Servo-Assisted Lower-Body Exoskeleton With a True Running Gait

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DARPA Workshop on
Exoskeletons for Human Performance Augmentation (EHPA)
March 1-3, 2000
Washington, DC

Military performance from powered SpringWalker

Photo from Discover Magazine, December, 1992

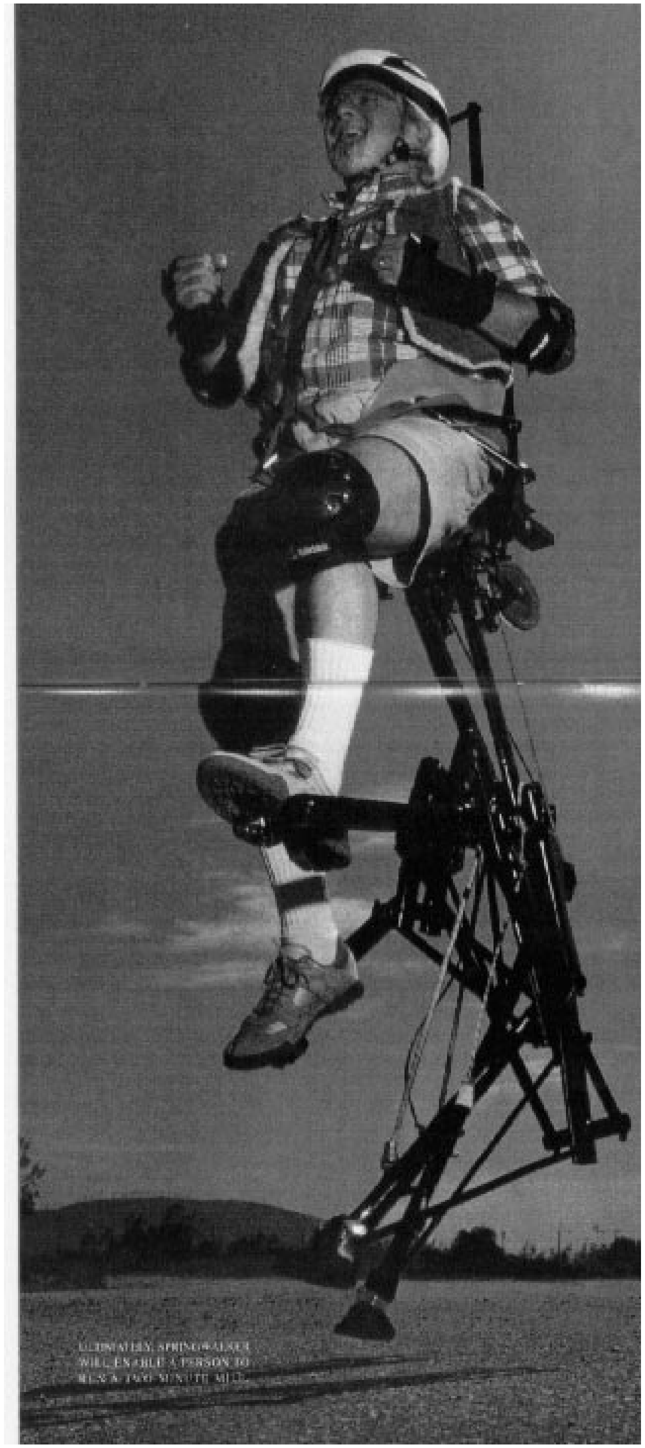


Photo by Brian Smale

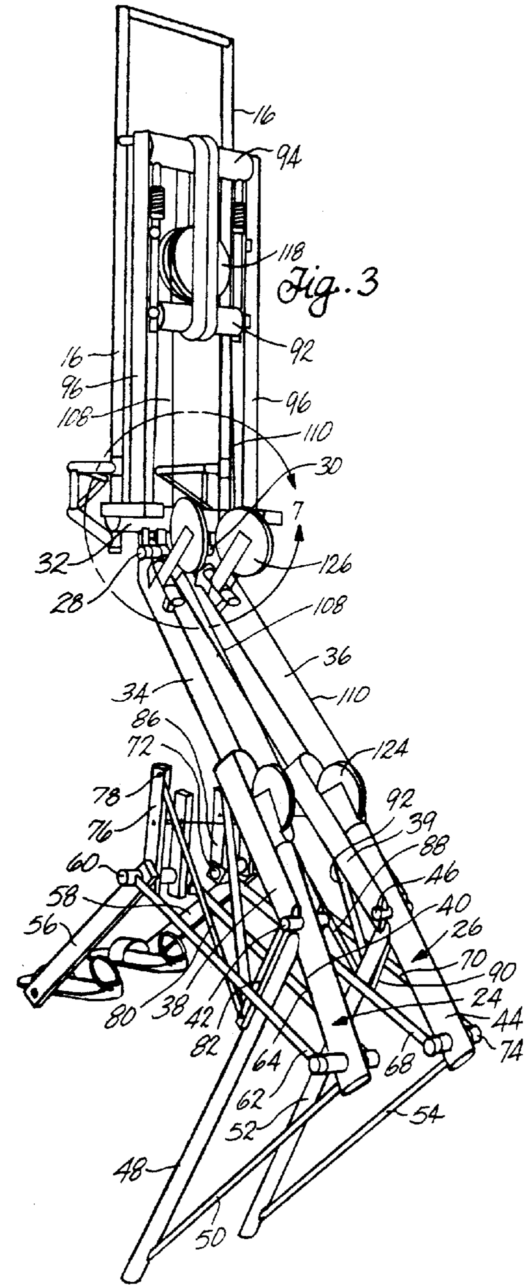
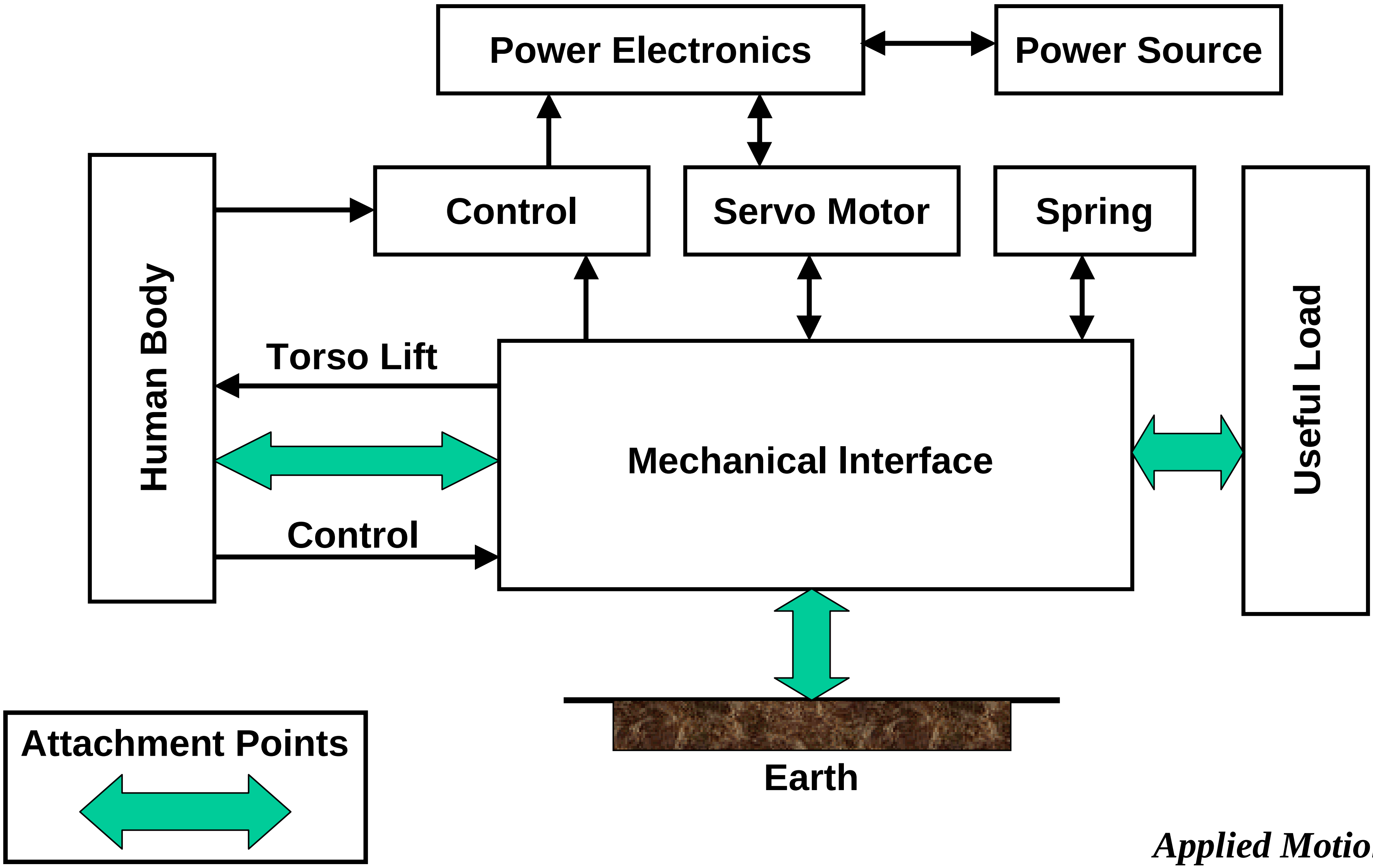


Figure from US Patent 5,016,869

Promise of "Amplified Man"

- **Amazingly Difficult Problem**
  - **150 Years of Mechanical Technology and 30 years of high power servos, and still No Powered Exoskeleton**
  - **An Important Problem -- Equivalent of Auto, Airplane, Space Flight**
- **Problem deserves our Respect**
  - **Performance, Performance, Performance**
  - **Must Not constrain solution at this Early Stage**
    - **We're sure to continue to fail**
    - **Would we tell the Wright Bros. "Gliders are good but IC Engine too loud, Must use Steam"?**
    - **Once found, adapt solutions to needs**
- **Opportunity is Now**
  - **On the verge of breaking through -- precursors everywhere**
  - **Once done, will be everywhere**

Exoskeleton Sub-Systems



Exoskeleton Mechanical Interface

- **Mechanical Interface is a part of all Exoskeleton designs to date**
  - **Mechanical coupling to user's own feet**
    - **Provides absolute feedback to user**
    - **Allows user input into gait**
      - **Energy**
      - **Control**
  - **Direct interface not required in principle**
    - **Physical attachment could be replaced by 'Walk by Wire'**
    - **Not practical now**
- **Several different interfaces have been studied**
  - **Parallel Interface -- adds force**
  - **Series Interface -- adds motion**
  - **Leveraged Leg Interface -- adds force and/or motion**
- **High exoskeleton performance requires added force AND motion**
  - **Increased load requires added force**
  - **High performance gaits require added motion**
    - **Load leveling required by fast walking gaits**
    - **Stride lengthening required by enhanced running gaits**

