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Lower extremity kinematics and kinetics during level walking and stair climbing in subjects with triple arthrodesis or subtalar fusion

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Abstract

The purpose of this study was to identify the kinematic and kinetic strategies used by patients with unilateral triple arthrodesis or subtalar fusion during level walking, stair ascent, stair descent and to determine the influence of these different conditions on kinematics and kinetics. Nine subjects with unilateral triple or subtalar fusion and five normal control subjects were recruited for this experiment. Temporal distance, kinematic and kinetic data were collected using a six camera 3-D motion analysis system and a custom fabricated set of stairs with five steps; the second and third steps were each instrumented with one force platform. During level walking, affected limbs lost all of the plantarflexion at the ankle joint during push-off and showed greater knee flexion angle during the same period of stance. During stair ascent, affected limbs showed a different movement pattern at the knee, a greater knee flexion angle during the whole stance phase and a near zero degree of plantarflexion angle during the forward continuance (FCN) phase. During descent, affected limbs showed a greater knee flexion angle during the whole stance phase and less ankle dorsiflexion angle during the same period of stance phase. At the ankle, peak moment and power values were significantly different between the affected side and the limbs of the control subjects during level walking in the push-off phase, stair ascent in the FCN phase, and stair descent in the weight acceptance (WA) phase, where the affected limbs had a lower plantarflexion moment and power values.

Keywords: Triple arthrodesis; Stair climbing; Gait

1. Introduction

Triple arthrodesis is a procedure that fuses the subtalar joint, talonavicular joint, and calcaneocuboid joint. It is a useful operation for the relief of chronic pain and treatment of instability and deformity in the rearfoot. The clinical results of triple arthrodesis have been reported in several long-term studies; in general, these have been found to be favorable, although the development of radiological evidence of tibiotalar arthritis has been of concern [1–8]. Subtalar arthrodesis is a procedure that fuses only the subtalar joint and is performed mostly for the treatment of isolated subtalar arthrosis. In biomechanical studies, fusion of the subtalar joint not only limits the subtalar motion but also decreases the motion of the talonavicular joint and calcaneocuboid joint. Therefore, the gait pattern after subtalar fusion is very similar to the gait pattern after triple arthrodesis [9,10].

Ambulation on stairs is an important aspect of daily activities for many patients with triple arthrodesis; however, little is known about the kinematic and kinetic strategies that are used to accomplish this task. During stair ascent, the lower limb functions not only to support and balance body weight, but also raise that weight onto the supporting step. For patients with triple arthrodesis who use a reciprocal gait pattern, the primary responsibility for raising this weight on the affected side must be divided between the knee and hip, with the potential for some additional help from the unaffected

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side during periods of double support. The foot segment with arthrodesis probably has a minimal contribution to the lower-limb energy. A number of studies have investigated kinetics during normal stair ambulation [11–13]. McFadyen and Winter [12] partitioned the stance phases of stair ascent into three parts: weight acceptance (WA), pull-up (PU), and forward continuance (FCN); the swing phases into two parts: foot clearance (FCL) and foot placement (FP). The stance phase whilst walking down stairs was broken down into three sub-phases described as WA, FCN and controlled lowering (CL). The swing period had two phases again, including leg pull-through (LP) and preparation for FP. Similar divisions for ascent and descent phases were adopted in this study. The patterns for normal stair climbing show the dominant role of the knee during WA and PU, with supporting roles played by the hip and ankle. During FCN, the ankle has the major role, with relatively little contribution occurring from the knee and hip.

We believed that a kinetic analysis would allow for the assessment of the underlying strategy that distinguishes between the lower limbs of triple arthrodesis subjects. Knowledge of the moments and powers could be used to explain how the work is distributed among the different joints, thereby enabling a more complete understanding of level walking or stair ambulation after triple arthrodesis.

