Synthesis of a Rehabilitation Mechanism Replicating Normal Gait

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Abstract: Effective gait rehabilitation is challenging, often requiring strenuous effort from a therapist, or expensive technology, or both. One rehabilitation method involves assisting the patient’s foot through a gait-like trajectory. While numerous devices have been developed to address the gait training needs of adults, these tools do not always scale well to meet the needs of a child’s smaller body size. This paper describes the development of a gait-guidance device that could be scaled to address the gait retraining needs of individuals of vary body sizes from a child to an adult.

Keywords: Rehabilitation robotics, Rigid-body guidance, Gait rehabilitation, Path generation

1. Introduction

Gait (walking) impairments are detrimental to health and mobility as they can contribute to trips and falls and limit access to community and social activities [1]. In 2013, approximately 20.6 million Americans (7.1% of the population) had an ambulatory disability, of whom approximately 330,000 (1.6%) were children [2]. To improve or sustain walking capacity, many individuals partake in physical rehabilitation programs that include intensive practice of gait-like activities. Clinicians and/or technology help guide the patient through repetitive gait cycles to strengthen not only the muscles important for walking, but also the neural connections that help control gait.

One challenge is that sophisticated technology that has been developed for adults does not always scale well to meet the needs of those with smaller bodies (e.g., young, pre-pubescent children). As a result, clinics and school settings providing rehabilitation services for children may need to purchase separate equipment to address the needs of smaller vs. larger stature children. This need for additional equipment can be difficult, particularly in light of the budget and space constraints faced by many institutions.

To address this challenge, our team sought to develop an affordable and scalable gait guidance system that could be used to address the walking needs of adults and children.

2. Gait Path Selection

Children as young as seven years old demonstrate a kinematic gait profile that is very similar to that of adults [3]. Hof offered normalization methods for comparing pediatric data to standard adult gait [4]. Stansfield et al. showed that children’s gait data between ages 5 and 12 were very consistent following normalization [5].

Regardless of the velocity at which the child was travelling, there were only minor differences in step length, cadence, and other factors. Other studies with normalized parameters showed no correlation between age and gait parameters after the age of 7 [6-8]. The foot is composed of a complex set of articulations across 26 bones that are controlled by a myriad of muscles often spanning multiple joints. Due to the similarity of normalized paths, a single foot trajectory could be chosen and scaled to match the gait path of various leg lengths. However, unique points on the foot traverse different trajectories during gait. To simplify observational and biomechanical analysis of gait, the foot’s trajectory is often simplified to include an analysis of the forefoot and rearfoot. Using this approach, the foot is often modeled as two hinged, rigid bodies. With the toes affixed to a solid surface, the metatarsal heads serve as the juncture between the two rigid bodies. A heel marker provides an appropriate biomechanical reference for the proximal aspect of the rearfoot.

A normalized sample path of a child’s third metatarsal and heel trajectory are shown in Figure 1. These data are taken relative to the center of mass of the body, causing the trajectory to be a smooth, closed loop.

Figure 1. Smoothed, Normalized Trajectories of Foot Points

Initial attempts to model the foot trajectory involved tracing the path of the metatarsal only. However, if the foot angle is taken into consideration, all points on the foot would travel through a gait-like trajectory. This tracking of one point vs. two points on the foot is analogous to the difference between the path-generation and rigid-body-guidance problems in kinematic synthesis.

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3. Existing Technology
Currently, gait training methods are expensive and/or labor-intensive, placing notable demands on the clinician’s body to deliver the intervention [9]. Treadmill and elliptical training are less expensive, but often require significant effort from the therapist and may require that the patient have significant strength to support themselves. To address this problem, gait rehabilitation techniques have been developed by researchers using treadmills with body weight support [9] and robotic-assisted driven-gait orthoses [10]. Gait training methods are usually specialized for different body sizes, meaning that different gait training devices are required for pediatric and adult gait therapy [11]. Robotic gait-training devices can be extremely expensive, and readjusting link lengths to match leg parameters is cumbersome. In addition, some potential gait training equipment options do not propel the foot through a gait-like trajectory [12,13], thus reducing the task-specific training thought to be beneficial for strengthening not only the muscles, but also the neural pathways responsible for controlling the movements.