Parallel Configuration

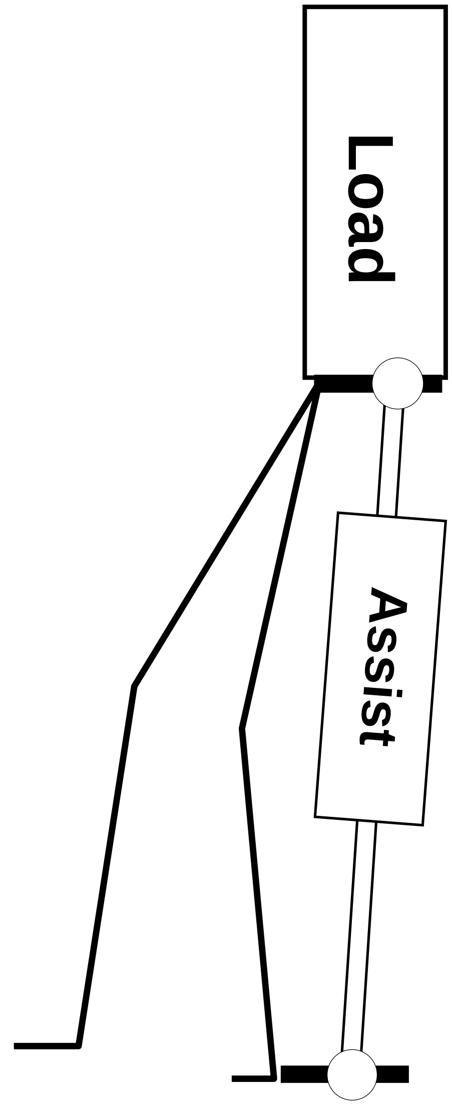
INCREASES STRENGTH

- Load Carrying
- High-g Gaits
- Energy Recovery
- Power Assist

CONTROLLABILITY

- User Force is directly effective
- Gives Position feedback to user
- Passive assist requires disengagement to allow foot lift
- Active assist needs ∞ Impedance to allow direct user control
- Exoskeleton assist adds Force

EXAMPLE -- Active-Skin Exoskeleton



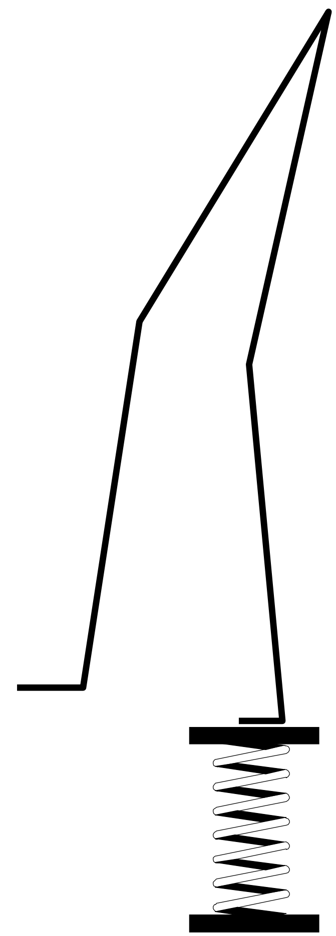
Series Configuration

INCREASES EXTENSION

- **Shock Reduction**
- **Energy Recovery**
- **Possible Increased Joint Stress**
- **Can be added in combination with parallel assist**

CONTROLLABILITY

- **User Motion is directly effective**
- **Passive Assist can cause foot-dragging, interfere with normal gait**
- **Gives direct Force feedback to user**
- **Active assist adds Motion**



EXAMPLE: Active Boot

Leveraged Leg

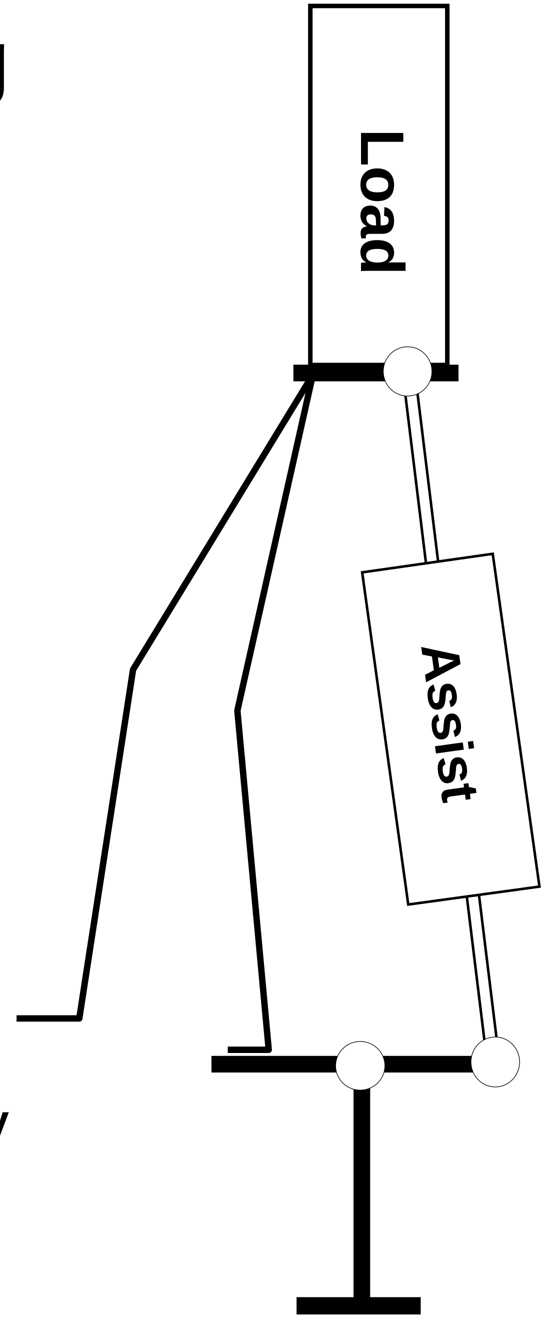
LEVERAGE RATIO from 1:1 to ∞ :1

- **Leverage increases Strength, Assist adds Extension**
- **Load Carrying Capability**
- **High-g Gait**
- **Shock Reduction**
- **Power Assist**
- **Energy Recovery**

CONTROLLABILITY

- **User Motion is directly effective**
  - **Even with Lock-up of Assist**
- **Continuous Force feedback**
- **Active assist adds Motion**
  - **Single assist gives proportionally increased Strength and Motion**

