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An insight into biomechanical study for replacement of knee joint

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ABSTRACT

A knee joint sustains entire body load and there is surface contact between femur-patella and femur-tibia bounded with quadriceps muscles. An injury in knee joint may occur due to osteoarthritis disease which causes wearing between surfaces and also due to accident which causes muscle breakage, patella failure, tibiofemoral failure. The methodology involves an analytical approach using applied mechanics, biomedical and mechanical experimentation and validation with finite element analysis. The paper discusses a study on different methodologies used for replacement in tibiofemoral and patellofemoral component of knee joint. The methodologies are mainly playing an important role in various movements such as walking, running, jumping, climbing at various flexion, extension and squat position. A computer aided design tool is used and discussed to prepare exact shape of knee implant model for smooth performance at all conditions.

Selection and peer-review under responsibility of the scientific committee of the 3rd International Conference on Advances in Mechanical Engineering and Nanotechnology.

1. Introduction

Biomechanics means the study, using mechanical methods, of the structure, function and movement of the human body parts, from organisms, cells, and cells at all stages. Biomechanics is a biophysics industry. The articulation of the knee is flipped to the thigh bone. Muscles of Quadriceps under the knee are bound. It is the important and crucial joint in the physical body. The knee may be a modified hinge joint, which allows flexion and extension also as slight internal and external rotation. The knee is susceptible to injury and to the event of osteoarthritis. Knee joint have two compounds named as tibiofemoral and patellofemoral components. It plays an important role in movement associated with carrying the weight in horizontal (running and walking) and vertical (jumping) directions. At birth, the kneecap is formed simply by cartilage, which is classified between 3 and 5 years [1,2].

Different forces acting on the knee and excessive ligament pressure due to overload are exerted at several actions, which affects knee function due to injuries such as ligament rupture. The two different forces which act on the knee joint are static and dynamic forces. Static strength is used if the body rests or not in movement, while the Dynamic force is moving or accelerating when the body is moving. The knee joint can be examined with the help of the ANSYS software and other forces may be applied to the knee by produces a two and three-dimensional model for the CAD software. The sustainability of the knee bones helps to know this [3,4].

1.1. Knee joint

The knee joint is nothing but a synovial joint. It allows for flexion and extension (and a small degree of medial and lateral rotation). It is the most complex joint in a human body. The knee provides mobility and support during various activities. It also supports during weight bearing and provides mobility during non-weight bearing. Involved with almost and functional activity of the lower extremity. It is formed by joining between the patella, femur and tibia as shown in Fig. 1. The thigh bone (Femur) the shin bone (Tibia) and the kneecap (Patella) articulate through tibiofemoral and patellofemoral joints as shown in Fig. 2. These bones are covered with an extremely hard and smooth articular cartilage designed to reduce frictional forces. The patella is located in a tincture called the intercondylar groove.

The knee is tibiofemoral and patellofemoral with two articulations. The surfaces of the joints are covered with cartilage hyaline. In one joint cavity they are enclosed. The tibiofemoral joint is a synovial articulation that connects the remote femur to the tibia. It is the main component that can carry weight in the knee joint.

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Nomenclature

Symbol	Description	Unit
BW	Body Weight	kg
λ_3	Dimensionless, intersected femur length function	–
λ_1	Dimensionless, intersected tibia length function	–
λ_p	Dimensionless length of patellar tendon	–
λ_t	Dimensionless thickness of shin	–
λ_f	Dimensionless thickness of thigh	–
F_{pt}	Patellar tendon force	N
F_{pf}	Patellofemoral force	N
F_q	Quadriceps force	N
α	Angle between axis of tibia and femur	Degree
β	Angle between the axis of tibia and the patellar tendon	Degree
γ	Angle between the axis of tibia and the line of action of BW	Degree
δ	Angle between the axis of femur and the line of action of BW	Degree

The frontal aspect of distal femur with patella is patellofemoral. Patellofemoral joint can be inserted directly over the knee by insert the tendon of the femoris quadriceps (knee extender), which increases muscle effectiveness.

1.2. Biomechanical role in knee joint

The knee joint enables the movement to accommodate 12 different terrains, with (a) minimum muscle energy needs and (b) stability. Forces produced during the daily activity are transmitted, absorbed and distributed. It is a joint hinge in which the bones are only flexed or extended along one axis as shown in Fig. 3. The degree of knee freedom is 6 where three are rotating and three are translative. The functional range of motion at the knee is given in table 1.

An insight details has been carried out for medical and mechanical treatment over knee joint in context to the present work is presented in classified manner (Fig. 4). The purpose of this study is to show and summarize the important aspects of knee joint failure or replacement categorized as biomedical research, an application of mechanics approach, mechanical experimentation and computer aided engineering. The time frame for this literature review is considered up to 2020.

