Mechanical characterization of the adaptability of prosthetic feet in the frontal plane

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Summary
This study investigated the design-related ability of prosthetic feet to adapt to cross slopes and derived a theoretical model. The mechanical adaptation to cross slopes was studied for six prosthetic feet, measured by a motion capture system. A theoretical model linking the measured data with adaptations was proposed.

The type and degree of adaptation depends on the foot design, for example, stiffness, split toe or continuous carbon forefoot, and additional ankle joint. The proposed model shows high correlations with the measured data for all feet.

Introduction
For lower leg amputees an everyday task like standing and walking on uneven ground is challenging due to the limited adaptivity of conventional prosthetic feet. To enhance the adaptability in frontal and sagittal plane, manufactures have developed prosthetic feet with various design features.

The American Orthotic and Prosthetic Association described a setup of mechanical tests\cite{1} to evaluate this multiaxial range of motion of prosthetic feet. However, only a few researchers have investigated how the tilt of the ground or, similarly, inversion/eversion of the foot influences the behavior of prosthetic feet\cite{2,3}.

The aim of this study was to analyze the adaptations of prosthetic feet to cross slopes and to derive a geometric model that describes these adaptations. For this purpose continuous carbon forefoot, split toe, and split toe with a novel ankle joint for inversion/eversion designs have been considered.
Methods

- 6 different energy-storage and return (ESR) feet with 5 different designs were considered.
- A mechanical test device consisted of a self-locking crank for lowering and lifting the prosthetic foot within a solid metal frame was used, figure 1.
- A L.A.S.A.R-Posture (Ottobock, D) was placed at the bottom of the frame to measure the applied vertical force and to align the feet similarly.
- Wooden blocks of 0° and 9° inclination were placed at the L.A.S.A.R-Posture and were used to simulate level and cross-slope conditions.
- Loads from 0 to 100kg were applied.
- A pair of antenna markers were attached on top of each split toe in order to estimate the twist in the frontal plane with a motion capture system (Vicon Motion Systems, UK).

![Mechanical test device with a split-toe ESR foot. The attached reflective markers were used to estimate the adaptations in the frontal plane with a the motion capture system for certain loads.](image1.png)

**Figure 1.** Mechanical test device with a split-toe ESR foot. The attached reflective markers were used to estimate the adaptations in the frontal plane with a the motion capture system for certain loads.

![Model used to describe the adaptation of prosthetic split-toe feet on cross slopes. For parameter details and derivation of the model’s equations, see reference. The picture shows the Triton side flex and the two design features to enhance the adaptability to uneven ground.](image2.png)

**Figure 2.** Model used to describe the adaptation of prosthetic split-toe feet on cross slopes. For parameter details and derivation of the model’s equations, see reference. The picture shows the Triton side flex and the two design features to enhance the adaptability to uneven ground.
Results

- Distinct adaptations to cross slopes were found for all investigated feet.
- Split-toe ESR feet showed a mixture of twist and shift (between toes) whereas the ratio depends on the foot type tested.
- The foot with the additional ankle joint achieved a full adaptation with the lowest load.
- The model used, figure 2, match the measured data with minor deviations and show high correlations for all feet, figure 3.
Conclusion

The ability of prosthetic feet to adapt to cross-slopes is design dependent. It was shown for the first time that tested ESR feet that feature a split-toe design adapt better to cross slopes than continuous carbon forefoot feet tested. An ankle joint allowing for additional inversion and eversion further enhances the adaptability. Furthermore, a theoretical model was successfully derived which described the feet dependent adaptations. The influence of the ESR foot adaptability on biomechanical and clinical parameters of standing and walking on uneven ground should be investigated in future and correlated to these findings. These findings may help prosthetists and clinical decision makers in the prescription process for selecting an appropriate prosthetic foot to persons with a lower limb amputation.

References