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How does ankle power on the prosthetic side influence loading parameters on the sound side during level walking of persons with transfemoral amputation?

Eva Pröbsting[1], Björn Altenburg[1], Malte Bellmann[1], Kerstin Krug[2] and Thomas Schmalz[1]

Abstract

Background: Increased ankle power on the prosthetic side seems to decrease biomechanical loading parameters on the sound side. This assumption is based on biomechanical comparisons of different foot constructions. However, such study designs could not show whether the amount of ankle power solely influences the sound side.

Objective: To analyze the influence of divergent ankle power, resulting from different foot constructions and from different ankle power settings, on the sound side loading parameters.

Study design: Interventional cross sectional study.

Methods: Level walking of transfemoral amputees with a microprocessor knee joint and Solid Ankle Cushioned Heel (SACH), energy storing and returning (ESR) and powered foot (PF) was analyzed. The PF was adapted in three configurations: without power (np), low power (lp), and optimal power (op). An optoelectronic camera system with 12 cameras and two force plates were used.

Results: The ankle power on the prosthetic side shows significant differences about foot types and different settings of the PF. The knee adduction moment, the knee flexion moment, and the vertical ground reaction forces on the sound side were significantly reduced with PF_op and ESR in comparison to SACH. When analyzing these parameters for the different PF configurations, only some show significant results at normal velocity.

Conclusions: The additional positive mechanical work for an active push off in the PF tends to have a relieving effect. The biomechanical sound side loading parameters are reduced with PF_op in comparison to SACH and ESR, resulting in a relief of the sound side of lower limb amputees.

Keywords

ankle power, knee loading, powered foot, ankle push off

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Introduction

The human foot, as the distal lower limb segment, has an outstanding role in controlling human locomotion.[1] Most lower limb amputations are accompanied by a complete loss of this segment. Therefore, the complex functionality of the human foot, including ankle power generation, is to be replaced by a prosthetic foot in a prosthetic fitting. There is a broad variety of prosthetic feet, starting from very basic ones, such as the Solid Ankle Cushion Heel foot (SACH) with a wooden keel, to modern Energy Storing and Returning feet (ESR) with carbon reinforced elements, up to Powered Foot (PF) concepts with an active element generating ankle power. However, a unique property of all passive feet is the missing active plantar flexion at the end of stance, often described in the literature as one of the most visible differences between persons with and without amputation.[2] In contrast to passive feet, the newly introduced powered feet[3,4] are able to generate net positive mechanical work to provide an active push off.

Besides this specific gait deviation of lower limb amputees with passive feet on the prosthetic side, the sound side parameters are mainly characterized by increased magnitude of the first peak of the vertical ground reaction force (vGRF) and increased first peak of the external knee adduction moment (EKAM) and external knee flexion moment.[5-8] The alterations of these parameters are discussed to have a significant role in the development of knee osteoarthritis,[3,9-12] a condition that unilateral lower limb amputees may be at a higher risk to develop.[13]

There are clear hints that the ankle push off at the end of stance, described by ankle power, affects the load on the sound side knee of amputees.[3,4,8,14,15] With increased ankle power on the prosthetic side, EKAM,[4,8,14] vGRF,[3,4,8,14] and external knee flexion moment[3] can be decreased. In all of these studies, different foot constructions with different ankle power generation in late stance were analyzed and compared. Such a study design does not allow to evaluate whether the amount of ankle power is the only factor influencing the sound side load or if other effects based on the individual foot

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construction can influence this biomechanical parameter as well. The question of which prosthetic foot properties influence the release on the sound side seems to be continuing point of discussion. In addition to the lack of studies comparing the same active foot with defined different settings for ankle power generation, there neither exists any study that compares the three different ankle-foot principles (SACH, ESR and PF) in biomechanical terms.[16]

