Simplified Analysis of Stanford - Jaipur Knee

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Abstract

One of the signature product development activities at the Department of Mechanical Engineering Universities Diponegoro is the design and prototyping of artificial knee for above knee prosthesis. The activities are acknowledged as four credit unit for final project as the final requirement for graduation of undegraduate degree. This product development activity has received many research and commercial grants respectively. All of the projects follow the course of synthesis and prototyping without adequate analysis, in particular kinematics and dynamic analysis. This article explains exactly those missing step of analysis with the hope that future designs can get better and better. The focus of design is limited to the triple rocker Stanford Jaipur-Knee along with its variants of configuration. The analysis includes position, velocity, acceleration, and force analysis, all of which are adopted from textbook by Norton.

Kata kunci: Stanford-Jaipur Knee; artificial knee; kinematic and dynamic analysis

Abstrak

Salah satu kegiatan pengembangan produk tanda unggulan di Departemen Teknik Mesin Universitas Diponegoro adalah desain dan prototyping lutut buatan untuk prostesis lutut di atas. Kegiatan ini diakui sebagai empat unit kredit untuk proyek akhir sebagai persyaratan akhir untuk kelulusan gelar undependenced. Kegiatan pengembangan produk ini telah menerima banyak hibah penelitian dan komersial. Namun demikian, hampir semua riset dan pengembangan hanya melakukan sintesis dan pembuatan prototipe tanpa analisis yang memadai, khususnya kinematika dan analisis dinamis. Artikel ini menjelaskan langkah-langkah analisis yang hilang dengan harapan bahwa desain masa depan bisa menjadi lebih baik dan lebih baik. Fokus desain terbatas pada triple rocker Stanford Jaipur-Knee bersama dengan varian konfigurasinya. Analisis ini meliputi analisis posisi, kecepatan, dan percepatan.

Kata kunci: Jaipur knee; mechanism; kinematicsRe

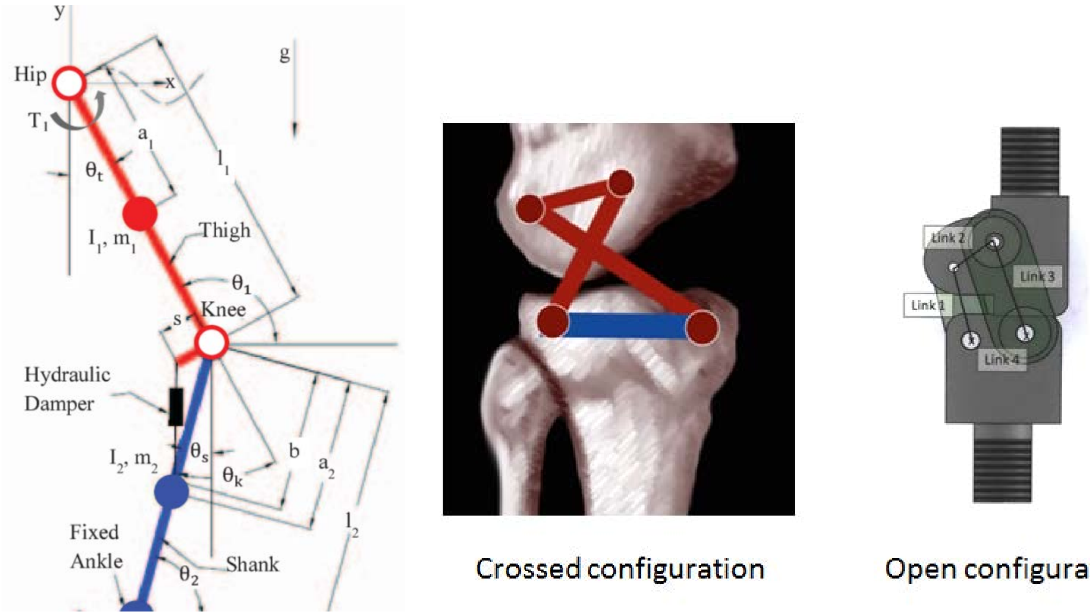
1. Introduction

Available knee join designs in the developing world differ greatly from those in the developed world. As of today, cuurent options for above knee amputees in the developed countries range from the most basic option of the single-axis knee to joins with onboard microprocessor phse control – the most advance available on the market doay. Individuals are prescribed specific knee prostheses based on age and expected level of activity and stability; elderly amputees will often employ more stable designs incorporating mechanical swing control while younger, more active amputees benefit greatly from the cadence and terrain variance achievable by designs utilyzing hydraulic and pneumatic phase controls.

