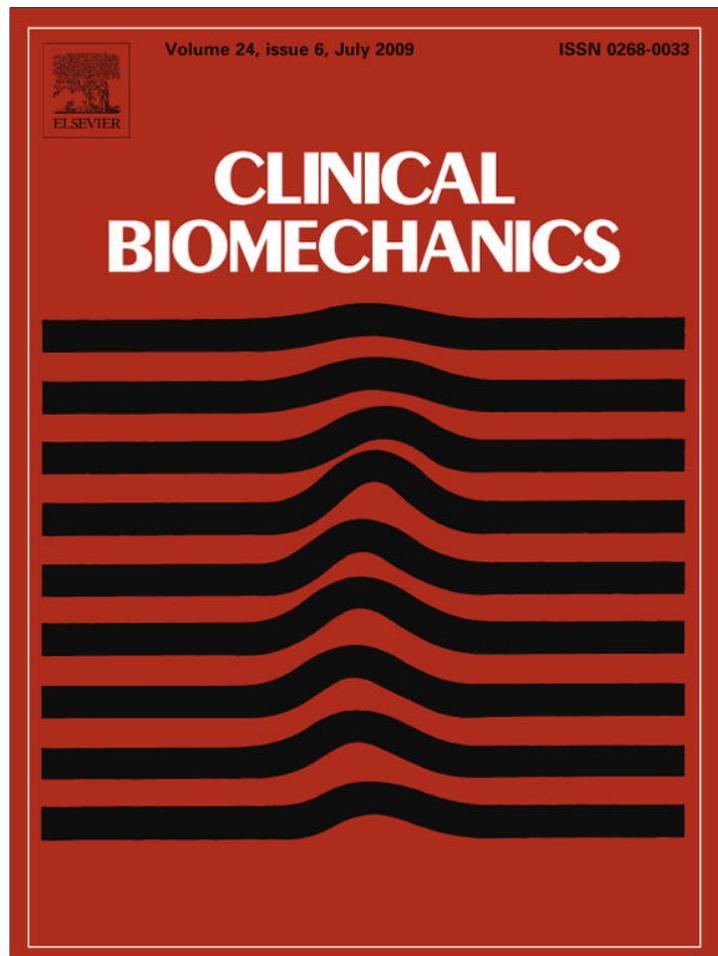


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Biomechanics of walking with silicone prosthesis after midtarsal (Chopart) disarticulation

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ABSTRACT

Background: Currently accepted understanding is that silicone foot prostheses have little influence on biomechanics of walking; however clinical observations suggest several beneficial effects. The objective of this study was to characterize biomechanics of gait in a group of subjects with disarticulation through the talonavicular (T-N) and calcaneocuboid (C-C) (midtarsal) joints wearing two different prosthetic solutions: silicone prostheses and conventional prostheses.

Methods: Four subjects that underwent Chopart partial foot amputation were included in the study. Silicone prosthesis was custom manufactured for each individual subject. Instrumented gait analysis was performed in each subject in four experimental conditions: barefooted, barefooted and wearing silicon prosthesis, wearing footwear with conventional prosthesis and wearing footwear with silicon prosthesis. Comparisons and statistical analysis were made between both barefooted conditions and both foot-wearing conditions.

Findings: Our results show that silicone prosthesis without reinforced sole increases gait velocity, improves generation of ankle plantarflexion moment throughout the stance phase and enables greater power generation at push-off. The most important changes, however, occur in the frontal plane, where improved hip adduction angles and higher hip abduction moment in the stance enable more normal pelvic movement and consequently also less trunk inclination toward amputated side.

Interpretation: We conclude that silicone prostheses are not solely for cosmetic reasons but may be also biomechanically superior over other prosthetic solutions, especially for walking barefoot.

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1. Introduction

There are several levels of partial foot amputations, from partial toe amputation to Chopart disarticulation, which is done through talonavicular (T-N) and calcaneocuboid (C-C) joints, leaving only calcaneus and talus. All ankle dorsiflexors are divided (Bowker, 2007) since their insertions are distal to the midtarsal (T-N and C-C) joints. If ankle dorsiflexors are not reattached to the hindfoot bones, the unopposed action of both the triceps surae and gravity, the equinovarus deformity may develop (Sanders, 1997; Leonard et al., 2000). The main consequences of Chopart amputation are almost completely absent ability of push-off and unstable subtalar joint causing compensatory changes in the kinematics and kinetics of pelvis, trunk and hip (Dillon, 2007). Ankle power generation may be further reduced by relative elimination of ankle motion using high-profile prosthesis (Dillon, 2007; Dillon and Barker, 2006a). Unstable subtalar joint may result also in excessive anterior weight bearing with skin breakdown (Bowker, 2007).