EXAMPLE -- SpringWalker



SpringWalker Approach

- Spartan approach enables true running gait without servo assist
  - Enhances only the highest power mechanical circuit--leg extension
    - Leveraged Leg provides increased foot force
    - Spring energy recovery
    - Other degrees of freedom controlled directly by user’s legs
  - Significant Problems Identified and Solved
    - Leveraged Leg provides fail-safe user control and feedback
    - Foot-dragging prevented by Single Spring acting in parallel on two legs
    - Cable tension is proportional to lift--use to move effective support point directly under user’s center of gravity
  - Shows Walking gaits and a True Running gait with natural user leg action
- Provides Excellent Interface between needs of human walking and running gaits and Servo Capabilities
  - Without breaking new ground, enables new servo-powered capabilities
    - 15 MPH for extended periods
    - Carry 200 lb. at a fast walk for extended periods

Fig. 2

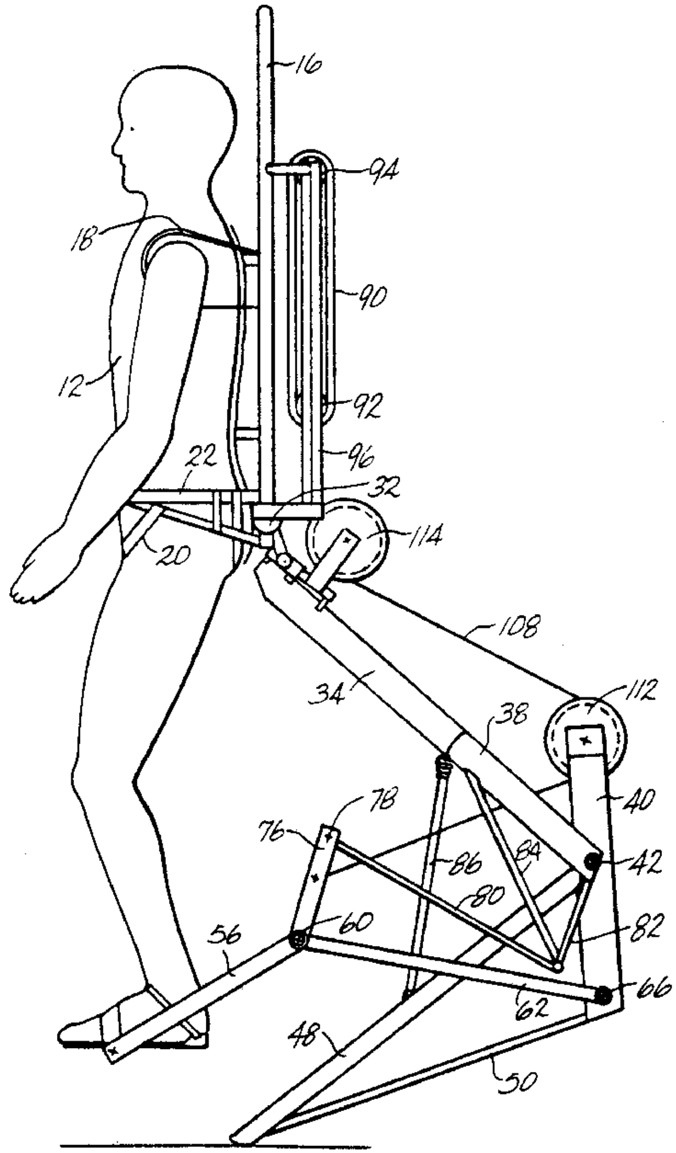
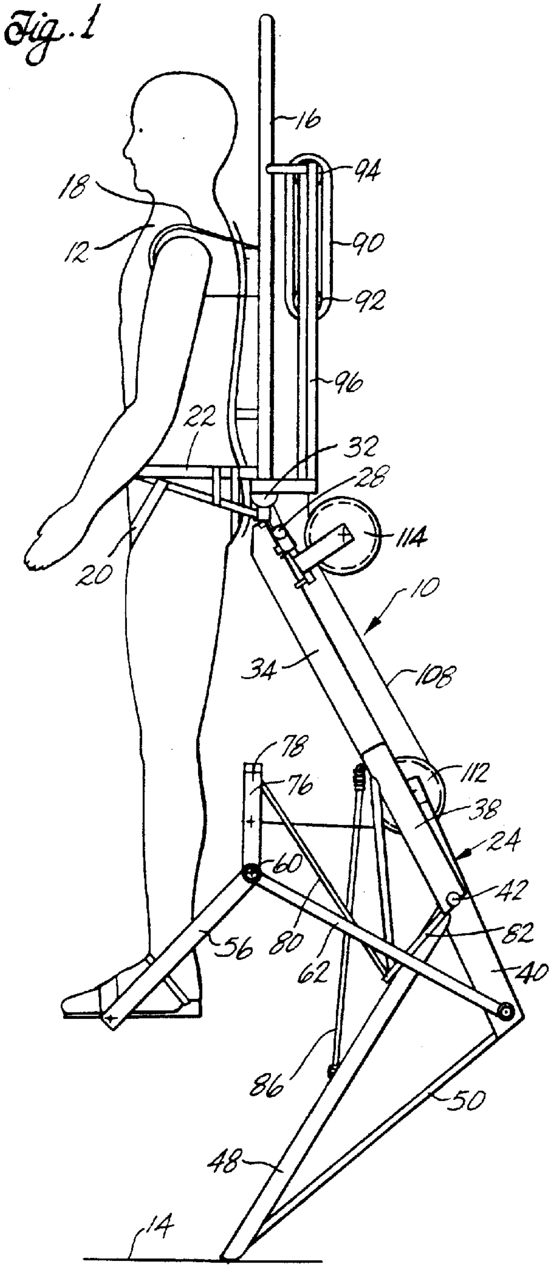