All studies focusing on ankle power of prosthetic feet have analyzed transtibial amputees. These amputees are able to actively control the prosthetic side knee joint by means of neuromuscular algorithms. Based on experience and as shown in the literature,[17] the amount of knee flexion under load varies individually between transtibial amputees. Therefore, the interaction between the knee and prosthetic foot during roll over, including the (powered) push off, is also patient-specific. In the case of transfemoral amputees, the movement of the prosthetic knee joint mainly depends on the type of knee joint, prosthetic alignment, and the individual gait pattern. Usually, the amount of stance flexion is reduced in the TF-amputee population compared with transtibial amputees.[18]

The purpose of this study was to biomechanically analyze the influence of the prosthetic side ankle power generation on the sound side knee load with transfemoral amputees during level walking. Thereby, the different ankle power that can be generated should result from different foot constructions on the one hand and different ankle power settings for the same foot construction on the other hand. The hypothesis was that with increasing ankle power, the knee loading parameters on the sound side can be generally decreased. This hypothesis applies regardless of whether the different ankle power results from different settings of active power generation with the same foot type (first hypothesis) or from different foot types (second hypothesis).

Methods

Prosthetic components

All measurements were conducted with the C-Leg 4 (Otto Bock Healthcare Products GmbH, Austria). Three different foot constructions (SACH, ESR and PF) were evaluated:

SACH

The 1D10 (Ottobock SE and Co, Germany) is a modified SACH foot, which provides basic functions. This foot consists of a wooden keel, a soft heel, and rubber regions in the forefoot (Figure 1(a)).

ESR

The Triton (Otto Bock HealthCare LP) features a split toe forefoot and a flexible heel made of carbon fiber composite, both connected by a polymer base spring. The foot was used in the individual categories with the individual optimal heel wedge (Figure 1(b)).

PF

The Empower (Otto Bock HealthCare LP)[19] mainly houses an ankle joint, a ball screw actuator (motor), a carbon foot blade, an elastic series spring, and sensors (Figure 1(c)). The amount of powered propulsion is adjustable to the individual user needs. For this study, three settings were analyzed:

- no power (np)—no active ankle power generation
- low power (lp)—individually low active power generation: The setting for the active power was increased until the patient could feel the support for the first time.
- optimal power (op)—individually optimized active ankle power generation: In a first step, the generated power was adjusted to given target ranges in the setup software over the user's individual gait speed range. After at least 1 hour accommodation time, a finetuning of the power settings was done according the users preference within the given ranges.

Therefore, taken together, patients walked with five different foot scenarios:

- three different foot types (SACH, ESR, PF)
- three different settings of the PF (PF_np, PF_lp, PF_op).

For all individual test prostheses, the same microprocessor-controlled knee joint C-Leg 4 (Otto Bock Healthcare Products GmbH, Austria) was used.

Participants

Six male participants with unilateral transfemoral amputation (age: 47 [34–58] years; weight: 81 [60–113] kg; height: 1.84 [1.68–1.97] m; BMI: 27.1 [18.1–30, 8] kg/m^2) were recruited for this study. The amputees' mobility level (K-Level), using the Medicare functional classification system,[20] was 3, except one case, who had a K-Level of 4. The details of the patients are listed in Table 1. All participants were experienced C-Leg 4 users. Inclusion criteria were the fit of an ischial containment socket of the everyday prosthesis without any problems and restrictions and no further impairment of the musculoskeletal system or other comorbidities. The subjects were

