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Title
Effects of cross-slopes on the gait of transtibial amputees

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Summary
Walking on level ground and walking on cross-slopes for four different conditions were investigated with unilateral transtibial amputees. Side and inclination dependent adaptations in the gait characteristics of transtibial amputees were observed.

Introduction
Walking outdoors is challenging for amputees especially on uneven grounds. Compensational movement strategies by the amputees become necessary due to the limited adaptability of prosthetic components and additionally limiting deficits in force generation in the residual limb. Walking on cross-slopes, a form of an uneven ground where the path is titled, are situations amputees face regularly. In contrast to ramp walking only few studies investigated adaptations of amputees while walking on cross-slopes [1-3]. For example, Villa et al. [3] observed adaptations in the swing phase on the prosthetic side. They showed that transtibial amputees (TTA) mainly adapted with an increased residual hip and knee flexion to the situation. However, they only investigated cross-slope walking while the prosthesis was on the hill side and at a 6° tilt.
In this study we highlight the effects of cross-slopes on the gait characteristics of TTA and compare it with adaptations found in level walking.

Methods
The present study included 12 TTA. Participants were provided with energy-storage and return feet (ESR: Triton LP n=6; Proflex LP n=6) for the time of the study. After an acclimatization period of minimum four weeks level and cross-slope walking on 5° and 10° (tilt) were investigated in a gait lab. Thus, in total four different situations for cross-slope walking were

investigated– prosthesis on hill-side (HS) and on valley-side (VS) each for a 5° and 10° cross-slope walkway.
Kinematik data were recorded with a Vicon System (12 cameras) and a dedicated marker set. A Kistler force plate was embedded in the track to measure the ground reaction forces (GRF). After processing the data spatio-temporal and biomechanical parameters (GRF, sagittal ankle and knee angles, pelvis inclination and upper body tilt) were analyzed with respect to situation and side. For a statistical analysis a repeated measurement ANOVA with post-hoc tests were used to show possible differences to level walking.

Results

The spatio-temporal gait characteristics showed well known differences between prosthetic and sound side but reveled only minor adaptations for the different cross-slope situations. For example, trends were observed for velocity (highest for level and 5° with 1.27m/s and slightly lower for 10° with: HS 1.24m/s, VS 1.25m/s), step length (slightly increased for 10° HS by about 0.02m and decreased for the 10° VS by about 0.02m) and step width (decreased from 0.22m for level to 0.20m and 0.21m for HS and VS).
The GRF showed differences between prosthetic and sound side (about 10% body weight) but again only minor adaptations for the different cross-slope situations were observed. The first peak of the ground reaction force increased for the 10° VS leg about 4% body weight and was unchanged for the HS leg.
Statistically significant adaptations to the different situations were observed in the sagittal knee and ankle angles as well as in the pelvis inclination and upper body tilt compared to the level situation. The sagittal ankle angle at the sound side showed a reduced range of motion for VS and an increased one for HS while the prosthetic side was unaffected by the cross-slope. For the sagittal knee angles adaptations were observed for the sound (in stance and swing phase) and the prosthetic side (in swing phase), fig.1A. Pelvis inclination and upper body tilt showed similar adaptations to the cross-slope tilt independent of the prosthetic side, fig.1B.

Conclusion

This study investigated cross-slope walking and its effects on the gait of transtibial amputees in comparison to level walking more systematically then previous studies (e.g.[3]). Adaptations

to the cross-slopes were observed for the prosthetic and sound side in some parameters.
Its effect size increased with increasing cross-slope tilt (5° to 10°). The results confirm and extend findings of previous studies [3]. However, most observed effects had the same order of magnitude or were smaller compared to general adaptation effects in the gait of TTA (compared to non-amputees, e.g. GRF).
A main finding shows that the effective leg length on the sound side was mainly altered by knee and ankle angle to aid better toe clearance on the HS both for the prosthetic and the sound side. The adaptation of the upper body tilt in combination with the pelvis inclination seems to be a compensation and/or stabilization mechanism of the upper body on cross-slopes.

References

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Figure 1: (A) Sagittal knee angle of sound and prosthetic side for different cross-slope conditions (relative to static trial). Adaptations were observed in stance phase and swing phase of the sound side and in swing phase of the prosthetic side. (B) Upper body tilt in the frontal plane for prosthetic gait cycles.