In the developing world, due to economic conditions, most knee models tend to user purely mechanical means. Most individuals in developing countries have very limited access to medical care. As a consequence, these designs also must emphasize longevity and low failure rates in addition to the basic design. The most common model is the single axis knee with no swing phase control. This joint design suits the little to no maintenance lifespan seen by prosthesis and offers the lowes cost of manufacture and material supply. This design is notorious for its unstability and practically is used for static standing position. The schematic of this design is shown below.

An advancement of artificial knee joint was design is known as the Stanford Jaipur knee. It is an invention designed by the Stanford University, USA, working with a team from the Bahgwan Mahaveer Viklang Sahayata Samiti of India (hereafter will be referred as BMVSS). The Stanford-Jaipur Knee has been hailed by Time magazine (issue of November 23, 2009) as one of the 50 Best Inventions of the World in the year 2009. The Stanford-Jaipur Knee, also known as the Jaipur Knee, mimics normal human gait by providing stability in stance and easy movement. The Jaipur knee is based on the polycentric concept and is designed using the four-bar linkage geometry. It is made from oil-impregnated nylon. It comprises an upper and lower body block, two side linkages and a mid linkage, held together by four steel bolts. The body blocks have segments for socket and pylon attachment. The Jaipur Knee has been fitted on over 9,250 patients and BMVSS has received a very positive feedback in terms of acceptability, compliance, durability and performance. The mechanism of the Jaipur knee is a double rocker fourbar mechanism. Currently there are two variants of fourbar mechanism, i.e. the crossed and the open configurations respectively as shown in Figure 1.

The objectives of this research are to present the critical mechanism analysis and to highlight the key indicators for performance of Stanford-Jaipur Knees.



Crossed configuration

Open configuration

Figure 1. The mechanism of the Jaipur knee is a double rocker fourbar mechanism

2. Method of Research

To achieve these objectives, this research is conducted using the following methodology: (1) A kinematic and mechanism model for the knee is identified and mapped to the type of non-Grashoff fourbar linkage. The purpose of this identification and mapping is to model the best matching fourbar linkage. (2) As stated earlier in the abstract, this paper is aimed at providing framework for analysis of mechanism to be used to develop the mechanics of artificial knees developed by the affiliation of the author. Thus, this article follows the methodology of analysis of fourbar linkage in regular textbooks by Meriam [1], Beers [2], Norton [3], and Erdman [4]. Description of the foot are presented by Arya [5], Madeleine [6] and Kabra [7]. The social aspect of the foot can be found in many resources [8,9,10].

3. Model and Position Analysis of Fourbar Linkage

Once a tentative mechanism design has been synthesized, it must then be analyzed. The analysis starts with position analysis to express all the translational and rotational position of all linkages. Position analysis also aims to indicate the toggle positions if any. The next task of analysis is velocity analysis, and followed by acceleration analysis. The accelerations serve as the basis for analysis of all forces which load linkages and joints of the mechanism. The loading forces will in turn serve as the basis for dimensioning the actual linkages that satisy important and required safety measures.

The figure below shows a fourbar linkage along with its dimension and a particular position measured by three angles for. Usually, the angle θ_2 is given, and the angles θ_3 and θ_4 are calculated.

