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Prosthetic restoration of the forefoot lever after Chopart amputation and its consequences onto the limb during gait

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ABSTRACT

Background: In subjects with Chopart amputation the foot lever is clearly diminished. Usually high or low profile prostheses are routinely utilized to re-establish the lost forefoot lever.
Research question: The aim of this study was to investigate to what extent the proposed prostheses were able to replace the forefoot lever in chopart-amputees.
Methods: An instrumented 3D gait analysis, including plantar and socket pressure measurements, was performed in thirteen subjects with Chopart amputation using a clamshell and/or a Bellmann prosthesis including an ankle foot orthosis during level ground walking.
Results: The largest range of motion ($p < 0.05$) in the ankle joint was seen for the Bellmann prosthesis (32 ± 3°) followed by the Bellmann prosthesis with ankle-foot orthosis (22 ± 6°) whereas in the clamshell prosthesis (10 ± 4°) almost no ankle motion was seen. Conversely, the highest ankle joint moment ($p < 0.05$) was seen for the clamshell prosthesis (1.04 ± 0.24Nm/kg) followed by the Bellmann prosthesis with ankle-foot orthosis (0.66 ± 0.14Nm/kg) and, finally, the Bellmann (0.37 ± 0.11Nm/kg) alone offering the lowest joint moment.
Conclusion: High-profile prostheses with ventral shell are more suitable to reacquire the lost forefoot lever after Chopart amputation. However, the issue of restricted range of motion in the ankle joint with the clamshell prosthesis needs to be addressed.

1. Introduction

Partial foot amputations (PFA) in Germany are typically caused by diabetes, vascular diseases, trauma, or tumors [1]. In amputations more proximal of the trans-metatarsal heads the lost base of support has a direct, negative impact on the forefoot lever [2–4]. In particular, amputations in the Chopart joint suffer from a major loss of foot length because only the hindfoot remains [5]. An advantage of this amputation level over transtibial amputations is leg length preservation, ankle joint function, and weight-bearing skin on the sole, which enables these individuals to walk barefoot and acquire proprioceptive feedback along normal pathways [6]. However, the decreased foot length results in a loss of biomechanical leverage, leading to a complete absence of the ability to push off during gait [2]. Therefore, prosthetic devices are needed to provide this base of support by restoring biomechanical leverage in order to improve standing and walking ability as well as to reduce the pressure at the distal end of the stump during roll over [7]. Overall, both low-profile prostheses (e.g. Bellmann prosthesis) and high-profile prostheses (e.g. clamshell prosthesis) are routinely utilized. The choice of prosthesis is individually determined by the remaining range of motion (ROM) in the ankle joint (ROM of unimpaired subjects usually is about 20/40 Dorsi-/Plantarflexion), residual limb status (deformities, skin conditions, etc.), cosmetic aspects, and the level of activity of the patient. Generally, subjects with Chopart amputation (ChA) with a mobile ankle (at least 10/20 Dorsi-/Plantarflexion), full weight-bearing capacity of the residual limb, and lower functional demands are typically provided with low-profile prostheses such as the Bellmann prosthesis (BP). For times of higher demands on the prosthesis, i.e., when more effort is expected owing to the need for longer walking or standing periods, an AFO (e.g., Toe-Off, Allard, USA) can be added to the low-profile prosthesis. High-profile devices such as the clamshell prosthesis (CSP) are typically prescribed to ChA with no or

Abbreviations: PFA, partial foot amputation; ChA, subjects with Chopart amputation; ROM, Range of motion; BP, Bellmann prosthesis; CSP, clamshell prosthesis; CoP, Center of pressure; BP + AFO, Bellmann prosthesis and an ankle foot orthosis; NORM, Norm data; SACH, Solid ankle cushioned heel; FP, Force plates; GRF, ground reaction forces; TDP, Time distance parameters

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only a nonfunctional ankle ROM and in highly active ChA (high K4 [8]) independently of their ankle ROM [7].

So far, the CSP, independent of the subjects' remaining ROM in the ankle joint, seems more beneficial in terms of center of pressure (CoP) progression in the forefoot as it enables a high dorsiflexion moment relative to the low-profile Chopart prosthesis due to the rigid construction of the CSP [3,9,10]. The rigid construction of the CSP is beneficial for regaining proper leverage; however, it prohibits any physiological ankle motion [4]. This is not necessarily a disadvantage for patients with no or nonfunctional ankle motion, but it is a hindrance for patients with a still-mobile ankle joint. Low-profile prostheses, on the other hand, allow a full ROM in the ankle joint, but do not seem to be as efficient in creating a comparably high ankle joint moment compared to high-profile devices [10].