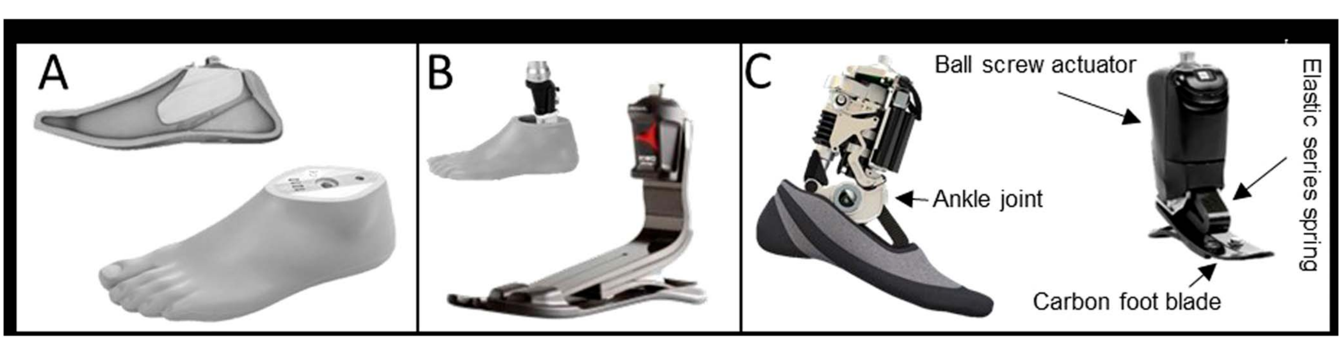

Figure 1. Analyzed prosthetic feet. (a): 1D10 (Ottobock SE and Co, Germany), (b) Triton (Otto Bock HealthCare LP, Salt Lake City, Utah), and (c) Empower (Otto Bock HealthCare LP, Salt Lake City, Utah).

Table 1. Patient demographic data.

Patient [#]	Amputated side	Height (m)	Bodyweight with prosthesis (kg)	Age (y)	Mobility level (K-level)
1	Left	1.87	76.0	47	3
2	Right	1.86	106.5	58	3
3	Right	1.78	85.5	53	3
4	Right	1.97	113.0	35	3
5	Left	1.68	77.0	47	3
6	Right	1.82	60.0	34	4

informed about the scope and requirements of the upcoming study and gave their written consent to voluntarily participate in this study. Ethics approval was granted by the Ethics Committee of the Medical University Göttingen (33/5/18).

Procedure

The order of testing the different foot scenarios was randomized. The bench alignment followed the manufacturer's specifications and was reproducibly adjusted using a L.A.S.A.R. Assembly (Ottobock SE & Co, Germany), followed by a static optimization using the L.A.S.A.R. Posture (Ottobock SE & Co) according to the biomechanically based recommendations.[21]

During the gait analyses, the subjects were instructed to walk on the level walkway, first with self-selected comfortable velocity and afterward with fast velocity. Nine valid trials were measured for each condition. The subjects had at least 1 hour's time for acclimatization to get accustomed to each of the different foot scenarios.

Measuring system

An optoelectronic camera system with 12 Bonita cameras (Vicon Motion Systems Ltd., Oxford, UK) was used to record the kinematics, together with two linked force plates (Kistler Instrumente AG, Winterthur, CH) to record ground reaction forces. Three-dimensional marker trajectories were tracked from 17 passive markers placed on anatomical landmarks (both sides: acromion, epicondylus lateralis humeri, processus styloideus ulnare, trochanter major, compromise knee center of rotation according to Nietert,[22] malleolus lateralis, caput os metartasale 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.[17] The ankle power was calculated as validated by Proebsting 2019[23] as the sum of the rotational and translational power in the sagittal plane.

Data analysis

For each foot scenario and velocity condition, the gait cycle normalized mean of the valid single trials for each subject was calculated for the prosthetic and sound side gait cycles. Subsequently, median values and range of values (minimum and maximum) were calculated over the entire group of participants.

In addition to gait velocity as a tempospatial-parameter, the following kinetic and kinematic parameters have been examined in detail:

- Prosthetic side parameters: ankle power and sagittal ankle angle. The last peak in terminal stance of ankle power and the range of motion from the maximum of dorsiflexion to the maximum of plantarflexion (between 40% and 70% gait cycle) of ankle angle are used for the statistical analysis. (The ankle angle for the ESR and SACH is described by the deflection of the foot structure. For the Empower, this is the combination of ankle joint movement and deflection.)
- Sound side parameters: vGRFs, frontal, and sagittal knee moments. The first peaks (GRF, EKAM, KFM) are used for the statistical analysis of these parameters.

Statistical analysis

Owing to the relatively small sample, an examination for normal distribution was not conducted, and the parameter-free Friedman test was used for group comparison. It was checked whether the mean values in a group differed significantly from each other. If the mean values of a group differed significantly, the WILCOXON test was carried out as a post hoc test for pairwise comparison of the samples about a specific feature used. The significance level was set at $P < 0.05$ for two-tailed tests.

