ISSN 2250-3153

A Proprioceptive Discussion on Mechanism Used for Knee Joint from 2000-2012: A Literature Review

Prashant Choudhary *, Pawan Mishra **, Vinayak Ranjan Dwivedi ***

*Department of Mechanical Engineering, Krishna Engineering College
** Department of Mechanical Engineering, Krishna Engineering College
*** Department of Mechanical Engineering, ISM, Dhanbad

Abstract- A variety of active above knee prosthesis have been manufactured over the past decade and there has been ambiguity over the advantages and disadvantages of the various counterparts.

The most Therefore, this study involves analysis and comparison of various prosthesis based on the mechanism employed.

Index Terms- Mechanism, Above-knee, Prosthesis, Trans-femoral, Four-bar, Six bar, spherical;

I. Introduction

Loss of limb has been a problem as long important part of an above knee prosthesis is the mechanism employed for satisfactory flexion and extension functions of the knee joint. as man has been in existence. The earliest report regarding the prosthetic usage returns to the time of Rig-Veda period, which is between 3500- 1800 BC. [1,2]Ever since the beginning of humanity, man has been using wooden cane as a support for walking. Later this was replaced by roughly crafted peg legs and hooks. With technological advances during the world wars, this field saw major leap and first real prosthesis based on Solid Ankle Cushioned Heel was developed by J E Hanger.

A type of surgical operation that severs thigh section between the knee and joint is known as Above Knee Amputation. It generally happens when the amputee has gone through some disease or some accident. The foot and shank sections are completely lost post amputation while the thigh section is partially lost. The purpose of this study is to review current information regarding current prosthetic designs which can emulate the unharmed limb with varying degrees.

II. Types of Mechanisms Employed in Above Knee Prosthesis

The function of the knee mechanism is to exercise control over absorption of motion of a knee in a prosthesis. This is achieved in devices either by mechanical friction, or by resistance offered to fluid flow. The swing control component of a knee mechanism therefore is the mechanical control to dampen the swing of the knee at the extremes of flexion and extension Over the last decade the various mechanisms employed in above knee prosthesis are 4-bar mechanisms,6-bar mechanisms and Spherical mechanisms which exercise control over various angles of flexion and extension.

The four bar linkage is of three types ,namely : the four bar linkage with elevated instantaneous centre, the hyper-stabilized four bar knee mechanism and the voluntary control four bar mechanism. The elevated instantaneous centre provides for stability at heel contact while the hyper-stabilized knee is more of a locked knee mechanism which provides alignment stability for less active amputees. The voluntary control four bar mechanism provides stability at heel contact as well as heel push off as it provides more control and is preferred by aggressively active amputees.[3]

Six-bar mechanisms have been successfully used in some knee joints by the Otto Bock Company. Also a few articles on kinematic as well as design and performance of the six-bar mechanism have also been published till date. Van de Veen outlined the general constitution of multiple-bar linkage for the prosthetic knee. A particular six-bar knee-ankle mechanism to provide coordinate motion between knee and ankle joint during walking and squatting was also designed by Patil and Chakravorty. The six-bar mechanisms have much more design variables as compared to four bar mechanisms. Therefore, six-bar mechanisms can provide more functional advantages based on appropriate design.[4]

Despite its simple structure, the spherical mechanism represents knee motion with good accuracy. With respect to the previous more complex mechanism, though the results of replication of natural motion were less satisfactory but are counterbalanced by a reduction of computational costs, by an improvement in numerical stability of the mathematical model, and by a reduction of the overall mechanical complexity of the mechanism.[5]

III. Constitution and Design of Mechanisms

A. Four Bar Mechanisms:

The above-knee prosthesis as shown in figure 1 has a four-bar linkage arrangement at the knee by which the motion can be transmitted from the thigh to foot during squatting action and during the swing phase of walking. The four-bar linkage is formed by four-bar link 1,2 3,and 4 with a short posterior link 2 designed after several trials, such that it creates an instantaneous center which is located well above a corresponding single axis knee center and posterior to the hip ankle line in full extension. This results in stability of the prosthesis during stance phase. Initiation of and moving of the Instantaneous center rapidly down to the natural position of the anatomical knee joint can be done with a little effort of the hip muscles. Up to 10° of knee flexion, the center of rotation is well above the location of a single axis knee joint, which helps the amputee in being able to control both extension and flexion voluntarily over this critical range of motion. With this linkage arrangement a flexion angle of 150° can be achieved, this enables the amputee to squat and kneel comfortably. [3,6]

