

DESIGN AND ANALYSIS OF A 1-DOF WALKING MECHANISM

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ME6710: THEORY OF MECHANISMS

Abstract: This report describes the synthesis and analysis of a Single-Degree-of-Freedom (1-DOF) device to enable walking for people with locomotor difficulties. There are two designs described in the report. The first design is inspired by the Jansen Linkage, which is used in Theo Jansen's 'Strandbeests'. This design is closer to the human running gait. The second design emulates the 1-DOF leg for walking machines designed and built at the The Ohio State University.

Introduction

Walking is a gait of locomotion among legged animals, including humans. It is a complex motion, with actuation of muscles and nerves, and modeling this motion has been the focus of hundreds of researchers over the years. Research areas range from developing intelligent control mechanisms to biologically inspired walking mechanisms for various terrains. Various humanoid robots have been developed over the years, including Hadaly-2, WABIAN¹ and Honda's much-hyped Asimo².

The same area of research into the mechanism of walking has led to different types of exoskeletons and orthotic devices to assist human motion. Applications for these devices usually fall into either of two broad categories³: (1) augmenting of muscular force of healthy subjects, and (2) rehabilitation of people with motion impairments.

Between the extremely complex humanoid robots like Asimo (with twelve degrees of freedom) and the class of passive-dynamic walkers (that can walk stably down a slope and require gravity as their only source of energy⁴) there exist many robots that employ reduced actuation strategies and whose motions are restricted to the sagittal plane.⁵ While reduced DOF means restriction of motion to a single gait, it also has the benefits of increased simplicity and reduction in the number of actuators required.

TABLE 1: PROS AND CONS OF A SINGLE DOF MECHANISM COMPARED TO A HIGH DOF ROBOT⁶

PROS	CONS
Only one motor is needed	Range of motions is limited
Fewer sensors are needed	Motions may not be optimal
Control strategy is simplified	Structural integrity of robot may suffer
Cheaper and lighter	--

¹ Hashimoto, S. et al, *Humanoid Robots in Waseda University – Hadaly-2 and WABIAN*, 2002

² Masato, Hirose et al, *Development of Humanoid Robot ASIMO*, 2001

³ Aguirre-Ollinger, Gabriel et al, *Design of an active one-degree-of-freedom lower-limb exoskeleton with inertia compensation*, 2001

⁴ McGeer, T., *Passive Dynamic Walking*, 1990

⁵ McKendry, J., *Kinematic Design and Dynamic Analysis of a Planar Biped Robot Mechanically Coordinated by a Single Degree of Freedom*

⁶ Brown, B., *Design of a Single-Degree-of-Freedom Biped Walking Mechanism*, 2006

Biped Walking Theory

The motion of the human leg can be simplified to the swinging motion of the **femur** and the **tibia**. The walking motion is usually modeled as an inverted pendulum. There are two distinct phases in the walking gait – stance phase and swing phase.

The gait cycle begins when one foot contacts the ground and ends when that foot contacts the ground again. Thus, each cycle begins at initial contact with a stance phase and proceeds through a swing phase until the cycle ends with the limb's next initial contact. Stance phase accounts for approximately 60 percent, and swing phase for approximately 40 percent, of a single gait cycle.

Each gait cycle includes two periods when both feet are on the ground. The first period of double limb support begins at initial contact, and lasts for the first 10 to 12 percent of the cycle. The second period of double limb support occurs in the final 10 to 12 percent of stance phase. As the stance limb prepares to leave the ground, the opposite limb contacts the ground and accepts the body's weight. The two periods of double limb support account for 20 to 24 percent of the gait cycle's total duration.