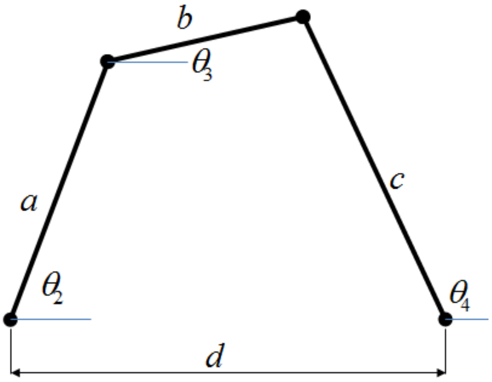


Figure 1. Dimension and rotational position of fourbar linkage

There are three methods for position analysis; they are the graphical analysis, the algebraic position analysis, and the vector loop analysis. The vector loop will be used in this article for conformance with computerized-based algorithm of position analysis. The calculation below is proposed by Norton in his text to find the angles of output output rocker, coupler, and toggle position of input rocker if any.

a. Calculation of Output Rocker

$A\tan^2\left(\frac{\theta_4}{2}\right)+B\tan^2\left(\frac{\theta_4}{2}\right)+C=0$ where $A=\cos\theta_2-K_1-K_2\cos\theta_2+K_3$, $B=-2\sin\theta_2$,

$C=K_1-(K_2+1)\cos\theta_2+K_3$, $K_1=\frac{d}{a}$, $K_2=\frac{d}{c}$, and $K_3=\frac{a^2+b^2+c^2+d^2}{2ac}$

The solutions are $\tan\left(\frac{\theta_4}{2}\right)=\frac{-B\pm\sqrt{B^2-4AC}}{2A}$ so that $(\theta_4)_{1,2}=2\arctan\left(\frac{-B\pm\sqrt{B^2-4AC}}{2A}\right)$,

$(\theta_4)_1=2\arctan\left(\frac{-B+\sqrt{B^2-4AC}}{2A}\right)$ for crossed configuration, and

$(\theta_4)_2=2\arctan\left(\frac{-B-\sqrt{B^2-4AC}}{2A}\right)$.for open configuration.

The term crossed and open are based on the assumption that (i) the linkage is a Grashof crank-rocker one and (ii) the position of the input link is $0\le\theta_2\le\frac{\pi}{2}$.

b. calculation of coupler position

Once the value of θ_4 is obtained, the remaining angular positions can be calculated as the followings:

$D\tan^2\left(\frac{\theta_3}{2}\right)+E\tan\left(\frac{\theta_3}{2}\right)+F=0$ where $D=\cos\theta_2-K_1+K_4\cos\theta_2+K_5$, $E=-2\sin\theta_2$,

$F=K_1+(K_4-1)\cos\theta_2+K_5$, $K_4=\frac{d}{b}$, and $K_5=\frac{c^2-d^2-a^2-b^2}{2ab}$.

The solutions are $(\theta_3)_1=2\arctan\left(\frac{-E+\sqrt{E^2-4DF}}{2D}\right)$ and $(\theta_3)_2=2\arctan\left(\frac{-E-\sqrt{E^2-4DF}}{2D}\right)$.

c. Position of coupler point and toggle

The position of any point on the coupler can be expressed as

$$\mathbf{r}_P=(r_2\cos\theta_2+p\cos(\theta_3+\delta_3))\mathbf{i}+(r_2\sin\theta_2+p\sin(\theta_3+\delta_3))\mathbf{j}$$

The toggle positions of link 2 can be expressed as $(\theta_{2,\text{toggle}})_1=\arccos\left(\frac{a^2+d^2-b^2-c^2}{2ad}\right)+\frac{bc}{ad}$ and

$(\theta_{2,\text{toggle}})_2=\arccos\left(\frac{a^2+d^2-b^2-c^2}{2ad}\right)-\frac{bc}{ad}$

4. Derivative A.k.a. Velocity and Aceleration

After position analysis, the next calculation is the velocity analysis; here the velocity refers to the rotational speed. Again, Norton proposes the followings for the analysis.