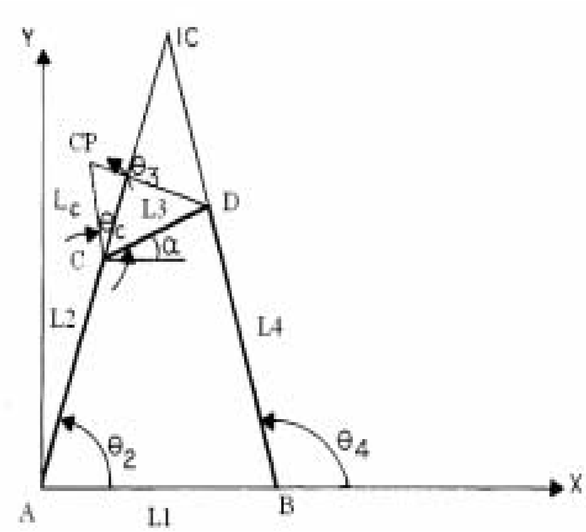

Fig. 1 A typical four bar mechanism

B. SIX BAR MECHANISMS:

Fundamental types of six-bar mechanisms are the Watt type and Stephenson type as shown in figure 2.The particular objective of design parameters is to constitute the six-bar knee mechanism so that the shank is fixed to link 5 or 6 while the thigh is fixed to link 1. Otherwise, if the shank is connected to link 3, then the function of the six-bar knee mechanism will be the same as that of four-bar mechanisms.

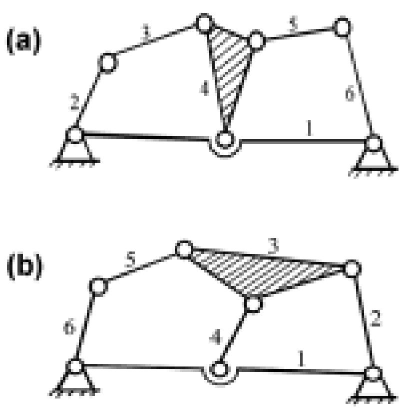

Fig.2. (a)Watt type six bar mechanism
2. (b) Stephenson type six bar mechanism

Based on these two types, the knee joint has four configurations as shown in figure 3 :

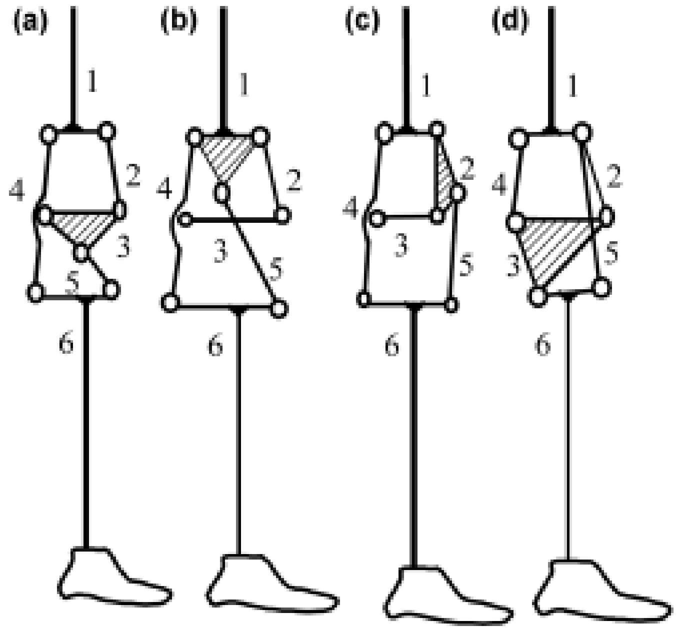

Fig. 3 Configurations of six bar mechanism

KINEMATIC DESIGN OF SIX BAR MECHANISMS:

Considering the following six bar mechanism:

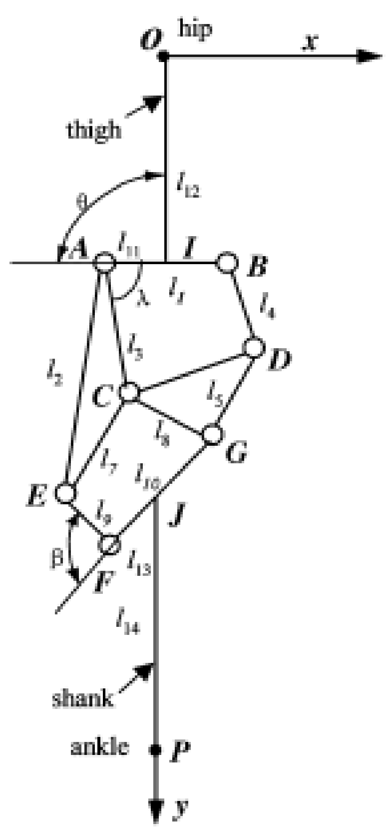

Fig. 5 A six bar mechanism

The geometric center of the knee mechanism can be calculated by the equations

$$x_{gc} = \frac{1}{7}\sum_{i=1}^{7} x_i$$

$$y_{gc} = \frac{1}{7}\sum_{i=1}^{7} y_i$$

where x_{gc} and y_{gc} are the coordinates of the geometric center of the knee mechanism and x_i and y_i are are the coordinates of the seven joints of the mechanism. After the optimization method of Complex Penalty Function is applied, the design parameters are obtained as [4,7] :

$$X = [x_1, x_2, ...x_{16}]^T = [l_1, l_2......l_{14,} \theta, \beta]^T$$

=[25,71.6,40,37.9,28,21.8,31.7,19,17,35,32,383,14,26.7,88°,11°]