One device which addresses some of these concerns is the Intelligently Controlled Assistive Rehabilitation Elliptical (ICARE) system [14,15]. The ICARE is a relatively low-cost, ergonomic, effective gait rehabilitation device for adults. The device is a modified, motorized elliptical machine that has been designed to push a patient’s feet through an approximation of gait-like motion. Unlike other systems, the ICARE was designed so that little muscular strength is required to operate the machine. However, if the patient has sufficient muscular strength, they are able to drive the machine themselves without requiring the motor [16]. Studies have shown that this device effectively meets many of the requirements for gait rehabilitation. While the device closely emulates the kinematic and EMG demands of adult gait [17], the foot path is not perfect, nor has it yet been optimized to accommodate the needs of individuals of small stature (e.g., a young child).

4. Design Goals
Based on the shortcomings of existing technology, a new design was sought. The target user set for this mechanism was fairly broad. This device must be usable by adults and children alike, accommodating a broad range of step lengths. However, if the mechanism was excessively expensive or large, it would be inaccessible to much of the target population. Hence, the device must be designed to be usable in rehabilitation clinics, for in-home therapy, in hospitals, and even in schools and community centers. The mechanism was required to meet the following set of guidelines.

- **Gait-Like Trajectory:** The mechanism must constrain the feet to a trajectory similar to normal gait motion.
- **Scalable:** The mechanism must accommodate individuals with a step length between 20 and 102 cm while producing a linearly-scaled gait trajectory, such that the size of the foot path is variable, but not its shape. Also, the entire scaling process must be performed by one actuator, eliminating the possibility of accidental misalignment or inaccurate mechanism trajectory.
- **Adjustable:** The mechanism should be able to accommodate specific impairments, such as different step lengths for each foot or reduced step heights.
- **Cost-Effective:** The mechanism must be affordable so that smaller rehabilitation centers and in-home users could afford to purchase the device.
- **Small Footprint:** The mechanism must not require excessive space to store or operate.
- **Motorized:** The mechanism must utilize a motor or other actuator that propels the patient’s foot through a gait-like trajectory. The motor component is critical to assist patients with low muscular strength.
- **Backdrivable:** The mechanism must be able to be manually driven without requiring significant effort, which would make it usable as an exercise device.
- **Ergonomic:** The mechanism must not impair the normal gait motion of the user in any way, and must avoid uncomfortable interferences that may prevent effective rehabilitation. Ideally, the mechanism will mimic the trajectory of the foot during normal gait and create a comfortable, enjoyable exercise/rehabilitation experience.

A gait-like trajectory is difficult to replicate mechanically. Without the use of multiple motors, a mechanical device that traces a highly nonlinear path can prove difficult to synthesize. The scaling and backdriveability requirements further complicate the mechanism design problem. Two approaches for solving the problem include: (1) attempting to replicate the path using a single, scalable, path-generating mechanism, or (2) parametrizing the path and using multiple systems in tandem to produce the desired output.

5. Path-Tracing Mechanisms
There are several benefits to using path-tracing mechanisms. Using one mechanism to drive the motion of the foot makes it far easier to meet the backdriveability requirement. Also, the simplicity of the mechanisms would make them more affordable and easier to construct. Two path-tracing mechanisms were evaluated here. Other path-tracing mechanisms may exist, but were not specifically evaluated in this study.

5.1. Four-Bar Linkage
A four-bar linkage can be used to produce a variety of paths, and was a natural first choice for consideration. Several methods were employed to attempt to fit the trajectory to a four-bar linkage, including nonlinear optimization, consulting a four-bar linkage coupler curve atlas [18], classical linkage synthesis for rigid-body guidance [19], and trial-and-error methods in simulation software [20]. The long, flat shape of the metatarsal trajectory was difficult to match, though, and all best-fit methods resulted in an elliptical shape without the desired flatness. The generated paths would not provide significant improvement over existing technology, much of which is based on this type of mechanism. In order to scale the four-bar linkage according to the design requirements, each individual link would have to be scaled proportionately. Links with changing lengths would likely require multiple motors, and would result in an incorrect trajectory if one of the link lengths was incorrectly scaled. For these reasons, the four-bar linkage as a method of tracing the full foot path was considered inadequate.
Other closed-loop mechanisms such as six- or eight-bar linkages could also be considered, and would be expected to allow higher-order paths closer to natural gait, but the increased mechanical complexity and space requirements ruled out these options from consideration.