Stance phase of gait is divided into four periods: loading response, midstance, terminal stance, and preswing. Swing phase is divided into three periods: initial swing, midswing, and terminal swing. The beginning and ending of each period are defined by specific events.⁷

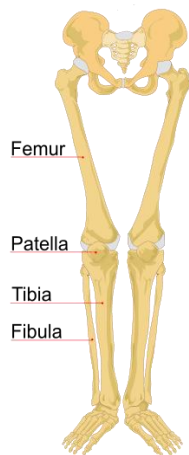


FIGURE 2: BONES IN A HUMAN LEG

IMAGE COURTESY:

[HTTP://ATEC.UTDALLAS.EDU/MIDORI/HANDOUTS/WALKINGGRAPHS_FILES/GAIT.JPG](http://ATEC.UTDALLAS.EDU/MIDORI/HANDOUTS/WALKINGGRAPHS_FILES/GAIT.JPG)

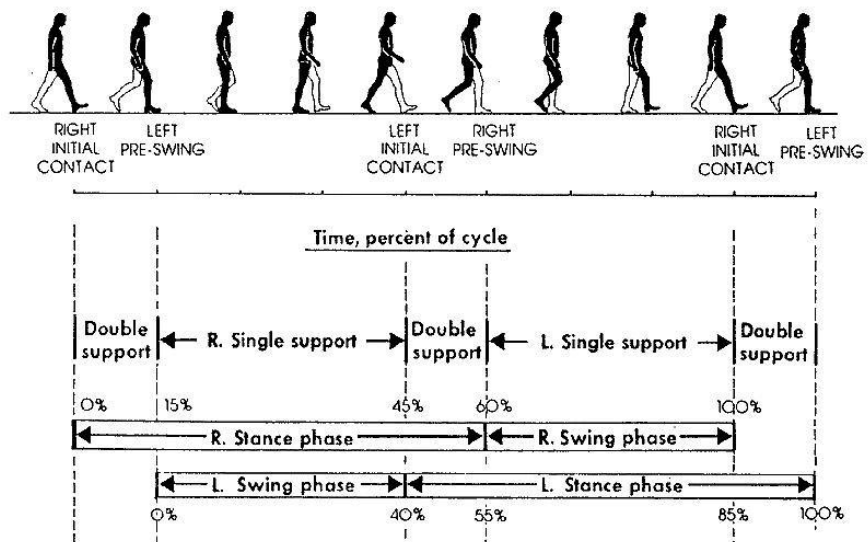


FIGURE 1: WALKING GAIT OF A HUMAN BEING

IMAGE COURTESY:

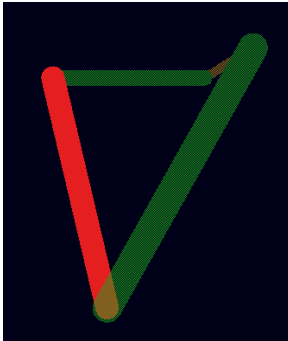
[HTTPS://UPLOAD.WIKIMEDIA.ORG/WIKIPEDIA/COMMONS/THUMB/7/7E/HUMAN_LEG_BONES_LABELED.SVG/436PX-HUMAN_LEG_BONES_LABELED.SVG.PNG](https://upload.wikimedia.org/wikipedia/commons/thumb/7/7E/Human_Leg_Bones_Labeled.svg/436px-Human_Leg_Bones_Labeled.svg.png)

⁷ <http://moon.ouhsc.edu/dthompson/GAIT/TERMS.HTM>

Mechanism I: Design

Initial Assumptions and Approach

We note that the femur and the tibia execute a rocking motion. The approach taken is to first achieve the motion of the femur, and then add to it the motion of the tibia.

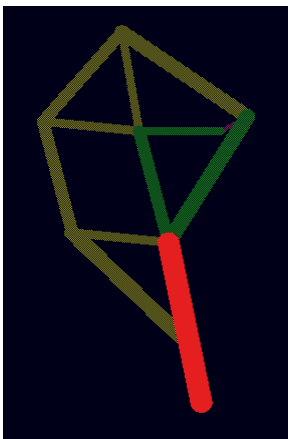


Femur Motion Consideration

To achieve the motion of the femur, we use a four-bar, as shown in the Figure 3 (left).

- The red link represents the femur.
- The horizontal link is the (fixed) hip
- The shortest link is used as the input crank.

FIGURE 3: FOUR-BAR TO ACHIEVE ROCKING MOTION OF THE FEMUR



Tibia Motion Consideration

The tibia is represented by the red link in the figure on the right.