Then the six-bar knee mechanism can be designed, and the trajectory generated by the mechanism is shown below :

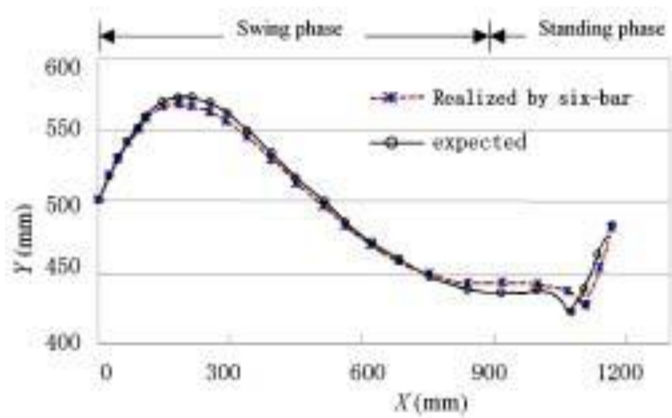

Fig. 6 Trajectory generated by six bar mechanisms

C. SPHERICAL MECHANISM:
5-5 PARELLEL MECHANISM

A 5-5 model of the human knee which reproduces the passive flexion of this prosthesis was discovered in the past. It has proved to be particularly effective and provides a good simulation of the passive motion compared to other models of the knee and its implementation is very simple for optimization.

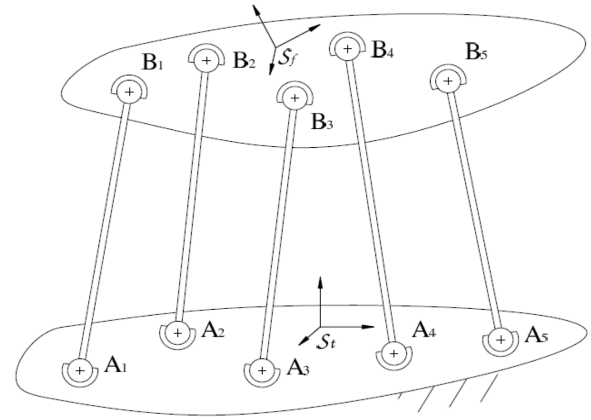

Fig. 7 A 5-5 Parallel mechanism

The geometry of the 5-5 mechanism is shown in figure 7. The relative positions of the ligament insertions from total extension to maximum flexion were analysed and for each ligament the pair of points (one on the femur and the other on the tibia) which showed the minimum change in distance were chosen. The three points on the tibia (A1, A2 and A3) and those corresponding on the femur (B1, B2 and B3) are the centers of the spherical pairs on three of the five legs of the equivalent mechanism. The four condyles were then replaced by four best fitting spheres whose centers (A4, A5 on the tibia and B4, B5 on the femur) are also the centers of the two remaining legs. The length L_i of each leg is the distance between the spherical pairs on each link at the initial position (full extension).

The closure equations of the mechanism constrain each pair of points Ai–Bi to keep the same distance at each imposed flexion angle:

$$\| A_i - R \cdot B_i - P \|^2 = L_i^2$$ (where i=1,2,3....so on)

where points Ai and Bi are expressed in St and in Sf respectively, $\|\cdot\|$ is the L^2 -norm of the vector,R the 3x3 rotation matrix for the transformation of vector components from Sf to St, and P the position of the origin of Sf in St. Matrix R can be expressed as function of three rotation parameters α , β and γ :

$$R = \begin{bmatrix} C_\alpha C_\gamma + S_\alpha S_B S_\gamma & -S_\alpha C_\gamma + C_\alpha S_\beta S_\gamma & -C_\beta S_\gamma \\ S_\alpha C_\beta & C_\alpha C_\beta & S_\beta \\ C_\alpha S_\gamma - S_\alpha S_\beta C_\gamma & -S_\alpha S_\gamma - C_\alpha S_\beta C_\gamma & C_\beta C_\gamma \end{bmatrix}$$

where c and s indicate the cosine and sine of the angle in subscript and α , β and γ represent the flexion, ab/adduction and intra/extra rotation angles of the femur relatively to the tibia. Expression (2) can be applied for right legs. If knee flexion is fixed, the five equations of system (1) depend only on five unknowns, i.e. the three components of vector P and the angles β and γ only.[21,22,23,24,25,28,34,37,40,41]

1-DEGREE OF FREEDOM (DOF) SPHERICAL MECHANISM:

A 1-Dof spherical mechanism is shown figure 8:

