JRRD Volume 41, Number 4, Pages 547–554
July/August 2004
Journal of Rehabilitation Research & Development

Effects of shoe heel height on biologic rollover characteristics during walking

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Abstract—This study investigated the effects of shoe heel height on the rollover characteristics of the biologic ankle-foot system. Ten nondisabled adult female volunteers walked using three pairs of shoes with varying heel heights and at three walking speeds with each pair of shoes. Kinematic and kinetic data needed to calculate the rollover shapes of the ankle-foot systems of the participants were collected. Rollover shapes are the effective rocker geometries that ankle-foot systems conform to between heel contact and opposite heel contact. Parameters of the best-fit circular arcs to the rollover shapes were used in an examination of the effects of shoe heel height on the ankle-foot system. The results support the notion that nondisabled humans automatically adapt their ankle-foot systems to accommodate a range of shoe heel heights, resulting in rollover shapes that do not change appreciably. Given physiologic constraints, this adaptation may not be possible for very high heels.

Key words: ankle, foot, gait, human movement, shoes.

INTRODUCTION

Nondisabled ambulators wear shoes of different heel heights with little or no difficulty. However, persons who use lower-limb prostheses are often restricted to the use of a narrow range of heel heights. When the shoe heel height is changed beyond this small range on a prosthesis, an alignment change is necessary to accommodate the higher or lower heel height. The general aim of this study is to examine the automatic adaptations that occur in the nondisabled ankle-foot system in an effort to gain insight for the development of improved prostheses.

Previous studies of nondisabled persons wearing high-heeled shoes have measured numerous biomechanical factors, including standing posture, walking kinematics and kinetics, pressures applied to the plantar surface of the foot, and energy cost [1–10]. One particular measurement that was made in many of these studies is the amount

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Abbreviations: ANOVA = analysis of variance, COP = center of pressure, SD = standard deviation, VA = Department of Veterans Affairs, VACMARL = Department of Veterans Affairs Chicago Motion Analysis Research Laboratory.

This material was based on work supported in part by the National Institute on Disability and Rehabilitation Research of the U.S. Department of Education, grant H133E980023, and the Department of Veterans Affairs (VA) Rehabilitation Research and Development Service, administered through the Jesse Brown VA Medical Center, Chicago, IL.

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of lordosis of the lumbar region of the spine [1–5,9]. The results of these studies were generally not consistent with the belief of many clinicians that lumbar lordosis is increased when one walks with high-heel shoes to accommodate the tendency of the person to fall forward in these shoes. The studies imply that the person's major adaptation is occurring below the trunk, which is consistent with de Lateur et al., who said ". . . the greatest compensation [when walking with shoes of different heel heights] is at the ankle and knee [5]." Because the compensation appears to occur in the leg and not the trunk, we believe the effective rocker geometries created by lower-limb systems may provide important information about the adaptations one uses when walking with high-heel shoes [11,12]. This information may be useful for the design and alignment of new prostheses that could better adapt to changes in heel height, giving users of these devices more footwear options.

The ankle-foot rollover shapes used by nondisabled ambulators wearing shoes of different heel heights were measured and characterized in this study. Ankle-foot rollover shapes are the effective rocker (cam) shapes that the foot/ankle complex conforms to during the period between heel contact and opposite heel contact of walking. During this period of gait, the body rotates over, or rolls over, the stance leg (where "leg" refers to the entire lower limb and foot). When shoes are worn, their effects are also included in the ankle-foot rollover shapes [11,12].

The hypothesis of the study, based on results of preliminary experiments [11,12] was that the nondisabled human adapts (primarily at the ankle) to maintain a similar rollover shape for a wide range of heel heights. This similar shape would allow the head, arms, and trunk (HAT) unit [13] to roll over the leg in a similar manner with shoes of different heel heights, leading to similar movements of the body's center of mass. A change was expected in the vertical positioning of the rollover shapes—and hence in the effective length of the leg—because the taller shoes would position the ankle higher above the ground than the lower-heel shoes.