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The main objective in rehabilitation of these patients is to restore or improve their functioning, that is walking and standing. This we try to achieve by using a wide range of devices. There are two basic types of prostheses that can be used for persons after Chopart amputation, perimalleolar and high-profile design (Condie and Bowers, 2004). Some of them have to be used together with either regular or special footwear. The primary objective of these devices is to restore biomechanical leverage in order to improve diminished push-off function and by this to improve walking. Other objectives are also to stand with a good balance, to redistribute pressures during walking, prevent ulcerations, development of deformities, such as plantar contracture or varus of the calcaneus and to restore appearance (Dillon, 2007; Condie and Bowers, 2004; Soderberg et al., 2001). The major shortcomings of perimalleolar designs are related to suspension problems at the terminal stance phase of walking and inability to generate adequate push-off. Because of this they are not recommended for active subjects (Leonard et al., 2000; Condie and Bowers, 2004; Lange, 1991). On the other hand the use of rigid high-profile prosthesis prevents movement about the remaining joints. In spite of this they are still recommended for active, or pressure sensitive subjects (Leonard

et al., 2000). Condie and Bowers (2004) stressed that if the user attempts to simulate normal push-off, requiring the generation of a significant forefoot ground-reaction force, the construction of the device must be stiff enough to withstand the resulting dorsiflexion moment without deforming. Dillon and Barker (2006b) states that only high-profile prostheses can restore the effective foot length in subjects after Chopart amputation. Most authors still agree on Cohen-Sobel's statement that these patients perform best with a formal or high-profile prosthesis (Cohen-Sobel et al., 1994).

Requests for cosmetic restoration after partial foot amputations are high and are almost equal by males and females (Stills, 1987). We found two articles reporting on different types of silicone prosthesis for subjects after partial foot amputation (Lange, 1991; Stills, 1987), but none of these studies did any functional evaluation. Stills mentioned that they initially intended to improve cosmesis only, but later subjects reported increased comfort and functional levels (Stills, 1987). From the article it is not clear if the silicon prostheses were fit also to subjects after Chopart amputation. Lange (1991) developed supramalleolar silicone prosthesis and fit it to seven patients after Chopart amputation. He also reported that it is contraindicated for patients after Chopart amputation who may wish to participate in very strenuous sports. To the best of our knowledge there does not exist any study related to instrumented gait analysis of walking with silicone prostheses in subjects after Chopart amputation, which would examine the biomechanical effects of silicone prostheses on kinematics and kinetics of walking.

The objective of our study was to perform instrumented gait analysis in a group of subjects that underwent Chopart amputation wearing two different prosthetic solutions: silicone and conventional prostheses. The specific objective was to characterize biome-

chanics of gait under four conditions: walking barefooted (directly on partial foot), walking while wearing silicone prosthesis alone, walking while wearing footwear with conventional prosthesis (Fig. 1) and walking while wearing footwear with silicone prosthesis. Additionally, we wanted to examine currently accepted understanding that silicone prostheses have little influence on biomechanics of walking since our clinical observations suggest several beneficial effects.

2. Methods

2.1. Subjects

To select appropriate patients we checked medical records of all patients with partial foot amputation due to trauma (ICD codes for medical diagnosis S98) visiting out patient clinic for prosthetics and orthotics at the Institute for Rehabilitation in the last 5 years. We also checked medical records of all patients who received partial foot amputation prosthesis in the last 2 years to find out all with Chopart amputation. To be included patients already had to have a conventional prosthesis. Patients with other orthopaedic or neurological problems were excluded and not invited to participate in the study. Twelve subjects were invited by post to participate in the study. One changed his address in between, one was excluded due to limb length discrepancy of 2 cm and six did not answer to our invitation. The remaining four subjects were included into the study. Their clinical data are given in Table 1.

Study was approved by ethical committee of the Institute for rehabilitation. All subjects were properly informed about the study procedures and gave informed consent.



Fig. 1. An example of conventional foot prosthesis.



Fig. 2. An example of a silicone foot prosthesis.

Table 1
Clinical characteristics of included subjects.

Subject	1	2	3	4
Gender	Male	Male	Male	Female
Age	54	55	42	18
Time from amputation to the study (years)	33	2	15	1
Cause of amputation	Injury	Injury	Injury	Injury
Walking distance barefoot (m)	100	100	100	0 ^a
Walking distance with conventional solution (km)	1	1	5	3
Walking with silicone prosthesis (km)	2	1	2	2.5
Type of conventional prosthesis	Shoe with filler	Shoe with filler	Conventional prosthesis + shoes	Normal shoes without any adaptation

^a Does not practice barefoot walking.

2.2. Silicone prosthesis

Casting was done by plaster of Paris in weight bearing position with calcaneus in neutral position whenever possible. For all patients, an initial check socket was made from transparent silicone to check the fit. This was adjusted until an optimal fit was achieved. Then a test prosthesis was made from room temperature vulcanizing silicone (Pastasil). This was added to the check socket and patients practice walking with it for 2–3 weeks. If patients had no problems the final prosthesis was made from Enhance tear resistance silicone (ETR silicone or Chlorosil) 35 shore. Soles of the prosthesis were about 5 mm thick, but were not additionally reinforced by any material, not even with silicone. The trim lines

went under the malleoli on medial and lateral side, and above the malleoli in the front and back part of the prostheses (Fig. 2). In subjects with correctable calcaneus varus, the prosthesis also included lateral wedge.

