Published in final edited form as:

Gait Posture. 2010 June ; 32(2): 181–184. doi:10.1016/j.gaitpost.2010.04.014.

Effective Rocker Shapes Used by Able-Bodied Persons for Walking and Fore-aft Swaying: Implications for Design of Ankle-Foot Prostheses

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Abstract

The use of rocker models to understand functional tasks of the human lower limb is attractive because of their simplicity. Recent studies have determined a consistent feature of able-bodied walking termed the roll-over shape (ROS), which is the effective rocker shape that the lower limb system conforms to between initial contact and contralateral initial contact during walking. However, it is unclear what effective rocker shapes are used for fore-aft swaying. A better understanding of these shapes could be used to develop improved prostheses for this task, perhaps improving balance and balance confidence, and reducing the occurrence of falling in lower limb prosthesis users. We measured effective rocker shapes used by eleven able-bodied persons during walking and fore-aft swaying. We hypothesized that the curvature of the swaying shapes would be smaller (radius larger) than that of the walking shapes, providing a more stable interface with the ground during swaying. The radius (measured as the inverse of the curvature of the shape) was found to be about 1/3 of the leg length for walking, but over two times the leg length for swaying. A model examining the effective ankle stiffness necessary to achieve these curvatures suggests that the stiffness of a biomimetic prosthetic ankle would need to be over 3 times higher for fore-aft swaying than for walking. These results suggest that two separate modes would be needed in an ankle-foot prosthesis to mimic the physiologic system for walking and swaying.

Keywords

roll-over shape; balance; mobility; prosthesis

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Conflict of interest statement

The authors have no financial or personal relationships with other people or organizations that could influence their work or pose conflicts of interest.

Introduction

The physiologic ankle-foot system is amazingly complex. However, its functions for particular tasks may be simple. As an example, the physiologic system has been modeled as a rocker (or rockers) by many researchers in attempts to better understand its functions during able-bodied walking. Perry [1] described this system as anatomical rockers that aid in forward progression, consisting of the heel rocker, ankle rocker, and forefoot rocker. Morawski and Wojcieszak [2] studied a walking toy with circular walking feet and found that increasing the rocker foot radius improved its stability during walking. McGeer [3] estimated from computer and physical models that the “equivalent radius” for human walking would be about 0.3 times leg length. Using a circular rocker to replace the ankle-foot system, McGeer's physical models could walk down a gentle slope without the use of external power.

Knox [4] concluded that the effective rocker shapes of prosthetic feet are important to their function for walking. He developed a method to measure these effective shapes and compared the shapes for prosthetic and physiologic ankle-foot systems during walking. The effective rocker that the ankle-foot system conforms to from heel contact to opposite heel contact of walking was later termed the ankle-foot roll-over shape (ROS) [5]. The ROS may be a useful and simple tool for design and evaluation of lower limb prostheses because it has been shown to be nearly circular and resistant to changes in walking speed [5], added weight to the torso [6], and heel height [7] during able-bodied walking on level ground.

Standing and swaying within the base of support are also important functional tasks of daily living. Winter et al. [8] described the center of pressure (COP) as a response mechanism to corral a person's center of mass (COM), allowing the person to maintain balance during standing. During intentional, controlled swaying, the person's COP would also need to move ahead of the COM to prevent the body from losing balance. This behavior might contribute to a swaying effective rocker shape that is flatter (or a larger radius rocker) than that used for walking. A flatter effective rocker shape for standing and swaying may be a logical goal of the complex lower limb system, because it would offer inherent mechanical stability to the body.

Prosthesis users fall frequently and many have a lowered confidence in their balance [9]. A better understanding of functional activities in able-bodied persons could lead to improved prosthesis designs, prosthesis prescriptions, and balance of prosthesis users during standing and swaying, for example. Improved designs or prescriptions could reduce the incidence of falling and increase balance confidence in lower limb prosthesis users, possibly resulting in increased participation in social activities and improved quality of life [10].

Although previous studies have found that the walking ROS is nearly circular, it is unclear what the effective rocker shapes are for able-bodied persons during gentle swaying. Therefore, the purpose of this study was to measure the effective rocker shapes used during fore-aft swaying and walking in order to enhance our understanding of these tasks, providing insight for design of improved prostheses. We hypothesized that the effective rocker shapes of fore-aft swaying would be flatter than those found for walking, providing a more stable base for this activity. Lastly, we created a simple model to investigate ankle stiffness values that could be used in an ankle-foot prosthesis to mimic the able-bodied ankle-foot system for these two tasks.