The researchers or medical officers worked over the replacement in knee joint based on the injury occurred in tibiofemoral or patellofemoral joint. Most existing TKA implants have been developed to suit the Western Population knee anatomy. Studies show that the knee morphology between the Asian and Western people is markedly different. Many researchers have done case studies for investigation of injuries and also designed various implants with the help of modern software and machineries. A detail survey regarding replacement in knee joint which includes tibiofemoral and patellofemoral joint is discussed here.

Several case studies were carried out for the study of Indian arthritic knee anthropometry through three-dimensional knee modeling and morphologically tested against commercial TKA implants. Mediolateral width (ML), anteroposterior width (AP), and the tibia and femur aspect ratio were included. Indian women had lower tibia and femur dimensions than the Indian men and both of them had lower aspects ratio to the West. The morphological flaw between implants and Indian arthritic knees has been shown by our research. This may cause Western implants to be inconvenient in Indian patients implanting [8].

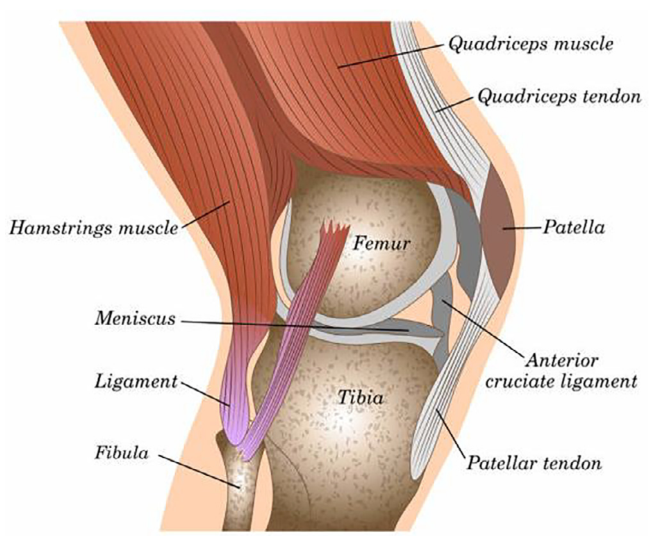

Fig. 1. Muscles and bones in knee joint [5].

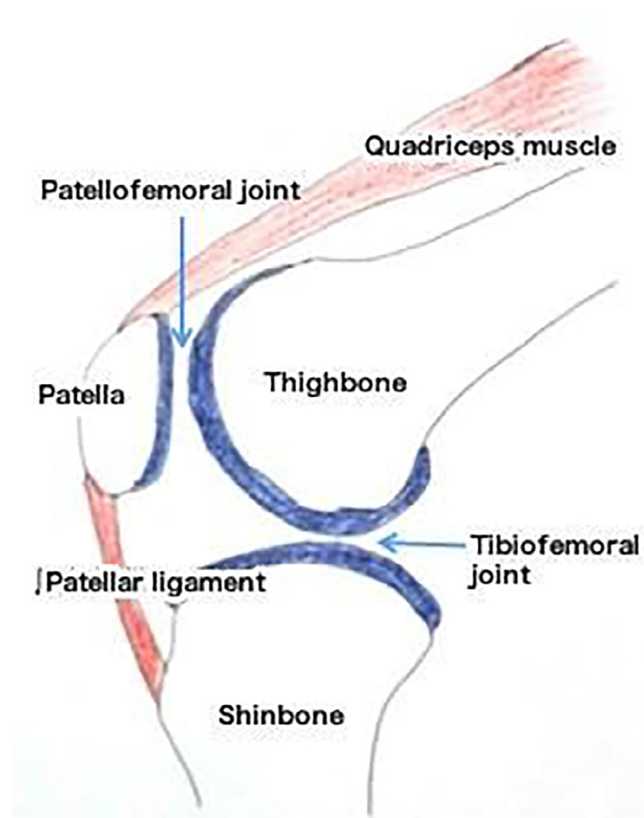

Fig. 2. Tibiofemoral and patellofemoral joint [6].

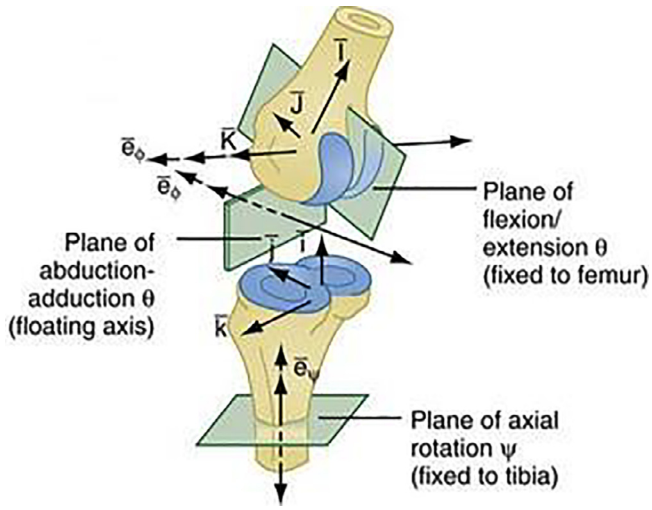

Fig. 3. Plane of action in knee joint [7].