METHODS

Subjects and Footwear

Walking data were acquired from 10 nondisabled adult female volunteers. The sample size was not determined by a power analysis, and convenience sampling was used as the recruitment method. Female subjects were exclusively selected because we believed they would be experienced with a wider range of shoe heel heights than male subjects, and we wanted to eliminate any possible effects of gender on the experiment. The mean age of the subjects was 25 years (standard deviation [SD] = 3 years). Their mean height and weight were 166 cm (SD = 7 cm) and 65 kg (SD = 10 kg), respectively. For the data acquisition session, the subjects wore t-shirts and shorts and walked with three pairs of shoes with varying heel heights. Subjects were asked to bring in pairs of "mid-heel" and "high-heel" shoes for the study (shoes with stable heels; i.e., not stiletto-heel shoes). The laboratory supplied a third pair of "no-heel" shoes. All the subjects signed approved institutional review board consent forms prior to their participation in the experiment. The forefoot and rearfoot sole thicknesses of the shoes brought in by the participants were measured. The heel height recorded was the difference between the rearfoot and the forefoot sole thicknesses (**Figure 1**). An example of a set of shoes worn by a participant is shown in **Figure 1**. The mean heel height for the mid-heel shoes was 37 mm (SD = 10 mm), while the mean heel height for the high-heel shoes was 71 mm (SD = 17 mm). Shoe heel heights were not standardized in this study because we wanted the participants to be comfortable, and we felt they would be most comfortable using shoes to which they were accustomed. The variability of shoe heel heights also allowed us to examine characteristics of rollover shapes over a range of shoe heel heights instead of a smaller, standardized set.

Gait Data Acquisition

Gait analysis measurements were taken at the Department of Veterans Affairs (VA) Chicago Motion Analysis Research Laboratory (VACMARL). VACMARL is equipped with an eight-camera Motion Analysis System (Motion Analysis Corporation, Santa Rosa, CA) and six Advanced Mechanical Technology, Inc. (AMTI) force platforms (Watertown, MA), although only one force platform and a two-dimensional motion tracking system are needed to perform the analysis. Motion capture was performed at 120 Hz, while the force platforms were sampled at 960 Hz. The force data were later resampled at 120 Hz (i.e., every eighth sample was used) for synchronization with the motion data. A Helen Hayes marker set was used for the gait collection [14], although the only necessary markers for finding the rollover

Figure 1.
Set of shoes used by one participant in experiment. Top shoe is no-heel shoe (heel height = 0), provided by laboratory. Participant brought other shoes into laboratory. Middle shoe is this participant's mid-heel shoe, and bottom shoe is her high-heel shoe. Heel height was calculated by subtraction of forefoot height of shoe sole from rearfoot height of shoe sole, as shown on high-heel shoe.

shapes were the markers on the lateral malleoli and the femoral condyles.

Participants walked first with no-heel (flat-soled) shoes (provided by the laboratory), then with the mid-heel shoes, and last with the high-heel shoes. For each pair of shoes, the subject was asked to walk at three speeds: slow, self-selected, and fast. Data trials were collected until at least five "clean" hits were made on force platforms for each side (right and left). A clean hit was one in which only one foot contacted a force platform and in which that foot did not overlap any boundaries of the force platform.

Gait Data Analysis

Following the gait analysis, the ankle-foot rollover shapes were computed. First, a shank-based coordinate system was created with the ankle (lateral malleolus) and knee (femoral condyle) markers (**Figure 2**). The *y*-axis of this coordinate system starts at the ankle marker and goes through the knee marker. The *x*-axis of the coordinate system is perpendicular to the *y*-axis, is contained in the plane of forward progression, and points "forward." The ankle-foot rollover shape is found by a transformation of the forward progression component of the center of pressure (COP) of the ground reaction force under the foot from a laboratory coordinate system into the shank-based coordinate system for each sample between the times of heel contact and opposite heel contact. The ankle-foot rollover shape shows the effective rocker shape to which the ankle-foot-shoe system conforms during the period between heel contact and opposite heel contact of walking, by showing where the net force is being applied to the system in the shank coordinates. Because the shoe interacts with the walking surface at the COP, the rollover shape indicates the shoe-floor interaction sites with