The capability to progress the CoP in a stiff forefoot with a controlled dorsiflexion during terminal stance enables a high ankle-joint moment, good forefoot lever, and the ability to create a push off during gait [11,12]. A comparison of high- and low-profile Chopart prostheses in terms of their capability to progress the CoP in the forefoot and thus enable high dorsal flexing moments during terminal stance is still lacking. In particular the question of which prosthesis offers the best combination of a relatively large ROM in the ankle joint, simultaneously good leverage due to a stiff forefoot, and additionally not too high of a load on the soft tissue has not been addressed.

Therefore, the aim of this study was to investigate a low-profile prosthesis (BP) as well as two different high-profile prostheses (BP + AFO, CSP) for ChA with different ROM restrictions in the ankle joint, in terms of their capability to restore the missing forefoot lever as well as their effects on the knee and hip joint during gait.

2. Methods

2.1. Subjects

Thirteen individuals with unilateral Chopart amputation and K-Level 3–4 [8] were recruited through our in-house prosthetics and orthotics department and the outpatient clinic of the hospital. The included subjects possessed at least a BP, a BP + AFO, or a CSP (Fig. 1) and provided written informed consent to participate in this study. Exclusion criteria were residual limb issues such as pressure sores, wounds, and the need for walking aids (e.g., crutches, canes, etc.). For reference (NORM) a group of 26 subjects (average age 29 ± 6 years, 175 ± 8 cm, 73 ± 12 kg) without walking restrictions were monitored.

Prosthetic alignment was conducted following alignment recommendations of Blumentritt [13] for below knee prostheses. Therefore, the load line measured with L.A.S.A.R. Posture (Otto Bock, GER) on the prosthetic side was taken as 10–30 mm anterior of the knee joint center in the sagittal plane, while standing still.

Eleven subjects possessed a CSP, two of which also possessed a BP and a CSP. Four out of in total thirteen subjects were equipped with a Toe-Off orthosis (Allard, USA) in addition to their custom-made Bellmann prosthesis (Table 1).

2.2. Prostheses

The BP is a slipper socket with a silicon socket to hold the stump. Underneath the silicon socket is an acrylic laminate plate which ends at 45° upwards, a little more distal to the stump end. Multiform plates are attached to the 45° plate until the foot length is reached [7]. The AFO used in this study is a ToeOff Orthosis (Allard, USA) which is additionally attached to the BP prosthesis. The CSP is a shank high, carbon-fiber construction, holding the residual limb volume in a distal socket and transferring load to the shank via a ventral support similar to a ground reaction AFO [14–16] but without a dedicated ankle joint, reducing the physiological ankle joint ROM to zero. A carbon-fiber plate (i.e., Chopart Plate, Össur, Reykjavik, Iceland) attached beneath the socket allows for foot motion by the deformation of the foot plate comparable to a SACH foot (Solid ankle cushion heel).

2.3. Protocol and procedure

The participants underwent an instrumented 3D gait analysis including socket and plantar pressure measurements during level ground walking. In addition, a clinical examination was performed to determine residual limp length, status, and mobility in the ankle joint [17]. Reflective markers were placed on the subjects in accordance with conventional clinical gait analysis procedures using the Plug-in-Gait Model (PiG; using a modified Helen-Hayes marker set [18,19]). In three subjects with CSP the malleolus was covered by the prosthesis; therefore, the marker was placed on the prosthesis instead of the skin at the position of the underlying lateral malleolus. The four subjects using the Bellmann prosthesis were measured additionally with their orthosis during the same appointment. A Vicon 3D motion analysis system (Vicon, UK), including 12 cameras, and two force plates (FP) (AMTI, Inc., Newton, USA) were used to collect the data. The plantar pressure was measured with portable insoles (Novel, Munich, Germany) inside the shoe in all devices. In devices with a ventral shell, a 15 x 6 cm rectangular pressure pad (Novel, Germany) was placed along the shin between the tuberosity of the tibia and the mortice to assess the pressure of the ventral shell.