Table 1
. Functional range of motion (ROM) at the knee [2].

Action	Knee flexion
Normal gait/level surfaces	60°
Stair climbing	80°
Sitting/rising from most chairs	90°
Sitting/rising from toilet seat	115°
Advanced function	>115°

The author presents an insight survey about various methodologies used for the analysis over knee joint and also to prepare its implant. The motivation of the paper is the dynamic analysis carried out by the researcher on knee joint at various condition to obtain the exact results for its damage so that implant can be prepare with that shape and strength which will work like an original knee joint. The methodologies used for dynamic analysis are very important and discussed in the next section.

2. Medical research

The typical knee replacement is inserted at the femoral ends with metal femoral element and the tibia is inserted with a metal tibial part and plastic insert. The cyclic loads caused by fatigue failure in the knee joint prosthesis and sliding between insert and femoral component improve the wear process in plastic insert during the walking process. Modified Archard's laws are utilized to estimate wear, taking into consideration cross-shear wear motions. These findings are used to measure the life cycle of the prothesis. The approach to fatigue phenomena is based on the Finite Element Method (FEM), which provides knee prosthesis life expectancy with a diverse combination of materials and the combined effects of wear and fatigue that gives knee prosthesis life expectancy [9].

Anoop Jhurani et al. [10] carried experiment on patient of osteoporosis. They replaced the patella of patient and keep them in observation for any future problem. They got a result 6.2 mm patellar buttons option is useful for restoring preoperative thick-

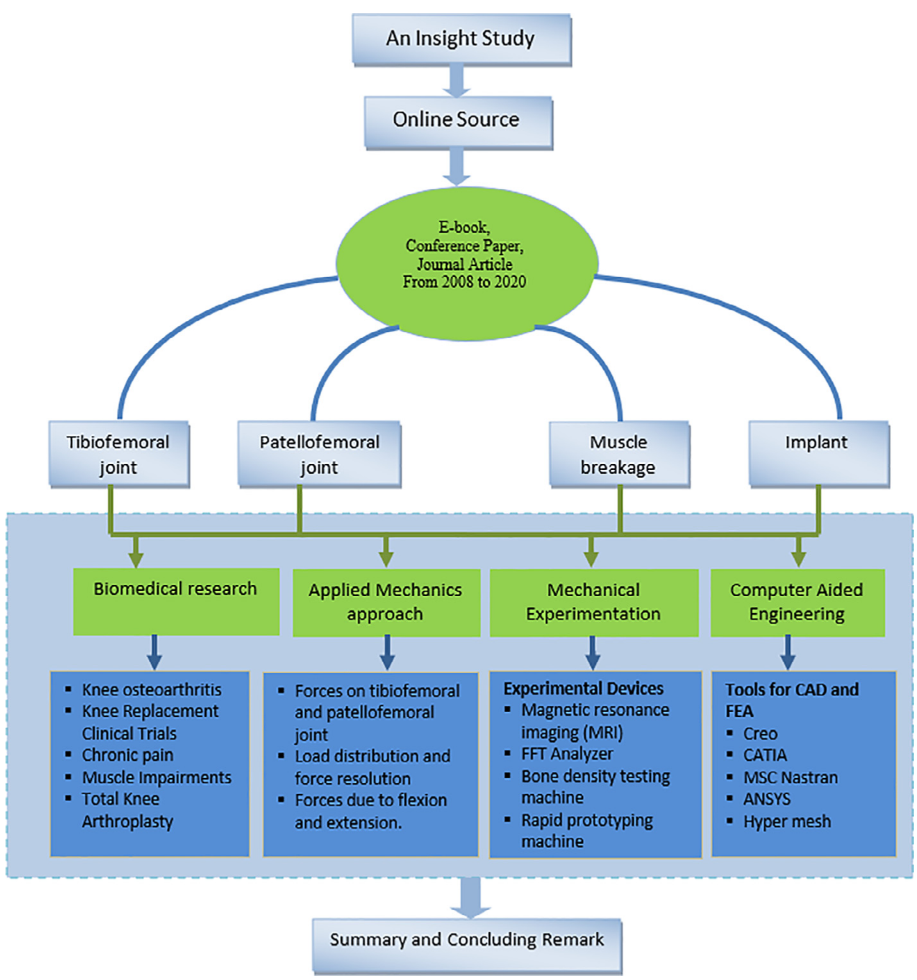

Fig. 4. Methodology for literature review.

ness in patients with a patellar thickness less than 20 mm. Its use did not lead to plastic fracture, button wear or failure.

Followed by total knee arthroplasty (TKA) in Balgrist University Hospital in July 2016 to March 2017, the effect of preoperative physiotherapy is assessed on the functional, subjective and socio-economic parameters with 20 patients scheduled for use of TKA. The IG has performed five to nine PT sessions including neuromuscular proprioceptive facilitation, endurance training and personally specified interventions three to four weeks before the surgery. The process was finished. Overall CG cost was 21.4 per 100, more analgesics were taken and pain levels preoperatively exceeded IG [11], respectively.