Methods

Subject Recruitment

We recruited eleven able-bodied subjects (six male and five female) between the ages of 24 and 35 years. Their demographic information is reported here as mean $\pm$ standard deviation: age = 28.2 ± 3.5 years, height = 175.7 ± 10.0 cm, body mass = 71.2 ± 14.2 kg, and shoe size = 8.2 ± 2.3 (US men).

After the subjects gave written consent, approved by Northwestern University's Institutional Review Board, we conducted ankle range of motion and strength tests. For ankle range of motion (non-weight bearing), the subjects needed to demonstrate maximum ankle dorsiflexion between 8 and 16 degrees and maximum plantarflexion between 48 and 60 degrees [11]. They also needed to maintain endpoint range against resistance and gravity to demonstrate normal ankle strength. Those who did not qualify based on range of motion and strength criteria and those who had a history or fear of ankle injuries were excluded from participation in the study.

Experimental Protocol

The experiments were conducted at the Veterans Affairs Chicago Motion Analysis Research Laboratory, which is equipped with six force platforms that recorded data at 960 Hz (Advanced Mechanical Technology Inc., Watertown, MA, USA) and an eight-camera motion analysis system that recorded data at 120 Hz (Motion Analysis Corporation, Santa Rosa, CA, USA). The force and motion data were later synchronized at 120 Hz. A modified Helen Hayes marker set [12] was used to monitor joint locations, which were captured and recorded by the motion analysis system. Ground reaction forces (GRF) and their centers of pressure (COP) were measured by the force plates.

The eleven subjects were asked to perform several tasks while wearing high-top canvas sneakers (Converse All-Star®) provided by the laboratory. This type of shoe was chosen primarily because of another part of this study, but also because it has a flat and flexible sole and does not restrict ankle motion. First, the subjects were asked to establish their freely-selected walking speed. Then, they walked back and forth in the laboratory space at that speed until they achieved four “clean” hits for each foot on the force plates. A “clean” hit was defined as a foot strike where the entire foot was within the boundaries of a platform during single support and no part of the other foot landed within these boundaries before or after that step. For each trial, the subjects were timed with a stopwatch as they went through a set distance (16 feet) in the laboratory to ensure that their speeds were within $\pm 5\%$ of their established self-selected target. If the speed was not in range, the trial was discarded and the subjects were instructed to increase or decrease their pace accordingly. Next, the subjects were asked to step onto two force platforms, perform low amplitude, low frequency, fore-aft swaying, and then step off. They were instructed prior to beginning that they should sway forward and backward, without lifting their heels or toes off the ground. They were given a brief demonstration, but were not instructed further regarding knee or arm motions. Three trials of 20 seconds were recorded.

Data Analysis

The data collected were first processed with EVARealTime 5.0.3 and Orthotrak 6.5.2 (Motion Analysis Corporation, Santa Rosa, CA, USA), yielding ankle kinematics and joint center coordinates. These commercial software programs were used to interpolate missing data points (momentarily hidden markers) and filter the data (bidirectional Butterworth filter with cutoff frequency at 6 Hz).

A MATLAB script was used to determine the ankle-foot roll-over shape by transforming the center of pressure of the ground reaction force under the shoe from a laboratory-based to a three-dimensional shank-based coordinate system [13]. The script used the lateral ankle marker and two virtual markers at the ankle and knee centers. First, a unit vector (u_1) was drawn from the virtual ankle center to the lateral ankle marker. A second unit vector (u_2), drawn from the ankle center to the knee center, formed the z-axis of the shank-based coordinates. The cross product of the first and second unit vectors ($u_3 = u_1 \times u_2$) produced the x-axis for the left side; for the right side, we took the cross product of the second vector with the first ($u_3 = u_2 \times u_1$). The cross product of the z- and x-axes ($u_4 = u_2 \times u_3$) established the y-axis of this coordinate system and the virtual ankle center became the transformed system's origin. The ankle-foot ROS is thus a time progression of the COP of the GRF in the three-dimensional shank-based coordinate system and represents the effective rocker shape of the ankle-foot system during walking. The same transformation was carried out for swaying COP data as well, yielding its effective rocker shapes.

