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Effects on ankle power and sound limb load with an active prosthetic foot

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Abstract: The performance of conventional prosthetic feet depends on material and construction principles. Certain powered feet can even generate net positive mechanical work in order to provide an active push-off. The aim of this study was to evaluate the influence of ankle power on the gait of transfemoral amputees. For this purpose level walking of six transfemoral amputees was analysed with a basic and an active foot and three different power settings of the latter. The results show clear advantages of the active foot in comparison with a basic foot. However, a strong relation of the sound side knee loading parameters with the varied ankle power outputs of the active foot couldn't be shown.

Keywords: active prosthetic foot; amputees; ankle power; knee loading parameter; push-off; sound limb load.

Introduction

Lower limb amputation is accompanied by loss of the human foot with its sensitivity, muscular control and possibility of generating ankle power. This complex mechanism is more or less replaced by a prosthetic foot in a lower limb prosthesis. There is a broad variety of prosthetic feet starting from very basic ones like the Solid Ankle Cushion Heel foot (SACH) to modern Energy Storing and Returning feet (ESR) up to powered foot concepts. Most commonly used are the ESR which are designed to store and release energy during stance. The performance of them depends on material and construction principles. However, an active plantarflexion at the end of stance is missing for all passive feet and is described in the literature as one of the most visible differences between amputees and non-amputees [1]. A powered foot can generate net positive

mechanical work in order to provide such an active push-off in contrast to the conventional passive feet. Caused by this development, the clinical importance of the ankle power is discussed frequently. It is supposed that this parameter affects the load on the sound side of amputees [2–4]. The first peak of the external knee adduction moment during stance [5, 6], the peak external knee flexion moment [6] and the first peak of the vertical ground reaction force [5] are considered as predictors of knee loading and the development of knee joint degeneration. Therefore, the aim of this study was the biomechanical evaluation of the question whether the generated ankle power influences the gait of transfemoral amputees, particularly the knee load on the sound side. The correlation between the ankle power and the sound side knee loading parameters will be analysed.

Methods

Prosthetic components

The Empower (Otto Bock HealthCare LP, USA) is currently the only commercially available prosthetic foot that can generate positive mechanical work for an active push-off. It mainly houses an ankle joint, a motor and a carbon base spring, which enable for active and passive walking. The amount of powered propulsion is adjustable to the individual user needs (see Figure 1A). The 1D10 (Ottobock SE & Co, Germany) is a modified SACH foot, which provides very basic functions. This foot has a wooden wedge with a soft heel and rubber regions in the forefoot (see Figure 1B). In all studied prostheses the same microprocessor controlled knee joint C-Leg 4 (Otto Bock Healthcare Products GmbH, Austria) was used.

Subjects

Six male transfemoral amputees (age: 46 ± 10 years; weight: 86.3 ± 20.0 kg; height: 1.83 ± 0.10 m) were recruited for this study. All patients were experienced prosthetic users walking with their prosthesis all day without using walking aids. The details of the patients are listed in Table 1.

Procedure

All prosthetic assembling was done by the same certified prosthetist. The bench alignment followed the manufacturer's specifications and was reproducibly done using an L.A.S.A.R. Assembly, followed by a

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Figure 1: Analysed prosthetic feet. A: Empower (Otto Bock HealthCare LP, USA), B: 1D10 (Ottobock SE & Co, Germany).

Table 1: Details on patients.

Patient	Amputated side	Height, m	Weight with prosthesis, kg	Age, Years
1	Left	1.87	76.0	47
2	Right	1.86	106.5	58
3	Right	1.78	85.5	53
4	Right	1.97	113.0	35
5	Left	1.68	77.0	47
6	Right	1.82	60.0	34

static optimization on the L.A.S.A.R. Posture and finally a dynamic optimization to the prosthetists and subjects satisfaction. Level walking with both feet was biomechanically analysed. The Empower was adapted in three different configurations:

- without power (np),
- less power (lp) and
- optimal power (op).

For the measurements, the amputees walked with two different velocities (normal and fast).

System

An optoelectronic camera system with 12 Bonita cameras (VICON, GB) was used to record the kinematics and two linked force plates (KISTLER AG, CH) recorded the kinetics. Three-dimensional marker trajectories were tracked from 17 markers placed on anatomical landmarks (both sides: acromion, Epicondylus lateralis humeri, Processus styloideus ulnare, Trochanter major, compromise knee centre of rotation according to Nietert [7], Malleolus lateralis, Caput os metatarsale IV and three asymmetric markers: left tibia, right thigh and left shoulder blade). External joint moments were calculated based on ground reaction forces and coordinates of joint axes according to a previously described method [8]. The ankle power was calculated as validated by Proebsting 2019 [9] as the sum of the rotational and translational power in the sagittal plane.