Fig. 1



Figures from US Patent 5,016,869

Fig. 10

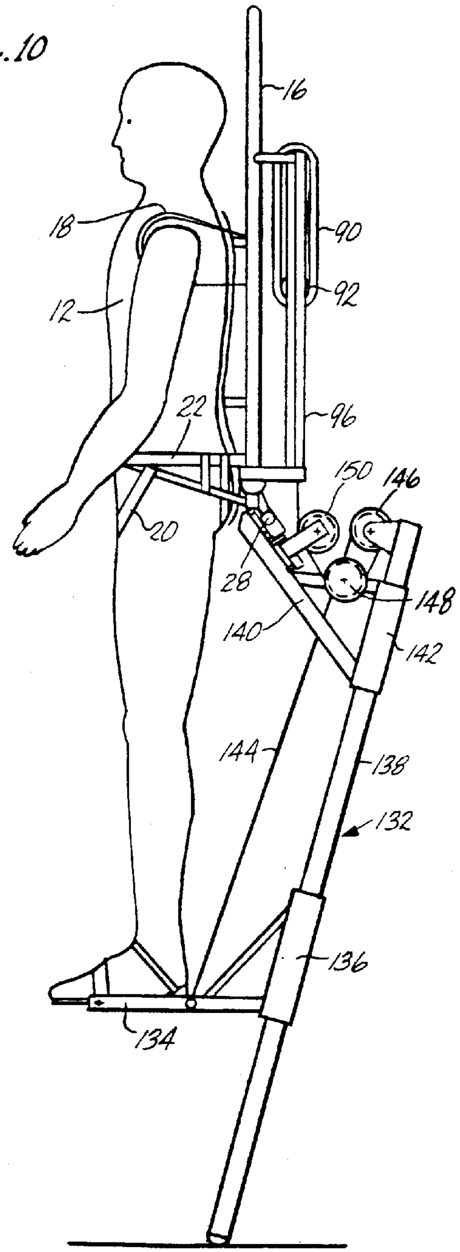
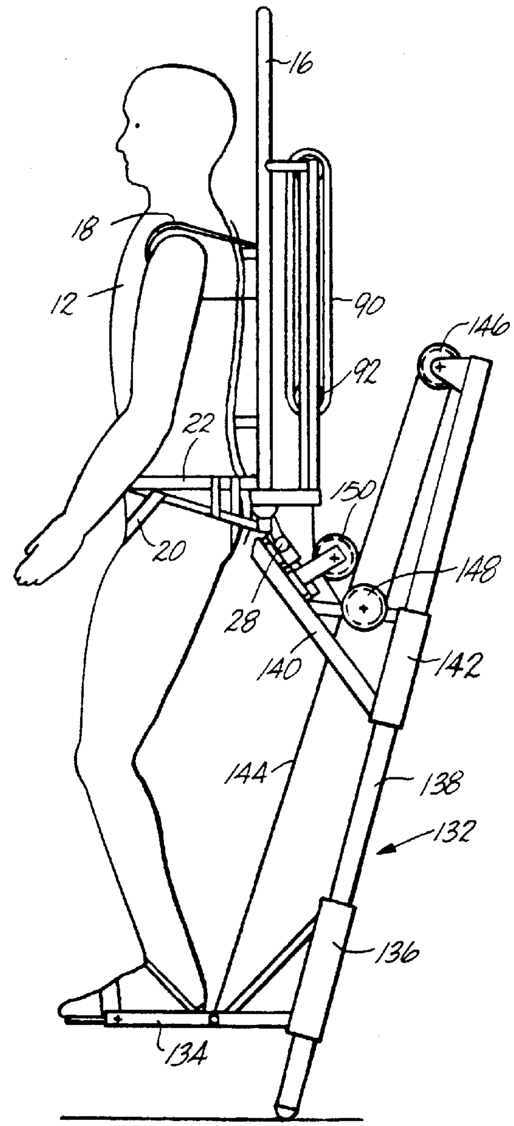


Fig. 11



Alternate Configuration, 2:1 Fixed Leverage Ratio

Recent Accomplishments

- Designed 1 kW/leg dc Servo Assist
  - Action in direct proportion to user's motion
    - Motion adds to that directly generated by user
    - Enhanced extension--overcomes 2:1 leverage motion loss
- Constructed complete servo-assist system for one leg
  - 10 lb NiCad battery pack for 15-30 minutes duration
  - Commercial components -- weight 25 lb/leg
- Tested operation in a single leg
  - Motion appropriate for walking and running
  - Demonstrated > 1:1 leg extension ratio
    - Able to easily step up onto curb, stairs for first time

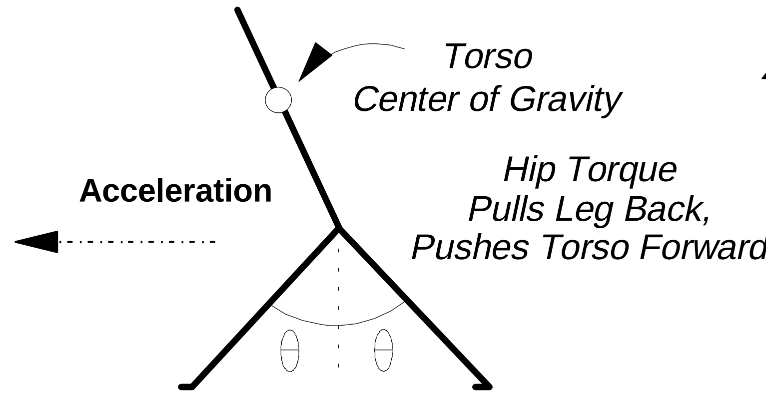
Technology Needs

- Mechanical Design
  - Prototype Leg is bulky but continuously adjustable
    - Matches spring force characteristic to gait requirements
    - Good test bed for Gait and Control Studies
  - Much more compact designs are practical with active assist
    - Show fixed linear response, assist provides match to gait requirements
- Gait Analysis is crucial in order to inform technology
  - Maybe someday technology can “do it all” -- breakthroughs will be accomplished by “doing what’s needed”
- Control Analysis and Implementation
- Servo Power Management
- Energy Management
  - Spring energy storage within one step
  - Battery or other accumulator storage for short periods
  - Prime Mover for long-term operation

