Bioengineering Fundamentals and Applications in Biomechanics

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http://www.cityrehab.co.uk/file/images/Biomechanical-Movement-Analysis-Liverpool-3.jpg

Version 2016

Bioengineering

Combining the tools and methods of engineering for the benefit of living systems.

Chemical	Civil	Computer	Electrical	Mechanical
•Pharmaceuticals •Plastic Materials •Blood Analysis	•Bone Structures •Dental Structures	•Imaging Software •Expert Diagnosis •Monitoring Software	•Medical Instruments •Monitoring Eqpmt. •Imaging Equipment •Signal Processing •Digital Electronics •Hearing aids •Heart Pacers	•Sports Equipment •Prosthetic Devices •Motion Studies •Orthotics •Rehabilitation Aids •Blood Flow/Pumps •Heart Valves •Surgical Equipment •Dental Equipment

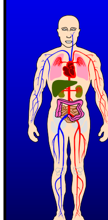




What is required to work in the field of bioengineering?

- An interest in applying your engineering knowledge to living systems.
- Most generally an undergraduate degree in engineering coupled with a graduate degree in either engineering or medicine is required.

In this presentation:



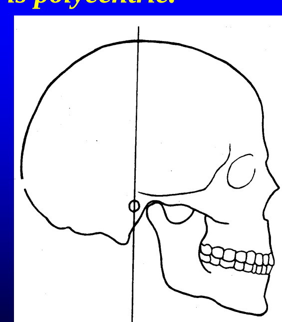
- A discussion of research involving polycentric motion of human joints.
- A discussion of research involving new types of crutches to assist the disabled.
- A look at recent advances in the fitting of prosthetic limbs.
- A look at the use of alginate molds for prosthetic limb fitting.
- A demonstration of some research dealing with the prediction of human growth.

What is polycentric motion?

- Polycentric motion is motion that does not have a single fixed pivot center but where the pivot can move as the motion takes place.
- Polycentric motion can allow the “mechanical advantage” of a system to change as rotation takes place.
- Polycentric motion can allow a joint to be “self locking.”
- Most joints of the human body are polycentric.

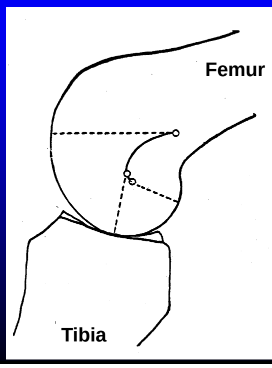
The human jaw is polycentric.

We can exert more chewing force when our upper and lower teeth are nearly touching each other than we can when our mouths are wide open. This is because of the changing mechanical advantage of the pivot center as well as the changing orientation of the muscle attachments.



Coronal Plane

The Human Knee Joint is Polycentric



The human knee also has the ability to be "self locking." This means that we can remain upright without the need to exert muscle forces.

The hood on most cars is pivoted using a polycentric mechanism:

- Rather than a single pivot, the polycentric joint of a car hood makes it easier to open the engine compartment and makes it easier to keep the hood safely latched while the car is in motion.

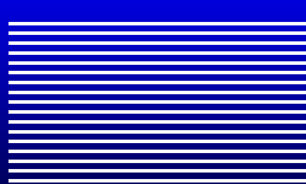
Why seek to understand polycentric motion?

- If we can understand polycentric motion, we can design better prosthetic limbs and braces.
- Better prosthetic joints can provide enhanced utility:
  - Better stability and the ability to "self lock"
  - More natural appearance in the movement
  - Less energy required to use.

How can we measure the location of the pivot center of a human joint?

- Dissect the joint and measure its structure.
  - Unfortunately, because every person is of a different size, every joint is unique.
- Attach targets to the bones of the two joint segments and take photographs of closely spaced positions.
  - This can be painful if attachments to the bones are needed, and has inaccuracies if the motion range is small.
- Take multiple x-ray pictures.
  - This has radiation hazards.
- Develop a new method.