Results

Within both velocity groups no significant differences were found between the studied feet or the Empower

configurations (mean velocity normal: 1.27 ± 0.01 m/s, fast: 1.60 ± 0.01 m/s). The SACH showed the smallest ankle power maximum with 0.85 ± 0.37 W/kg for the normal and 1.12 ± 0.44 W/kg for the high velocity. For both velocities the ankle power maxima with the Empower were significantly ($p < 0.05$) increased (normal: np: 1.48 W/kg, lp: 1.77 W/kg and op: 2.37 W/kg; high velocity: np: 2.13 W/kg, lp: 2.83 W/kg and op: 3.63 W/kg) and also the values for the different configurations differ significantly ($p < 0.05$).

The ranges of plantarflexion at push-off differ between the different configurations of the Empower significantly ($p < 0.05$). With less or optimal power an increased plantarflexion could be observed with the higher velocity in comparison to the normal velocity (lp: 13.4 vs. 17.4 deg and op: 16.2 vs. 20.5 deg) (see Figure 2).

The maximum external knee adduction moment (EAM), the maximum knee flexion moment (KFM) and the first peak vertical ground reaction forces (vGRF) on the sound side are significantly ($p < 0.05$) reduced with Empower op and lp in comparison to the SACH for both velocities. For the Empower np in comparison with the

Figure 2: Mean results of the peaks of ankle power and range of motion of plantar flexion at push-off for the normal and high velocity. Statistical significant difference was defined with $p \leq 0.05$. Mean peak results with one identical alphabetic character do not differ significantly.

SACH these differences are also significant except for the EAM at normal speed (see Figure 3).

By comparing these parameters for the different configurations of the Empower only some comparison show significant results (see Figure 3):

- vGRF: no significant differences;
- KFM: only one significant difference between np (0.33 Nm/kg) and op (0.20 Nm/kg) at normal velocity;
- EAM: np (0.55 Nm/kg) shows significant increased moments in comparison with lp (0.50 Nm/kg) and op (0.51 Nm/kg) at normal velocity.

Figure 3: Mean results of the peaks of the sound side knee loading parameter: Peak knee adduction moment, peak knee flexion moment and first peak vertical ground reaction forces (GRF) for the normal (left) and high velocity (right). Statistical significant difference was defined with $p < 0.05$. Mean peak results with one identical alphabetic character do not differ significantly.

Discussion

The aim of this study was the biomechanical evaluation of the question whether the generated ankle power influences the gait of transfemoral amputees, particularly the knee load on the sound side.

The ankle power shows a very clear differentiation respective between both foot concepts and the different tested power configurations of the Empower by showing a significant difference between all mean values of the ankle power. Additionally it was shown, that the amount of plantar flexion increased with additional ankle power, showing significant differences between all settings of the Empower for this range of motion. With no active ankle power (1D10 and empower np) no significant differences for this parameter could be found.

The plantarflexion at push-off with the active ankle power results in a more physiological gait pattern compared with passive feet. Sound side knee loading parameters EAM, GRFv and KFM are reduced using the active foot especially with optimized power settings in comparison to the 1D10. This results in a relief of the sound side.

In the literature it is suggested that an increase of ankle power may reduce the knee loading on the sound side [2–4]. On the one hand we see a general sound side relief by the active foot generating significantly more ankle power. On the other hand we do not see a strong correlation of the sound side load parameters and the ankle power when adjusting the latter systematically. There is a trend but the parameter do not differ significantly comparing the different settings np (no power), lp (less power) and op (optimal power). Other factors seem to affect here. This needs further investigations.

Conclusion

The overall results prove clear advantages using the Empower generating positive mechanical work for an active push-off over a SACH foot. Especially a relief of the sound side of amputees with the active foot could be seen.

However a strong correlation between the varied ankle power settings on the prosthetic side and the different parameters of sound side knee loading couldn't be shown.

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Conflict of interest: Eva Pröbsting, Björn Altenburg and Dr. Thomas Schmalz are employees of Ottobock, the manufacturer of both prosthetic feet investigated.

Informed consent: Informed consent has been obtained from all individuals included in this study.

Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the ethics committee of the University of Göttingen.

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