- We have to achieve a swinging motion of the tibia
- The motion of the tibia has to be coordinated with the motion of the femur
- The same input crank must provide the motion for the tibia
- This is achieved using a set of parallelogram linkages

FIGURE 4: THE MECHANISM TO ACHIEVE ROCKING OF TIBIA. THE TIBIA IS SHOWN IN RED.

Figure 5 highlights the different linkages required for constraining and causing the rocking motion of the tibia. The crank (seen in 1) is a part of the four-bar (seen in 2), which actuates the tibia (red link in 5) through the four-bar (seen in 4).

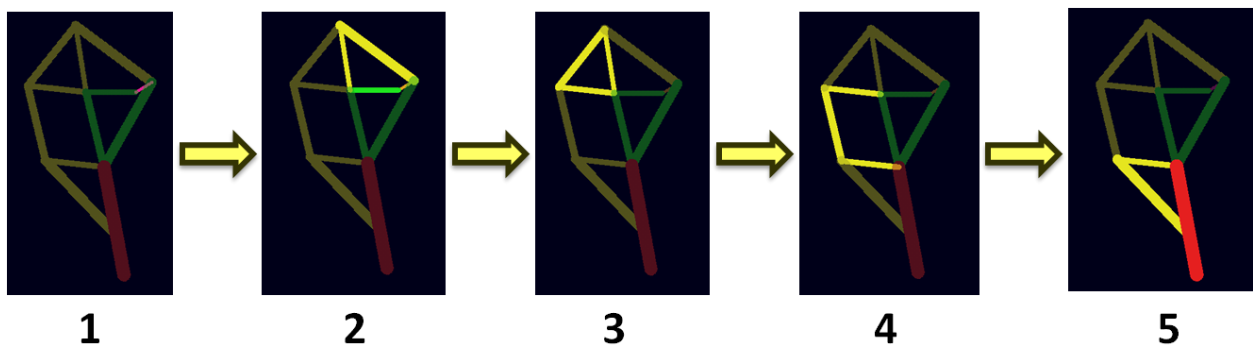


FIGURE 5: DESIGNING THE PANTOGRAPH FOR THE MOTION OF THE TIBIA

Final Design (Mechanism I)

Figure 6 shows the 12-bar final design of Mechanism I. Please view the file “ME09B053_ME09B128_Mechanism1.avi” for an animation of the same.

The bottom-most point of link 5 represents the foot. The trace of the foot is close to an airfoil shape, and this trace is close to the human running gait.

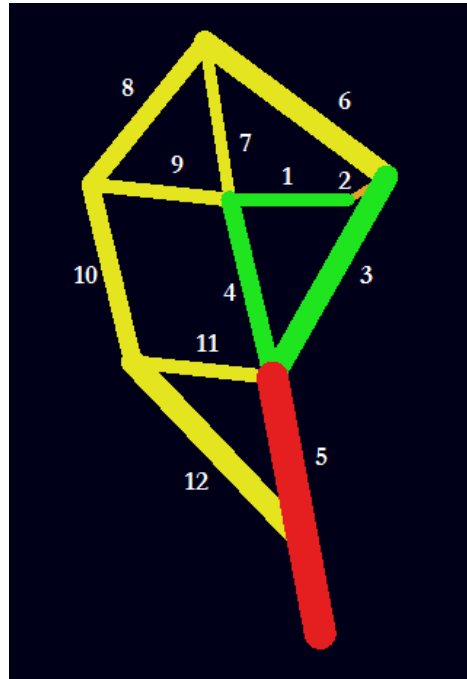
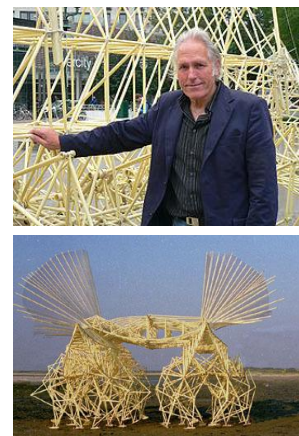


FIGURE 6: FIRST DESIGN OF 1-DOF MECHANISM FOR WALKING

Inspiration: Theo Jansen and Strandbeests

‘Mechanism I’ designed above is inspired by Jansen’s linkage, which is a planar mechanism designed by the kinetic sculptor Theo Jansen to simulate a smooth walking motion⁸. He used these linkages in designing large mechanical animals called ‘Strandbeests’ (literally meaning ‘beach beast’) that can live on their own. He optimized the lengths of the linkages of the linkage to best simulate the gait of an animal⁹. The optimization of the link lengths for the Strandbeest was done using a genetic algorithm (evolutionary method).