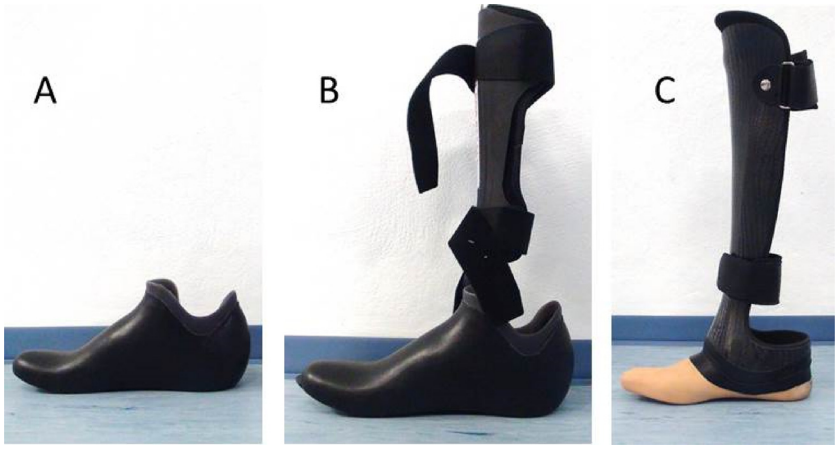

Fig. 1. The three prosthesis designs investigated: (A) Bellmann prosthesis (BP) without and (B) with ankle-foot orthosis (BP + AFO), and (C) the clamshell prosthesis (CSP).

Table 1
The anthropometric data of the subjects measured with their prosthetic devices, separated in groups.

Sex (m/f)	Time since amputation (years)	Reason for amputation	Age (years)	Height (m)	Weight (kg)	Ankle ROM (Dors/Plan)	Bony or soft tissue revision	Prosthesis
m	6	Trauma	49	1,79	92	5/15	No	CSP; BP; BP + AFO
f	5	Trauma	54	1,68	62	10/20	No	CSP; BP; BP + AFO
m	16	Tumor	51	1,76	76	10/25	No	BP; BP + AFO
f	30	Deformity	31	1,58	86	10/40	No	BP; BP + AFO
m	18	Trauma	35	1,84	95	5/10	Soft tissue	CSP
m	4	Trauma	51	1,82	80	0/5	Soft tissue	CSP
m	35	Trauma	56	1,79	91	10/30	No	CSP
m	30	Trauma	73	1,85	105	5/5	No	CSP
m	23	Tumor	60	1,8	92	10/10	No	CSP
m	5	Tumor	64	1,94	110	0/0	No	CSP
m	22	Trauma	64	1,83	98	10/5	Soft tissue	CSP
m	11	pAVK	52	1,81	128	10/20	Soft tissue	CSP
m	6	Trauma	43	1,71	69,7	0/0	Arthrodesis	CSP

2.4. Data analysis

In total there were four different groups, three groups according to the prosthetic device (BP, BP + AFO, and CSP) and normal reference (NORM) data. A comparison among all four groups was performed. The data analysis focused on the forefoot lever; therefore, the maximum values for kinematics (ankle ROM), external moments of the ankle joint in the sagittal plane, as well as the socket, hind-, and forefoot normal force were determined in terminal stance and pre-swing. Also the insole CoP was obtained during contralateral heel strike, when the highest physiological leverage is achieved [11]. Additionally the hip and knee joint kinematics and kinetics in the sagittal plane, the total GRF and time distance parameter (TDP) were determined.

All parameters were resampled to the base frequency of the motion capture system of 120 Hz if necessary, extracted using custom Matlab codes [20] (Version R2009a). The joint moments were calculated using the inverse dynamics of the standard gait model “Plug-in-Gait” [19].The synchronized [21] and resampled pressure data were calculated into normal force by summing the pressure data of each cell of the area of contact and then normalized by body weight. The pressure insoles were divided into a forefoot and hindfoot area, based on the stump length (from the heel to the distal end of the stump) divided by the shoe length. The anterior-posterior progression of the CoP calculated from the insoles was normalized by shoe length.

Statistical tests were performed among all four groups (BP, BP + AFO, CS, and NORM) for the kinematic and kinetic data. Pressure data were only compared between the three prosthetic groups. Statistical analysis between group BP and BP + AFO was based on a Wilcoxon test. Unpaired tests were used between groups CSP, BP, and BP + AFO as well as between norm data and each group based on the normal distribution. The normal distribution of the data was tested using the Shapiro Wilk test. For normally distributed parameters, an unpaired *t*-test was used; if not normally distributed, a Mann-Whitney-U-Test was used instead. Level of statistical significance was set to $p = 0.05$ by also acknowledging Bonferroni corrections in case of interdependencies between parameters of kinematics and kinetics. The results are shown in Table 2.