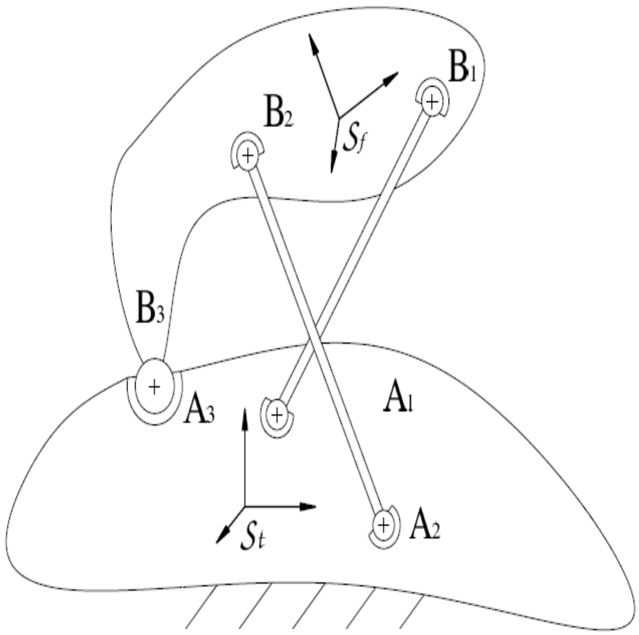

Fig. 8 1-Degree of freedom (Dof) spherical mechanism

The closure equations for design in this case is given below :

$$\| A_i - R \cdot B_i - P \|^2 = L_i^2 \quad \text{(where i=1,2)}$$

and $$A_3 - R \cdot B_3 - P = 0$$

where R and P have the same values as above.[5,16,17,18,26,27]

IV. STABILITY OF DIFFERENT MECHANISMS

A. Four bar mechanism :

The stability diagram of the various types of four bar mechanisms are given in figure 9,figure 10 and figure 11. .The four bar mechanism with raised instantaneous centre has been designed to give extreme stability at heel contact by having the instantaneous centre for full extension of the knee located considerably posterior to the load line at heel contact. The physical arrangement of a hyper-stabilized knee is often similar to the four bar mechanism with elevated instantaneous centre but it has very positive alignment stability built in to it. The voluntary control four bar knee is designed not only to give amputee ability to control knee stability at both heel contact and push-off, but to have complete control of knee stability over a limited range of knee flexion.[3,6,12,13]