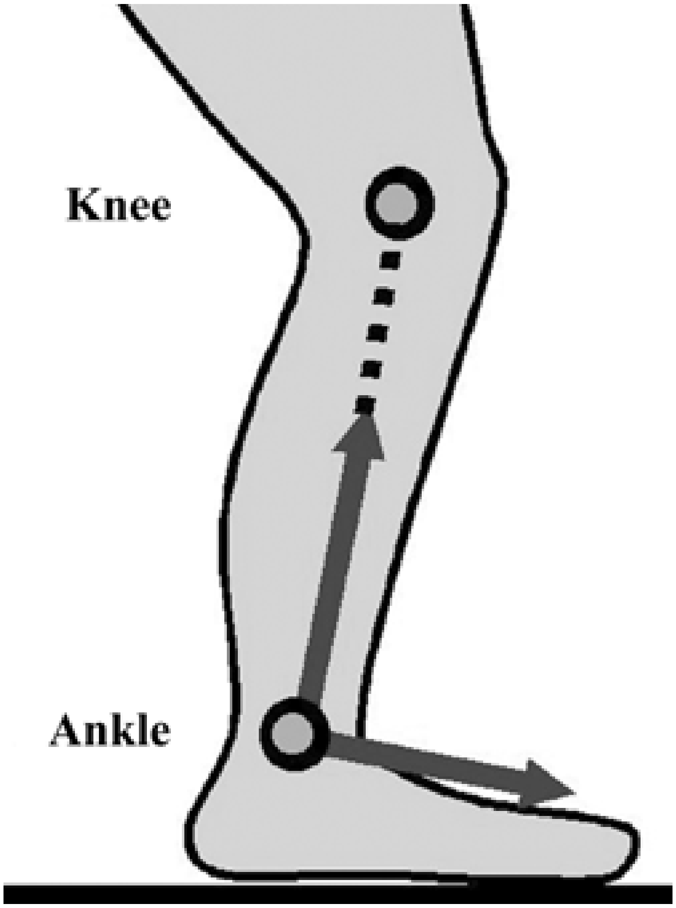

Figure 2.
Shank-based coordinate system. Ankle and knee markers (circles on leg) indicate markers placed on lateral malleolus and lateral femoral condyle, respectively.

respect to the shank as time progresses. The rollover shape is not a literal geometry because the system does not conform to the shape at any distinct time. The rollover shape is an *effective* geometry that describes a mechanical cam or roller (or other device that deforms to this shape under loads of walking) that could be fixed to the shank to approximate the function of the ankle, foot, and shoe complex during walking. This perspective lends itself to the design of prosthetic systems that are attached to the shank (e.g., prosthetic ankle-foot mechanisms rigidly attached to a residual limb [shank] sockets for use as transtibial prostheses).

Rollover shapes were normalized by the time of the rollover period (time between heel contact and opposite heel contact). We then set these time-normalized shapes into equal-length arrays with the use of a cubic spline routine to allow averaging of shapes for similar conditions (i.e., same walking speed and heel height trials). These normalized, equal-length shapes could also be used to determine the variability of the rollover shapes by a determination of the SD for Shape *X* (the horizontal or *x*-components of the rollover shapes) and for Shape *Y* (the vertical or *y*-components of the rollover shape) for each indexed data point in the equal-length arrays. The mean and SD of Shape *X* and Shape *Y* were used to draw out the mean rollover shapes and ellipses of error around each point.