Results

Tempospatial parameters

For both velocities, no significant differences were found between the different foot scenarios. The median normal velocity was 1.27 (1.26–1.29) m/s, and the fast velocity was 1.57 (1.53–1.63) m/s. Table 2 shows the respective velocities.

Prosthetic side parameters

The average of the initial plantar flexion during early stance phase (0%–12% gait cycle) for all subjects and test conditions is

Table 2. Median gait velocities for the different velocity conditions and foot scenarios.

Foot types and settings, if applicable	Normal velocity median (min-max) [m/s]	Fast velocity median (min-max) [m/s]
SACH	1.27 (0.95–1.56)	1.57 (1.30–1.88)
ESR	1.28 (1.04–1.50)	1.63 (1.30–2.00)
PF_np	1.26 (1.03–1.60)	1.58 (1.31–1.91)
PF_lp	1.26 (1.02–1.62)	1.55 (1.33–1.95)
PF_op	1.29 (1.04–1.62)	1.53 (1.33–1.97)

Abbreviations: ESR, Energy storing and returning; PF, Powered Foot; SACH, Solid Ankle Cushioned Heel.
SACH =1D10, ESR= Triton, PF_ np= Empower with no power, PF_lp= Empower with low power, PF_op= Empower with optimal power.

approximately 5° when walking with normal speed. This range of movement increases by 1° when walking at increased speed. The average of the following dorsiflexion movement for all subjects and test conditions is 14° for normal velocity. This range of movement also increases by 1° when walking at a fast pace. For both velocities, the plantar flexion at the end of stance phase shows significant differences between all the different settings of PF (range of plantarflexion for normal velocity: 8.4° (PF_np) − 15.9° (PF_op) and for fast velocity: 9.0° (PF_np) − 20.0° (PF_op)). The SACH, ESR, and PF_np show no significant differences among each other. However, these three conditions differ significantly from PF_lp and PF_op, which reveal increased plantar flexion (Figure 2).

The SACH showed the smallest ankle power maximum with 0.85 (0.33–1.42) W/kg for the normal and 1.02 (0.77–1.88)W/kg for the fast velocity. For both velocities, the ankle power maxima for the different configurations of the PF differ significantly ($P < 0.05$) (normal: PF_np: 1.39 [0.73–2.24] W/kg, PF_lp: 1.61 [0.70–2.73] W/kg, PF_op 1.99 [0.97–4.01] W/kg; fast velocity: PF_np: 2.08 [1.50–3.14] W/kg, PF_lp: 2.53 [1.89–4.33] W/kg, PF_op: 3.04 [2.28–6.87] W/kg). The ESR shows significantly higher ankle power than SACH and significantly lower ankle power than PF_op (normal: 1.75 [0.66–2.96] W/kg and fast velocity: 2.57 [1.28–4.30] W/kg). There were no significant ankle power differences between ESR and PF_lp nor between ESR and PF_np. Figure 2 shows the values and statistical significance at normal and fast speed.

Sound side parameters

The vGRF shows an average of 116% BW for all subjects and foot scenarios with normal walking speed. At fast speed, the first peak is increased by approximately 21% BW. ESR and PF with the three different settings do not differ significantly from each other. However, with SACH, the first maximum is significantly increased at both speeds compared with the other foot types.

The EKAM over all subjects and foot scenarios averages 0.53 Nm/kg at normal speed. At fast speed, the amount of the average maximum increased by 17%. In addition, SACH shows again a significantly increased peak in comparison with all other foot scenarios, which do not differ significantly among each other.

The KFM of all subjects and foot scenarios averages 0.34 Nm/kg at normal speed. At increased speed, this peak is almost 2.5-fold increased. The peak with SACH is significantly increased in comparison with all foot scenarios and for both velocities. For normal velocity, no significant differences could be found between ESR, PF_np, and PF_lp. Moreover, PF_op shows the smallest peak of all foot scenarios with a significant difference to SACH, ESR, and PF_np. However, at faster speed, no significant differences could be found between the peaks of the different settings of the PF, but PF_op also differs significantly from ESR and SACH with the lowest peak. The values and statistical significance of the sound side parameters are shown in Figure 3. A qualitative summary of all statistical results is shown in Table 3.

