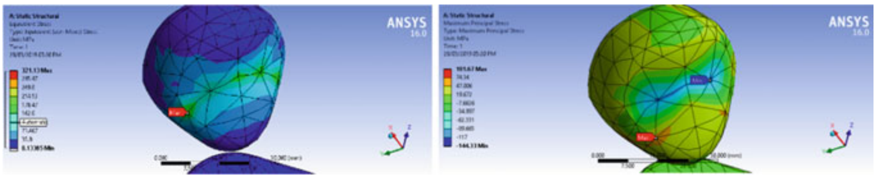


Fig. 9 Equivalent stress and maximum principal stress acting on patella

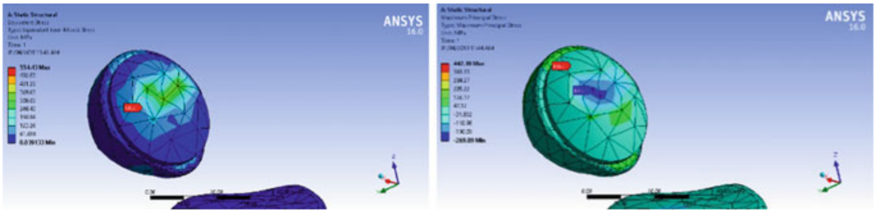


Fig. 10 Equivalent stress and maximum principal stress on patellar implant using finite element analysis

Table 4 Maximum principal stress and equivalent stress result for host patella and patellar implant for various condition at 110° and 65° flexion angle

Angles		65°			110°		
Condition	Stresses	Host patella	8 mm implant	6 mm implant	Host patella	8 mm implant	6 mm implant
Static	Max principle stress	4.146	14.115	8.109	12.926	56.241	53.608
	Equivalent stress (von misses)	8.8343	24.579	22.4	40.827	70.487	69.158
Walking	Max principle stress	5.438	18.515	10.637	16.946	73.729	70.277
	Equivalent stress (von misses)	11.58	32.24	29.38	53.522	92.405	90.662
Climbing	Max principle stress	13.804	46.998	27.001	43.016	187.16	178.39
	Equivalent stress (von misses)	29.412	81.84	74.58	135.86	234.56	230.14
Running	Max principle stress	32.629	111.08	63.817	101.67	442.38	421.66
	Equivalent stress (von misses)	69.521	193.43	176.29	321.13	554.43	543.97

4 Results Validation

Dr. Anoop Jhurani et al. [2] carried out an experimentation on 54 female patient knees to restore the native patellar thickness less than 20 mm. This experimentation has been observed for the period of two year which proved that the 6.2 mm thickness plastic patellar button can be used instead of 8 mm thickness to restore native patellar thickness less than 20 mm. A vernier caliper was used to measure and restore intraoperative patellar thickness during total knee arthroplasty as shown in Fig. 11.

Shelburne et al. [8] and van Eijden et al. [13] reported critical force analysis to estimate the quadriceps force, patello tendon force, and patellofemoral force at different gait cycle and flexion angles shown in Fig. 12. At maximum extension of patellofemoral joint quadriceps force is obtained as 2000 N, whereas the maximum force is obtained as 8000 N at 75° flexion angle. Patello tendon force becomes progressively smaller than quadriceps force at large flexion angles and reaches a maximum of 5000 N at 60° flexion angle. At all flexion angles, a patellofemoral force is smaller than quadriceps force [13].

Also, the forces acting on patella for two different cases during walking (Fig. 13) are revealed that the quadriceps force produced for maximal extension is 2243 N at 65° flexion angle and maximum patellofemoral force is 8335 N at 110° flexion angle. The forces acting in the literature paper nearly equal the forces acting on the patella for the cases considered in research.

A finite element analysis has been carried out to find stresses in patellofemoral cartilage due to internal and external rotations of the femur influencing contact areas, pressures, and cartilage stress distributions [14]. Besier et al. [14] analyzed a finite element mesh model of patellofemoral joint as shown in Fig. 14 which illustrated the element contact between quadriceps and patellar tendon and also within the femoral and patellar cartilage. The simple joint stresses due to contact area and stresses in patellar cartilage shown in Fig. 14 by finite element method revealed that the peak

Fig. 11 Intraoperative measurement of patellar thickness using vernier caliper [2]