Circular arcs were fitted to the rollover shapes as described previously [12]. The fittings yielded the radius (R), horizontal positioning of the arc's center (X_0), and vertical positioning of the arc's center (Y_0) for each ankle-foot rollover shape. These characteristics are illustrated in **Figure 3**. A parallel study showed that rollover shapes of nondisabled ankle-foot systems do not change appreciably with changes in walking speed [12]. For this reason, data were analyzed based on heel height only. Each subject's median radius, horizontal positioning, and vertical positioning were calculated for each of the three heel height conditions. The medians were then used in a repeated measures analysis of variance (ANOVA). The assumption of sphericity was examined with Mauchly's Test. The Greenhouse-Geiser correction factor was used in cases where the assumption of sphericity was violated. Post hoc analyses were performed with the use of the Bonferroni adjustment for multiple comparisons. Statistical analyses were computed using SPSS software (SPSS, Inc., Chicago, IL).

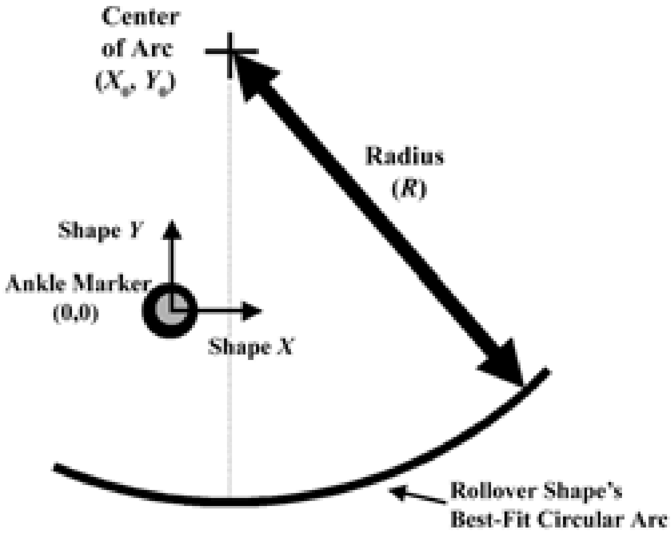

Figure 3.
Diagram showing circular arc parameters. Radius (R), horizontal positioning (forward shift) (X_0), and vertical positioning (Y_0) were found for each rollover shape's best-fit circular arc.

RESULTS

Walking Trials

The ankle-foot rollover shapes for a typical subject are shown in **Figure 4**. Results were similar for the other nine subjects. The graph in **Figure 4** has three average rollover shapes and envelopes of error corresponding to 1 SD in each direction of the Shape *X* and Shape *Y* variables. Each average rollover shape corresponds to one of the three pairs of shoes (i.e., no-heel, mid-heel, and high-heel shoes). Data in **Figure 4** are for this subject's self-selected walking speed. Rollover shapes found for slow and fast walking speeds were comparable to the data for self-selected walking speeds. Sagittal plane ankle, knee, and hip kinematic data were examined. The largest adaptations were at the ankle and can be summarized as an overall shift in the direction of plantar flexion as shoe heel heights were increased.

Rollover Shape Characteristics

The radii for the best-fit circular arcs to the rollover shapes are shown versus heel height in **Figure 5(a)**. The radii are normalized by the body heights of the research participants. Individual median values for radii are shown in **Figure 5(a)**, with a different symbol representing the data for each participant. Radii did not change significantly