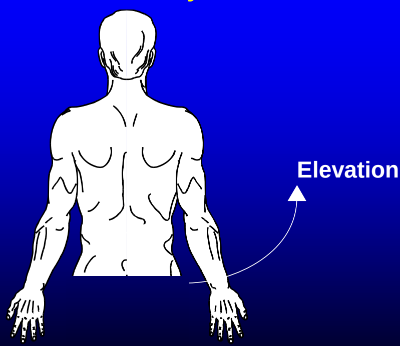
Moire Fringe Optics



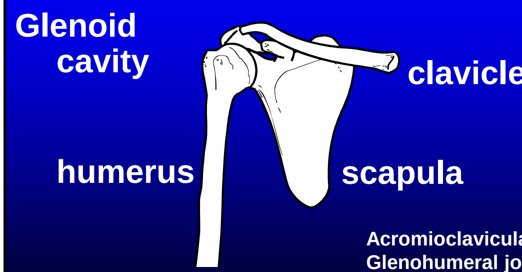
The Fundamental Theory of Moire Fringe Optics.

- The p=0 fringe goes through the pivot center.
- Two grid patterns will be needed to completely define the pivot center.
- As the two positions get closer together, the fringes are wider and thus easier to identify.

The motion we will study.



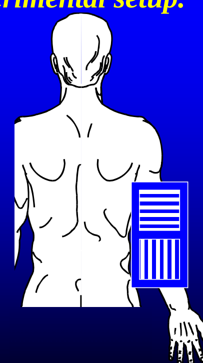
The anatomy of the human shoulder joints.



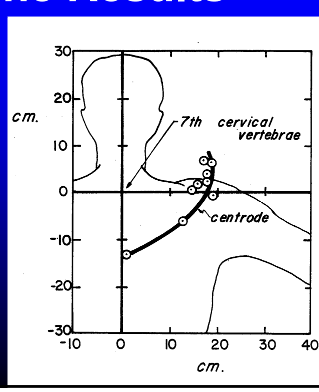
Acromioclavicular joint
Glenohumeral joint
Sternoclavicular joint
Scapulothoracic joint

To provide a landmark for experimental reference, the spinous process of the 7th Cervical Vertebrae was used.

The experimental setup.



The Results



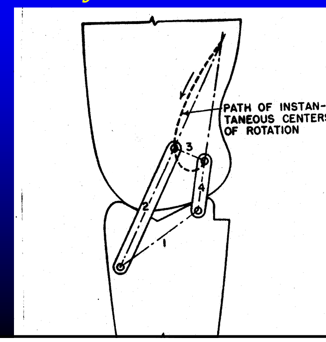
What we've learned from the development of the Moire' Fringe Method.

- We have developed a reliable method for determining pivot centers for the relative motion of two members.
- The method is not harmful to the subject.
- The method is especially well suited for closely spaced positions, where other methods fail.
- The method is based on simple optics and gives excellent results.

The Work of other Researchers.

There is always a need for improved designs to assist the disabled.

The University of California Knee is one of the best polycentric designs available today.



Let's look at the difference between a single axis knee and a polycentric knee by using some models:

Polycentric motion of a prosthetic knee takes less energy to use, provides better stability, and a more natural appearing gait.

- A polycentric joint is often implemented with the links layered as shown on the photos below.
- The hardware may be made of titanium, steel, aluminum, fiber reinforced composites or high quality plastics.

The walking gait cycle is divided into two major phases: stance phase and swing phase.

- The stance phase happens when your foot is on the ground, when you are applying weight to your prosthetic leg.
  - During this phase you want the knee joint to be locked and the leg to give you maximum support.
  - You may also want the leg to flex a small amount to act as a shock absorber.
- The swing phase is when your prosthetic foot is in the air and swinging forward.
  - During this phase you want the knee joint to be flexible and the lower leg to be able to swing in order to return it to the forward position.
  - You may want the leg to swing at a prescribed rate in order to bring it to the front position at just the right time.