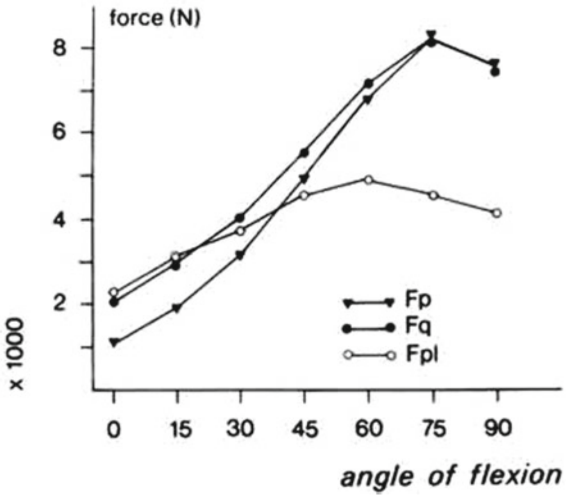


Fig. 12 Forces acting on patella versus flexion angle [8, 13]

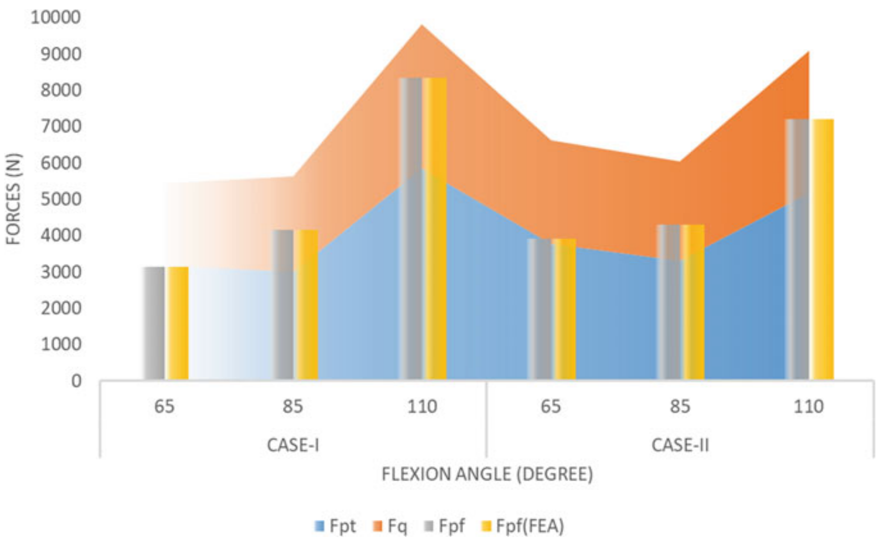


Fig. 13 Force acting on patella during walking for two different cases and at various flexion angles

stress values is obtained as 3.5 MPa at static or neutral condition for 15° internal and external femoral rotation which is lower than mean stress values.

A finite element analysis of patellar knee joint also revealed that the maximum principal stress is obtained as 4 MPa at static condition for host patella which is increased to 8 MPa for 6 mm patellar implant at 65° flexion angle. The stresses in patella are increased for different conditions, i.e., walking, climbing, and running.

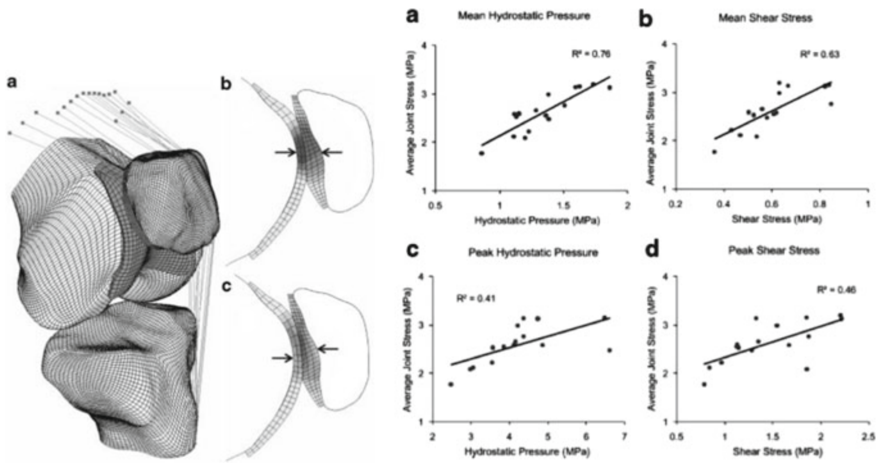


Fig. 14 Finite element mesh of the patellofemoral joint and correlations between simple measures of joint stress and stresses estimated in the patellar cartilage by the finite element method [14]

From finite element analysis, it is observed that the stress in 6.2 mm patellar implant is less than 8 mm patellar implant for every condition as shown in Fig. 15.