FIGURE 7: THEO JANSEN AND A STRANDBEEST MADE FROM PVC



⁸ http://en.wikipedia.org/wiki/Jansen's_linkage

⁹ http://www.strandbeest.com/beests_leg.php

Mechanism II: Design

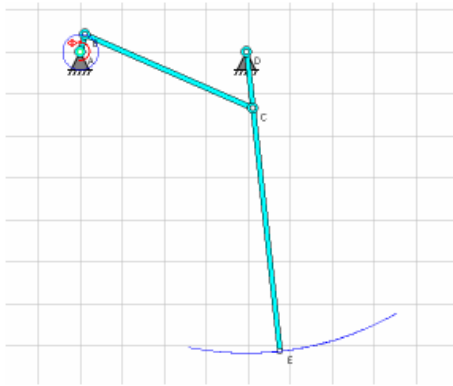


FIGURE 9: FEMUR CONCEPTUAL DESIGN

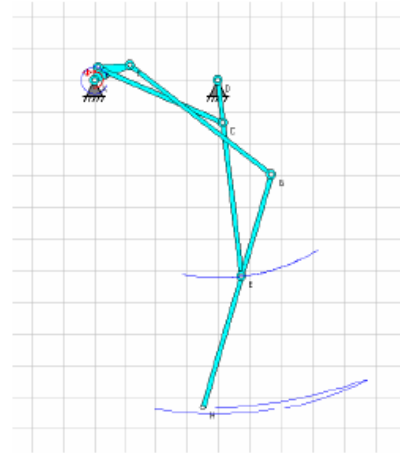


FIGURE 8: TIBIA CONCEPTUAL DESIGN

The second design emulates the design of the single degree-of-freedom kinematic mechanism to accomplish biped walking for the robot BIRT, developed in The Ohio State University. In the paper 'Design of a Single-Degree-of-Freedom' by Brett C. Brown (Undergraduate Honors Thesis), the design of the motion for BIRT is discussed. Starting from the desired walking motion, the design considerations of the femur and tibia, using four-bar mechanisms are considered.

Using the values of the scaled link lengths given in optimized Four-bar Femur with Tibia mechanism, calculations (found in 'Appendix') were done to model the mechanism in a given position. The model was then made in MSC Adams.

Final Model

Figure 6 shows the 12-bar final design of Mechanism I. Please view the file "ME09B053_ME09B128_Mechanism2.avi" for an animation of the same.

The bottom-most point of link 7 represents the foot. The trace of the foot is closer to a straight line than that of Mechanism I, and this trace closely resembles the human walking gait.

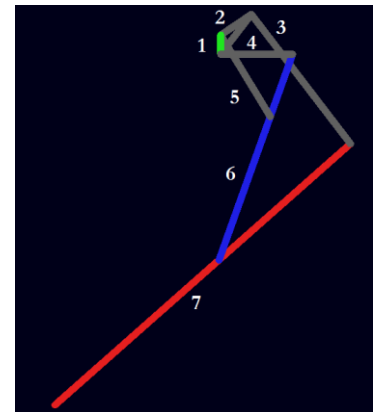
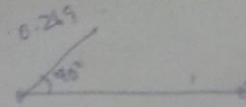
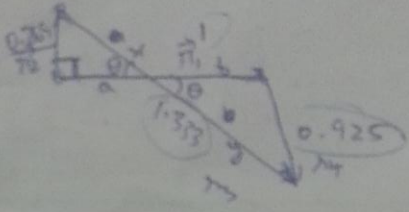


FIGURE 10: MECHANISM II

Summary and Conclusions

Thus, by simulating the human walking and running gait, two linkages have been designed, which can be included in an assistive device for use by people with locomotor difficulties.