Beischer et al. [14] in their follow-up study of patients who had had triple arthrodesis, noted that abnormal moments and power generation at the ankle and decreased angular range of motion in the ankle and increased angular range of motion in ipsilateral knee joints were associated with triple arthrodesis. While information for level walking is available [14], data on the high demand activities of stair ascent and descent, after triple arthrodesis or subtalar fusion, remain to be documented. The purpose of the present research was to identify the kinematic and kinetic strategies used by patients with unilateral triple arthrodesis or subtalar fusion during level walking, stair ascent, stair descent and to determine the influence of these different conditions on kinematics and kinetics.

2. Method

2.1. Subjects

Informed consent was obtained from nine subjects with unilateral arthrodesis, including two right and seven left, triple arthrodesis or subtalar fusions who participated in the study (Table 1). They had a mean age of 44.33 ± 14.28 years (range from 27 to 65 years). The mean duration since operation was 40.22 ± 19.34 months. There was no history of neurological impairment. The pre-operative diagnosis necessitating triple arthrodesis or subtalar fusion was post-traumatic osteoarthritis (3 ft) and congenital cavovarus deformity (6 ft). All could ascend and descend the stairs without support. A group of five normal control subjects also participated in the present study. Their mean age was 31.6 years (range 23–37 years), mean mass 67.6 kg (range 51–76 kg), and mean height 168 cm (158–178 cm).

2.2. Equipment

We performed analysis of the motion of the lower limbs by using passive light reflecting markers (ExpertVision System, Motion Analysis Corp., CA) and force assessment using two floor mounted force plates (Kistler Instrument Corp., Switzerland). Marker coordinate data was collected online at 60 Hz. Two Kistler force plates were used to collect the three-dimensional force data at a sampling frequency of 1000 Hz while the subject was walking barefoot. Ground reaction forces of multiple trials were collected synchronously with motion analysis. Kinetics were obtained by combining the outputs from the force-plates with the outputs from the motion analysis system.

2.3. Stair design

A wooden stair was created by the use of five non-connected wooden sections, as shown in Fig. 1. The second and third sections of the stair were placed on force plates for kinetic

Table 1
The length of the follow up, the age of the patient, type of surgery performed, and anthropometric data in nine patients treated with a triple arthrodesis or subtalar fusion

Case no.	Age (years)	Gender	Height (cm)	Weight (kg)	Duration after surgery (months)	Etiology	Surgical type	Affected side
1	59	Female	160	79	41	Congenital foot deformity	Triple arthodesis	Left
2	23	Male	168	63	30	Congenital foot deformity	Triple arthodesis	Left
3	58	Female	155	83	18	Congenital foot deformity	Triple arthodesis	Left
4	27	Male	174	79	42	Post-trauma	Triple arthodesis	Left
5	42	Female	159	78	54	Post-trauma	Triple arthodesis	Right
6	43	Female	157	65	40	Congenital foot deformity	Subtalar fusion	Left
7	44	Female	158	50	78	Congenital foot deformity	Triple arthodesis	Left
8	65	Male	160	88	13	Post-trauma	Subtalar fusion	Right
9	38	Male	164	66	46	Congenital foot deformity	Triple arthodesis	Left
Average	44.33		161.667	72.33	40.22			
S.D.	14.28		6.02	12.04	19.34			