5.2. Pantograph

Pantographs rely on geometrical constraints of similar triangles or parallelograms to produce similar motions at different points on a linkage. Several pantograph designs were considered to trace the trajectory of the foot from a template and then map out an identical, scaled path for the foot.

In one design, two long beams connect with two shorter beams to create a scaling mechanism, as shown in Figure 2. Triangles ABC and ADF are similar. Point A is rigidly attached to the ground, and point F is attached to a foot pedal. Point C attaches to a pin (Point P) that rolls in a track that matches the gait path.

To power the pin through the track, a Cardan gear was selected, as shown in Figure 3. Cardan gears can generate perfectly elliptical trajectories with some similarities to gait paths [21]. Since the desired path is not a true ellipse, the mechanism utilizes a sliding connection between Point P and the Cardan gear. This allows the pin to follow the gait path and not be constricted to an elliptical trajectory. Other ways of generating the gait path are possible.

While this mechanism would be a simplistic method of accurately tracing the gait trajectory, scaling would be difficult. A motor would have to change link lengths so that the geometric similarities of the triangles were preserved. Also, the size of triangle ADF would be fairly cumbersome in order to achieve a scaling between 20 and 102 cm.

In another design, a telescoping pantograph extends outward, as shown in Figure 4. Again, point A is rigidly attached to the ground, and point B traces the gait path similar to the design shown in Figure 2. The foot pedal would be located at point C. In order to scale the motion, point C would be moved to different joints along the pantograph assembly. While this would provide discrete, accurate scaling, the scaling would not be linear, and it would be nearly impossible to scale by increments of 25 mm or less.

While the pantograph designs showed good potential for mimicking the gait trajectory, difficulties in scaling and size proved to be too significant, and the designs were deemed insufficient.

6. Parametric Solution to Path Generation

The gait path can be separated into Cartesian coordinates, where each coordinate is a function of time. The X and Y position coordinates of the metatarsal trajectory were separated, and the graphs of these variables are shown in Figure 5. Both X- and Y-position coordinates are highly nonlinear functions of time, but separating the X and Y positions allows independent mechanisms to be constructed to control the horizontal and vertical motions.
of the foot pedal. This is simpler than attempting to construct a single mechanism that generates the entire path. Scaling in Cartesian coordinates can be cumbersome for this scenario. Parametrization in polar coordinates offers several benefits. In a parametrized system, one mechanism controls the angular position of a point relative to a fixed reference frame, while another mechanism controls the radial position. With the angle held constant, the radius of an arc and the arc length are linearly correlated, meaning that simple scaling of the radial position scales the entire trajectory. The coordinates are highly sensitive to the location of the origin. If the origin is placed inside the closed loop, the angular position will undergo a complete revolution. If the origin is outside of the loop, the angular position will oscillate. For first iterations of the parametrized design, the origin was located at a point just outside of the loop at a point on the ground. The resulting trajectory is shown in Figure 6.

6.1. Cam-Scotch Yoke
Defining the problem in terms of radial and angular coordinates allows for a parametrically defined, scalable mechanism to be generated. As shown in Figure 7, a beam (link A) is oscillated up and down by a cam (link E) about its connection with Link B. This defines the angular position of the beam. Rotating link B defines the radial position of the foot pedal (link D), which is sliding along the beam. By interfacing with the slot in link C, link B is able to drive the radial position with the offset from zero as seen in Figure 7. In a linearly-scaled system, the angular position would not need to change at all, and the radial position could be adjusted to produce proportional changes in stride length and trajectory. This could be performed by lengthening or shortening link B, although this would also require adjusting the offset (link C).

While this design is simple and effective, it requires simultaneous adjustment of two links – rotating link B and the offset attached to link C. This would be challenging to perform simultaneously. Also, scaling from the origin increases the footprint of the device significantly as both the step length and the offset are scaled.

Despite its shortcomings, this mechanism fulfilled many of the other requirements. It showed potential to be backdrivable and ergonomically appropriate, and simple geared connections between link B and link E would allow the mechanism to be driven by a single motor per foot pedal.