Valgus stress angle (SA), varus SA and varus valgus SA (VVD were compared when predicted the degree of varus medial release during total knee arthroplasty (TKA). Around 108 TKAs (78 patients) were divided into three medial releases retrospectively by the degree of primary arthritis with a varus knee deformation (group A, mild release; group B, moderate release; and group C, severe release). There was a marked disparity between the angles of valgus in groups A and B and A to group C, but not in group B to group C. The VVD was not substantially different in all inter-group measurements, but expected media communications were more beneficial [12]. A clinical image of a meta-diaphysical junction intraoperative measurement that shows the level up until midpoint is shown in Fig. 5.

No drain has gained popularity, despite the long history of drainage usage in total arthroplasty (TKA). The aim was to investigate if the drainage is linked to the duration of hospital stay. A total of 166 unilateral TKAs were conducted retrospectively in 135 patients with osteoarthritis. Hospital stays were smaller than drains (25.2 ± 3.7 days) in no drains (21.7 ± 4.8 days). Long hospital stays have linked another generation, drainage and comorbidity cases. TKA without drain, as shown in the report, is medically and economically effective [13].

Villonodular pigmented synovitis (PVNS) is a rare, locally aggressive benign condition. It can damage the soft tissue and bone surrounding, causing the joint and limb to lose functionality. The knee is the most affected joint (range between 28% and 70%), but it is not common to see an involvement of the bone [14].

The efficacy and safety of early operations of the patients with arthroscopic knee surgery, oral meloxicam and post-operative treatment, VAS, global patient assessment (PGA) and rescue consumption, pain score and severity, Analgesia (pethidine) and adverse effects were evaluated during preoperative operations. The IKDC, the Knee Range of Motion Score (ROM) at Baseline, and the Lysholm score were assessed 3 months after AKS [15].

3. Biomechanics of knee joint

The common disease of osteoarthritis (OA) affects the human knee joint, in particular, joints and meniscus. The diagnosis of early OA is essential since it enables the procedure in due course. Tibiofemoral, patellofemoral and menisci biomechanical joint have been performed. This interaction was considered by implant manufacturers with the aim of designing and developing a broad spectrum of TKR implant replacement solutions. For runner patella resurfacing, knee arthroplasty is normally performed overall. Restricted effect on the role of the patient at primary TKA would be postpatellar thickness. Analysis was carried out using an effect on PFJ reaction and stress on the knee joint bending angle and extension time. In the negotiations on the PFP it is measured the effect of knee extension and biomechanical joint load [1,16–18].

After knee surgery, the biomechanical knee model is studied. The wide spectrum of diseases is covered by patellofemoral joint (PFJ) disorder. Pathologies may cause trauma, dislocation, improper use or persistent maltracking. The PFJ was used for MRI, CT scans and X-rays. The alignment of the knee was tested. In order to help explain the interplay between natural joints and artificial recovery exo-skeleton architecture and control systems, a knee-joint model has been introduced. The anatomically based knee model remedies many traditional theories that approximate the human knee in a configuration with the exoskeleton as a technical pin-j joint. The authors propose to combine finite element analysis based on an approach run, a hop, a bound and a jump where charging data from an MDA were collected in the knee joint region and then applied for loading a FE modal [19–22].

The axial tibiofemoral contact forces for the squatting of two high range of movements (high flexion). Knee kinematics and kinetics are valuable in identifying and developing or improving treatment options to identify possible causes of joint diseases. Two different options have been used to treat patellofemoral arthritis: one is non-operative therapy and the other is non-arthroplasty [4,23–25]. The stress reaction of the patella joint associated with three kinematic patellar: shift, spin and tilt in femoral conditions of retroversion is observed. On 12 models, four different loads were applied: 600, 657, 706 and 753 N. A combination of design variables has been identified which led to the least cinematic deviation from the design goal. The creation of customized surface-guided candidates was considered by six major design variables. In a key component study considering the input variables designs and the effects of a deep squatting virtual simulation, the contribution of these variables has been evaluated. The

Fig. 5. Clinical image of a meta-diaphysical junction intraoperative measurement that shows the level up until midpoint (Reprinted with permission from Ref. [12] Copyright 2019 Korean Knee Society).

effect of a concept parameter implant is accessed on the kinematic actions [26–29].