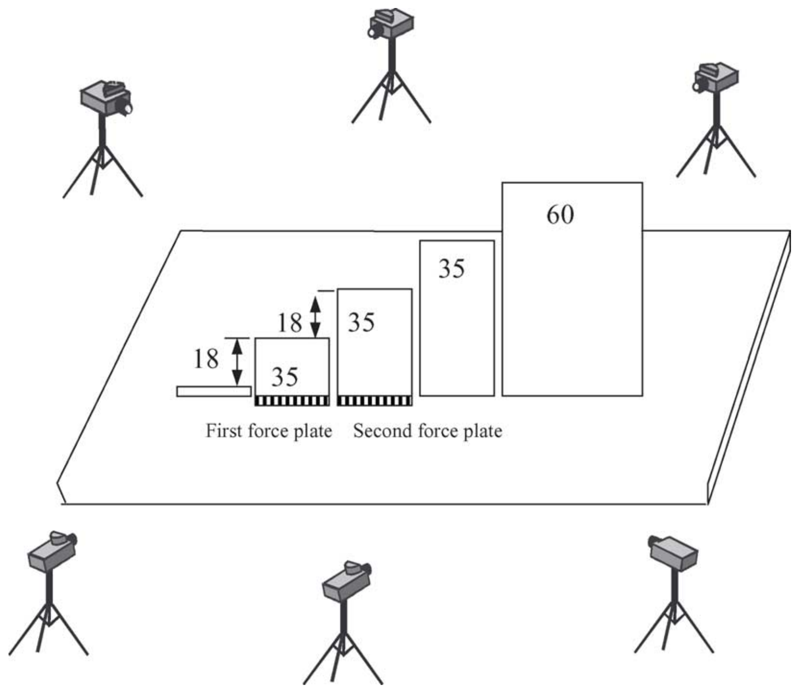

Fig. 1. Schematic sketch of the experimental setup (cm).

data collection. The sections were designed so that each step was 120 cm wide, with a rise of 18 cm from step to step. The first step was 1 cm above floor level to ensure consistent kinematics as the patient stepped on the second step. The first four steps had a depth of 35 cm, and the final a depth of 60 cm.

2.4. Experimental procedures

A full history of each patient was obtained, followed by a careful biomechanical examination of the foot by the same doctor. Anthropometric data was recorded for joint centering and normalization of data with respect to leg lengths and joint widths in the calculation of joint moments and powers.

A twenty-one simplified point (Helen Hays) marker set for full body gait analysis was used in this study [15] and data were collected for both sides. Only the results from the lower limbs were analyzed in this study. After attaching the marker set, subjects walked barefoot under different conditions, including on a level surface and up and down stairs. They were instructed to walk toward the stairs, ascend using a reciprocal pattern, and stop at the top. After turning around, they were instructed to descend using a reciprocal pattern and continue walking forward. No instruction was given regarding speed, or whether to lead with the right or left leg. The subjects walked at a self-selected comfortable walking speed during level walking, ascending and descending the stairs for five trials. For level walking followed by ascent and descent of the stairs, the three trials closest to the subject's average speed were selected for analysis. For ascent, the gait cycle of interest began with foot contact on the second riser and ended with the same foot contacting the fourth riser. For descent, the gait cycle of interest began with foot contact on the fourth riser and ended with the same foot contacting the second riser. Data were processed using Orthotract software.

2.5. Data analysis

Apart from temporal/stride measurements (e.g. walking velocity, cadence, step length, and the percentage of stance phase) to characterize the gait cycle, kinematic and kinetic information were analyzed to evaluate the degree of deformity at each of the major joints. The results of gait analysis of the surgical limbs (9 ft) were compared with the data obtained from the unaffected limbs (9 ft) and normal subjects (5 right ft). For data analysis, the terminology used in this study to describe the phases of stair ascent and descent is shown in Fig. 2.

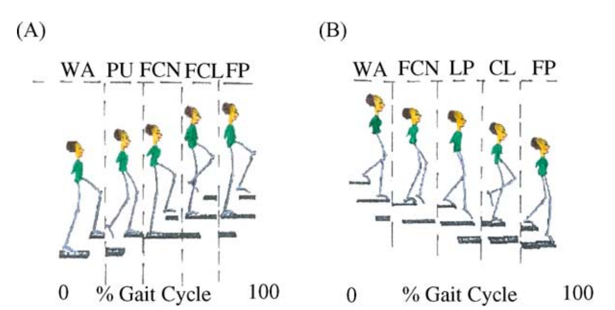

Fig. 2. The terminology used in this study to describe the phases of: (A) stair ascent and (B) descent.