Discussion

The hypothesis that increasing ankle power generally decreases the knee loading parameters on the sound side could be supported by trend. All studies supporting this hypothesis[3,4,8,14,15] analyzed different types of feet with various constructions, similar to our analysis of different foot concepts with varying amounts of ankle power.

Same foot type with different settings of active power generation (first hypothesis)

The motor drive of the active foot requires extra weight, which could also influence the load on the sound side and the discomfort of the prosthetic side. These influencing factors are excluded in the comparison presented here because the foot remains unchanged. The ankle power shows a clear differentiation between the different tested power settings of the PF (np, lp, op) by revealing a significant difference between all mean ankle power values. Furthermore, it was shown that the amount of plantar flexion at the end of stance phase increased with additional generated ankle power. In addition, the differences in range of motion between all settings of the PF (np, lp, op) were statistically significant.

The ankle power of PF_lp is significantly higher than PF_np at both walking speeds. Nevertheless, it can be seen that the peak ankle power of this prosthetic foot variant is still comparable with ESR, whereas the range of plantar flexion at the end of stance is increased for PF_lp. In addition to the existing carbon foot blade construction, the elastic series spring is controlled by the motor drive and thus enables a supportive plantar flexion in the push off phase. The PF with optimized push off activity (op) shows the highest maximum values for ankle power and plantar flexion at normal and fast speed. This foot scenario generates a significantly increased plantar flexion, which conforms to the repelling force reported by the user.

With these clear and systematic differences in prosthetic side values for the settings (np, lp, op) and the assumption that the ankle power influences the sound side knee load, significant differences were expected for EKAM, vGRF, and KFM at the three ankle power settings. Nevertheless, our results do not show a strong relation of the sound side load parameters and the ankle power, when adjusting the latter systematically (Table 3). There is a trend, but most differences in the sound side parameters for the different settings np, lp, and op do not reach significance. Especially for the fast velocity, no significant differences could be found. Some studies also discussed that the greater range of motion at push off in addition to the increased ankle power can be assumed as a reason for decreasing load on the sound side.[15,24] The systematically increased plantar flexion at the end of stance among the different settings is a result of the differences in ankle power generation acting on the elastic series spring and correlates with the increased ankle power, as discussed above. This differs from other study designs supporting this hypothesis.[15,24] These studies analyze different foot types with varying constructions. The different amount of ankle power results from the different designs of energy storage and return.

In summary it can be stated that, apart from ankle power, foot construction also seems to be important. A systematic reduction of the knee loading parameters with increased ankle power could not be observed. Nevertheless, when using the same foot type (e.g. Empower) with different settings of active power generation, it is shown that the knee loading parameters are smaller with additional positive mechanical work (PF_op) than without (PF_np).