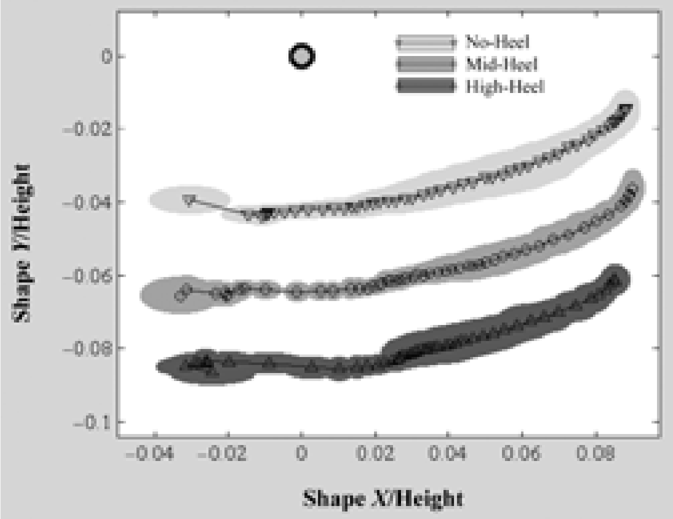

Figure 4.
Ankle-foot rollover shapes for different heel heights for one participant. Plots show shapes for self-selected walking speeds. Rollover shapes for slow and fast walking speeds were similar to these shapes. Shading around shapes signifies ellipses of error (1 standard deviation) from mean rollover shapes. Darkness of shading indicates heel height of shoes. Rollover shapes are center of pressure of ground reaction force transformed into shank-based coordinate system (**Figure 2**).

according to the repeated measures ANOVA (p = 0.24). The radii data support the hypothesis that rollover characteristics do not change when nondisabled persons wear shoes of different heel heights. The human image superimposed onto the graph in **Figure 5(a)** is intended to illustrate that the center of the best-fit circular arcs of the rollover shapes tend to be between the ankle and the knee joints. The median ankle-foot radius for all walking trials was 19 percent of the height.

The body-height-normalized forward shifts (X_0/height) for the best-fit circular arcs to the rollover shapes are shown versus heel height in **Figure 5(b)**. The forward shift measure is related to the amount of shift of the arcs but also changes when a circular arc is rotated about a point that is not located at the arc's center [12]. The individual medians of normalized forward shift for each subject walking at each heel height condition are shown in **Figure 5(b)**. The forward shift did not change significantly from no-heel to mid-heel heights (p = 0.53), but did change significantly between no-heel and high-heel (p = 0.04) and between mid-heel and high-heel heights (p = 0.04). This implies that the hypothesis was supported, but only for shoe heel height changes including no-heel and mid-heel heights.