For comparison, both walking and swaying shapes for each subject were fitted to a second order polynomial:

$$Z = a_2 X^2 + a_1 X + a_0 \quad (\text{Equation 1})$$

where X and Z were the anterior and proximal components, respectively, of the effective rocker shapes. Curvature could then be found by the following [14]:

$$k(x) = \frac{|Z''(x)|}{[1 + (Z'(x))^2]^{3/2}} = \frac{|2a_2|}{[1 + (2a_2x + a_1)^2]^{3/2}} \quad (\text{Equation 2})$$

Since curvature k is a function of x , it has a value at each x location along the shape. Therefore, we used its average over the entire range that the effective rocker shapes spanned to get an idea of the overall average curvature for each shape. For each subject, we averaged the curvatures found for “clean” hits on the right side (assuming symmetry between sides, which was supported by comparison of data between sides for two subjects). These average curvatures for each of the eleven subjects were then examined using a box-plot and by calculating the medians for the walking and standing effective shapes. The radii of the shapes were found as the inverse of the median curvatures. The medians were used instead of the means to reduce the effects of outliers on the data. The walking shape was also fitted to a circular arc (using the technique of Hansen et al. [5]) to obtain the best-fit radius. This radius was compared with the inverse of the curvature found using the new approach in this paper to validate the new technique. The new technique was preferred in this study due to the expected “flat” effective shapes for swaying (best-fit radius for a flat shape approaches infinity, while its curvature is close to zero). All values were normalized to the subjects' heights (H) initially. In order to compare with other studies that normalized results to leg length (LL), we also normalized the results to each subject's leg length.

We chose to do non-parametric statistical analyses because of our small sample size. SPSS (SPSS Inc., Chicago, IL, USA) was used to perform a Wilcoxon Signed Ranks Test to see if the curvature for the effective rocker shape of swaying was significantly lower than that found for walking [15].

Ankle Stiffness Modeling

A model was developed to determine the ankle stiffness levels that could be used with a rigid foot piece to mimic the effective rocker shapes of able-bodied ankle-foot systems during swaying and walking. The purpose of the model was to compare the stiffness levels predicted for swaying and walking to determine whether one or two stiffness modes would be needed to mimic physiologic function for these tasks.

The model assumes a load (W) applied to the bottom of the foot, which starts anterior to the ankle joint center and progresses toward the toes of the foot (see Figure 1). At each anterior loading location (x), the ankle must displace an angle (θ) that would yield a vertical displacement (d). The anterior loading location (x) and the vertical displacement (d) are related by the lower arc of a circle:

$$d = R - \sqrt{R^2 - x^2} \quad (\text{Equation 3})$$

where R is the goal radius of the effective rocker shape, either swaying or walking. For a series of x locations and each effective rocker shape radius (R), the displacement (d) was calculated to match the effective rocker shape goal. At each x location, the angle of rotation of the ankle (θ) was estimated as the arc tangent (d/x) and the torque at the ankle was estimated as the load (W) times the anterior lever arm (x).

To determine stiffness needed in walking, we assumed a person with a mass of 71 kg (mean mass of the subjects in the study) loading the foot with full body weight ($W = 695.8$ N) at anterior locations of 1 cm to 15 cm (in one cm increments) and used the inverse of the curvature for the walking roll-over shape as the goal radius for the design. We also assumed a leg length of 1 meter to scale the roll-over shape radius. To determine stiffness needed in swaying, we changed the loading to half body weight ($W = 347.9$ N) (double support) and used the inverse of the curvature for the swaying effective rocker shape as the goal for the design. The ankle torque was plotted versus ankle angle for each model and the curve was fit with a line with the intercept set at zero. The slope of the line was considered to be the rotational stiffness required to achieve the biomimetic effective rocker shape goal for each activity. We used a Microsoft Excel spreadsheet to perform the calculations.

Results

We hypothesized that the effective rocker shapes for fore-aft swaying would be flatter than those for walking, i.e. the curvature would be smaller or radius larger. Visual inspections indicate that the walking ROS looks nearly circular and that the effective rocker shape of swaying is much flatter (Figure 2A). The figure also includes the effective rocker shape of quiet standing for comparison, which is small and appears to reside at a crossing point of the walking and fore-aft swaying curves. The curves shown in Figure 2A are data collected from one subject, but are representative of the entire subject pool. The median curvature (of all subjects), found by fitting the data to a second order polynomial, was significantly lower for swaying (0.9) than for walking (5.8) ($p = 0.003$; see Figure 2B). By approximating radius as the inverse of this median curvature, the radius of the swaying effective shape (116% height (H) or 219% leg length (LL)) was significantly higher than that of walking (17.2% H or 32.5% LL) ($p = 0.003$). For comparison, the radius found by fitting the walking ROS to a circular arc was 16.0% H or 30.3% LL , showing close agreement between the results of the fitting routine used in this study and those from previous studies [5-7, 16].