3. Results

The comparison between the three prosthetic devices (BP, BP + AFO, and CSP), as well as the normal reference data showed differences in the kinematic and kinetic characteristics (Fig. 2) and in all the measured parameters during terminal stance and pre-swing (Table 2).

3.1. Forefoot leverage

The greatest extent of ROM was observed in BP followed by BP + AFO up to CSP. Only BP showed the same ROM in the ankle joint as the NORM, whereas BP + AFO ($p < 0.001$) and CSP ($p < 0.001$) showed significantly lower values than the NORM. Additionally, the peak dorsiflexion in the condition BP was the largest but with all comparisons between groups barely reaching the level of significance. The external ankle dorsiflexing moment of the NORM demonstrated the highest value, followed by CSP, BP + AFO and lastly BP with strong statistical differences between groups. For the pressure sensor data, CoP excursion was the highest in CSP compared to BP + AFO and BP (Fig. 3), but BP + AFO also showed higher values than BP. Forces calculated by the pad sensor showed a 2.0 N/kg higher pad force in CSP than in BP + AFO ($p < 0.002$). Analysis of the force distribution found a significantly higher forefoot and lower hindfoot force in CSP than for the other two devices.

3.2. Proximal joint parameters

Additionally a hyperextension in the knee joint was present in all three prosthetic groups with no significant differences between the devices. However, BP + AFO ($p = 0.018$) and CSP ($p < 0.001$) showed a significantly higher knee extension than NORM, whereas BP did not. When using the BP, the subjects showed a slightly reduced hip extension compared to CSP and the NORM but not reaching significance after Bonferroni correction.

The knee-extending moments in CSP and BP + AFO condition were slightly higher than in BP condition, again barely significant. However, the BP ($p < 0.001$) and BP + AFO condition ($p = 0.008$) showed strongly significant lower external knee-extending moments compared to the reference subjects (NORM).

The hip-extending moment in the CSP condition was higher compared to the BP ($p < 0.001$) and relative to BP + AFO ($p < 0.001$). As in the knee joint, the external hip-extending moment showed a lower value in BP ($p = 0.001$) and BP + AFO ($p = 0.001$) than the NORM. No significant differences in total GRF were observed between the three prosthetic groups; however, values were lower for all prosthetic devices than for NORM. Speed and cadence, showed no significant differences between the three prosthetic devices; however, they were lower in all subjects than the NORM. The contralateral heel strike did not show any significant differences between the three prosthetic devices either; yet, the values for BP were significantly lower than for NORM ($p = 0.011$).

4. Discussion

The aim of this study was to investigate high- and low-profile Chopart prostheses with differing ROM restrictions due to their

Table 2
Peak mean values of the different groups for kinematics and kinetics in the sagittal plane, the GRF, pad force, and forefoot force in terminal stance and pre-swing as well as the insole CoP at contralateral heel strike. Also the mean values of the positive integrals of the hindfoot and forefoot force. The p-values and significant differences are also illustrated. Significant differences between the groups are marked with A, B, C, D, E, F (A = BP vs. BP + AFO, B = BP vs. CSP, C = BP + AFO vs. CSP, D = BP vs. NORM, E = BP + AFO vs. NORM, F = CSP vs. NORM).