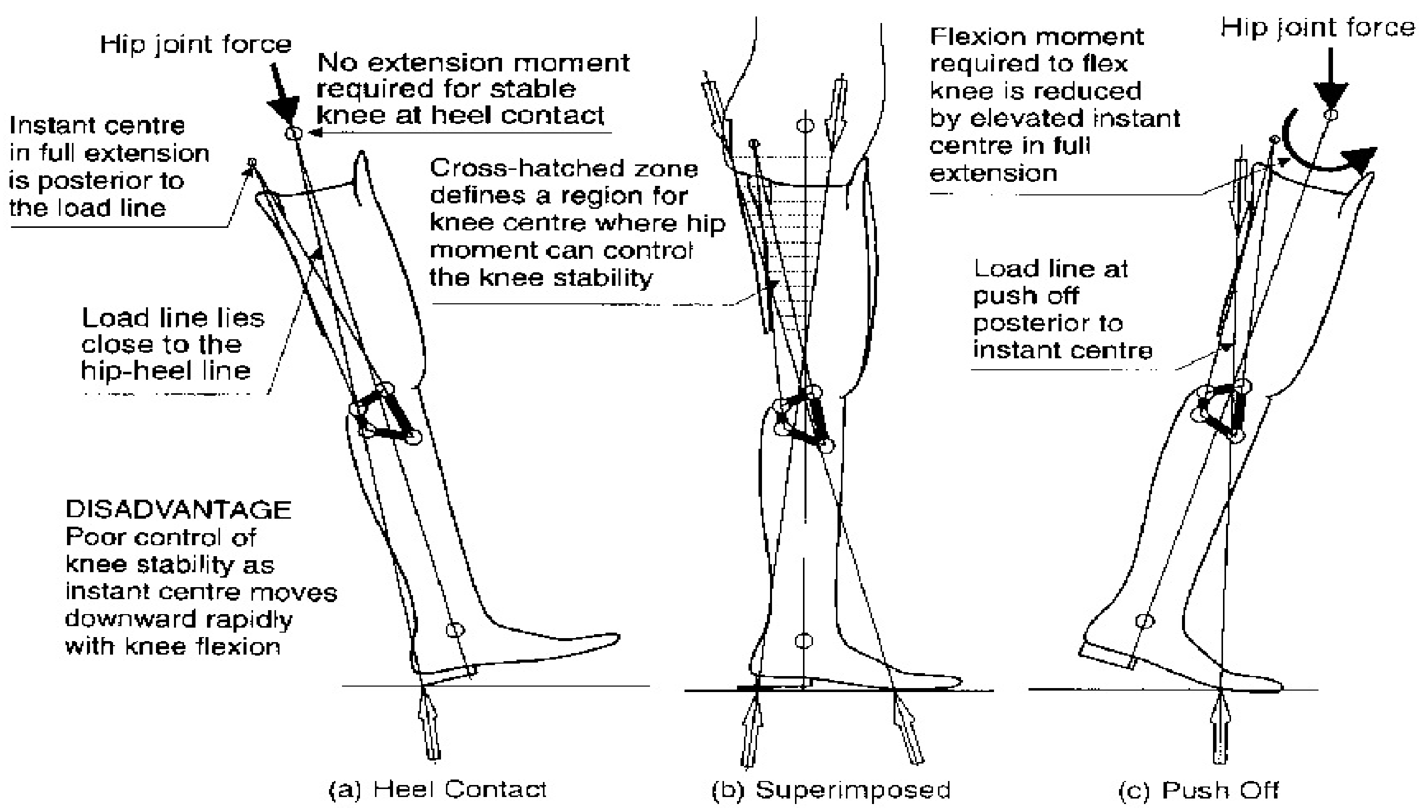

Fig. 10 Stability diagram of a 4 bar mechanism with raised instantaneous centre

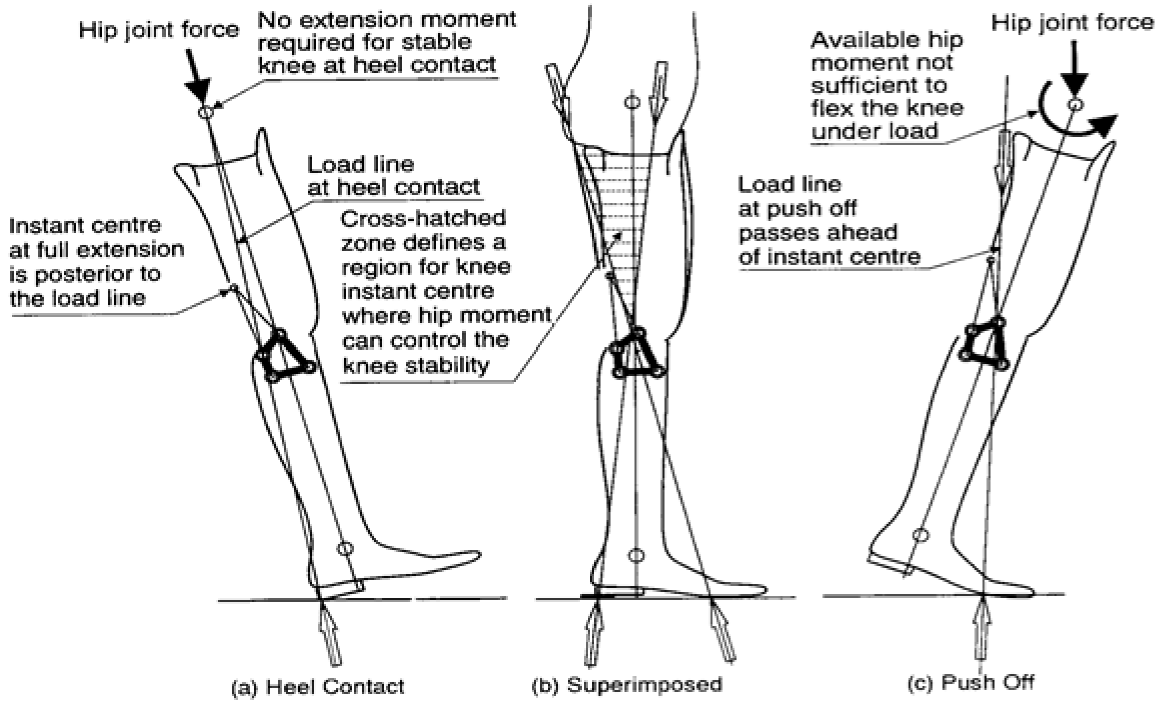

Fig. 11 stability diagram of a hyper-stabilized 4 bar mechanism

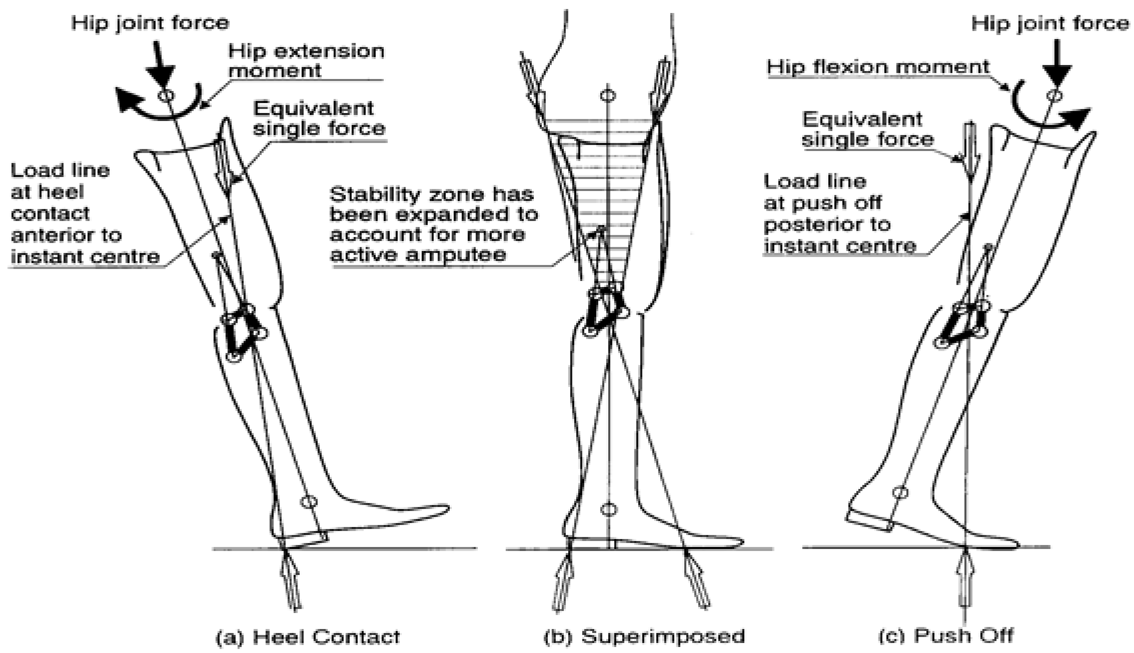

Fig. 12 stability diagram of voluntary control 4 bar mechanism

B. SIX BAR MECHANISM:

If two links connected by a revolute joint in a six bar kinematic chain, they have the same angular velocity at the same instant and position, which means that the links have no relative motion between them , the joint is referred to as Instant Inactive Joint. For example, if the 4-bar kinematic chain, shown in figure 13 (a), is in such a position that links 3 and 4 are collinear and links 1 and 2 have the same angular velocity, then the revolute joint *A* is an Instant inactive joint in this position. For a self locking mechanism, the Instant inactive joint (IIJ) must exist. In figure 13(b), if link 1 (or 2) is fixed, link 2 (or 1) cannot drive the mechanism no matter how large the driving moment is. Obviously, the more IIJ exists, the more stable the mechanism is. In the four-bar kinematic chain, only one IIJ can exist. However, depending on the design, the six-bar kinematic chain can have as many as four Instant inactive joints exists.[4,14,15,30,32]

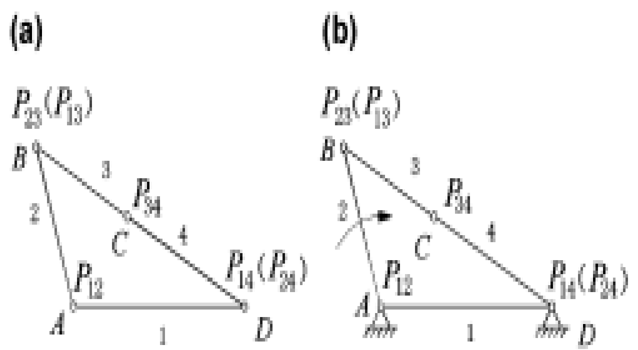

