

Changes in Ankle Kinematics to Preserve an Invariant Roll-over Shape

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INTRODUCTION

The roll-over shape (ROS), which is the effective rocker that the ankle-foot system conforms to from heel contact to opposite heel contact, may be a useful tool for design and evaluation of lower limb prostheses because it has been shown to be invariant to changes in walking speed, added weight to the torso, and heel height during able-bodied walking [1-3]. However, it is uncertain whether ankle kinematics also remain unchanged during this part of the gait cycle (GC) or whether they adapt to preserve the same ROS. By studying able-bodied persons walking on rocker shoes of different radii, we could invalidate the idea of ankle kinematics invariance, ROS invariance, or both. We hypothesized that ankle flexion during single support of walking would change in response to different shoe rocker radii in order to maintain an invariant roll-over shape radius. Based on a model that assumes ROS invariance, we also hypothesized that for decreasing shoe rocker radius, the difference in ankle flexion angle between the end and the beginning of single support would decrease.

METHODS

Ten able-bodied subjects were asked to walk in four different pairs of rocker shoes at three different speeds (Figure 1). The rockers added to the bottom of the shoes had radii of 25%, 40%, and 55% of the subject's leg length. The fourth shoe had a flat elevated bottom. These were coded R25, R40, R55, and FLAT. The three speeds were freely self-selected speed, 30% faster, and 30% slower. Data were collected at the VA Chicago Motion Analysis Research Lab, equipped with six force platforms and an eight-camera motion analysis system. A modified Helen Hayes marker system [4] was used to monitor joint kinematics during gait. We also measured the subjects' ground reaction forces (GRF) as they walked on the force plates. The data collected were first processed with commercial software, EVA Realtime and Orthotrak, yielding ankle kinematics and joint center coordinates.



Figure 1: High top canvas shoe with stiff crepe material attached. Different radii were obtained by cutting along the lines drawn on the sole (lines in the picture are not drawn to scale).

Custom MATLAB scripts were used to overlay trials with different shoes but at the same walking speed. Range of motion (ROM) of the ankle, defined as the ankle flexion at opposite heel strike (50% GC) subtracted by that at opposite toe off (10% GC), was measured and compared for different shoes and walking speeds. Knee flexion, hip flexion, and pelvic obliquity curves were visually inspected as a function of the GC. Another script was used to transform the center of pressure of the GRF under the shoe from a lab-based to a shank-based coordinate system, yielding the roll-over shape [5]. This curve was fitted to a circular arc to find its radius and center to aid in the comparison of the different conditions.

SPSS was used to perform a 3x4 two-way repeated measures ANOVA to see if there were significant differences in ankle flexion range of motion and ankle-foot-shoe roll-over shape radius between the three walking speeds and four shoe rocker radii. Additionally, pairwise comparisons were performed for statistically significant factors.

RESULTS AND DISCUSSION

The results shown are data collected from one subject, representative of the entire pool, at freely self-selected speed. Ankle kinematics were not affected by walking speed ($p = 0.65$), but they were clearly changed by the shoes (Figure 2). The differences in ankle ROM between the four rocker shoes at each speed were highly significant ($p < 0.001$). At freely self-selected speed, the ROM (mean \pm SD deg) for all the subjects were 24.2 ± 4.0 , 14.7 ± 2.9 , 10.5 ± 3.1 , and 5.7 ± 3.4 for FLAT, R55, R40, and R25, respectively. The data showed a consistent decrease in ROM with decreasing shoe rocker radius, supporting our hypothesis. Based on the pairwise comparisons, each rocker shoe resulted in a significantly different ankle ROM from each other ($p < 0.04$ for all comparisons).

On the other hand, the ankle-foot-shoe roll-over shapes were remarkably invariant, independent of walking speeds ($p = 0.38$) and shoe rocker radii ($p = 0.37$) (Figure 3). The ROS radius (mean \pm SD) of all twelve conditions for the ten subjects was $17.7 \pm 2.4\%$ of height or $33.4 \pm 4.6\%$ of leg length. This radius agrees with previous studies [6] and is in the range of the radii of rocker shoes we made. Since, the other joint kinematics analyzed were almost unaffected by the changing rocker radii, it can be concluded that ankle kinematics adapted to preserve an invariant ankle-foot-shoe roll-over shape.

This ankle adaptation may indicate a neurological goal to maintain an ideal roll-over shape, regardless of changing walking conditions. Understanding the ideal ROS for able-bodied gait can improve prosthetic and orthotic designs that may enable their users to achieve gaits closer to able-bodied gait.

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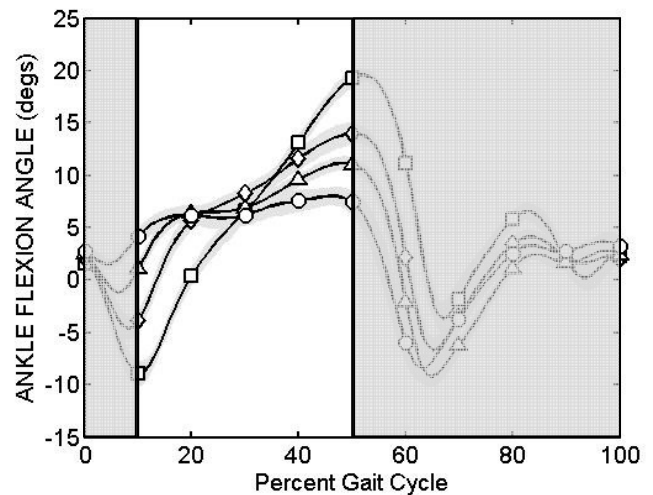


Figure 2: Ankle flexion over the entire gait cycle (GC) of a subject's right foot at freely self-selected speed. During single support (10%~50% GC), the ankle range of motion fluctuates significantly ($p < 0.001$) between rocker shoe conditions. (Note: square = FLAT, diamond = R55, triangle = R40, circle = R25.)

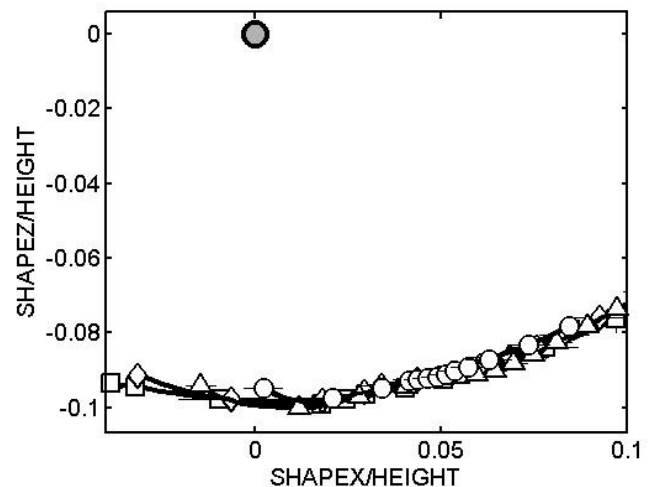


Figure 3: Ankle-foot-shoe roll-over shape (normalized by height) of a subject's right foot at freely self-selected speed. The curves are almost identical for all shoe conditions. The mean roll-over shape radius of all the subjects was $17.7 \pm 2.4\%$ of height or $33.4 \pm 4.6\%$ of leg length. (Note: square = FLAT, diamond = R55, triangle = R40, circle = R25; (0,0) is the ankle center.)

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