Parameters	Peak values averaged for each group				
TDP	BP	BP + AFO	CSP	NORM	p-value
Speed [m/s]	1.05 ± 0.25^{D}	1.09 ± 0.19 ^{E}	1.21 ± 0.17 ^{F}	1.42 ± 0.05 $^{D, E, F}$	p = 0.022^{D} p = 0.005^{E} p < 0.001^{F}
Cadence [Steps/Min]	99 ± 7 ^{D}	100 ± 5 ^{E}	104 ± 7^{F}	111 ± 2 $^{D, E, F}$	p = 0.007^{D} p = 0.004^{E} p = 0.004^{F}
Contralateral heel strike [% GC]	48 ± 0.7 ^{D}	48 ± 1.1	50 ± 0.9	50 ± 1 ^{D}	p = 0.011^{D}
Kinematics [°]					
Hip extension	4.0 ± 6.0$^{B, D}$	6.0 ± 5.0	10.0 ± 4.0^{B}	10.8 ± 0.8 ^{D}	p = 0.090 ^{B} p = 0.062^{D}
Knee extension	−1.6 ± 4.5	−3 ± 0.7	−4.5 ± 4.5 ^{F}	2.6 ± 4.3 ^{E,F}	p = 0.018^{E} p < 0.001^{F}
Dorsiflexion	20 ± 3 ^{A,B,D}	15 ± 0.8^{A}	12 ± 6 $^{B, F}$	15.6 ± 1.1 $^{D, F}$	p = 0.050 ^{A} p = 0.074 ^{B} p = 0.044 ^{D} p = 0.052^{F}
Ankle joint ROM	32 ± 3 ^{A,B}	22 ± 6$^{A, C, E}$	10 ± 4 $^{B, C, F}$	33.0 ± 1.3 ^{E,F}	p = 0.060^{A} p < 0.001^{B} p < 0.001^{C} p < 0.001^{E} p < 0.001^{F}
Kinetics [Nm/kg]					
Hip-extending moment	0.76 ± 0.25 $^{B, D}$	0.88 ± 0.23 ^{C,E}	1.29 ± 0.21 $^{B, C}$	1.37 ± 0.25 ^{D,E}	p < 0.001^{B} p = 0.020 ^{C} p = 0.002^{D} p = 0.002^{E}
Knee extending moment	−0.24 ± 0.12^{A,BD}	0.00 ± 0.05 $^{A, E}$	0.14 ± 0.2^{B,}	0.16 ± 0.05 ^{D,E}	p = 0.040 ^{A} p = 0.060 ^{B} p < 0.001^{D} p = 0.016^{E}
Dorsal-flexing moment	0.37 ± 0.11^{A,B,D}	0.66 ± 0.14^{A,C,E}	1.04 ± 0.24^{B,C,F}	1.57 ± 0.05^{D,E,F}	p = 0.040 ^{A} p < 0.001 ^{B} p = 0.020 ^{C} p < 0.001^{D} p < 0.001^{E} p < 0.001^{F}
Ground reaction forces [N/kg]					
Total GRF	10.0 ± 0.42 ^{D}	9.91 ± 0.46 ^{E}	10.75 ± 0.84 ^{F}	11.65 ± 0.27 ^{D,E,F}	p < 0.001 ^{D} p < 0.001^{E} p < 0.001 ^{F}
Center of Pressure [%]					
CoP excursion	36 ± 2 ^{A,B}	51 ± 5$^{A, C}$	71 ± 4 $^{B, C}$	n/a	p = 0.010 ^{A} p < 0.001 ^{B} p = 0.006 ^{C}
Plantar – and Socket force					
Pad force [N/kg]	n/a	0.3 ± 0.1 ^{C}	2.3 ± 1.3 ^{C}	n/a	p = 0.002 ^{C}
Forefoot force [N/kg]	2.8 ± 0.9 ^{B}	5.3 ± 1.0 ^{C}	10.4 ± 0.6 $^{B, C}$	n/a	p = 0.005 ^{B} p = 0.013 ^{C}
Hindfoot force [N/kg]	7.6 ± 0.5 ^{B}	4.6 ± 0.5^{C}	0.3 ± 0.1^{B,C}	n/a	P < 0.001^{B} P < 0.001^{C}

different physical properties and their ability to re-establish the forefoot lever with respect to their kinematic and kinetic effects onto the proximal chain.

For re-establishing the forefoot lever, our results indicate that high-profile devices are able to withstand higher external dorsal-flexing moments due to their restricted ROM, support of the ventral shell, and forefoot loading in comparison to low-profile devices.

Comparable to the findings of Dillon [3,4,22], the user was able shift the CoP in the forefoot with the clamshell prosthesis (CSP), creating good leverage, which resulted in the highest dorsal-flexing moment as compared to the other two investigated devices. However, the device was still not as efficient as a physiological foot due to the lower external dorsiflexing moment. CSP showed the highest moments in all measured joints compared to the other devices, comparable to healthy subjects in the knee and hip joint; however, the rigid construction of the CSP and the stiff forefoot produced a hyperextension in the knee joint corresponding to the pronounced external knee extending moment during terminal stance [4,23].