2.3. Instrumented gait analysis

Subjects were asked to walk along a 10 m-gait laboratory walkway at their preferred speed under four experimental conditions on two assessment sessions. The second session was always 3 weeks after fitting the final silicone prosthesis. This gave subjects enough time to stabilise their walking performance with silicone prosthesis. On the first session the subjects walked under two

Table 2
Temporal gait parameters. A – denotes amputated side; N – denoted non-amputated side.

	Experimental condition					
	BF mean (SD)	BF&SILICONE mean (SD)	P value	FW&CON mean (SD)	FW&SILICONE mean (SD)	P value
Gait velocity (m/s)	0.89 (0.19)	1.18 (0.2)	0.047*	0.99 (0.22)	1.16 (0.24)	0.07
Cadence – A (1/min)	102.2 (8.1)	106 (13.1)	0.36	97.5 (8.3)	105 (13.6)	0.13
Cadence – N (1/min)	101.5 (7.6)	105.8 (12.2)	0.28	96.8 (7.4)	105 (12.5)	0.11
Step length – A (m)	0.55 (0.1)	0.66 (0.07)	0.01*	0.66 (0.1)	0.71 (0.07)	0.06
Step length – N (m)	0.52 (0.08)	0.55 (0.1)	0.37	0.56 (0.09)	0.61 (0.07)	0.04*

* P < 0.05.

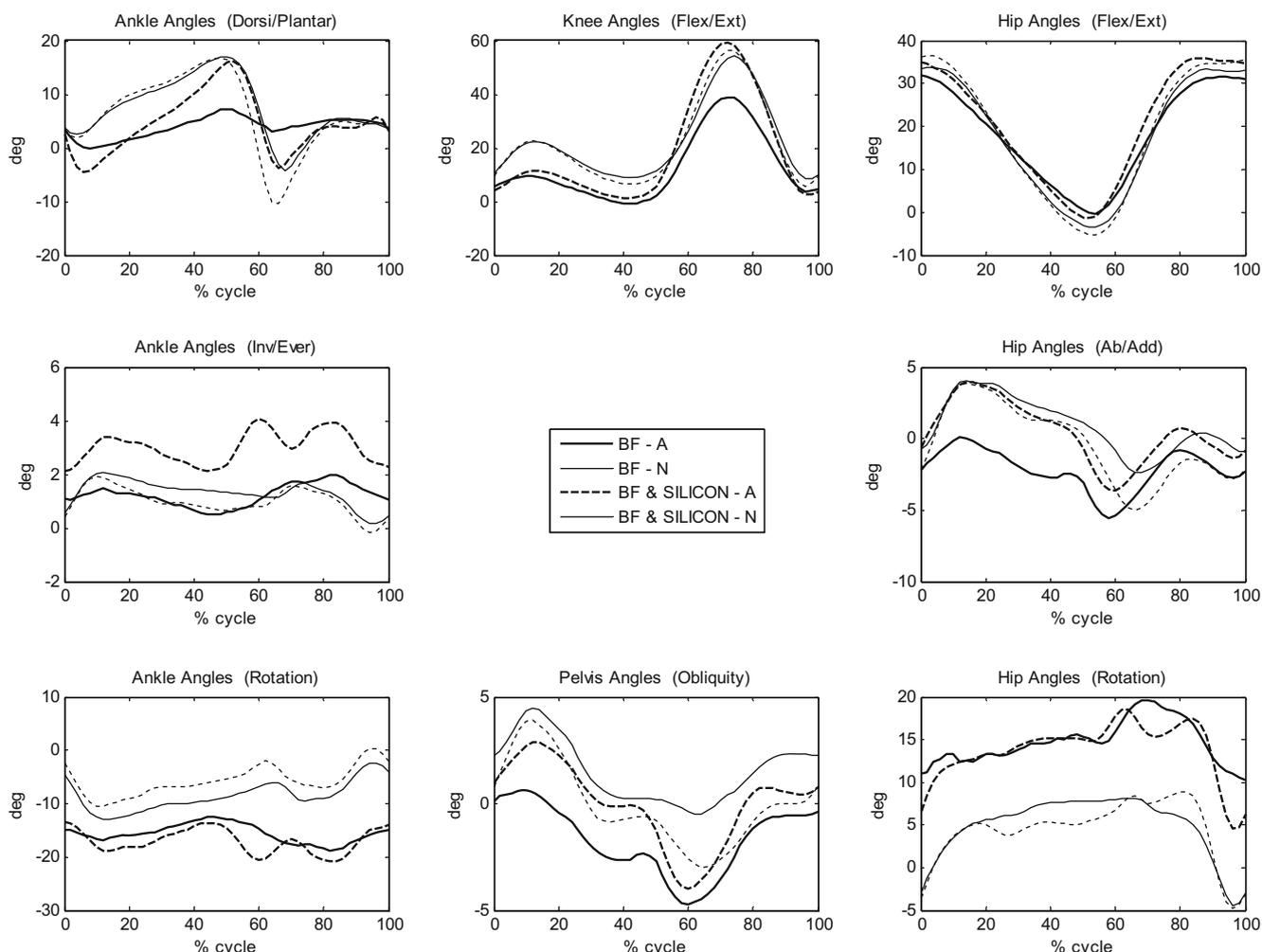


Fig. 3. Averaged kinematic gait patterns captured for amputated (A) and non-amputated (N) leg for experimental conditions BF and BF&SILICONE.

experimental conditions: barefooted (BF) and wearing footwear with conventional prosthesis (FW&CON). On the second session the subjects walked under further two experimental conditions: barefooted with silicone prosthesis fitted (BF&SILICONE) and wearing footwear with silicone prosthesis fitted (FW&SILICONE).