Table 2
Temporal/spatial data

Temporal distance variables (mean ± S.D.)	Level walking			Stair ascent			Stair descent		
	Unaffected limbs	Affected limbs	Normal subjects	Unaffected limbs	Affected limbs	Normal subjects	Unaffected limbs	Affected limbs	Normal subjects
Step length (cm)	49.22 ± 5.31	50.16 ± 4.87*	56.39 ± 5.74	35.19 ± 3.32*	39.13 ± 5.18	40.52 ± 5.13	42.20 ± 4.29	42.23 ± 4.23	42.97 ± 5.63
Walking speed (cm/s)	86.90 ± 12.56	84.29 ± 12.70*	95.94 ± 12.55	50.03 ± 8.75*	54.30 ± 9.38*	58.32 ± 9.30	56.92 ± 3.19*	65.13 ± 2.54*	70.78 ± 5.13
Cadence (steps/min)	106.13 ± 8.47	105.24 ± 6.05*	118.43 ± 10.60	75.60 ± 9.93*	87.75 ± 10.55*	92.03 ± 14.15	88.31 ± 8.67*	92.43 ± 8.27*	98.59 ± 10.59
Stance phase (%)	63.05 ± 4.32	63.66 ± 4.83*	66.03 ± 3.11	62.50 ± 4.33*	68.10 ± 4.25*	73.15 ± 7.54	60.27 ± 2.48*	64.90 ± 3.09*	73.07 ± 3.72

* Denotes difference ($P < 0.05$) between affected limbs, unaffected limbs, and normal subjects.

Descriptive statistics were used to analyze age, height, and weight measurements. The paired-*t* test was used to compare the differences in the temporal/spatial, kinematic, and kinetic parameters. Differences were considered significant when the *P*-value was less than 0.05.

3. Results

3.1. Stride characteristics

The temporal aspects of level walking and stair ambulation were investigated (Table 2). The patterns for patients and normal subjects were dissimilar, there were marked differences in step length, walking velocity, walking cadence and percentage of stance phase during level walking, and stair ascent and descent. Walking velocity, walking cadence and percentage of stance phases on the control subjects were greater than those seen on the non-operated limbs and operated limbs ($P < 0.05$). The control subjects had a greater step length during level walking than those seen on the non-operated limbs and operated limbs ($P < 0.05$). However, no significant differences between affected and unaffected sides were identified in the temporal data of the subjects during level walking. In general, the operated limbs had increased step length, walking velocity, walking cadence