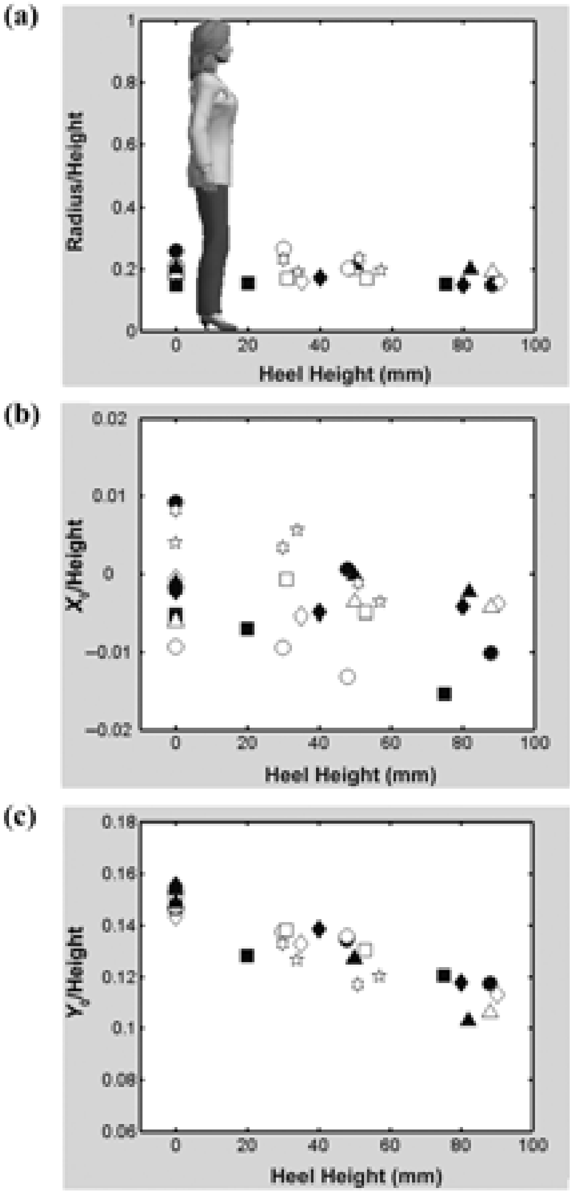

Figure 5.
(a) Radii of ankle-foot rollover shapes (normalized by body height) versus heel height. Median radius/height values for each heel height condition versus heel height of shoes that were worn are indicated on plot, with a different symbol for each participant's data. Superimposed human image, created with Poser 4 software (Curious Labs, Inc., Santa Cruz, CA), indicates that center of best-fit radius tends to be between ankle and knee (approximately 19% of body height). Radii did not change significantly with increased heel height. **(b)** Forward shifts of ankle-foot rollover shapes (normalized by body height) versus heel height. Forward positioning (shifts) did not change significantly between no-heel and mid-heel heights, but did change significantly for high-heel height. **(c)** Vertical positioning of rollover shapes (normalized by body height) versus heel heights. Vertical positioning changed significantly for all three heel heights.

The vertical positions of the centers of the best-fit circular arcs to the rollover shapes (normalized by body height) are shown versus heel height in **Figure 5(c)**. The vertical positions were significantly decreased with each increase in heel height ($p \leq 0.001$ for all comparisons).

DISCUSSION

The results of the walking trials, in general, support the hypothesis that one adapts when wearing shoes of different heel heights to maintain similar rollover characteristics (i.e., rollover shapes). Two important rollover shape characteristics (radius and forward shift of the shape) did not change significantly with moderate increases in shoe heel height (**Figure 6**). The shapes were displaced downward (distally) with higher heels. Humans appear to automatically adapt the resting level of their ankle joints into more plantar flexion when wearing shoes with higher heels. This plantar flexion results in an ankle marker trajectory that is higher above the ground, thus making the rollover shape move downward with respect to the ankle marker (since the rollover shape is COP data, which resides on the surface of the floor).

The hypothesis of invariant rollover shape breaks down somewhat when one wears very high heels (i.e., above 50–60 mm). At this point, the shapes begin to shift posterior with respect to the shank-based coordinate system. This apparent shift may reflect an effective dorsiflexion of the rollover shape [12], which could occur if the ankle were not able to fully compensate for the highest heels by the use of plantar flexion at the ankle. The heel heights at which changes in the forward shift were found in this study correspond closely with the heel heights above which changes, including increased energy cost, were found by Ebbeling et al. [8]. Perhaps the inability of the ankle to completely compensate for very high heels led to the changes found by Ebbeling et al. Other systems that are higher (e.g., knee, pelvis, and spine) may be employed for adaptations when one wears very high heels.

The radius of the ankle-foot rollover shape tends to be around 0.19 times a person's height. An assumption that the leg length is 0.53 times the height [15] yields a radius of 0.36 times the leg length. This value is similar to the "effective radius" of 0.3 that was suggested by McGeer for a human-like passive walking machine [16]. The agreement of data presented in this paper and McGeer's suggestion support the idea that the rollover characteristics of nondisabled lower-limb systems can be approximated by passive cams, even though the rollover shapes of these systems are created with both passive and active musculoskeletal elements.

Weaknesses of this study include small sample size, lack of randomization of the order in which shoes were used, lack of male participation, a young subject sample