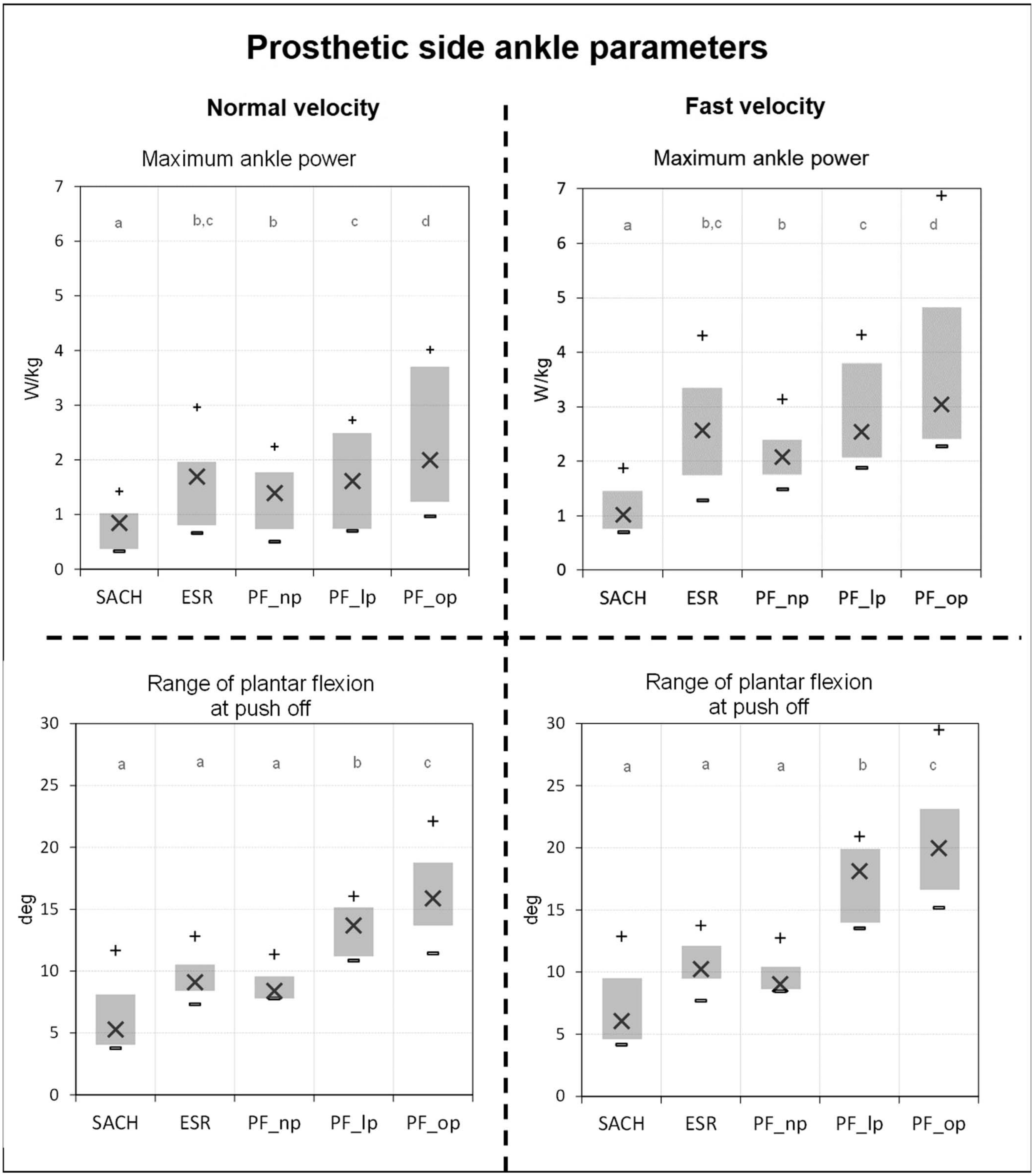

Figure 2. Median (X) of the peaks of ankle power and the range of motion of plantar flexion at push-off for normal and fast velocity with minimum (−) and maximum (+). The top and bottom margins of the box plots correspond to the 25th and 75th percentiles, respectively. The statistically significant difference was defined with $P \leq 0.05$. The median peak results marked with identical letters do not differ significantly.

Different foot types with different ankle power (second hypothesis)

ESR and PF_np have a similar range of plantar flexion at the end of stance phase, and the average maximum value of the ankle power at push off shows approximately the same values for both. This can be attributed to the Empower's fiber composite construction elements. It consists of a carbon elastic series spring and a carbon foot blade which both store and release energy during the roll over motion, similar to ESR concepts. For the PF_lp and PF_op conditions, motor power is added.