When the patella changes its location, the forces acting on the patella, tibia and femur change with the angle of bending. In recognition of various angular motions the three major forces acting on the knee joints, i.e. quadriceps strength and patella tendon strength and patellar femoral forces, are derived from the following equations [30], while Fekete et al., [2] and Mason et al., [25] present free body diagram of knee joint in Fig. 6. In two different cases, i.e. for different weights at different bending angles, the forces acting on a patella are explained in Fig. 7.

$$\textit{Patellar tendon force}, \frac{f_{pt}}{BW} = \frac{\lambda_1 . \sin\gamma}{\lambda_p . \sin\beta + \lambda_t . \cos\beta} \quad (1)$$

$$\textit{Quadriceps force}, \frac{f_q}{BW} = \frac{\lambda_3 \sin(\alpha - \gamma)}{\lambda_f} \quad (2)$$

$$\textit{Patellofemoral force}, \frac{f_{pf}}{BW} = \frac{\sqrt{f_q^2 + f_{pt}^2 - 2f_q . f_{pt} \cos(\beta + \delta + \gamma)}}{BW} \quad (3)$$

4. Mechanical experimental investigation

The study on the 3D femoral model of the bone has been done using different scanning systems that assist the doctor while the total knee replacement (TKR) is being tested on the femur bone. Predictions of fatigue life of knee component substances have been modeled on the Morrow approach. The use of biomaterial in hip and knee implants ensures that beneficial mechanical features are maximized and material degradation (e.g. corrosion and degradation) are minimized and that the implant can be integrated with the musculoskeletal system for longer. Various materials have been tested, such as stainless steel, titanium alloys, etc [31–33].

In both simple geometry pin-on-plate studies and total hip joint substitution, carbon-re-enforced PEEK has demonstrated good wear characteristics in the experimental simulation of wear. The study examined PEEK's and CFR-wear PEEK's performance in a low knee replacement configuration. Optimizing the design will aid in the production of a perfect implant. SDO helps to reduce implant weight and to reduce problems related to stress protection [34,35].

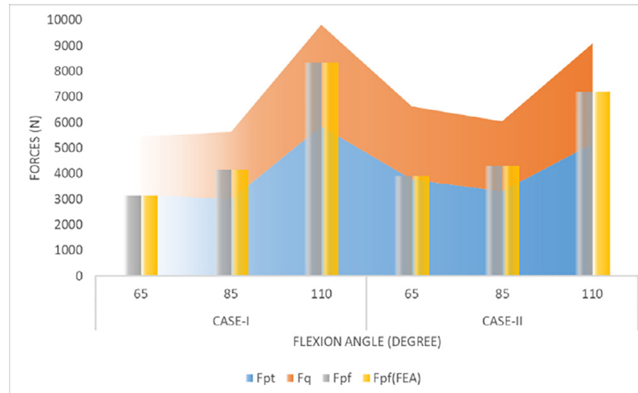

Fig. 7. Force acting on patella for two different cases at various flexion angle [30].

The forces on the human knee joint were experimentally measured. For both the healthy knee and all commercially available total knee replacements today, knee movement is well understood. The sensitivity of TKR was measured and correct ligament balance was also investigated. A new in vitro technique for testing the kinematics and laxity of TKR implants has been created to simulate wear in the laboratory. The wear rate in vitro is considered a crucial phase in the production of joint substitution prior to clinical research and can be verified by contrasting functional and patellar surface injury modes with medical outcomes. This technique has demonstrated a reproducible and repeatable reproduction of the prescribed in-vitro movies. A cohort of TKA patients was observed for a minimum of 12 months [36–39].

The study of biomechanics is how the body works to enhance walking and running conditions. The various phases of the gait cycle and the mechanics of your body need to be understandable. The following breaks down the various cycle phases and the way your body functions. Each phase has its own mechanical properties

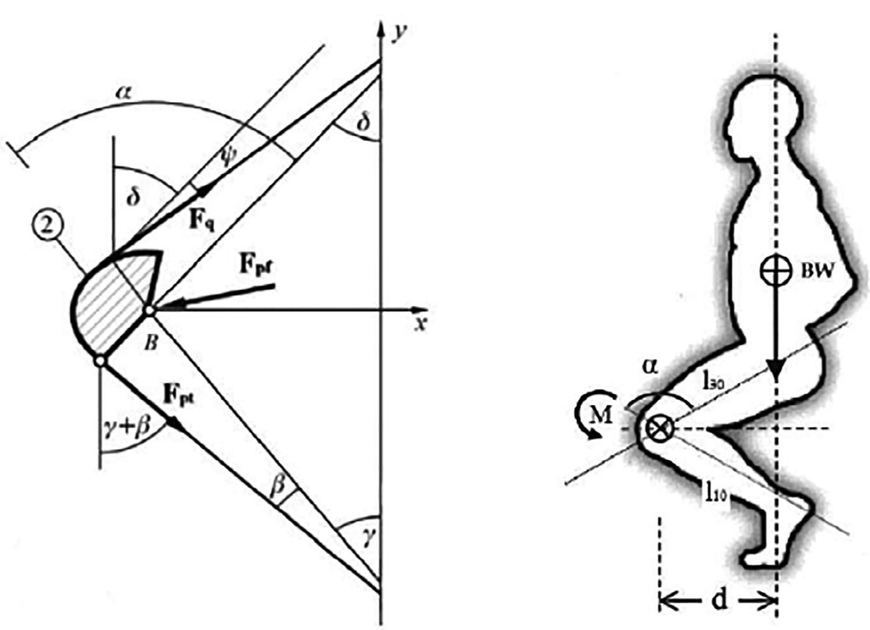

Fig. 6. Free body diagram of patellofemoral joint and joint flexion moment by Fekete et al., [2] and Mason et al., (Reprinted with permission from Ref. [25] Copyright 2008 Elsevier Ltd.)