Some challenges associated with the design of modern prosthetic legs:

- Although a polycentric knee is stable in its straight position, it is unable to carry weight when it is flexed.
- Different types of gaits require different amounts of flexibility on the return swing in order to get the timing right.
- Not all uses of a prosthetic limb are for walking. Other modes might include standing, running, dancing playing sports or rising from a chair.
- Cost can be an issue.

Microprocessor controlled legs:

- These legs have sensors to detect contact with the floor and to detect movement rates/positions.
- The microprocessor can control the flex rates of joints and can even lock the joints for protection against stumbling.
- Some of these are waterproof and have batteries that can last as long as 5 days.
- Some of these use bluetooth for selecting different operating modes such as walking, running, stair climbing, playing golf, bicycling, etc.

Let's look at a recent advance in the design of prosthetic limbs:

- One of the recent advances in prosthetics is the incorporation of a microcontroller along with artificial intelligence to control the knee in an artificial leg.
- https://www.youtube.com/watch?v=g3LpV2NXKX4
- This design, the RHEO Knee 3 from a company Össur in Iceland, utilizes a microcontroller to adapt the knee from fully locked to freely swinging. This knee uses artificial intelligence and automatically adapts to an individual's walking style and optimizes control. It has batteries that can last for up to 3 days without charging.

A mechanical engineer named Krista Donaldson, a graduate of Vanderbilt University and Stanford University, is the CEO of D-Rev, a company in San Francisco that has addressed affordability.

- https://www.youtube.com/watch?v=LIy2oVJtJsA

What about Future Work?

- A good research project will usually discover several additional projects that need to be undertaken.
- The motion of the knee joint is actually three dimensional. This suggests that there might be a need to measure three dimensional pivot motion with some optical method. Once measured, there is a need to design devices to duplicate this complex motion.

Crutches have not changed much in the past 4800 years!

Carving executed in 2830 B.C. on the entrance of Mekhu and Sabni's tomb in Egypt. *Note staff of crutch held by the right hand, left hand grasps arm rest.*

http://slsongtravel.blogspot.com/2010/08/tomb-of-mehku-and-sabni.html

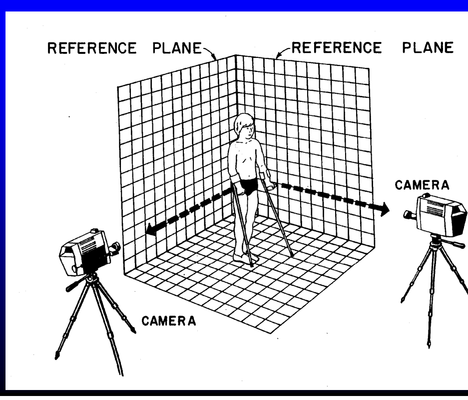
16th Century Dutch Woodcut known as the “Dance of Death.

Source: Epstein, S. “Art, History and the Crutch,” Annals of Medical History, 9:304-13, July 1937.

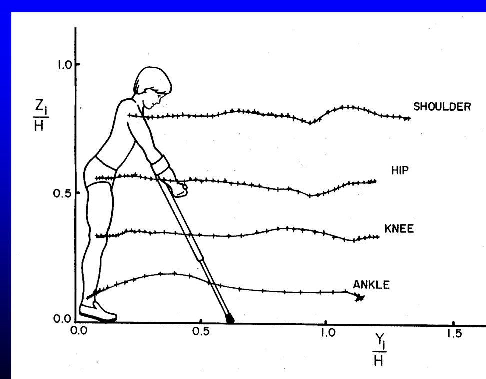
What is needed in a new type of crutch?

- Reduced need to raise and lower the center of mass of the body during the body-swing portion of gait.
- Mechanical energy storage that is conservative.
- Reduced impact to the upper body when planting the crutch tips.