Appendix

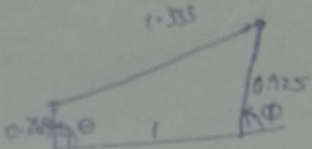



$$\vec{r}_2 + \vec{r}_3 = \vec{r}_1 + \vec{r}_4$$

$$r_2 e^{j\theta_2} + r_3 e^{j\theta_3} = r_1 + r_4 e^{j\theta_4}$$

$$r_2 \cos \theta_2 + r_3 \cos \theta_3 = r_1 + r_4 \cos \theta_4$$

$$r_2 \sin \theta_2 + r_3 \sin \theta_3 = r_4 \sin \theta_4$$



$$r_3 \cos \theta_3 = r_1 + r_4 \cos \theta_4 - r_2 \cos \theta_2$$

$$r_3 \sin \theta_3 = r_4 \sin \theta_4 - r_2 \sin \theta_2$$

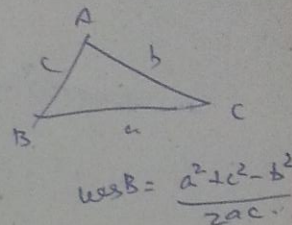
$$r_3^2 = [r_1 + r_4 \cos \theta_4 - r_2 \cos \theta_2]^2 + [r_4 \sin \theta_4 - r_2 \sin \theta_2]^2$$

$$r_3^2 = r_1^2 + (r_4 \cos \theta_4 - r_2 \cos \theta_2)^2 + 2 r_1 r_4 \cos \theta_4 - 2 r_1 r_2 \cos \theta_2 + r_4^2 \sin^2 \theta_4 + r_2^2 \sin^2 \theta_2 - 2 r_2 r_4 \sin \theta_2 \sin \theta_4$$

$$r_3^2 - r_1^2 = r_4^2 \cos^2 \theta_4 + r_2^2 \cos^2 \theta_2 - 2 r_2 r_4 (\cos(\theta_2 - \theta_4) + \cos \theta_4 \cos \theta_2)$$

$$\cos(\theta_2 - \theta_4) = \frac{r_1^2 + r_4^2 + r_2^2 - r_3^2}{2 r_2 r_4} + \frac{r_1}{r_2} \cos \theta_4 - \frac{r_1}{r_4} \cos \theta_2$$

$$\cos(\theta_4 - \frac{\pi}{2}) = \frac{0.303621 + 5.744 \cos \theta_4}{-1.08108}$$



$$\Phi = 85.4768$$

$$(0.169056, -0.90942)$$

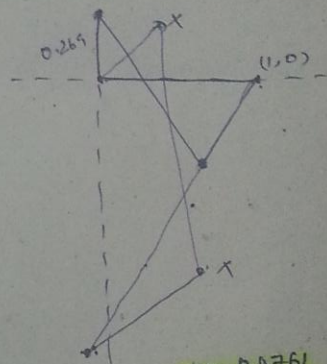
$$\alpha = 15.6562$$

$$\sqrt{1 - \alpha} = 70.4205$$

$$A = -2 \cdot 30 + 8$$

$$y = -4.9058$$

$$(-0.3099807, -0.1871514)$$



$$n = -0.4761$$

$$u = -3.2788$$

2. -

17 -

25

24-

$$g_5 = 0.703$$

$$\lambda_6 = 2.276$$

$$g_{17} = 2.450$$

$$-1.806509)^2$$

$$+ (y + 1.25133)^2$$

$$= \frac{2.053^2}{5.503}$$

$$\frac{2 + 1.025133}{2 - 1.8065} = 0.88824$$

• 1.806509

$$y + 1.25133 = 0.88824x$$

$$= 1.604612$$

$$\rightarrow p =$$

$\tan \phi = 0.88524$

29.836A

3.46457

2.856

$$(-0.02309, -2.87646)$$

74.68738

27.31908