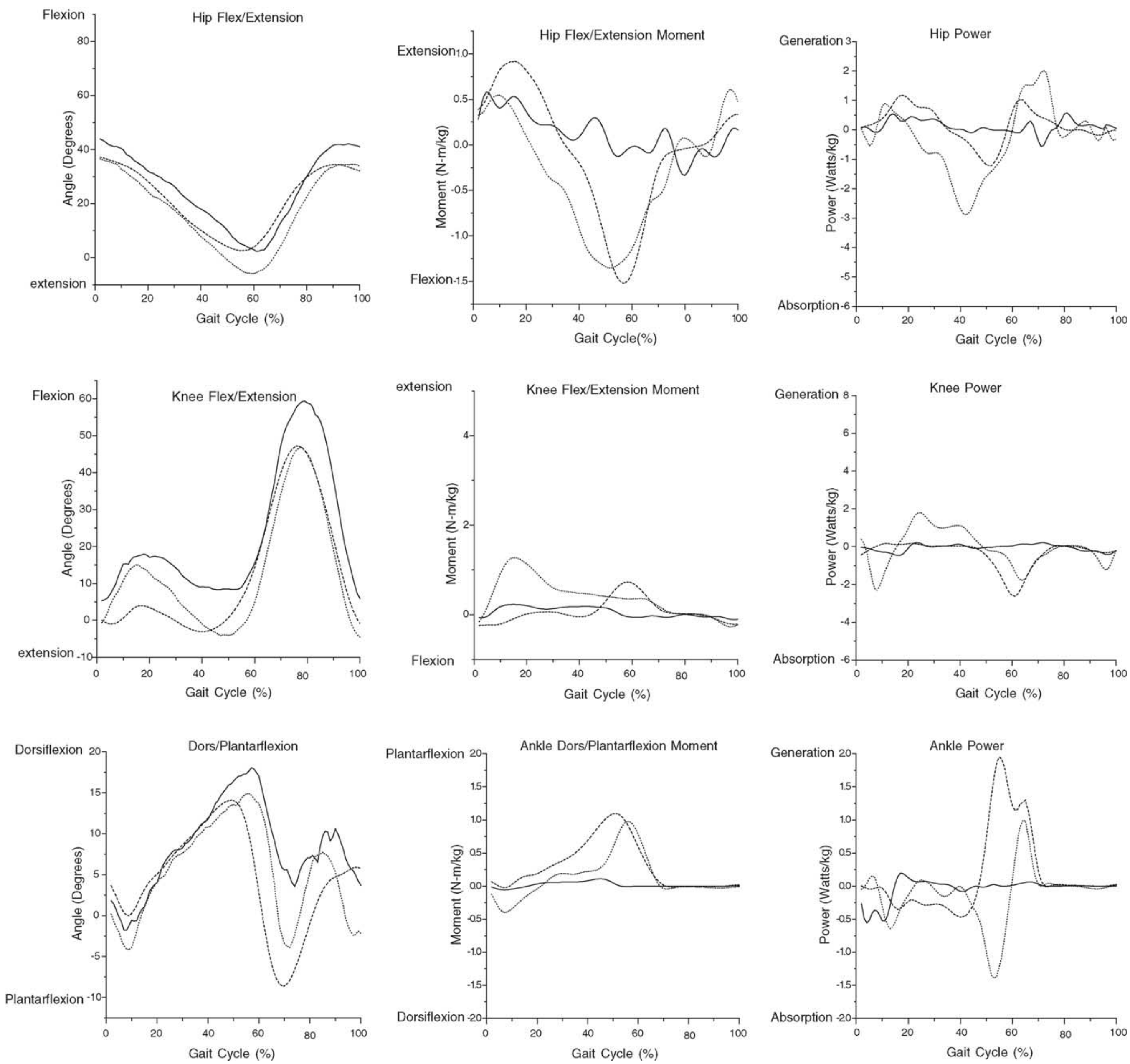

Fig. 3. Sagittal plane kinematics and kinetics of level walking. Solid line, patient's affected side; dotted line, patient's unaffected side; dashed line, normal subject.

and percentage of stance phase ($P < 0.05$) compared to the non-operated limbs during stair ascent and descent. The difference in step length was not obvious during stair descent.

3.2. Kinematic characteristics

The graphs of Figs. 3–5 show averaged kinematics and kinetics strategies used by patients and control subjects during level walking, ascending and descending stairs. The patterns within the group were similar and the positive and negative differences within a group were much lower than the differences observed between groups.

During level walking, affected limbs did not achieve plantarflexion during the push-off phase. There was an increase of 26% in the maximum knee flexion angle (nearly 13°) during the same period of stance when compared to controls (Fig. 3). During stair ascent, affected limbs increased the knee flexion angle by 25% (nearly 25°) during the whole stance phase when compared to controls. Affected limbs showed near zero degree of plantarflexion angle during the FCN phase (Fig. 4). During descent, the affected limbs showed a reduced range but the knee flexion angle in stance increased. It showed an increase of 36% of knee flexion angle (nearly 33°) during the whole stance phase when compared to controls. Lower ankle dorsiflexion angles occurred (13°, decreased by an average of 39%) during the second half of stance only when compared to control subjects (Fig. 5).