$$\omega_3 = \left(\frac{a\omega_2}{b}\right)\left(\frac{\sin(\theta_4 - \theta_2)}{\sin(\theta_3 - \theta_4)}\right) \quad \text{and} \quad \omega_4 = \left(\frac{a\omega_2}{c}\right)\left(\frac{\sin(\theta_2 - \theta_3)}{\sin(\theta_4 - \theta_3)}\right)$$

5. Acceleration analysis

$$\alpha_3 = \frac{CD - AF}{AE - BD} \quad \text{and} \quad \alpha_4 = \frac{CE - BF}{AE - BD} \quad \text{where}$$

$$A = c\sin\theta_4$$

$$B = b\sin\theta_3$$

$$C = a\alpha_2\sin\theta_2 + a\omega_2^2\cos\theta_2 + b\omega_3^2\cos\theta_3 - c\omega_4^2\cos\theta_4$$

$$D = c\cos\theta_4$$

$$E = b\cos\theta_3$$

$$F = a\alpha_2\cos\theta_2 - a\omega_2^2\sin\theta_2 - b\omega_3^2\sin\theta_3 = c\omega_4^2\sin\theta_4$$

6. Force Analysis

$$\begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ (-R_{12})_y & (R_{12})_x & (-R_{32})_y & (R_{32})_2 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & (R_{23})_y & (-R_{23})_x & (-R_{43})_y & (R_{43})_x & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & (R_{34})_y & (-R_{34})_x & (-R_{14})_y & (R_{14})_x & 0 \end{bmatrix} \begin{Bmatrix} (F_{12})_x \\ (F_{12})_y \\ (F_{32})_x \\ (F_{32})_y \\ (F_{43})_x \\ (F_{43})_y \\ (F_{14})_x \\ (F_{14})_y \\ T_{12} \end{Bmatrix} = \{\mathbf{q}\}$$

$$\text{where} \quad \{\mathbf{q}\} \quad \{m_2(a_{G,2})_x, m_2(a_{G,2})_y, I_{G,2}\alpha_2, m_3(a_{G,3})_x - (F_P)_x, I_{G,2}\alpha_2, m_3(a_{G,3})_x - (F_P)_x,$$
$$m_3(a_{G,3})_y - (F_P)_y, I_{G,3}\alpha_3 - (R_P)_x(F_P)_y + (R_P)_y(F_P)_x, m_2(a_{G,4})_x, m_2(a_{G,4})_y,$$
$$I_{G,4}\alpha_4 - T_4\}^T$$

7. Computation and Results

For testing purposes, a Jaipur knee is set-up to have links of the following lengths in milimeters 100, 150, 120, 130. A position analysis is calculated using an Excel tool by Slocum [11],

Crank Angle	Coupler Angle	Output Angle	Crank Angle	Coupler Angle	Output Angle
3.142	0.000	0.197	-0.063	4.130	0.197
3.079	0.067	0.197	-0.126	3.950	0.197
3.016	0.135	0.197	-0.188	3.780	0.197
2.953	0.202	0.197	-0.251	3.623	0.197
2.890	0.269	0.197	-0.314	3.480	0.197
2.827	0.337	0.197	-0.377	3.348	0.197
2.765	0.404	0.197	-0.440	3.226	0.197
2.702	0.471	0.197	-0.503	3.113	0.197
2.639	0.539	0.197	-0.565	3.007	0.197
2.576	0.607	0.197	-0.628	2.907	0.197