The modular approach of the Bellmann prosthesis with an ankle-foot orthosis (BP + AFO) showed a higher dorsiflexing moment due to a more anterior CoP than the Bellmann (BP), but was not able to reach that of the CSP. Modification of the BP by simply adding an AFO shifted the subjects' knee joint moment towards the norm, but still results in a hyperextension of the involved sides' knee. The supporting effects of the ventral shell provides a better forefoot lever, causing higher dorsiflexing and knee extending moments [23,24]. However, the observed effect of the AFO seems moderate, as the hip was not affected. Custom-built orthoses with individually adjusted stiffness might produce a

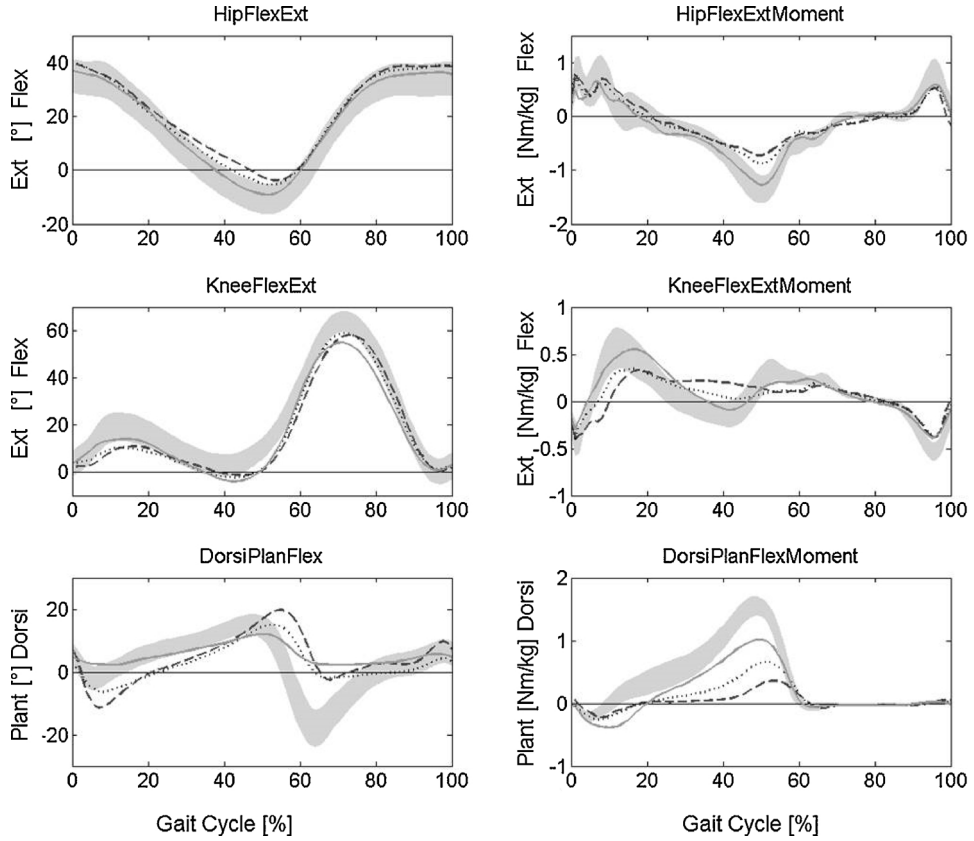

Fig. 2. Kinematics and external kinetics in the sagittal plane for all the three measured devices. BP (n = 4) = dashed line; BP + Adapt (n = 4) = dotted line; CSP (n = 11) = solid line; NORM = gray band.

