Prosthetic Foot Frontal Plane Adaptability: Finite Element Studies

Murray E. Maitland1, Simon Lau2, Gordon Cheesebro2, Jessica Zistatsis2, Kat M. Steele2,

University of Washington, Departments of 1. Rehabilitation Medicine, 2. Mechanical Engineering.

INTRODUCTION

Through the stance phase of gait, the foot adapts spontaneously to unanticipated ground-foot contact. There is not enough time for voluntary motor control at the moment of impact. Spontaneous adaptability is especially important with poor foot prepositioning, uneven ground, decreased cognitive attention or low lighting.

The foot contacts the ground at an angle in the frontal plane during many activities of daily living including simple weight shift. Torques produced at the foot affect the socket-residual limb interface. Adaptability at the foot may minimize these forces and improve prosthetic comfort.

The purpose of this study was to evaluate prosthetic approaches to frontal plane adaptability using finite element modeling.

METHOD

The four general approaches evaluated in this study were: 1. Radius of curvature of the heel at foot strike; 2. Material compliance and thickness of compliant materials; 3. A foot prosthesis with series 4-bar linkages that allowed 26° and 60° rotation at the forefoot and hindfoot respectively; and 4. Split toe versus flat forefoot designs.

LS-Dyna (Livermore Software Technology Corporation, California, USA) was used for finite element modeling (FEA). The stance phase of gait was simplified using an inverted pendulum model of the leg (virtual prosthetic foot and pylon). Foot length, shank length and body mass were determined using measurements of a single research participant. Cosmetic coverings were not used for the comparisons. Initial linear and angular velocities at a gait speed of 1.3 m/s were not varied. Angled slope of 15% and raised domes (1.3 cm high, 10.16 cm diameter) simulated side-slope and uneven ground. The raised domes were positioned to contact different regions of the foot during gait. Deviation of the proximal shank from an anterior-posterior trajectory was used to evaluate frontal plane stability.

RESULTS

Heel mediolateral curvature significantly affected torques acting on the upper shank and deviation from the forward path. A flat heel contacting with 15% side-slope or a raised dome caused a torque about the proximal leg that was proportional to the width to the heel. Modifying the radius of curvature of the heel reduced the effect of heel impact and path deviation could be eliminated.

Compliant materials (CMs) between the foot and side-slope or uneven ground dampened mediolateral accelerations. CMs also allowed for a lateral shift over the base of support permitting a wider range of equilibrium positions. CMs can be used throughout the foot to adapt to various geometries depending on position of the virtual raised dome. However, overly compliant components had detrimental effects on maintaining the forward trajectory.

Forefoot frontal plane motion at foot flat was critical for mediolateral adaptability. Variations of forefoot properties at forefoot contact was the principle determinant of deviation from forward progression. The crossed 4-bar linkages adapted to the angled ground and reduced mediolateral deviation of the shank. The moving center of rotation of the 4-bar linkages increased the number of stable positions and lowered the virtual center of rotation compared to without a linkage system. Forward velocity and direction were maintained on a 15% side-slope and during contact with raised domes. A compliant split-toe design, resulting in two-point contact, permitted a tripod contact of the foot by unlinking medial and lateral forefoot motion compared with a flat forefoot.

DISCUSSION

Each approach to mediolateral adaptability tested in this study had strengths and weaknesses, suggesting that an optimization process including multiple approaches may result in superior performance compared with any individual approach.

The anatomical foot has regional differences that function in side-to-side adaptability. At the heel, normal anatomy consists of relatively limited range of motion and rounded shape. The midfoot has been considered an adaptable energy return system. The forefoot has considerable adaptability and has two-point contact. This study reinforces the anatomical structure-function relationships of the foot.

Further research on these and other variables, in combination with feedback, actuators, and control systems can improve mediolateral adaptability in prosthetic feet.

CONCLUSION

Stance phase frontal plane proximal shank trajectory on side-slope and uneven ground can be improved depending on shape, compliance, and linkage systems.

CLINICAL APPLICATIONS

Prosthetic foot design impacts comfort, performance and quality of life for people with major lower extremity amputations. Clinicians and prosthetic foot developers might consider heel and forefoot geometry, properties of CMs and linkage systems as they relate to patient needs for frontal plane adaptability.