Fig. 13 Instant inactive joints in six bar mechanisms

C. SPHERICAL MECHANISM:

The numerical stability of spherical mechanism is quantitatively analysed starting from geometrical optimization. Optimized parameters are collected in a relevant vector s, having 35 or 16 components, depending on the model. For each vector s, 3000 error vectors ∂s are randomly generated whose components are chosen all inside the interval [-1; + 1]. Thus, for each optimized mechanism, 3000 modified geometries are defined by $s_m = s + \partial s$. The joint motion of each modified mechanism is compared with that of the relevant original optimal computing the mean squared and weighted error err_m .This error is an index of the sensitivity of each identified model to geometric parameter variation. Moreover, the number of singularity problems met during this procedure is counted,in order to quantify the tendency of a model to generate singularities. [5,9,10,18,20,29,31,32,38]

V. COMPARISON BETWEEN 4 BAR, SIX BAR AND SPHERICAL MECHANISMS

Mechanism	Advantages	Disadvantages
4-bar	Stable centre of rotation. Anterior weight bearing axis. Ease of slope and stair descent.	Higher cost.
6-bar	High Stability. Kinematic Stability on terrains and speed ranges.	More weight. Asymmetric gait pattern.
Spherical	Lower mechanical complexity . Light weight.	Replication of natural motion is less satisfactory.