and different factors are determined by each phase as shown in Fig. 8. Running mechanics are: heel contact to middle position, heel off, dog off, Initial swing, terminal swing and post-trauma. To make a steady foot to push the ground the Windlass Mechanism is activated. The hamstring and adductors work to stabilize the forward beam. The hamstrings, quads, glutes and TA move between a stabilizing and a concentrated function to help shock. The TA contributes to maintaining the foot and helps to avoid land catching [40]. An experimental dynamic force measured using vibration analyzer on knee joint is shown in Fig. 9.

5. Modeling and analysis of knee joint

The periprosthetic bone strain distributions in some of the typical cases of total knee replacement (TKR) are studied with regard to the selection of material, design and alignments of tibial components to ex- amine. Two designs and material properties (sacrifice cruciate and retention) have been considered [42].

SMA is an intelligent material with new functionalities including high strength, high fatigue strength, high wear resistance and biocompatible properties. The SMA is a smart material. The author analyzed the replacement and drawbacks of Polymethylmethacrylate (PMMA). CT data are loaded into DeVide for the purpose of acquiring a 3D Computer aided design (CAD) model of Digital imaging and communications in medicine (DICOM) (DICOM). The knee articular geometry differs greatly between individuals with effects on damage and pathology risk [43–45].

CT scans were used to create a general lower-finish bone model and to develop a 3D CAD knee joint model that has been supplemented with muscles and ligaments. The tibiofemoral motion of different post-cam designs in the course of high knee flexion was studied with a dynamical knee design. Two posterior stabilized knee models were designed with postcam contact surfaces on a flat-on-flat and curved contact surfaces. The study focused on examining differences in the knee joints through three-dimensional, dynamic simulations of the residual legs and intact legs during a continuous stage walk. There were 14 rigid body and 23° freedom segments of the model [22,46,47].

Analysis of knee anterior cruciate ligament (KAL) sensitivity, muscle, and contact forces plus asymptomatic gait dissipation stability is studied. At larger bending angles (all periods) and a smaller inner moment (only at 75 per cent), ACL force decreased significantly but increased at bending moment. Knee joint has the most complex design in human bodies, which in different moving conditions acquires critical loads. Sensitivity analysis of the knee joint response to gait kinetics variations is essential to improved comprise and prevention-treatment strategies. The stress is evaluated in several load cases and three highly loaded stages (25, 50 and 75%) for each of six knee joint corner moments [48,49].

The study under cyclic loading of the normal knee helps us to learn more about the assembly. Analysis of fatigue can help us to understand the cause of several knee disorders. Digital Imaging and Medical communication (DICOM), acquired from a CT scan, creates the 3D knee model. It would allow us to develop better ways of dealing with patients' problems [50,51].

The aim to present a graphical modeling approach for human anatomic structures such as femur and tibia. It also involves the analysis of finite elements in prosthetic implants for stress, displacement and deformations as shown in Fig. 10. This report focuses on condylar knees, namely the constrained Condylar type, of intercondylar stability. Specific software was proposed to interface with a CNC machine, and these knees could be designed and produced economically. The model was designed to parameterize only the knee dimensions A-P and M-L for a custom case. The software was developed and interfaced with customized CNC machines to make custom knees simple, effective and cheap. The Full-body movement capture recorded for multiple trial levels and step-downs was followed by a forward dynamic simulation that incorporated position, velocity, and contact force-feedback control (FFC) [3,22,52,53]. Fig. 11 shows the CAD model of knee implant with anterior-posterior motion of the low point femoral compared to the dual-radius design tibial insert.

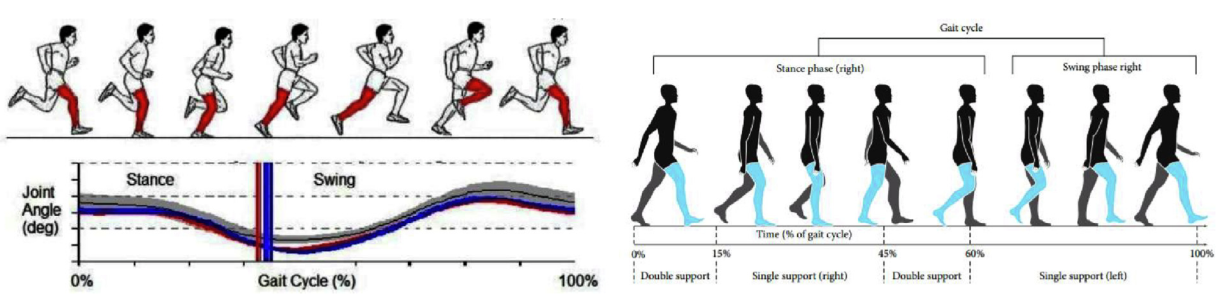

Fig. 8. Different phases of gait cycle in running [40] and walking (Reprinted with permission from Ref. [41] Copyright 2019 Mariem Abid et al., Hindawi Ltd.)