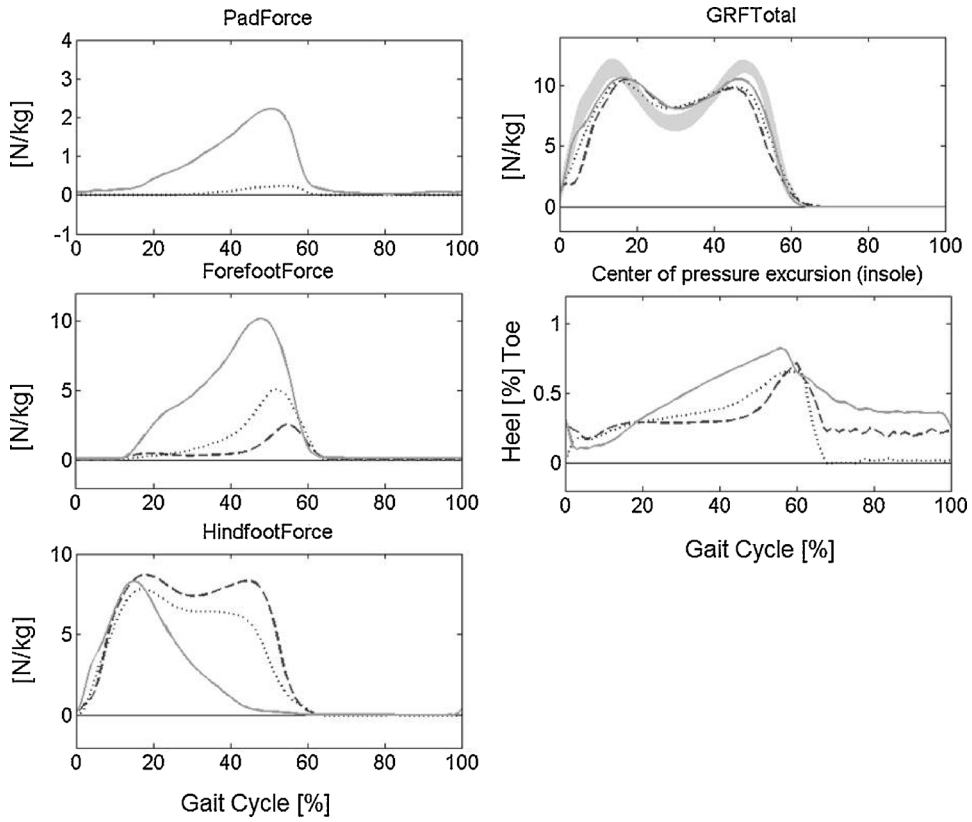

Fig. 3. The normal force acquired through the socket (pad force) and plantar pressure sensors (hind-, forefoot force), total ground reaction force (GRFTotal), and center of pressure excursion (CoP excursion) for all three devices. BP (n = 4) = dashed line; BP + Adapt (n = 4) = dotted line; CSP (n = 11) = solid line; NORM = gray band.

better effect, comparable to ground reaction AFOs [14].

Lastly, BP was not able to create a sufficient ankle moment due to the CoP remaining in the hindfoot, indicating a poor forefoot lever. Similar results were found by Burger, Erzar, Maver, Olenšek, Cikajlo and Matjačić [10], who investigated low-profile silicon Chopart prostheses. Hip, knee, and ankle joint moments with BP were very low compared to CSP and the norm. Corresponding to the low external dorsiflexing moment, the knee joint moments are rather externally flexing than having a more physiologic, external extending knee moment during terminal stance as achieved by the CSP. This insufficient leverage of the BP reduces not only the ankle moment, but also stresses the knee and hip joint as a compensatory mechanism.

All participants showed a tendency for knee hyperextension without a particular weakness of the knee muscles; possibly due to a rather stiff forefoot lever and the rigid coupling of the ventral shell which aggravates the plantarflexion knee extension couple in both, the BP + AFO and in particular in the stiff CSP approach. The induced force at the shank by the ventral shell to support the external moments applied at the forefoot seemed so high, that the knee surrounding muscles were not able to withstand the force resulting in a hyperextension.

All participants with high profile devices showed a tendency for knee hyperextension, possibly due to a rather stiff fore foot lever which aggravates the planter flexion knee extension couple in both, the BP + AFO and in particular in the stiff CSP approach. In particular one participant utilizing a CSP showed a pronounced knee hyperextension with a minimum knee extension of 15° in mid-stance.

The varying physical properties of the prostheses offer a suitable explanation for the differing CoP excursion and force distribution. An unimpaired physiologic ankle joint complex adjusts its stiffness by muscle contractions according to different situations as e.g. for different walking speeds [25,26]. In contrast, the conditions BP + AFO and CSP have a predefined stiffness of the fore foot given by their material properties and their structure. Hence, their stiffness cannot be adjusted according to needs as e.g. walking speed changes or adaptations different terrain conditions (e.g. slope walking).