The experimental setup



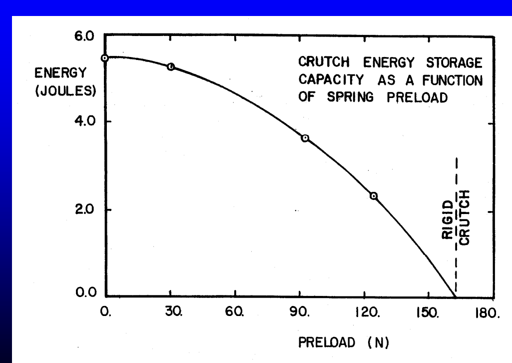
Experimental data for the rigid crutch.



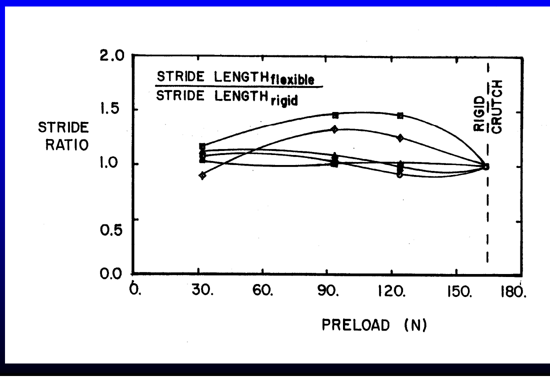
The “Pogo” Crutch

- Designed on the principle of the pogo stick.
- Designed with a variable preload to allow stability.
- Constructed with strain gages to allow measurement of load - vs - time.

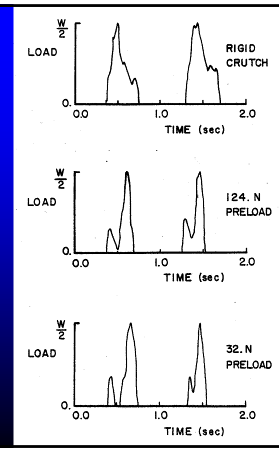
The energy storage capacity of the Pogo Crutch



Results for the Pogo Crutch



Load impact of the pogo crutch



What we have been able to achieve.

- **A new type of crutch with an energy savings of up to 25%.**
- **A crutch that cuts the initial impact load pulse by one half.**
- **A crutch that is more fun to use.**

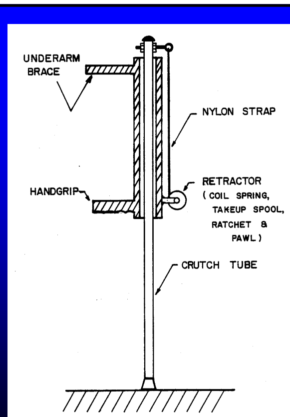
What about Future Work?

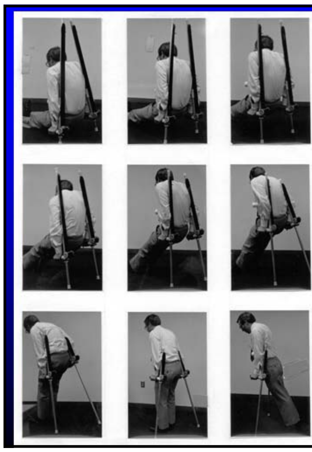
- **A good research project will usually discover several additional projects that need to be undertaken.**
- **There are a number of design innovations that are needed in the domain of crutches. Some of these center around the materials used, and others center around functional utility.**

The mechanical lift crutch.

Based on the use of a ratchet and pawl mechanism.

This crutch allows someone who has fallen to return to a standing position.

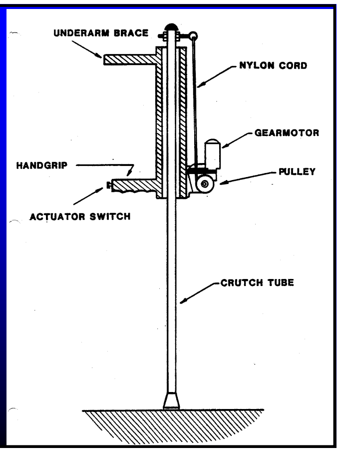




The use of the mechanical lift crutch.