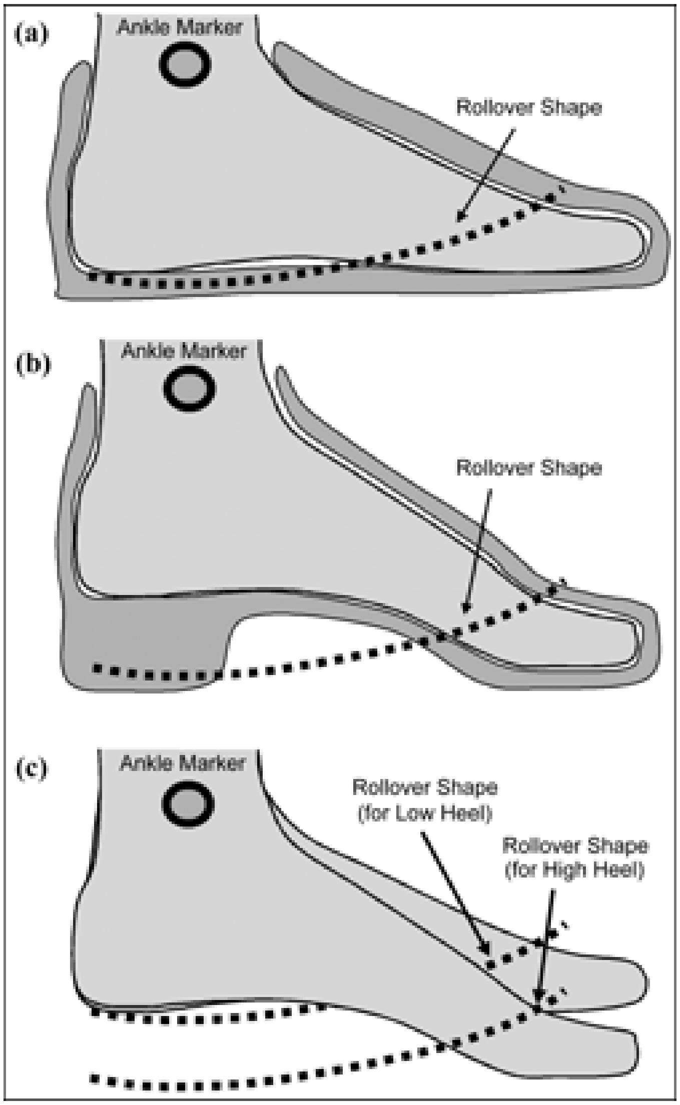

Figure 6.
Drawing of automatic adaptation that occurs with biologic ankle-foot system when one wears shoes of different heel heights. **(a)** Ankle-foot system in low-heel shoe. **(b)** Ankle-foot system in high-heel shoe. **(c)** Superimposed ankle-foot systems in low- and high-heel shoes to illustrate that adaptation results in equivalent walking rockers, or rollover shapes, that are not appreciably changed except for their vertical distance from ankle marker.

population, and the fact that shoes were not standardized for all the subjects. This study, however, illustrates a new idea regarding rollover characteristics of the ankle-foot system that could be examined further in a larger study, in which heel height is more closely controlled, the order of shoes used is randomized, and the subject sample population is more diverse (i.e., including men and women of a larger age range). Another weakness of the study is that we did not test stiletto heels, to eliminate a variable (medial-lateral heel instability) in the experiment. Nonetheless, we believe the findings of the study are applicable to the design and alignment of lower-limb prostheses.

CONCLUSIONS

Nondisabled persons automatically adapt their ankle-foot systems to changes in shoe heel height (up to 50–60 mm) to maintain generally invariant ankle-foot rollover shapes. This finding, along with previous findings that suggest invariance of rollover shapes to walking speed, proposes an underlying importance of maintaining proper rollover characteristics for walking. The study of rollover shapes of nondisabled lower-limb systems could provide an understanding of human walking and assist in the development of rehabilitation aids. Future designs of ankle-foot prostheses should be of systems that can adapt automatically to changes in shoe heel height. This feature could allow persons using prostheses the ability to walk comfortably in a larger variety of shoes (and to walk without shoes), without needing manual adjustments of their prostheses. Designers of future prostheses may want to use an invariant rollover shape as a goal, since complex biologic systems of the foot and ankle seem to achieve this result.

ACKNOWLEDGMENTS

We would like to acknowledge the use of the VACMARL of the Jesse Brown VA Medical Center, Chicago, IL. We would also like to thank Jill Brunner, Nicole Hennig, and Seema Gurnani for their help in collecting and processing the data for this project. The opinions contained in this publication are those of the grantee and do not necessarily reflect those of the Department of Education.

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Submitted for publication June 18, 2003. Accepted in revised form September 23, 2003.