Gait Analysis

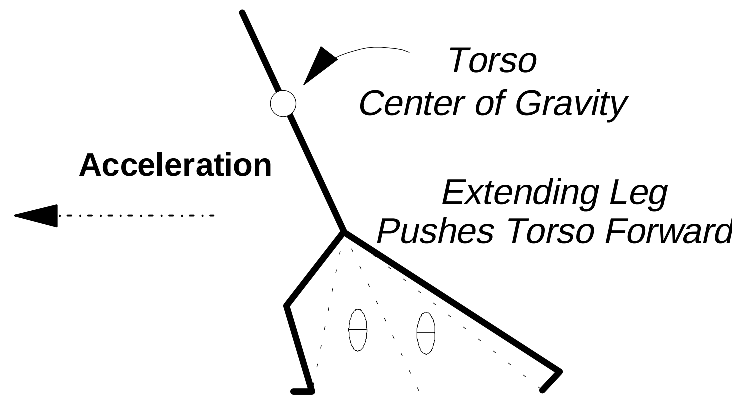
Hip-Torque Mobility Model

- Lateral Acceleration by Hip Torques
- No Net Leg Extension
- Upper body Tilts to Enable Torques



Leg-Push Mobility Model

- Lateral Acceleration by Leg Extension
- No Hip Torques
- Entire body Tilts to Enable Acceleration
- Mechanical Hoppers Demonstrate Feasibility

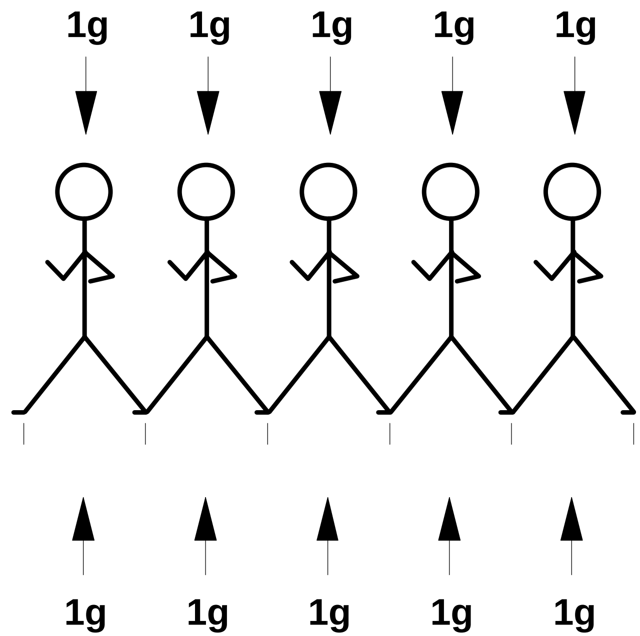


Human Mobility

- Our Legs Do Extend on Acceleration
- Where do we Fit on the Torque<---->Push Spectrum?
- Can Humans adjust to more emphasis on Leg Push?