A VICON motion capture and analysis system (VICON 370, Oxford Metrics Ltd., Oxford, UK) was used to capture motion of the lower limbs and pelvis. Reflective markers were attached to the subjects' skin over designated landmarks according to the specifications provided by the manufacturer of the system (Vicon Clinical Manager). Motion data were sampled at 50 Hz. Two AMTI force plates (AMTI OR-6-5-1000, Advanced Mechanical Technology Inc., Watertown, MA, USA) that were positioned in the centre of

the walkway were used for recording ground-reaction forces. Force data were sampled at 1000 Hz. Joint angles, moments and powers were calculated using Vicon Clinical Manager, which incorporates a full inverse dynamic model. At least three clear steps of each leg were captured for analysis under each experimental condition.

2.4. Data analysis

Gait velocity, stride length and cadence data were extracted and tested in an independent *t*-test for differences in comparisons between experimental conditions. Two discrete comparisons of walking performance were done: a comparison between the BF and BF&SILICONE, as these two experimental conditions represent

Table 3
Selected kinematic and kinetic peak values during stance phase. A – denotes amputated side.

	Experimental condition					
	BF mean (SD)	BF&SILICONE mean (SD)	<i>P</i> value	FW&CON mean (SD)	FW&SILICONE mean (SD)	<i>P</i> value
Pelvis angle lateral – A (°)	1.23 (2.9)	3.56 (3.74)	0.017*	1.74 (2.91)	3.61 (3.94)	0.048*
Hip adduction/abduction – A (°)	–1 (8.2)	3.75 (7.8)	0.005*	1.5 (5.8)	4 (6.97)	0.09
Ankle dorsi/plantarflexion – A angle (°)	7.8 (3.03)	18.6 (5.55)	0.009*	17.22 (2.29)	19.1 (3.1)	0.195
Hip abduction moment – A (Nm/kg)	0.54 (0.49)	0.83 (0.36)	0.21	0.6 (0.39)	0.9 (0.47)	0.047*
Ankle plantarflexion moment – A (Nm/kg)	0.18 (0.13)	0.52 (0.08)	0.04*	0.49 (0.18)	0.58 (0.08)	0.514
Ankle power – A (W/kg)	0.06 (0.02)	0.52 (0.22)	0.03*	0.12 (0.08)	0.59 (0.34)	0.119

* *P* < 0.05.