The electrical lift crutch.

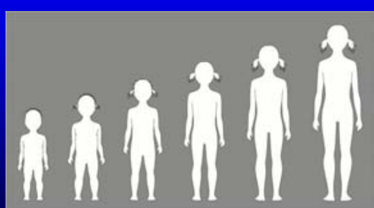
An electric version of the mechanical lift crutch.



A recent advance in materials has made it possible for enhanced comfort for those who wear prosthetic limbs.

- This material was also used to assist an injured dolphin in the movie "Dolphin Tale."
- https://www.youtube.com/watch?v=L_GlLW-kQDE
- The process of fitting a prosthetic limb is one of finding the shape of the socket that best matches the remaining part of the limb.
- One of the ways to do this is to use an alginate mold to create a model of the remaining part. This part then can be used to create the best possible socket for an artificial limb.
- Let's look at the process of making an alginate mold.

Development of a mathematical model to predict human growth.



Suppose you have been asked to design a cell phone app that will allow health care workers to predict the height of a child based on the age in number of years.

Development of a mathematical model to predict human growth.

- There is a need to develop a closed form mathematical equation for predicting growth of humans.
- This equation could be used to predict adult height based on intermediate size. It would also be useful to aid in the early prediction of growth difficulties.
- A number of researchers in the early 1960's made attempts at this problem, but the mathematical and computational tools available to them were somewhat limited.

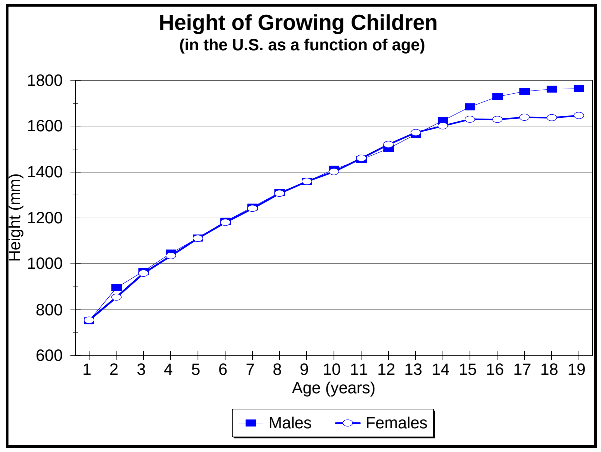
The Problem:

- Our problem is first to propose a suitable mathematical form.
- Next we must determine the best coefficients for this form. (This means that we must know how to determine goodness of fit.)
- Then we must look at the results and see if they are satisfactory. If not, we must go back and modify our proposed mathematical form.

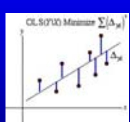
Height of Growing Children in the U.S.

Source: Krogman, W. M., "A handbook of the measurement and interpretation of height and weight in the growing child," Child Development publications, Evanston, IL, 1950.

Age (years)	Males Height (mm)	Females Height (mm)
1	751.67	754.17
2	896.19	854.29
3	967.50	959.13
4	1046.76	1035.29
5	1111.76	1110.75
6	1185.88	1180.54
7	1247.24	1241.00
8	1310.75	1307.40
9	1358.35	1359.10
10	1411.88	1401.18
11	1454.35	1460.54
12	1503.30	1520.24
13	1564.49	1571.93
14	1624.14	1601.11
15	1684.61	1629.79
16	1728.42	1629.42
17	1751.68	1629.19
18	1761.51	1637.25
19	1763.40	1646.15



Our research approach:



- **What we want is a mathematical formula that comes up asymptotically to the adult height.**
- **We will define data error as the square of the difference between the true value and the mathematically predicted value.**
- **We want to minimize the sum of the square of all 19 data errors. This is called a "least squared error process."**

We have decided to try two different forms:

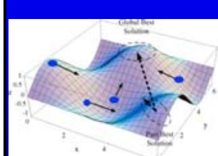
A simple inverse polynomial with various coefficients:

$$h = C_1\left(1 - \frac{C_2}{t} - \frac{C_3}{t^2} - \frac{C_4}{t^3} - \frac{C_5}{t^4} - \ldots\right)$$