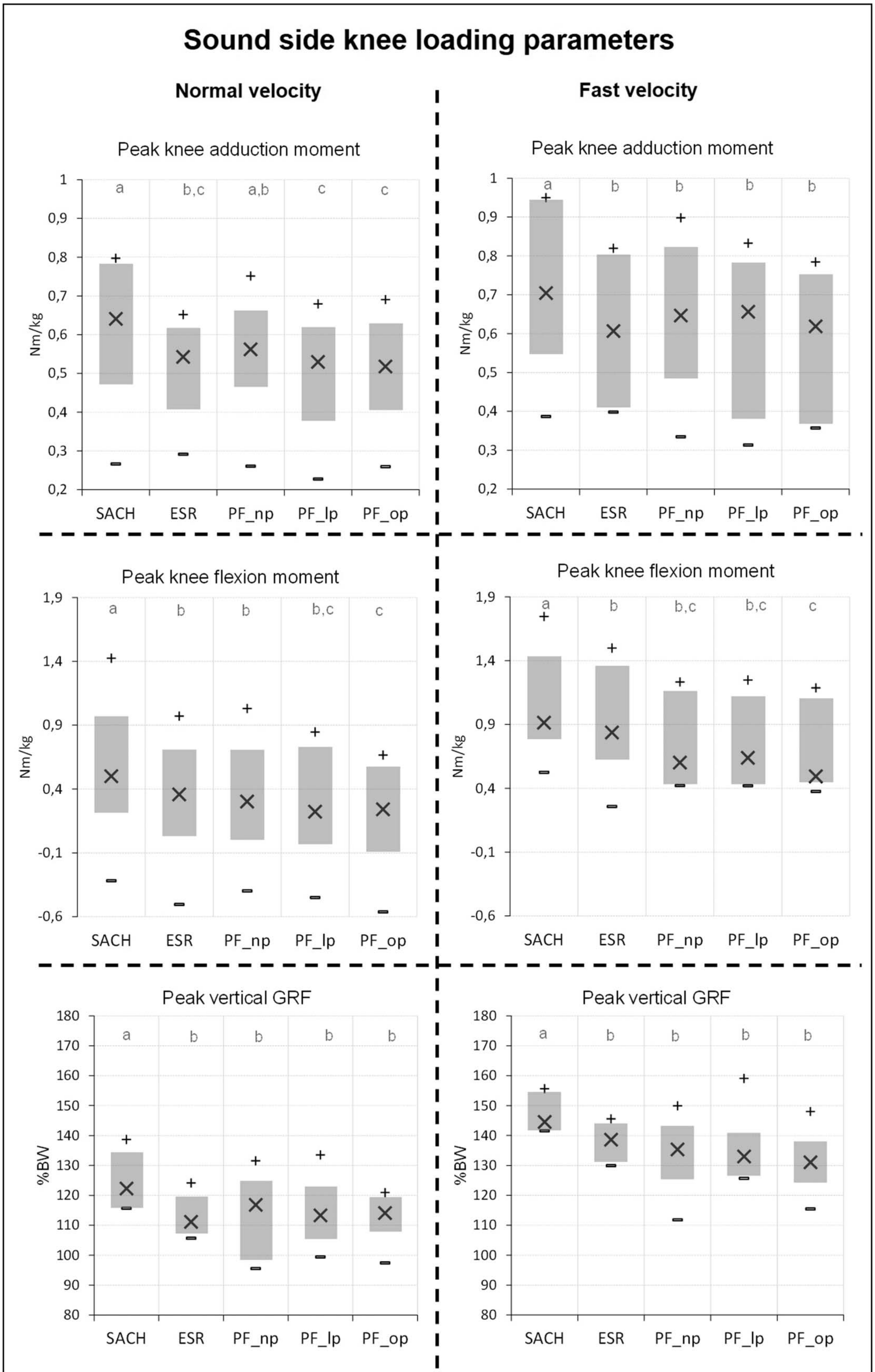

Figure 3. The median results with minimum (−) and maximum (+) of the peaks of the sound side parameters: Peak knee adduction moment, peak knee flexion moment, and first peak vertical ground reaction forces (GRF) for normal (left) and fast velocity (right). The top and bottom margins of the box plots correspond to the 25th and 75th percentiles, respectively. The statistically significant difference was defined as $P \leq 0.05$. The median peak results marked with identical letters do not differ significantly.