Gait Analysis

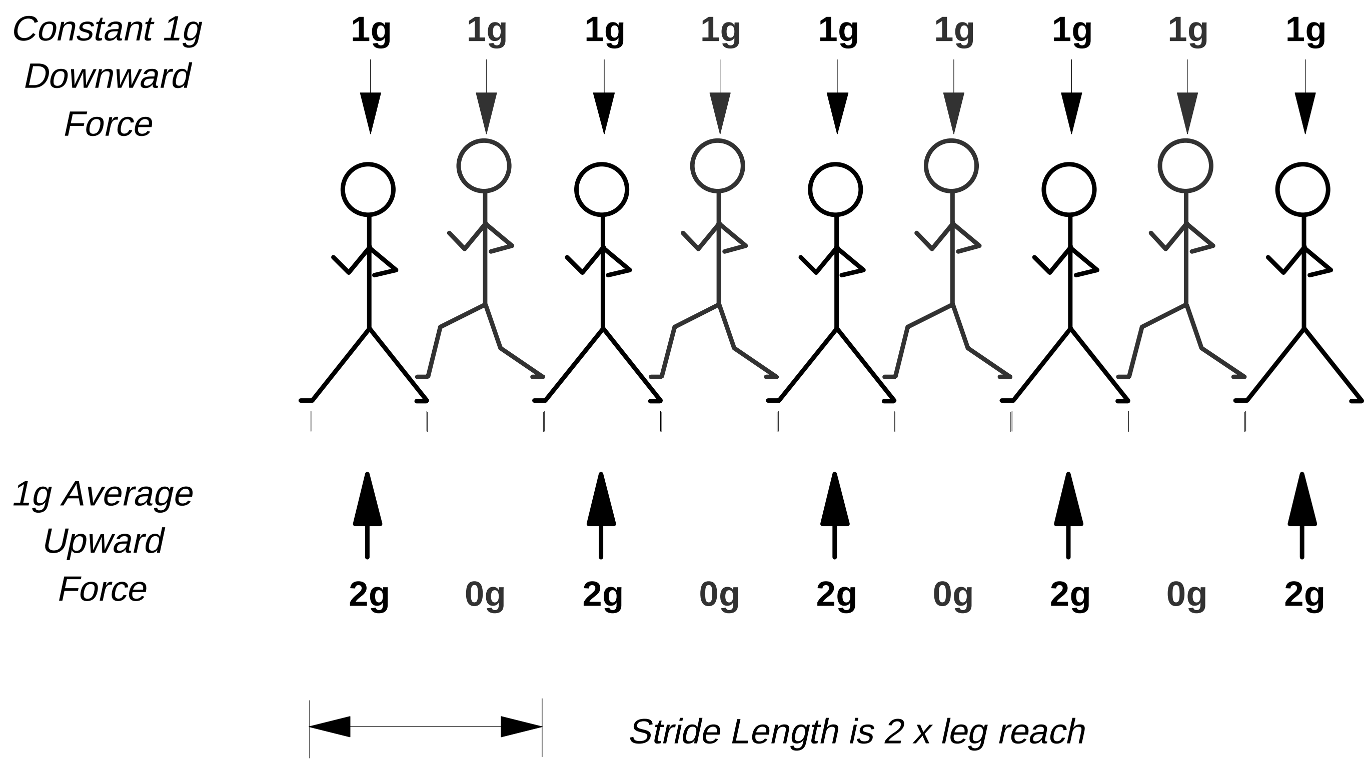
Walking Gait With Foot Force of 1g



Stride Length is equal to leg reach

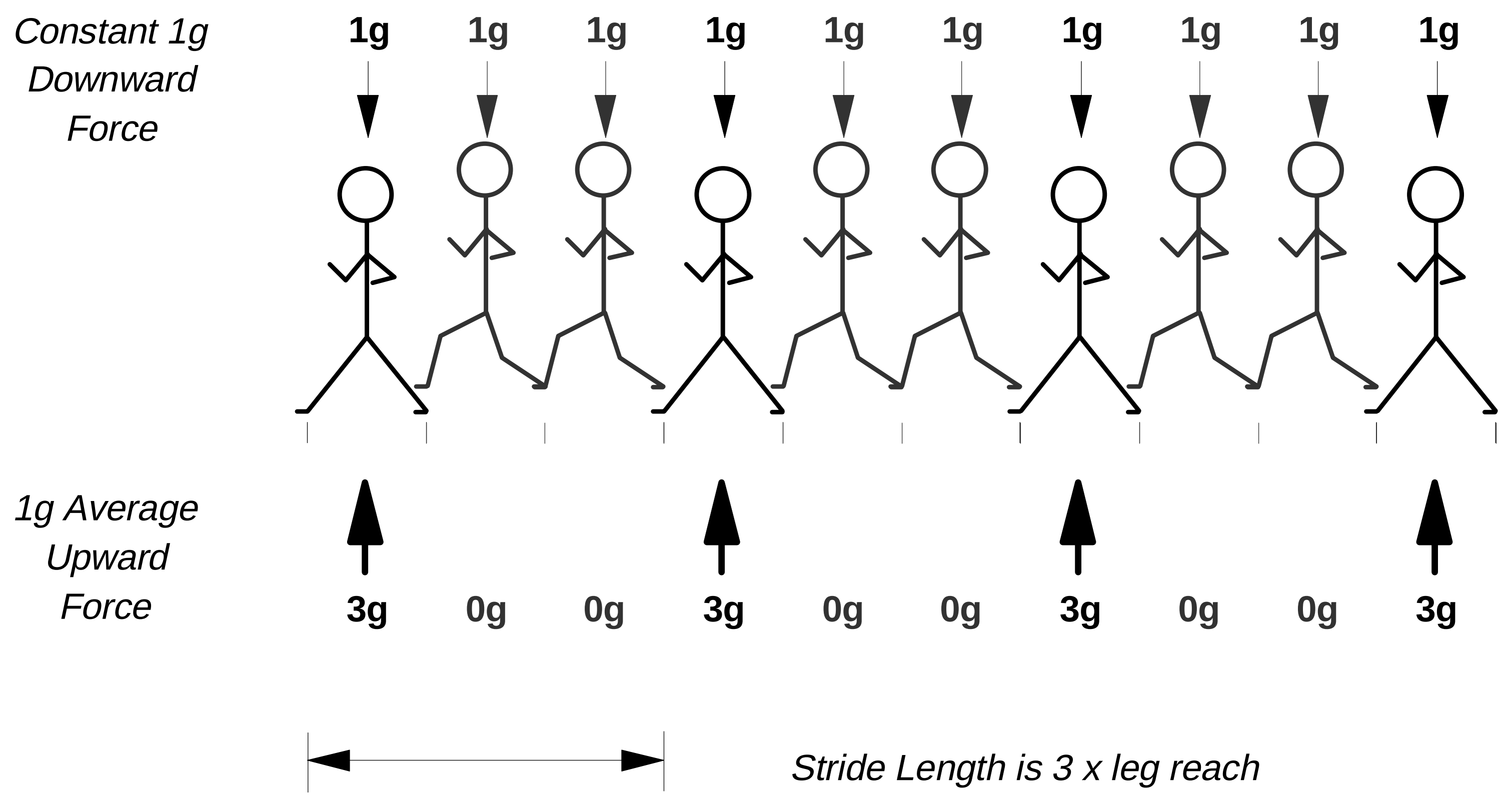
Gait Analysis

Running Gait With Foot Force of 2g

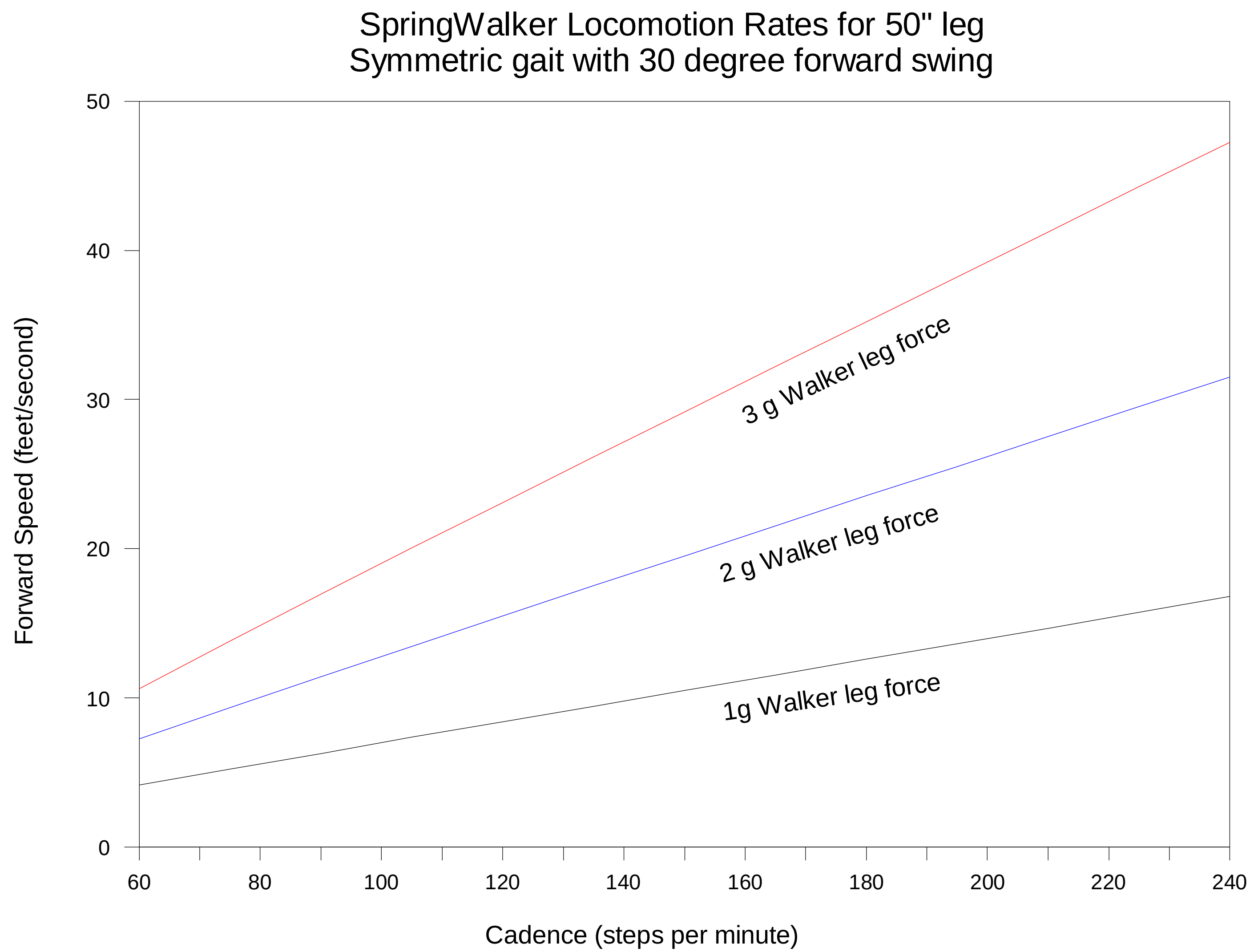