The BP + AFO and CSP device are high-profile devices, which benefit from the ventral shell with different ankle-joint ROM limitations [4]. Furthermore, the support of the ventral shell in the CSP and BP + AFO conditions began at approximately 20% of the gait cycle, when tibial progression started [11].The pad forces showed higher values in the CSP than the BP + AFO because the CSP has almost no dorsiflexion during terminal stance due to the low deformation of the carbon fiber plate (i.e., Chopart Plate, Össur). Therefore, the rigid construction of the CSP enables the users to use the provided toe lever by engaging force at the ventral shell through tibia progression. In contrast, BP + AFO allowed significantly more dorsiflexion during terminal stance, resulting in a lower CoP excursion than CSP. Hence, the various ankle restrictions indicate that the devices have different effects on the forefoot lever [4]. Unfortunately, an adequate forefoot lever requires reduced ankle mobility. However, even a slight restriction of the ankle seems to have a direct effect on the forefoot lever the subsequent dorsiflexing moment. An orthotic joint such as e.g. the Neuroswing (Fior&Gentz, Lüneburg, Germany), allowing for progressively damping dorsiflexion could represent a possible approach.

Comparably to Burger [10], the results of this study demonstrated that BP helps to use the full remaining ROM of the ankle joint but it cannot create a proper forefoot lever causing insufficient moments and low push off. Therefore, a BP alone should not be considered for highly active subjects, underlining the clinical prescription for low-profile Chopart prostheses [7].

Highly active patients so far have usually been provided with the CSP, which is able to restore the forefoot lever. However, for the cohort investigated in this study this results in a hyperextension in the knee joint during terminal stance, most likely due to the limited deflection of the prosthetic foot in combination with the rigid coupling of the ventral shell which results in a limited all over prosthetic ankle ROM, as explained earlier. Furthermore, the fixed ankle joint in the frame construction of CSP inhibits any remaining ankle ROM in these subjects, which is tried to be saved by the Chopart amputation. The ankle joint is a dominant benefit in relation to more proximal amputations [6]. The ability to use the ankle joint during gait, especially concerning the three rockers [11], is highly beneficial for a functional gait pattern, which was supported by the findings in the current study. In this context the ability to combine a BP with an AFO seems to offer a viable approach for highly active patients with a functional ROM in the ankle joint. The modularity allows activity-based decision making concerning the support the prosthesis needs to give. This makes it possible to maintain the remaining ROM in the ankle joint and supports a proper forefoot lever. However, there are also many highly active Chopart amputees with deformities or no ROM left in the ankle joint. So far, these subjects are reliant on the CSP. Therefore, the issue of hyperextension in the knee joint due to the rigid carbon-fiber plate needs to be addressed.

5. Conclusion

CSP undoubtedly provides the highest leverage, sacrificing the physiological ROM in the ankle joint and inducing hyperextension in the knee joint. In patients with no functional ROM or hindfoot equinus deformities, the CSP has to be prescribed as alternatives are lacking. Therefore, the issue of the stiff carbon fiber foot plate needs to be addressed, especially for patients without alternatives. In patients with at least functional ROM in the ankle joint, a modular approach seems beneficial, but this needs to be investigated further due to the small sample size of the present study. The combination of an AFO and BP produced a proper forefoot lever, allowing ROM and supporting external dorsiflexing moments, but the applied AFO did not seem stiff enough to achieve adequate leverage comparable to that of the CSP. In this context, articulated prostheses with adjustable stiffness and ROM restrictions to create proper leverage must be considered according to the present findings. Clinical decisions prescribing CSP to highly active patients with a functional ROM in the ankle joint should be reconsidered. The remaining ROM in the ankle joint of Chopart amputees is one of the most important advantages over amputations that are more proximal; therefore, mobility should be further promoted and maintained by means of articulated orthoses.

6. Limitations

Two main limiting factors have to be named. Firstly, the sample size of the BP and BP + AFO was rather small; limiting the generalizability of these results. However, this is the largest cohort study of which we know in this condition undergoing instrumented 3D gait analysis. Secondly, by using a standard gait model, the foot is modelled as a single rigid segment. Similar to a large body of literature investigating neurologic gait disorders, foot leverage insufficiency is not adequately modelled. Results of ankle kinetics may also be misleading ignoring the deformation of the rigid foot but nevertheless, the ankle moment obtained via this model should adequately represent the degree to which foot leverage is restored. A multi-segment foot model will help in getting a better understanding of foot kinematics and kinetics but marker-placement in this condition including the foot prosthesis and the shoe is rather difficult.

Author contribution

All authors contributed equally in the preparation of this manuscript.

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