Ankle stiffness modeling revealed that the stiffness at the ankle would need to be approximately 8 Nm/degree for walking and 25 Nm/degree for standing and swaying (see

Figure 3) for a person with mass of 71 kg and leg length of 1 meter. Ankle torque versus ankle dorsiflexion curves were closely fit by linear models with the intercept set at zero (see R^2 values for curves in Figure 3).

Discussion

A limitation of this study is the use of high-top canvas shoes, which required placement of ankle markers on the canvas of the shoe instead of the skin. It is possible that the canvas moved slightly relative to the skin surface during swaying and walking, leading to small errors in the measurement of the ankle position. We believe that these errors are small since the canvas part of the shoe fits snugly around the ankle and conforms closely to the ankle when tightly laced, which was the case in this study.

As expected, the radius of the walking ROS that we measured agrees with previous studies [16]. The consistency of the ROS despite changes in walking speed, added weight to the torso, and shoe heel height suggests that this rocker could be a useful goal for design [17], evaluation [18], and alignment [19] of prosthetic ankle-foot systems. Previous studies have also linked the increasing radius of a rocker inverted pendulum to its ability to withstand increasing perturbations [20]. Additionally, Adamczyk et al. [21] found that able-bodied persons using rigid rocker radii near 1/3 of leg length had reduced energy consumption compared with the consumption associated with smaller or larger radii. These studies suggest that the invariant rocker used by able-bodied humans may help to provide a stable and efficient interface for walking, although further work is needed to understand why humans seek an invariant roll-over shape in walking.

The results of this study suggest that able-bodied humans may control their complex lower limb systems in a way that results in simple effective rocker shapes for walking, standing, and swaying. These findings have important implications for design and prescription of prosthetic and orthotic ankle-foot systems. For example, the “flat” region in some prosthetic feet may be useful for prosthesis users with poor balance because these regions provide a biomimetic and inherently stable base for standing and swaying. The length of the “flat” region may determine the appropriate compromise between stability and mobility for each user. Curtze et al. [22] analyzed the roll-over profiles of several commercially available prosthetic feet and found that they do not have a constant curvature. The different locations and lengths of their “flat” regions may contribute to the perceived stability of each foot [22]. Similar analyses are also applicable to the rockers used on walking casts/boots and total contact casts. Choosing the appropriate rockers may help their users ambulate naturally during recovery while still supplying a flat, inherently stable section for standing.

Lastly, prosthetic and orthotic ankle-foot systems could be developed that recognize whether a person is walking or standing, and adjust their effective rocker shape to more or less curvature, respectively. These bi-modal systems could conform to a biomimetic effective shape for walking (a circular rocker with a radius of about 1/3 of the leg length) and a biomimetic effective shape for standing and swaying (a flat base or a rocker with a radius of about 2 leg lengths). A natural approach to this problem would be a prosthetic foot with a lockable single-axis ankle and a relatively stiff forefoot section. The ankle stiffness of the prosthesis could be set for walking when the ankle is unlocked and could provide a “flat” effective surface for standing and swaying with the ankle locked.

Prosthesis designs that conform to biomimetic effective rocker shapes for various functions such as standing and swaying may provide prosthesis users with improved balance and balance confidence for these tasks, possibly allowing them to be involved in more social activities and improving the quality of their lives. Also, prosthetic ankle-foot systems that

provide inherent mechanical stability in standing may reduce the number of falls experienced by their users, reducing injuries and health care costs.

Acknowledgments

The authors would like to acknowledge the use of the VA Chicago Motion Analysis Research Laboratory. We would like to thank Rebecca Stine, MS, for her help with data collection and analysis, Stefania Fatone, PhD, for her help with ankle strength and range of motion testing, and Sara Koehler, MS, and Brian Ruhe, PhD, for their help with statistics used in this study. This publication was made possible by Grant Number R03-HD050428-01A2 from the National Institutes of Health (NIH). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIH.