Gait Analysis

Running Gait With Foot Force of 3g

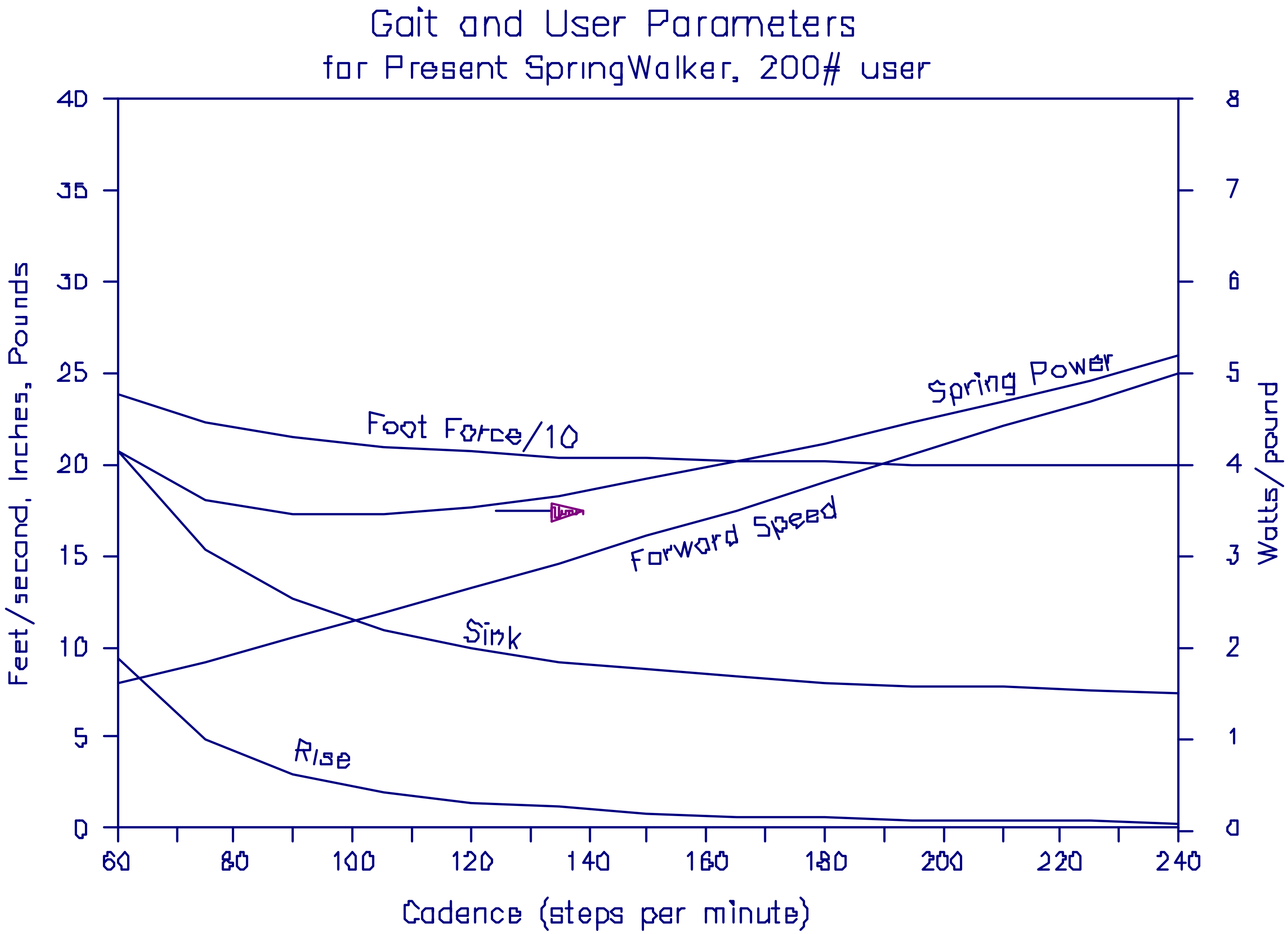


Gait Analysis



Computer Simulation based on Prototype Parameters

Gait Analysis



Computer Simulation based on Prototype Parameters