VI. CONCLUSION

The kinematic performance of the several different mechanisms such as four-bar linkage and six-bar linkage are shown in above figures. In this paper are compared with pure motion without reference to the masses or forces involved in it. The comparison of the trajectory of the joint in swing phase of the six-bar linkage knee with that of a four-bar knee mechanism shows that six-bar linkage knee has better performance than four-bar knee mechanism. Also the comparison between various six bar mechanism shows that the performance of six bar mechanism is better than other mechanisms.

REFERENCES

[1] Lim P. Advances in prosthetics: a clinical perspective. Physical Medicine Rehabilitation: 1997;11:13-33

[2] Global Lower Extremity Amputation Study Group. Epidemiology of lower extremity amputation in centres in Europe, North America and East Asia. The Global Lower Extremity Amputation Study Group. Br J Surg 2000;87:328-37.

[3] Radcliffe CW. Four-bar linkage prosthetic knee mechanisms:kinematics, alignment and prescription criteria. Prosthet Orthet Int 1994;18:159–73.

[4] Kinematic and dynamic performance of prosthetic knee joint using six-bar mechanism Dewen Jin, Ruihong Zhang, HO Dimo, Rencheng Wang, PhD, Jichuan Zhang,2003

[5] A one-degree-of-freedom spherical mechanism for human knee joint modelling N Sancisi, D Zannoli, V Parenti-Castelli, C Belvedere, A Leardini 2010

[6] Zarrugh MY, Radcliffe CW. Simulation of swing phase dynamics in above-knee prostheses. J Biomech 1996;9(5):283–92.

[7] Van de Veen PG. Principles of multiple-bar linkage mechanisms for prosthetics knee joints. Abstract of the 8th World Congress, ISPO; 1994 Apr 2–7; Melbourne, Australia.p. 55.

[8] Hobson DA, Torfason LE. Computer optimization of polycentric prosthetic knee mechanisms. Bull Prosthet Res 1975;(10–23):187–201.

[9] A 1-Dof parallel spherical wrist for the modelling of the knee passive motion N. Sancisi V. Parenti-Castelli 2007 12th IFToMM World Congress.

[10] Rahman E.A. and Hefzy M.S. A two-dimensional dynamic anatomical model of the human knee joint. ASME Journal of Biomechanical Engineering, 115:357–365, 1993.

[11] Hobson DA, Torfason LE. Optimization of four-bar knee mechanism—a computerized approach. J Biomech 1974; 7(4):371–76.

[12] Patil KM, Chakraborty JK. Analysis of a new polycentric above -knee prosthesis with a pneumatic swing phase control.J Biomech 1991;24(3,4):223–33.

[13] Nakagawa A. Intelligent knee mechanism and the possibility to apply the principle to other joint. Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology; 1998 Oct. 29–Nov 1; Hong Kong, China. p. 2282–87.

[14] Dewen Jin, Ruihong Zhang, Jichuan Zhang, Rencheng Wang, William A. Gruver. An intelligent above knee prosthesis with EMG based terrain identification. Proceedings of 2000 IEEE International Conference on System, Man and Cybernetics; 2000; Nashville, Tennessee. p. 1859 -64.

[15] Ruihong Zhang, Dewen Jin, Jichuan Zhang, Analysis of the temporal inactive joints in multi-linkage mechanisms. J Tsinghua Univ Sci Technol 2000;40(4):39–42.

[16] Wang Rencheng, Huang Changhua, Wang Jijun, Bai Caiqing, Yang Niangfeng, Jin Dewen. Human motion analysis system based on common video-camera. J Biomed Eng 1999;16(4):448–52.

[17] Blankevoort, L., Huiskes, R., and de Lange, A. The envelope of passive knee joint motion. J. Biomech., 1988, 21(9), 705–720. 11 Blankevoort, L., Kuiper, J. H., Huiskes, R., and Grootenboer, H. J. Articular contact in a threedimensional model of the knee. J. Biomech., 1991,24(11), 1019–1031.

[18] [18].Fuss, F. K. Anatomy of the cruciate ligaments and their function in extension and flexion of the human knee joint. Am. J. Anat., 1989, 184(2), 165–176.

[19] Wilson, D. R. and O'Connor, J. J. A three-dimensional geometric model of the knee for the study of joint forces in gait. Gait Posture, 1997, 5(2), 108–115.

[20] Ottoboni, A., Parenti-Castelli, V., Sancisi, N., Belvedere, C., and Leardini, A. Articular surface approximation in equivalent spatial parallel mechanism models of the human knee joint: an experiment-based assessment. Proc. IMechE, Part H: J. Engineering in Medicine, 2010, 224(9), 1121–1132. DOI: 10.1243/09544119JEIM684.

[21] Goodfellows J.D. and O'Connor J.J. The mechanics of the knee and prosthesis design. Journal of Bone Joint Surgery [Br], 60-B:358–369, 1978.