7. Final Design
The strengths of the cam-Scotch-yoke mechanism inspired the final design. The offset included in link C was causing the difficulties in adjustment and in the overall system footprint. The offset was necessary because the origin of the polar coordinate system defining the angular and radial positions was set on the ground away from the trajectory. If the polar coordinate origin could be placed on the trajectory, then no offset would be necessary. However, if
the origin were placed anywhere on the system, it would encounter angles exceeding 90 degrees, requiring the mechanism to flip orientations. This would not be possible with a cam, and driving the radial position of the mechanism would be difficult. It would be possible to place the polar coordinate origin on the gait path if the gait path intersected the origin.

In all of the previous mechanisms considered, the gait path was assumed to be the metatarsal trajectory. Both the metatarsal trajectory and the heel trajectory shown in Figure 1 are smooth, cusp- and loop-free paths. However, a different point on the foot may experience a trajectory that is tangent to itself. The bottom of the foot was defined by a line connecting the metatarsal and the heel. The position of every point on the bottom of the foot could be found using simple interpolation. To find the trajectory of point O on the foot, located on a vector traveling from the metatarsal to the heel, the following equation is used:

\[ \hat{X}_O = (1 - p)\hat{X}_{\text{metatarsal}} + p\hat{X}_{\text{heel}} \]

where \( X \) is the vector defining the horizontal and vertical position of the trajectory at any time and \( p \) is the percent distance from the metatarsal to the heel where the desired point is located on the foot.

Using the above equation, it was discovered that if \( p = -0.25 \), the path is tangent to itself at the origin, as shown in Figure 9. The position of point O, located at -25% of the distance from the metatarsal to the heel, occurs just in front of the toe on the foot. In healthy individuals, the toe joint flexes, causing the toe to diverge from the trajectory shown below. If the mechanism accounts for foot orientation, then as long as the foot is placed in the correct location on the foot pedal, the foot will travel through a gait-like trajectory.

The final design consisted of a beam rotating about an axis passing through its center (Point A), as shown in Figure 8. The beam consisted of two L-shaped channels separated by a small gap. A slider (foot pedal) travelled along the top of the beam, and the front-toe position of the slider was constrained to the beam. The slider was connected to a chain that looped around the beam, which was responsible for propelling the foot pedal forward and backward. The chain was connected through gears to the rocker arm of a four-bar linkage. The rocker arm rotated at angle \( \theta \) relative to the vertical axis, as shown in Figure 8. The oscillations of the rocker arm caused the chain to travel forward and backward along the beam, with timing matching that of natural gait.

In order to scale the radial distance that the foot pedal traveled, the vertical position of the rack and pinion were shifted. Moving the rack along the rocker bar meant that angular rotations of the rocker resulted in larger or smaller horizontal displacement of the rack. Because the arc distance and radial distance are correlated, changing the position of the rack’s connection to the rocker arm would linearly scale the motion.

The crank of the four-bar linkage was connected through gearing to a cam that defined the beam’s angular position. The angular position of the beam, combined with the radial position defined by the chain movement, created the trajectory seen in Figure 9.

To capture the foot angle, the foot pedal was connected to a second beam. The second beam rotated about Point A with the main beam, and raised and lowered through a cam. The vertical displacement of the second beam caused the angle of the foot pedal to change regardless of the position of the
foot pedal. This made the foot angle motion independent of the scaling.

7.1. Four-Bar Linkage Design
The four-bar linkage was designed to best replicate the radial position with respect to time, mimicking normal gait. The radial foot pedal trajectory is shown in Figure 10.

![Figure 10. Foot Pedal Radial Distance](image)

To convert between radial distance and rocker arm angle, the coordinates must be converted from Cartesian to polar form. The radial movement is directly influenced by the motion of the rack. The rack is constrained to only move horizontally. From polar coordinates,

\[
x = r \sin(\theta) \\
y = r \cos(\theta) = \text{constant}
\]

Here, \(x\) is the radial distance of the rack, \(y\) is the vertical position of the rack, \(r\) is the distance from the rotation point of the rocker arm to the connection point to the rack, and \(\theta\) is the angular displacement of the rocker arm from the neutral position. The \(y\)-position was constant here during operation of the machine. Vertical motion of the rack caused the rack trajectory to scale. Thus, the rack was held at a constant height, and the distance \(r\) was variable, dependent on \(\theta\). Rearrangement and combination of the equations solves for \(\theta\) in terms of \(x\) and \(y\).

\[
\theta = \tan^{-1} \frac{x}{y}
\]

In the design, to limit size while increasing power transmission, the maximum range of \(x\) was chosen to be \([-25 \text{ cm}, 25 \text{ cm}]\), which would occur at a length of 51 cm from the rocker arm pivot point. This would be the position of the system when outputting the maximum step length of 102 cm.