Table 3. A summary of the significant differences between the different settings and the different foot types.

Significant differences of prosthetic side parameters					
		Normal velocity		Fast velocity	
		Ankle Power	Plantar flexion	Ankle Power	Plantar flexion
Different settings of PF	np vs. op	<	<	<	<
	np vs. op	<	<	<	<
	lp vs. op	<	<	<	<
Different foot types	SACH vs. ESR	<	no	<	no
	SACH vs. PF_op	<	<	<	<
	ESR vs. PF_op	<	<	<	<

Abbreviations: <, is significantly decreased; >, is significantly increased; EKAM, external knee adduction moment; EKFM, external knee flexion moment; ESR, energy storing and returning; no, no significant differences; np, without power; op, optimal power; SACH, Solid Ankle Cushioned Heel.
For the comparison between foot types, the optimum setting (Empower op) was chosen for the Powered foot (PF). Example for the comparison between np vs. lp: the ankle power with Empower np is significantly decreased in comparison with Empower lp.

Significant differences of sound side parameters							
		Normal velocity			Fast velocity		
		GRFv	EKAM	EKFM	GRFv	EKAM	EKFM
Different settings of empower	np vs. lp	no	>	no	no	no	no
	np vs. op	no	>	>	no	no	no
	lp vs. op	no	no	no	no	no	no
Different foot types	SACH vs. ESR	>	>	>	>	>	>
	SACH vs. PF_op	>	>	>	>	>	>
	ESR vs. PF_op	no	no	>	no	no	>

The following comparison of the different foot types focuses on PF_op, SACH, and ESR. The ankle power shows a clear differentiation between the three foot types and reveals a significant difference between all mean ankle power values. In addition, it was shown that the amount of plantar flexion at the end of stance phase increased with additional generated ankle power. Therefore, with no active ankle power, there were no significant differences in this parameter for SACH and ESR. With PF_op, the amount of plantar flexion at the end of stance significantly increased.

The differences on the sound side of the knee loading parameters between SACH and the other two foot types reach significance. Therefore, these modern feet with increased ankle power generation offer an advantage over such basic, non-ESR feet. However, the increasing ankle power at push off in all three different foot types results in a clear systematic reduction of KFM for both velocities (SACH: weak, ESR: medium, PF: strong). The other knee loading parameters (vGRF and EKAM) show no significant differences between ESR and PF_op but reveal a trend of reduction for PF_op, especially compared with the SACH.

In summary, a reduction of the knee loading parameters with increased ankle power could be observed, especially for KFM. With the PF_op, unloading of the sound side was higher than with the other feet without active power although this foot has a higher weight.

In addition to the amount of ankle power and plantar flexion during push off, the construction of the foot component seems to be important. However, this influence needs more investigation.

Conclusion

Apart from the varied ankle power on the prosthetic side, the construction of the foot section seems to be important for the load on the sound side knee. However, the overall results prove clear advantages using the Empower, which generates positive mechanical work for an active push off over a SACH foot and also an ESR. Especially, a relief of the sound side of amputees using the active foot could be seen, particularly in the reduction of KFM.

Study Limitations

The limitation of the study is the low number of subjects (n=6). The participants had at least one hour time to accommodate to each foot scenario. Overall, the investigations exceeded 5 hours a day. For a representative comparison, it was important to take all measurements in one day caused by a potential interday variability. Therefore, only experienced C-Leg 4 users with a high mobility level, who were able to complete this test scenario without problems, could take part in the study.

Author contributions

The authors disclosed the following roles as contributors to this article: E.P.: Conceptualization, data curation, formal analysis, methodology, software, validation, visualization, and writing–original draft. B.A.: Conceptualization, investigation, methodology, project administration, supervision, and writing–review & editing. M.B.: Conceptualization, investigation, methodology, resources, supervision, and writing–review and editing. K.K.: Methodology, formal analysis, investigation, and project administration. T.S.: Conceptualization, methodology, project administration, supervision, and writing–review & editing.

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Supplemental material

There is no supplemental material in this article.

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