[22] O'Connor J.J., Shercliff T.L., Biden E. and Goodfellow J.W. The geometry of the knee in the sagittal plane. Proceedings, institute of Mechanical Engineering Part H. Journal of engineering in Medicine, 203:223–233, 1989.

[23] Woltring, H. Data processing and error analysis. In Biomechanics of human movement applications in rehabilitation sports and ergonomics (Eds N. Berme and A. Cappozzo), 1990, pp. 203–237 (Bertec Corporation, Worthington, Ohio, USA).

[24] Parenti Castelli V. and Di Gregorio R. Parallel mechanisms applied to the human knee passive motion simulation. In 7th ARK, International Symposium on Advances in Robot Kinematics, Piran-Portoroz, Slovenia, June 26-30, 2000.

[25] Parenti Castelli V., Leardini A., Di Gregorio R. and O'Connor J.J. On the modeling of passive motion of the human knee joint by means of equivalent planar and spatial mechanisms. Autonomous Robots, 16(2):219–232, March 2004.

[26] Merlet J-P. Kinematics and synthesis of cams-coupled parallel robots. In Proceedings of CK2005, International Workshop on Computational Kinematics, Cassino, May 4-6, 2005.

[27] Ottoboni A., Parenti Castelli V. and Leardini A. On the limits of the articular surface approximation of the human knee passive motion models. In Proceedings of the 17th AIMeTA Congress of Theoretical and Applied Mechanics, Firenze, Italy, September 11-15, 2005.

[28] Grood E.S. and SuntayW.J. A joint coordinate system for the clinical description of three-dimentional motions: application to the knee. Trans. ASME, 105:136–144, 1983.

[29] Fuss F.K. Helical axis surface of the knee joint. In 14th Congress of the International Society of Biomechanics, Paris, July 4-8, 1993.

[30] Blankevoort L., Huiskes R. and De Lange A. Helical axes of passive joint motions. Journal of Biomechanics, 23:1219–1229, 1990.

[31] Di Gregorio, R. and Parenti-Castelli, V. A spatial mechanism with higher pairs for modelling the human knee joint. J. Biomech. Engng, 2003, 125(2), 232–237.

[32] Amiri, S., Cooke, D., Kim, I. Y., and Wyss, U. Mechanics of the passive knee joint. Part 1: The role of the tibial articular surfaces in guiding the passive motion. Proc. IMechE, Part H: J. Engineering in Medicine, 2006, 220(8), 813–822. DOI: 10.1243/09544119JEIM180.

[33] Amiri, S., Cooke, D., Kim, I. Y., and Wyss, U. Mechanics of the passive knee joint. Part 2: Interaction between the ligaments and the articular surfaces in guiding the joint motion. Proc. IMechE, Part H: J. Engineering in Medicine, 2007, 221(8), 821–832. DOI: 10.1243/09544119JEIM181.

[34] Akalan, N. E., Ozkan, M., and Temelli, Y. Three dimensional knee model: constrained by isometric ligament bundles and experimentally obtained tibio-femoral contacts. J. Biomech., 2008, 41(4), 890–896.

[35] Belvedere, C., Catani, F., Ensini, A., Moctezuma de la Barrera, J. L., and Leardini, A. Patellar tracking during total knee arthroplasty: an in vitro feasibility study. Knee Surg. Sports Traumatol. Arthrosc., 2007, 15(8), 985–993.

[36] Grood, E. S. and Suntay, W. J. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J. Biomech. Engng, 1983, 105(2), 136–144.

[37] Walker, P. S. and Sathasivam, S. Design forms of total knee replacement. Proc. IMechE, Part H: J.Engineering in Medicine, 2000, 214(1), 101–119. DOI: 10.1243/0954411001535282.

[38] Walker, P. A new concept in guided motion total knee arthroplasty. Arthroplasty, 2001, 16 (Suppl 1), 157–163.

[39] Walker, P. S., Yildirim, G., Arno, S., and Heller, Y. Future directions in knee replacement. Proc.IMechE, Part H: J. Engineering in Medicine, 2010, 224(3), 393–414. DOI: 10.1243/09544119JEIM655.

[40] Rannou, F., Poiraudeau, S., and Beaudreuil, J. Role of bracing in the management of knee osteoarthritis. Curr. Opin. Rheumatol., 2010, 22(2), 218–222.

[41] Apkarian, J., Naumann, S., and Cairns, B. A three dimensional kinematic and dynamic model of the lower limb. J. Biomech., 1989, 22(2), 143–155.

AUTHORS

First Author – Pawan Mishra, Assistant Professor, Krishna Engineering College, pm.mech2008@gmail.com
Second Author – Prashant Choudhary, Student,Krishna Engineering College, rashkec@gmail.com
Third Author – Anuj sharma, Student,Krishna Engineering College, anujsharma2402@gmail.com

Correspondence Author – Pawan Mishra, Assistant Professor, Krishna Engineering College, pm.mech2008@gmail.com