To synthesize the four-bar linkage needed to produce the above output curve, Freudenstein’s equation was used [19]. Freudenstein’s equation is given by

\[
R_1 \cos(\theta) - R_2 \cos(\varphi) + R_3 = \cos(\theta - \varphi)
\]

where

\[
R_1 = \frac{d}{c}
\]

\[
R_2 = \frac{d}{a}
\]

\[
R_3 = \frac{a^2 + c^2 + d^2 - b^2}{2ac}
\]

\(a\) is the length of the crank
\(b\) is the length of the coupler
\(c\) is the length of the rocker arm
\(d\) is the length of the ground link, which is the distance between the fixed pivot on the crank and the fixed pivot on the rocker
\(\theta\) is the angle between the crank and the ground link
\(\varphi\) is the angle between the rocker arm and the ground link

Using the trigonometric difference identities, Freudenstein’s equation can be rewritten as

\[
R_1 \cos(\theta) + R_3 = \cos(\theta) \cos(\varphi) + \sin(\theta) \sin(\varphi) + R_2 \cos(\varphi)
\]

\[
R_1 \cos(\theta) + R_3 = (\cos(\theta) + R_2) \cos(\varphi) + \sin(\theta) \sin(\varphi)
\]

Assuming \(\theta\) to be constant, the \(\varphi\) term can be isolated by combining the sine and cosine terms using linear summation.

\[
R_1 \cos(\theta) + R_3 = A \cos(\varphi - \alpha)
\]

where

\[
A = \sqrt{[\cos(\theta) + R_2]^2 + \sin^2(\theta)}
\]

\[
\alpha = \text{atan}[(\cos(\theta) + R_2) / \sin(\theta)]
\]

Thus, the equation for the rocker arm angle in terms of the crank angle is given by

\[
\varphi = \text{acos} \left[ \frac{R_1 \cos(\theta) + R_2}{A} \right] + \alpha
\]

This equation was least-squares curve fit to the \(\varphi\) angle calculated from the observed radial displacement of the foot. Constraints were applied to the optimization to meet the Grashof conditions for a crank-rocker [19]. Also, to maximize backdrivability and power transmission, the crank was not allowed to be less than 15 cm long. As a result, after optimization, the crank length was 15.2 cm, the coupler was 36.5 cm, the rocker arm was 23.2 cm, and the ground link was 43.4 cm. The ground link made a -47.8 degree angle with the horizontal. The theoretical and optimized rocker angles are shown in Figure 11.
7.2. Beam Angular Cam Design
The timing for the four-bar linkage rocker angle is similar to the desired timing of the radial motion of the foot pedal. This is important, since it means no controller is required to change the crank rotation speed, and the crank can rotate at a uniform angular velocity. This also means that the cams defining the angular position of the beam and the vertical position of the secondary beam can be designed directly from the displacement requirements without needing any consideration for cam rotation speed changes.

In order to utilize a roller follower with a cam, no point on the cam pitch curve can have a curvature smaller than the follower radius [19]. With the cams located halfway between the pivot point of the beam and the end of the beam (25 cm away), the cams had to provide a maximum vertical movement of 4.4 cm. The beam angle and cam profile are shown in Figure 12.

8. Conclusions
A device that mimicked the foot trajectory of normal gait was designed. Stringent requirements made it difficult to produce a mechanism capable of accomplishing the design goals. The highly nonlinear path of the foot during gait is difficult to model mathematically, and provides complications when attempting to construct mechanisms that reproduce its trajectory. With the broad range of stride lengths that were accommodated for in this design, scaling was a major consideration. While many potential designs were evaluated, one candidate proved to be capable of matching all of the design goals effectively. Other designs may yet be feasible.

The designed mechanism provides backdrivability, can be powered by a single motor (reducing weight and size), has linear scaling that is easy to adjust, and does not pose a significant hazard for children in a gait training scenario.

Future work will involve detail design to enclose the chains and cams to provide protection for pediatric patients. To fully test this device, the design is currently being...
constructed. Further tests will prove how easily backdrivable the device is and to what extent it can be used in exercise and rehabilitation facilities.

9. References