References

1. Perry, J. Gait analysis : normal and pathological function. SLACK; Thorofare, NJ: 1992. p. xxxii-524.
2. Morawski, JM.; Wojcieszak, I. Biomechanics VIA Int Series on Biomechanics. University Park Press; 1978. Miniwalker - a resonant model of human locomotion.
3. McGeer T. Passive dynamic walking. The International Journal of Robotics Research 1990;9:62–82.
4. Knox, EH. The role of prosthetic feet in walking. Northwestern University; Evanston, IL: 1996.
5. Hansen AH, Childress DS, Knox EH. Roll-over shapes of human locomotor systems: effects of walking speed. Clinical Biomechanics 2004;19(4):407–14. [PubMed: 15109762]
6. Hansen AH, Childress DS. Effects of adding weight to the torso on roll-over characteristics of walking. Journal of Rehabilitation Research and Development 2005;42(3):381–90. [PubMed: 16187250]
7. Hansen AH, Childress DS. Effects of shoe heel height on biologic rollover characteristics during walking. Journal of Rehabilitation Research and Development 2004;41(4):547–54. [PubMed: 15558383]
8. Winter DA, Prince F, Frank JS, Powell C, Zabjek KF. Unified theory regarding A/P and M/L balance in quiet stance. Journal of Neurophysiology 1996;75(6):2334–43. [PubMed: 8793746]
9. Miller WC, Speechley M, Deathe B. The prevalence and risk factors of falling and fear of falling among lower extremity amputees. Archives of Physical Medicine and Rehabilitation 2001;82(8): 1031–7. [PubMed: 11494181]
10. Miller WC, Deathe AB, Speechley M, Koval J. The influence of falling, fear of falling, and balance confidence on prosthetic mobility and social activity among individuals with a lower extremity amputation. Archives of Physical Medicine and Rehabilitation 2001;82(9):1238–44. [PubMed: 11552197]
11. Boone DC, Azen SP. Normal range of motion of joints in male subjects. J Bone Joint Surg Am 1979;61(5):756–9. [PubMed: 457719]
12. Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. J Orthop Res 1990;8(3):383–92. [PubMed: 2324857]
13. Fatone S, Hansen AH. Effect of ankle-foot orthosis on roll-over shape in adults with hemiplegia. J Rehabil Res Dev 2007;44(1):11–20. [PubMed: 17551854]
14. Stewart, J. Calculus. 2nd ed.. Brooks/Cole Pub. Co.; Pacific Grove, Calif.: 1991. p. xviii-974.A112 P
15. Field, AP. ISM introducing statistical methods. Sage Publications; London ; Thousand Oaks: 2000. Discovering statistics using SPSS for Windows : advanced techniques for the beginner; p. xiii-496.
16. Hansen, AH. Roll-over characteristics of human walking with applications for artificial limbs. Northwestern University; Evanston, IL: 2002. p. 1v
17. Sam M, Childress DS, Hansen AH, Meier MR, Lambla S, Grahn EC, Rolock JS. The 'shape&roll' prosthetic foot: I. Design and development of appropriate technology for low-income countries. Medicine, Conflict and Survival 2004;20(4):294–306.
18. Hansen AH, Meier MR, Sessoms PH, Childress DS. The effects of prosthetic foot roll-over shape arc length on the gait of trans-tibial prosthesis users. Prosthetics and Orthotics International 2006;30(3):286–99. [PubMed: 17162519]

19. Hansen AH, Meier MR, Sam M, Childress DS, Edwards ML. Alignment of trans-tibial prostheses based on roll-over shape principles. *Prosthetics and Orthotics International* 2003;27(2):89–99. [PubMed: 14571938]
20. Wisse, M.; van Frankenhuyzen, J. AMAM Conference of Adaptive Motion of Animal and Machines. Kyoto, Japan: 2003. Design and construction of MIKE: a 2D autonomous biped based on passive dynamic walking.
21. Adamczyk PG, Collins SH, Kuo AD. The advantages of a rolling foot in human walking. *Journal of Experimental Biology* 2006;209(Pt 20):3953–63. [PubMed: 17023589]
22. Curtze C, Hof AL, van Keeken HG, Halbertsma JP, Postema K, Otten B. Comparative roll-over analysis of prosthetic feet. *Journal of Biomechanics* 2009;42(11):1746–53. [PubMed: 19446814]

Figure 1.
Drawing used to model the rotational stiffness needed in a prosthetic single-axis ankle-foot system to mimic effective rocker shapes for able-bodied walking and fore-aft swaying.

Figure 2.

(A) Effective rocker shapes for a representative able-bodied subject during walking (light gray), fore-aft swaying (dark gray), and quiet standing (black). (B) Boxplot of effective rocker shape curvatures for walking and fore-aft swaying.

Figure 3. Data from the model shown in Figure 1 when using the effective rocker shape goal for walking (circles) and for swaying (squares). The model assumes a person with mass of 71 kg and leg length of 1 meter.