A simple polynomial with various coefficients:

$$h = C_1 + C_2 t + C_3 t^2 + C_4 t^3 + C_5 t^4 \ldots.$$

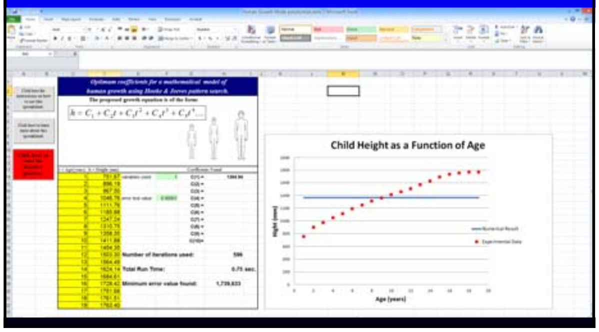
We developed two optimization programs that use the Hooke & Jeeves Pattern Search Algorithm.



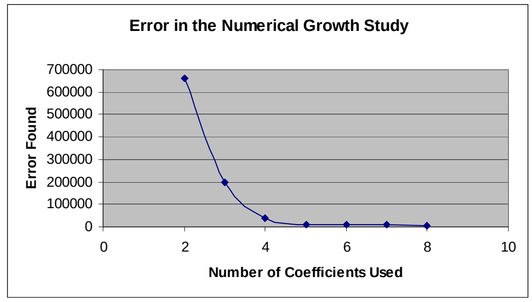
- **This algorithm is one that is very well suited to handling problems with many variables to be found.**
- **It involves making simple explorations in each of the design variable directions to find the best solution direction.**
- **This algorithm is one of the most efficient methods since it allows the computer to accelerate when a promising direction has been found.**
- **We developed our program so that we can experiment with different numbers of coefficients to be found.**

Lets look at the two programs that we developed. The first is for the inverse polynomial:

Lets look at the two programs that we developed. The second is for the regular polynomial:



This shows that the accuracy improves as the number of coefficients used is increased.



What we have learned so far is:

- **Using a higher number of coefficients gives better results to a point.**
- **Using a higher number of coefficients requires more computational time because there are more numerical experiments to be performed.**
- **Both of the proposed mathematical models have good utility, but the regular polynomial seems to be the best so far.**

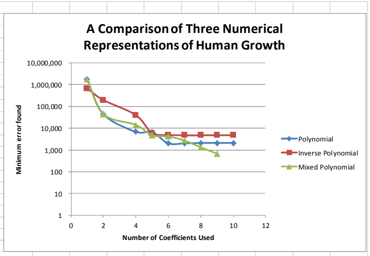
So we decided to try a blend of the two formulas to see if the blend might be better than any of the single methods alone. We proposed:

A blend of regular and inverted polynomials:

$$h = C_1 + C_2 t + \frac{C_3}{t} + C_4 t^2 + \frac{C_5}{t^2} + C_6 t^3 + \frac{C_7}{t^3} + \ldots\ldots$$

Results

Coefficients	Error Polynomial	Error inverse Polynomial	Error Mixed Polynomial
1	1,739,633	658,793	1,739,633
2	44,138	196,895	44,138
4	6,779	40,007	14,144
5	6,739	5,982	4,820
6	2,010	4,897	4,157
7	2,010	4,686	2,702
8	2,101	4,771	1,324
9	2,101	4,771	686
10	2,101	4,774	



Conclusions from this study:

- **Any good research project will create many more ideas for further study.**
- **There is a need to investigate other mathematical representations.**
- **There is a need to investigate other aspects of growth such as weight, size of the forearm, shoe size, girth of the head, etc.**
- **There is a need to investigate the impact of other factors on growth. For example, culture, environment, diet, amount of exercise, etc.**
- **There may be a similar relationship for the shrinkage of bone with age. This could be investigated.**