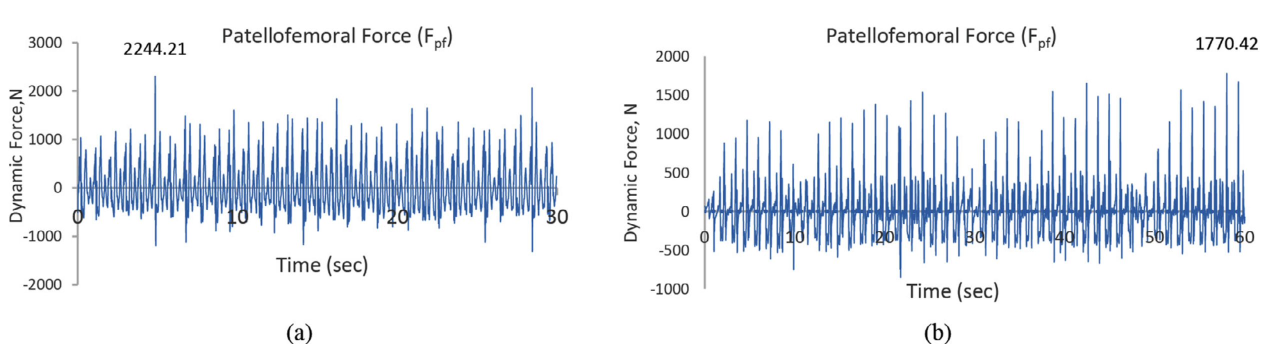

Fig. 9. Dynamic patellofemoral force during (b) running and (a) walking.

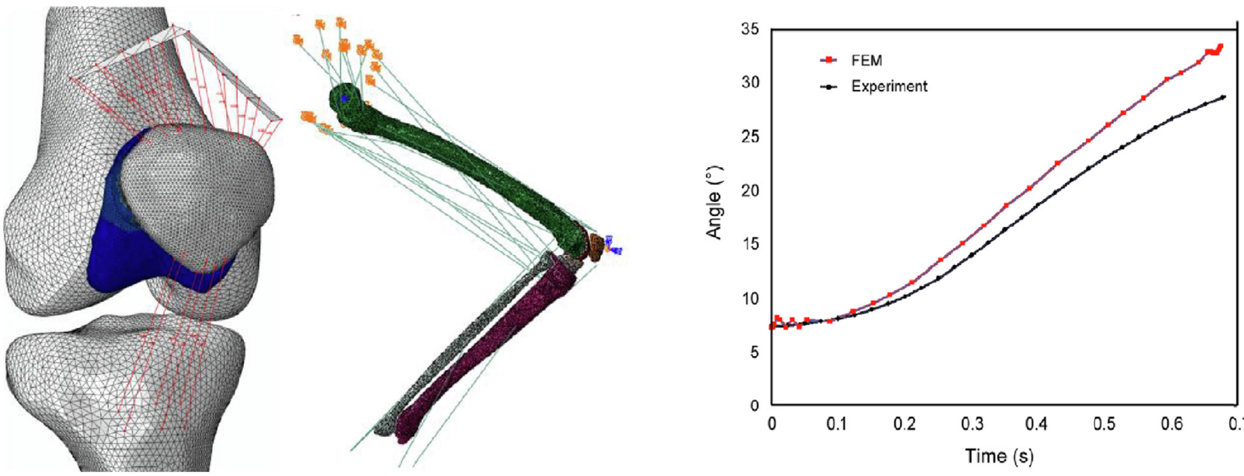

Fig. 10. Representation of finite element model (left) and comparison of flexion angle with experimental result (right) (Reprinted with permission from Ref. [22] Copyright 2014 Elsevier Ltd.)