2.513	0.674	0.197	-0.691	2.812	0.197
2.450	0.742	0.197	-0.754	2.720	0.197
2.388	0.810	0.197	-0.817	2.633	0.197
2.325	0.878	0.197	-0.880	2.547	0.197
2.262	0.946	0.197	-0.942	2.465	0.197
2.199	1.014	0.197	-1.005	2.384	0.197
2.136	1.083	0.197	-1.068	2.305	0.197
2.073	1.151	0.197	-1.131	2.227	0.197
2.011	1.220	0.197	-1.194	2.151	0.197
1.948	1.289	0.197	-1.257	2.075	0.197
1.885	1.359	0.197	-1.319	2.001	0.197
1.822	1.428	0.197	-1.382	1.927	0.197
1.759	1.498	0.197	-1.445	1.854	0.197
1.696	1.569	0.197	-1.508	1.782	0.197
1.634	1.639	0.197	-1.571	1.710	0.197
1.571	1.710	0.197	-1.634	1.639	0.197
1.508	1.782	0.197	-1.696	1.569	0.197
1.445	1.854	0.197	-1.759	1.498	0.197
1.382	1.927	0.197	-1.822	1.428	0.197
1.319	2.001	0.197	-1.885	1.359	0.197
1.257	2.075	0.197	-1.948	1.289	0.197
1.194	2.151	0.197	-2.011	1.220	0.197
1.131	2.227	0.197	-2.073	1.151	0.197
1.068	2.305	0.197	-2.136	1.083	0.197
1.005	2.384	0.197	-2.199	1.014	0.197
0.942	2.465	0.197	-2.262	0.946	0.197
0.880	2.547	0.197	-2.325	0.878	0.197
0.817	2.633	0.197	-2.388	0.810	0.197
0.754	2.720	0.197	-2.450	0.742	0.197
0.691	2.812	0.197	-2.513	0.674	0.197
0.628	2.907	0.197	-2.576	0.607	0.197
0.565	3.007	0.197	-2.639	0.539	0.197
0.503	3.113	0.197	-2.702	0.471	0.197
0.440	3.226	0.197	-2.765	0.404	0.197
0.377	3.348	0.197	-2.827	0.337	0.197
0.314	3.480	0.197	-2.890	0.269	0.197
0.251	3.623	0.197	-2.953	0.202	0.197
0.188	3.780	0.197	-3.016	0.135	0.197
0.126	3.950	0.197	-3.079	0.067	0.197
0.063	4.130	0.197	-3.142	0.000	0.197
0.000	4.318	0.197			

8. Concluding Remarks

The previous exposition is adopted from Norton’s book and the exposition explains the sequence of analysis from position until force and torque. The author hopes that the short exposition above can help the students improve the quality of their final projects by providing steps of kinematics and dynamic analysis for the derivative of the Stanford-Jaipur knee.

References

1. Meriam, J.L., Kraige, L.G., 2010, Engineering Mechanics: Dynamics. 6th ed. John Wiley & Sons Inc.
2. Beer, F.P., Russell, J.E., Clausen, W.E., Staab, G.H., 2004, Vector Mechanics for Engineers, Dynamics. 7th ed. McGraw-Hill Publishing.

3. Norton RL Design of Machinery: An Introduction To The Synthesis And Analysis Of Mechanisms Of Machines. 2nd ed. McGraw-Hill Publishing; 1999.
4. Erdman, A.G.,Sandor, G.N., 1999, Mechanism Design: Analysis and Synthesis. 1st ed. John Wiley & Sons Inc.
5. Arya, A.P., Klenerman, L., 2008, The Jaipur Foot. Bone & Joint Journal, DOI: 10.1302/0301-620X.90B11.21131
6. Madeleine, S., 1994, The Jaipur Limb and Foot. Medicine and War, Vol. 10, No. 3, DOI: 10.1080/ 07488009408409166.
7. Kabra, S.G., Naryanan, R., 1991, Equipment and Methods for Laboratory Testing of Ankle-Foot Prostheses as exemplified by the Jaipur food. Journal of Rehabilitation Research and Development, Vol. 28, No.3, pp. 23-34.
8. Jaipur Foot [document on the Internet]. Available from http:// http://jaipurfoot.org.
9. Jaipur Leg [document on the Internet]. Wikipedia; no date. Available from: https://en.wikipedia.org/wiki/Jaipur_leg.
10. Jaipur Foot [document on the Internet]. Available from: http://www.goodnewsindia.com/index.php/ Magazine/story/jaipur-foot.
11. 4_bar_analysis.xls [document on the Intenet]. Slocum A., Yang X., Available from http://web.mit.edu/2.70/ Resources/ Linkages/Linkage_4_bar_analysis.xls.