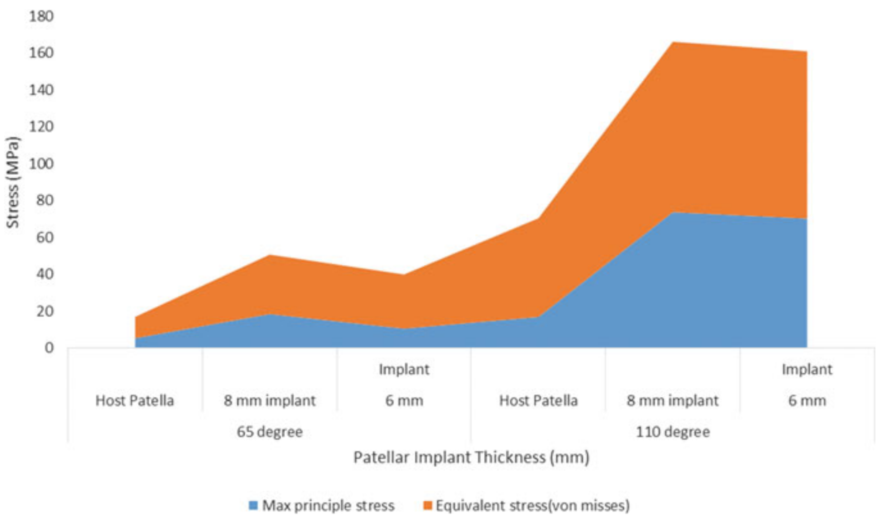


Fig. 15 Maximum principal stress and equivalent stress for host patella and patellar implant during walking

5 Conclusion

The mathematical formulation for biomechanical model of patellar knee joint is carried out to find forces acting on patella using free body diagram. The patellar tendon force, quadriceps force, and patellofemoral forces are calculated for two different cases of 61 and 73 kg person at various flexion angles, i.e., at 65°, 85°, and 110°. The analytical patellofemoral reaction forces are verified using finite element analysis which is obtained by applying patellar tendon force and quadriceps force at the end. The stress analysis on host patella and patellar implant with 8 mm and 6 mm thickness is carried out which reveals that the stress increases for 8 mm patellar implant than host patella and the stress reduces for 6 mm patellar implant than 8 mm. From the results, it can be concluded that the 6 mm patellar implant can be used instead of 8 mm implant during intraoperative arthroplasty for patella thickness less than 20 mm.

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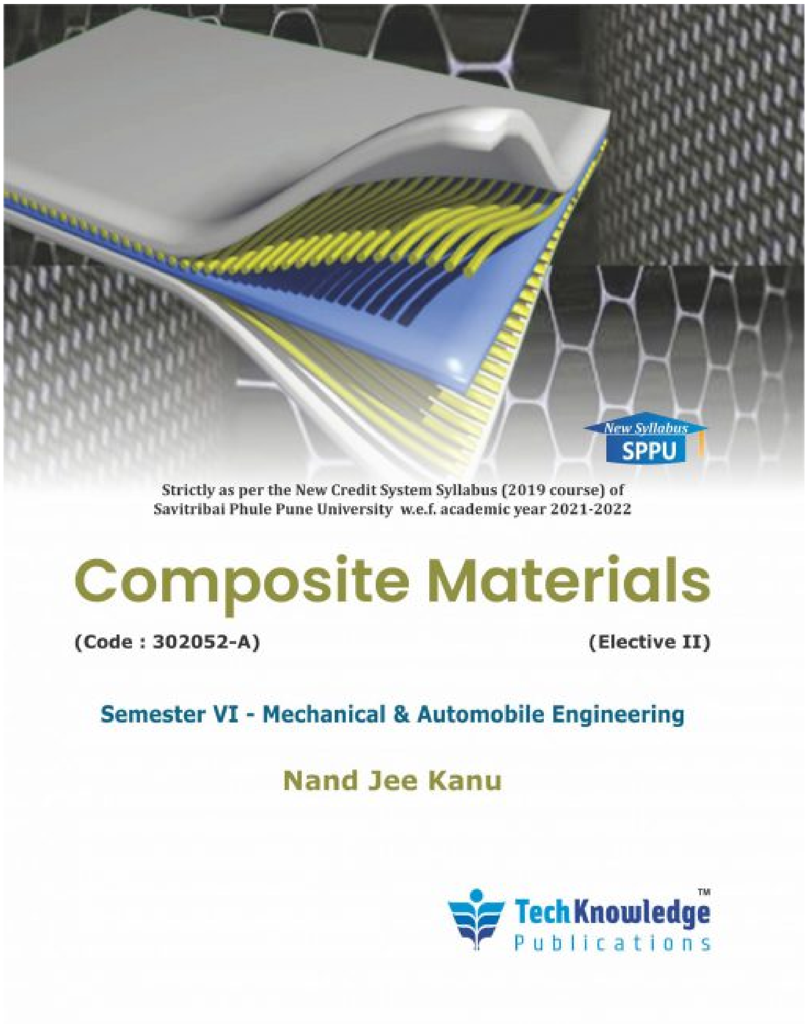

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