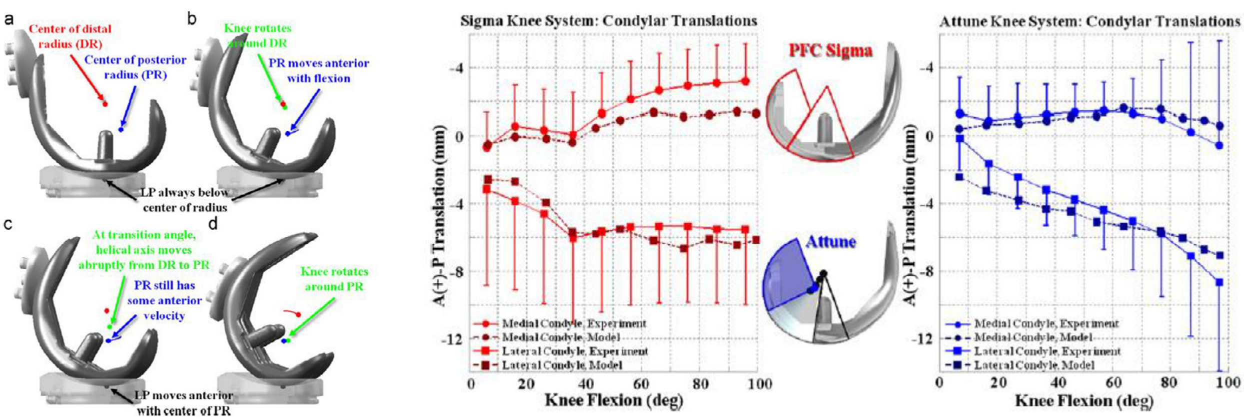

Fig. 11. CAD model of knee implant with anterior-posterior motion of the low point femoral compared to the dual-radius design tibial insert (Reprinted with permission from Ref. [54] Copyright 2013 Elsevier Ltd.)

6. Results and discussions

It is discussed as follows based on an insight study for analysis of the actual and artificial knee joint.

- In patients with a patellar thickness of less than 20 mm, a patellar button option was used to re-establish pre-operative thickness. The use of plastic fractures, wear of buttons or failures did not lead to any potential complications with the use of a thinner plastic implant.
- The biomechanical formulation of the patellar knee joint is done to find forces acting on the patella using a diagram. In different flexion angles i.e. 60°and 90°, different weight individuals are calculated for the patellar tendon force, quadriceps force and patollofemoral forces.
- Patellofemoral and tibiofemoral joint dynamic forces can be experimentally validated with the help of the use of a dynamic analyzer or a sensor for walking, running and jumping, and forces that act in better in running condition than any other condition have been observed.
- The KKS experimentally measured low point condylar movies for the traditional Sigma knee system showed a sudden anterior glide of 30^0 to 40^0 of flexion; the media condyle with minimal motion from the settled position in early bending shifted from the distal one to the posterior radii on an average articulation. Meanwhile, when articulated with the rear radius of the lateral condyle showing continual postural movement in early flexion, the A–P position was approximately static. The mean of condylar kinematics experimentally measured was good for the model-predicted films for the same implant, whereby the root-medium-square (RMS) differences were 1.3-mm and 0.8-mm respectively for medium and side condyles.

7. Concluding remark

A knee joint acquires entire load of body and behave differently at various condition like walking, running, climbing, jumping etc. An injured knee joint due to osteoarthrosis or due to accident cannot work properly at every condition and hence need to replace with exact dimension. This paper aims primarily to study an overview of the knee joint replacement by examining all aspects. A joint knee model should be thoroughly checked to gain strength in different conditions at least. A medical research can demonstrate the dimensional parameter of the patient by surgery and measurement which will be useful to prepare an exact model for replacement. The dimension of knee joint may vary as per the health or age of patient. Hence medical officer can play a vital role in manufacturing of exact knee joint model. Study of biomechanics has elaborated the force distribution over knee joint i.e., on tibiofemoral and patellofemoral joint. Mainly the forces acting on joint are patellar tendon force, quadriceps force and patellofemoral force. The force distribution over joint will vary with respect to the flexion angle and weight of the body. It has been observed that the patellofemoral and quadricep force is maximum at maximum flexion angle i.e., at 110°. Joint measures should also be implemented to validate numerical solutions. Recent testing work can provide data to validate kinematic/kinetic models. However, there are few experimental data needed for the validation of the common model. An experimentation to find dynamic forces on knee joint is very much helpful to identify the reason of damage in knee joint. Knee damage of an athletics is very common as the force acting during jumping and running is more as compared to steady condition or during walking. The study explained that the replacement in knee joint can work like original knee joint if the dimension of artificial tibia, femur and patella will match exactly with original joint. To understand an irregular gastronomy, a FE model is needed to assess touch pressure in the knee. Finite element analysis is a new technology for transmitting tension according to the complex experimental strengths. For comparison of stress distribution over the initial knee joint and implant common FE instruments are used. The comparison gives the idea to generate the appropriate shape and scale of the knee implant in relation to its CAD model used for FE research. For perfect involvement during arthroplasty, several researchers focus on the reduction in thickness of patella, tibia and femur implant. It is observed from the insight survey is that the biomechanics approach for replacement of knee joint helps many patients to work as a normal life with their routine activities and observe negligible pain in the joint. The future scope of the partial or total knee arthroplasty is an identification of composite material for an implant as favorable to human body to remove any other complications like infection, blood clotting etc. after surgery.

CRediT authorship contribution statement

M.A. Kumbhalkar: Conceptualization, Methodology, Investigation, Writing - original draft. **K.S. Rambhad:** Data curation, Validation. **Nand Jee Kanu:** Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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