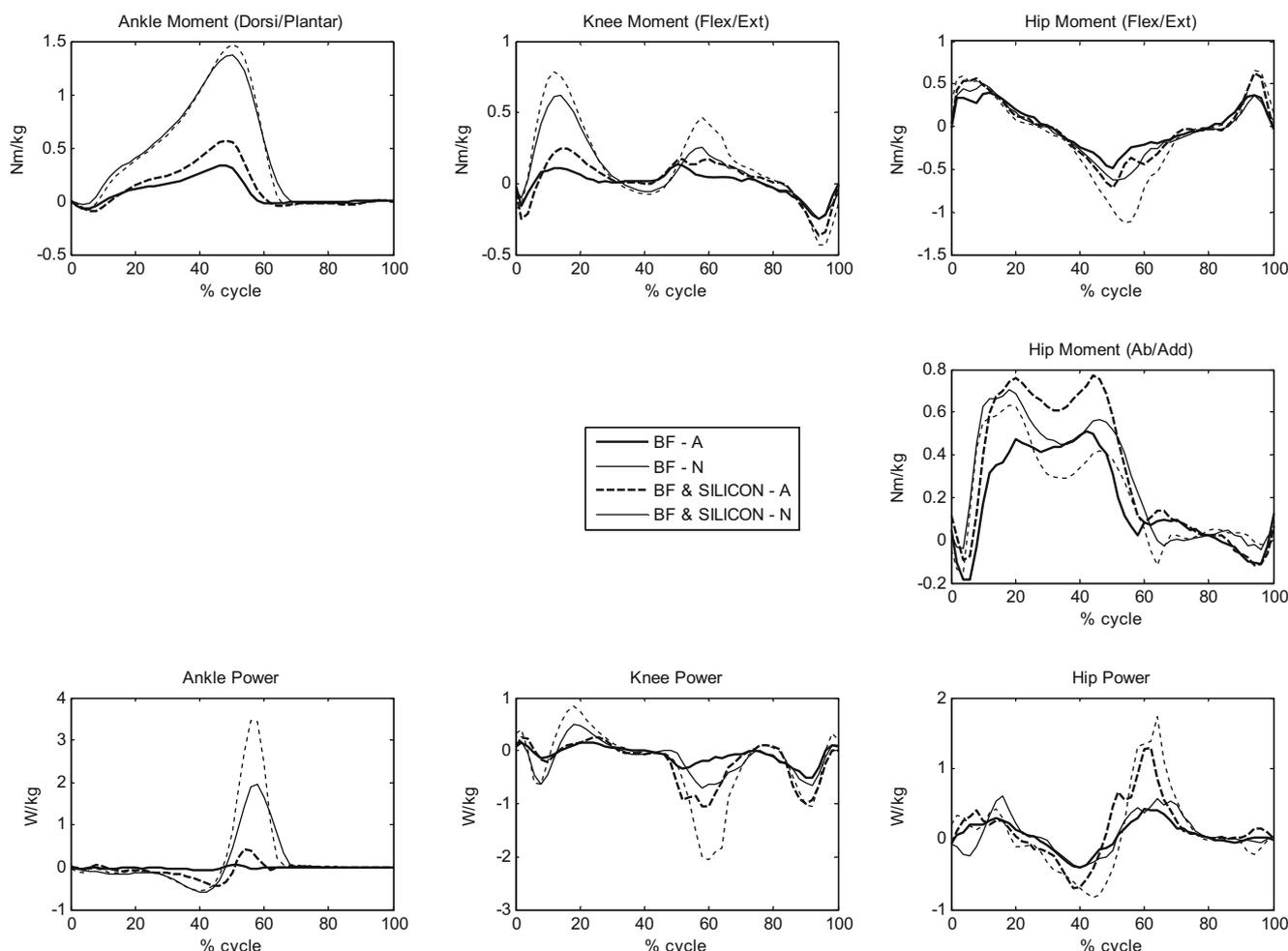


Fig. 4. Averaged kinetic gait patterns captured for amputated (A) and non-amputated (N) leg for experimental conditions BF and BF&SILICONE.

situation where no footwear was used (in the first also no prosthesis, walking directly on partial foot); and a comparison between FW&CON and FW&SILICONE as these two experimental conditions represent situation where footwear and prostheses were used.

Ankle (dorsiflexion/plantarflexion, varus/valgus and internal/external rotation), knee (flexion/extension), hip (flexion/extension, adduction/abduction and internal/external rotation) and pelvis obliquity angles were calculated. Joint moments were calculated for ankle (dorsi/plantarflexion), knee (flexion/extension) and hip (flexion/extension and abduction/adduction). Joint powers were calculated for the ankle, knee and hip joints. Joint moments and powers were normalized for body mass and reported in Nm/kg and W/kg, respectively. For each subject the averaged values from three trials for each leg were calculated and used in subsequent averaging and statistical analysis of the data for the whole group and for each experimental condition separately. Gait cycle terminology as introduced by Perry (1992) was adopted to define instants of characteristic peak values of kinematics and kinetic trajectories in the gait cycle.

Several averaged peak values for selected kinematics and kinetic data were statistically examined with an independent *t*-test in two discrete comparisons (BF vs. BF&SILICONE and FW&CON vs. FW&SILICONE), similarly as outlined above for the temporal gait data. We were interested particularly in the clinically observable changes in ankle angles and moments in the sagittal plane and ankle power as well as pelvis lateral angles, hip abduction/adduc-

tion angles and hip abduction moments in the stance phase of gait. Level of statistical significance was determined when $P < 0.05$.

3. Results

3.1. Temporal gait characteristics

The data on gait velocity, stride length and cadence are presented in Table 2. Comparison between both barefooted experimental conditions show increase in all temporal gait measures when wearing silicone prostheses. Similarly, comparison between both footwear experimental conditions show increase in all temporal gait measures when silicone prostheses were used. Some of these differences are statistically significant.

3.2. Kinematics and kinetics

Kinematic patterns for experimental conditions BF and BF&SILICONE are shown in Fig. 3 for both amputated and non-amputated side. There are only minor differences on non-amputated side between both experimental conditions on all kinematic patterns. On the amputated side the most pronounced differences can be observed in ankle dorsiflexion/plantarflexion angle pattern in the stance phase where much larger range of motion can be noticed with significantly different peak value of ankle dorsiflexion before push-off phase (Table 3). Another important difference in both