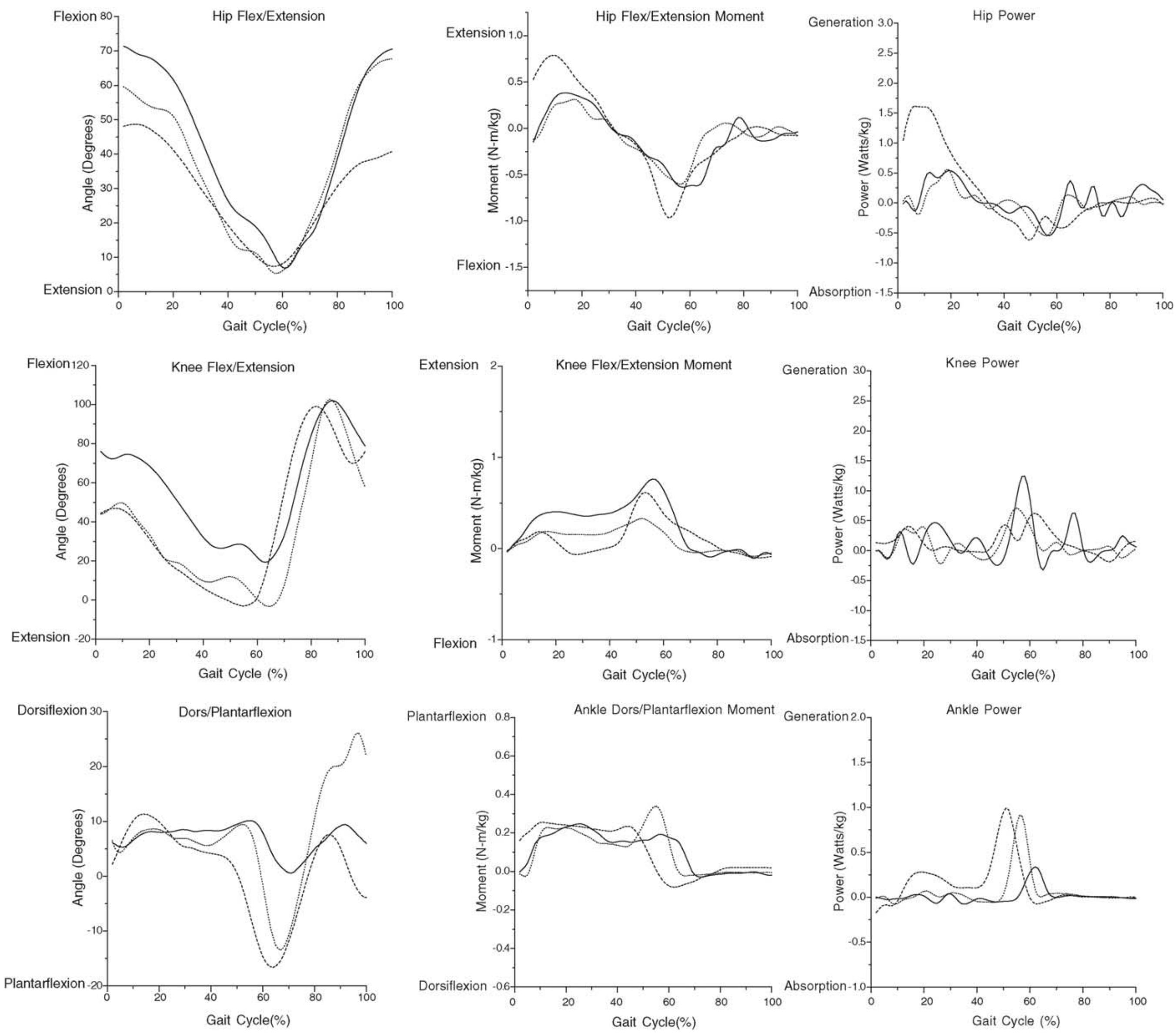

Fig. 4. Sagittal plane kinematics and kinetics of stair ascending. Solid line, patient's affected side; dotted line, patient's unaffected side; dashed line, normal subject.