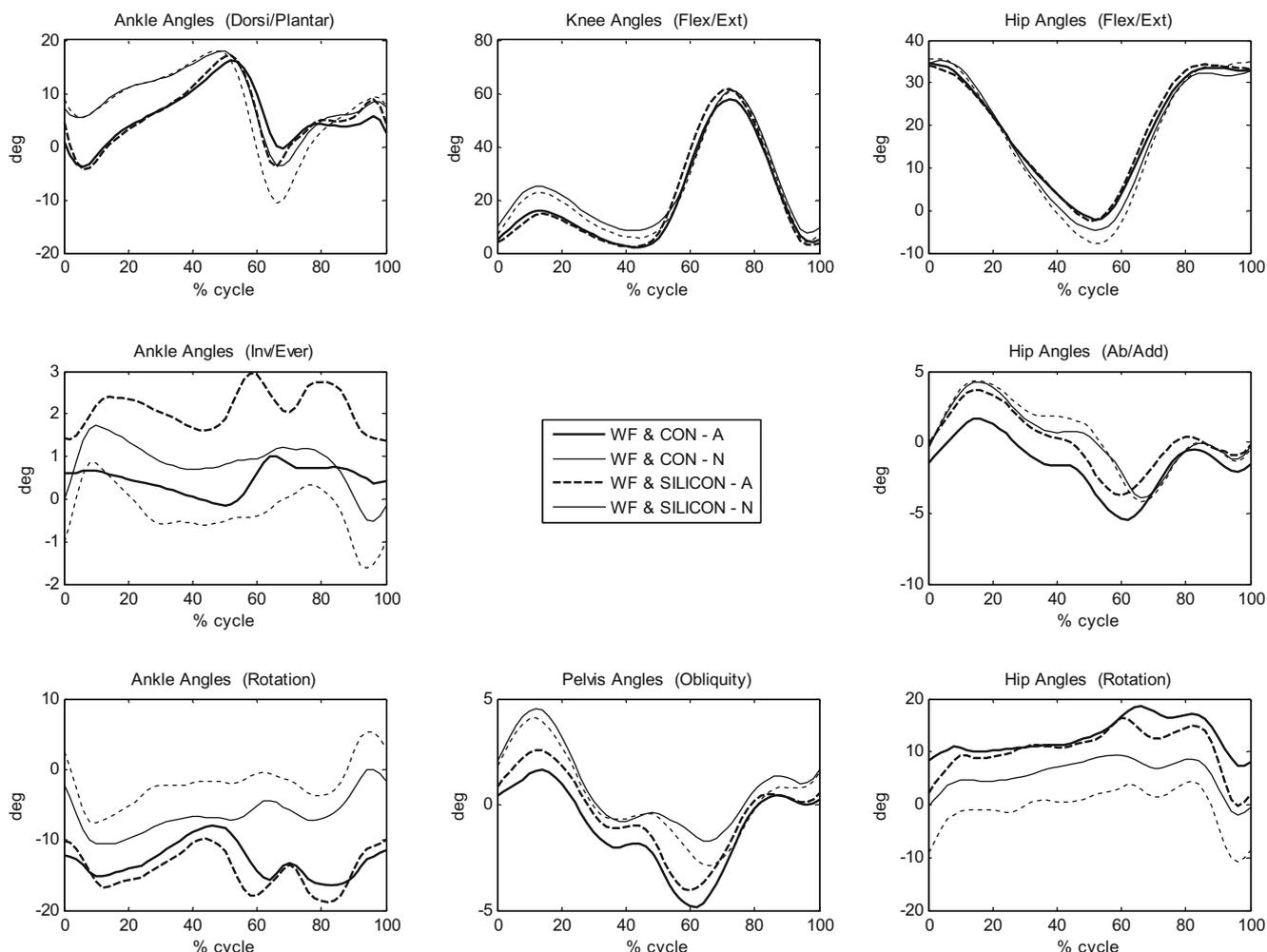


Fig. 5. Averaged kinematic gait patterns captured for amputated (A) and non-amputated (N) leg for experimental conditions FW&CON and FW&SILICONE.

experimental conditions is evident in hip adduction angle pattern throughout the stance phase where silicone prosthesis enables almost normal performance. Significantly different are also peak values of hip adduction during loading response (Table 3). The last significantly different changes are evident from pelvis lateral angle patterns where almost normal pelvis lateral inclination, when using silicone prosthesis, is observed throughout the stance phase, with significantly different changes in peak values during loading response (Table 3).

Kinetic patterns for experimental conditions BF and BF&SILICONE are shown in Fig. 4 for both amputated and non-amputated side. In contrast to kinematics there are more pronounced differences in the kinetic patterns for non-amputated side (especially ankle and hip power generation) between both experimental conditions, which can be attributed to different gait velocities. On the amputated side there are pronounced differences in ankle plantarflexion moment throughout the stance phase, with peak values during push-off being significantly higher when silicone prosthesis were used (Table 3). Another marked difference between both experimental conditions can be observed in hip abduction moment throughout the stance phase, where substantially higher values were observed when silicone prosthesis was used. Statistically significant differences are also evident in ankle power during push-off.

Kinematic and kinetic patterns for experimental conditions FW&CON and FW&SILICONE are presented in Figs. 5 and 6, respectively.

Similarly, changes as described for the barefooted experimental conditions can be observed. These changes are rather small for ankle dorsiflexion/plantarflexion angles, moments and powers while more marked changes in pelvis obliquity, hip adduction angles and hip abduction moments that are shift towards normal can be seen. Some of these changes are statistically significant (Table 3).

4. Discussion

In this study we have through instrumented gait analysis objectively examined a hypothesis that silicone prostheses after midtarsal or Chopart amputation may change biomechanics of walking resulting in improved overall gait performance. Our results on a small sample demonstrate that silicone prosthesis even without reinforced sole increases gait velocity, improves generation of ankle plantarflexion moment throughout the stance phase and enables greater power generation at push-off. The most important changes, however, occur in the frontal plane, where improved hip adduction angles and higher hip abduction moment in the stance enable more normal pelvic movement and consequently also less trunk inclination toward amputated side. It seems that silicone prosthesis significantly improves stability of the ankle in the frontal plane, which in turn enables, otherwise competent hip abductors, to restore their role of weight shifting in the frontal plane, which is significantly compromised for people with partial

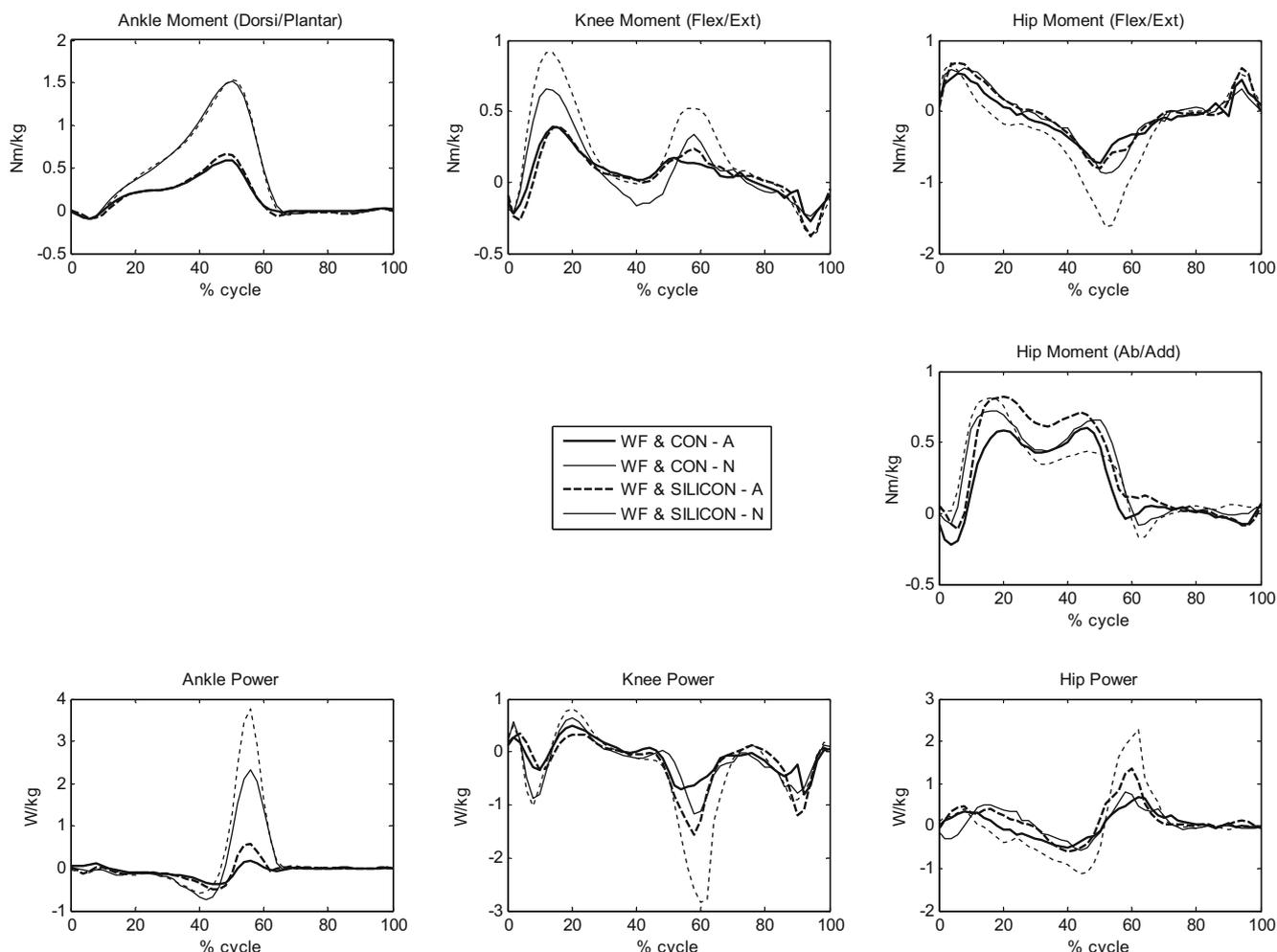


Fig. 6. Averaged kinetic gait patterns captured for amputated (A) and non-amputated (N) leg for experimental conditions FW&CON and FW&SILICONE.

foot amputation when barefooted or when using conventional prosthetic solutions.

We found only two studies on gait analysis that included also subjects after Chopart amputation (Dillon and Barker, 2006a,b). In both studies only two subjects, one bilateral and one amputated due to vascular problems, were included. Both used high-profile prosthesis. Findings of both studies have shown reduction in ankle motion due to action of high-profile prostheses. In our study normal degree of dorsiflexion during late stance and swing phase of walking were found even when walking barefoot with silicone prosthesis only. There has been only decreased plantarflexion at push-off. Because soles of our prosthesis were not reinforced it is according to findings of other studies not possible to achieve normal plantarflexion even if subject has full passive range of motion (Dillon and Barker, 2006a,b; Condie and Bowers, 2004).

None of the previous studies described knee and hip kinematics during walking in subjects after Chopart amputation. We found that these subjects while walking barefoot or with perimalleolar prosthesis had decreased hip adduction and pelvis lateral inclination during stance phase, which is significantly improved by the use of custom made silicone prosthesis. Subjects do not need to walk with secondary deviations, such as lateral trunk bending, which may decrease also secondary impairments such as low back pain.

In contrast with findings of Dillon and Barker (2006a), rather small amplitudes of plantar flexion moment in all conditions were observed. But Dillon's subjects had high-profile prosthesis, whereas we used perimalleolar without additional reinforcement of the sole. In spite of this, silicone prosthesis increased plantarflexion moment as much as conventional solutions the subjects wore before. Only one of our subjects complained about pain at the distal end of the stump, which depended on walking speed. Most probably the other subjects had already adopted the gait pattern in which with decreased ankle plantar flexion moment they spare the distal end of the stump from excessive pressures during the terminal stance and so reduce pain related problems. Silicone prosthesis significantly increased power generation in the ankle, however in comparison to the findings of Dillon's study this power generation is rather small.

Silicone prosthesis improved both ankle power on amputated but also on sound side in both testing conditions – walking barefoot and while wearing footwear. It seems that subjects felt much more confident and stable while walking with silicon prosthesis, which resulted in faster walking with greater ankle and hip power generation on both sides.

The most frequent cause of Chopart amputations are injuries, specially land mines and foot tumours (Bowker, 2007; Soderberg et al., 2001). This means that most of the victims are young and active. Especially land mine victims are often from areas where barefooted walking or using sandals is important. All this has to be

taken into consideration when deciding about the best and the most appropriate prosthetic solution. In Slovenia the classic prosthetic solution for Chopart amputation is application of leather prosthesis, but many subjects amputated in the last years are not satisfied with its appearance and also complain that is difficult to get regular shoes that will fit on prosthesis. Most of them also do not want even to try high-profile prosthesis.

The limitations of our study are small number of patients and no comparison with high-profile devices. But the number of patients is still twice as much as in both other studies. Increased number of subjects may have improved statistical significance of our findings, which are highly clinically relevant. Because our subjects do not like high-profile devices also measurements with them may be questionable.

We may conclude that silicone prostheses are not solely for cosmetic reasons but tended to be also biomechanically superior over other prosthetic solutions, especially for walking barefoot.

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References

- Bowker, J.H., 2007. Partial foot amputations and disarticulations: surgical aspects. *Am. Acad. Orthot. Prosthet.*, 62–76.
- Cohen-Sobel, E., Caselli, MA., Rizzuto, J., 1994. Prosthetic management of a Chopart variant. *J. Am. Podiatr. Med. Assoc.* 84, 505–510.
- Condie, DN., Bowers, R., 2004. Amputations and disarticulations within the foot prosthetic management. In: Smith, DG., Michael, JW., Bowker, JH. (Eds.), *Atlas of Amputations and Limb Deficiencies*. American Academy of Orthopaedic surgeons, Rosemont, pp. 449–457.
- Dillon, MP., 2007. Biomechanics of ambulation after partial foot amputation: a systematic literature review. *Am. Acad. Orthot. Prosthet.*, P2–61.
- Dillon, MP., Barker, TM., 2006a. Preservation of residual foot length in partial foot amputation: a biomechanical analysis. *Foot Ankle Int.* 27, 110–116.
- Dillon, MP., Barker, TM., 2006b. Can partial foot prostheses effectively restore foot length? *Prosthet. Orthot. Int.* 30, 17–23.
- Lange, LR., 1991. The Lange silicone partial foot prosthesis. *J. Prosthet. Orthot.* 4, 56–61.
- Leonard, EI., McAnelly, RD., Lomba, M., Faulkner, VW., 2000. Lower limb prostheses. In: Braddom, RI. (Ed.), *Physical Medicine & Rehabilitation*. WB Saunders, London, pp. 283–284.
- Perry, J., 1992. *Gait Analysis: Normal and Pathological Function*. SLACK Incorporated, Thorofare, NJ.
- Sanders, LJ., 1997. Transmetatarsal and midfoot amputations. *Clin. Podiatr. Med. Surg.* 14, 741–762.
- Soderberg, B., Wykman, A., Schaarschuch, R., Persson, BM., 2001. *Partial Foot Amputations*. Centre for Partial Foot Amputees, Helsingborg, pp. 51–59.
- Stills, ML., 1987. Partial foot prostheses/orthoses. *Clin. Prosthet. Orthot.* 12, 14–18.