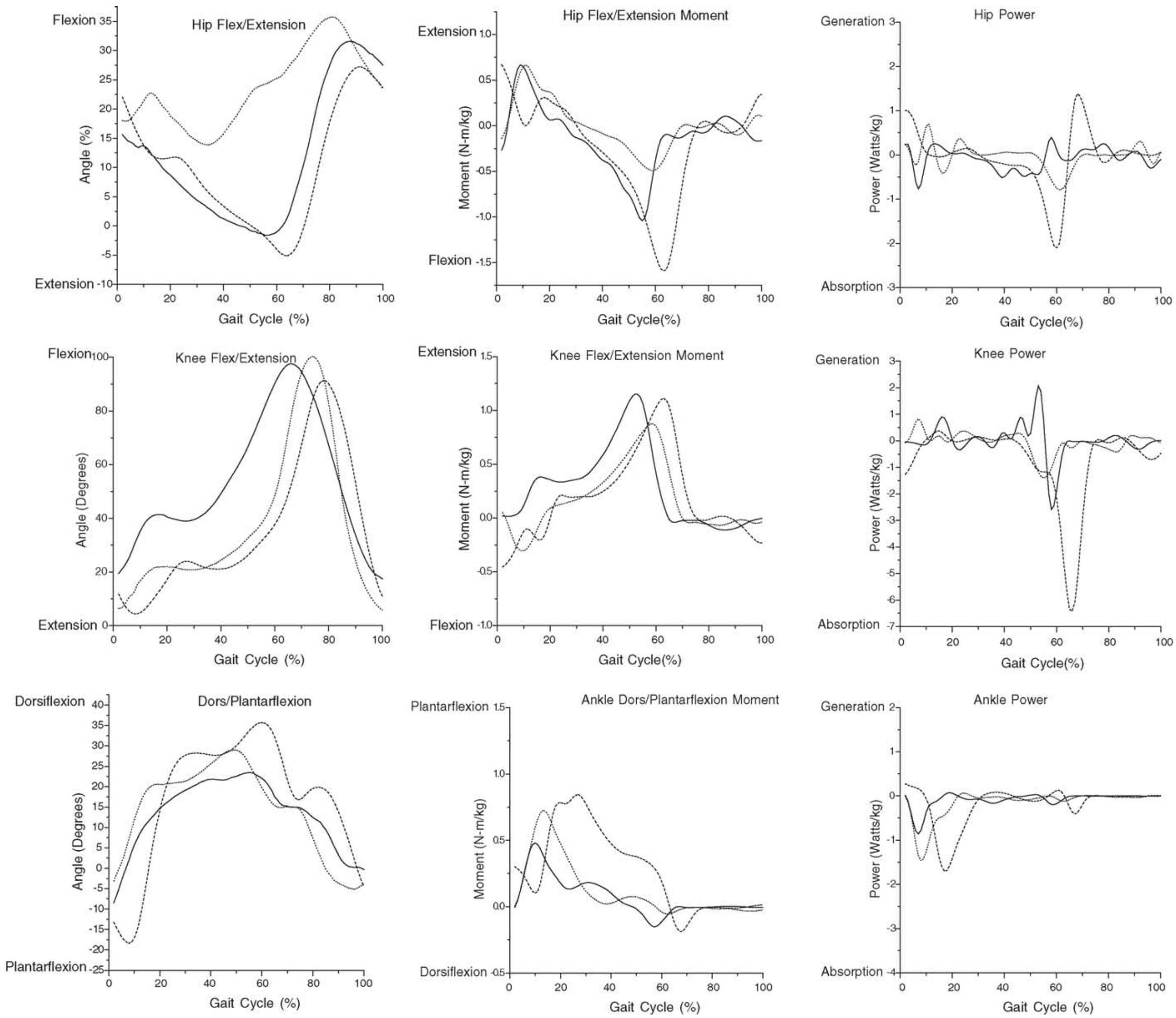

Fig. 5. Sagittal plane kinematics and kinetics of stair descending. Solid line, patient's affected side; dotted line, patient's unaffected side; dashed line, normal subject.

3.3. Kinetic characteristics

At the ankle, peak moment and power values were significantly different between the affected limb and the limbs of control subjects during level walking in the push-off phase (decreased 87% ankle plantarflexion moment and 88% ankle generation power). During stair ascent in the FCN phase, the operated side showed a decrease of 18% in the ankle plantarflexion moment and 63% in the ankle generation power when compared to control subjects. During stair descent in the WA phase, the operated side showed a decrease of 38% in the ankle plantarflexion moment and 49% in the ankle absorption power when compared to control subjects (Figs. 3–5).

During level walking, at 30–70% of the stride, a decreased hip flexor moment appears in the limbs with the triple arthrodesis. A similar trend is seen in the knee moment values where, on average, approximately one-third of the extension moment is performed by the ipsilateral knee. Differences were also seen in the knee moments during stair ascent and descent. Greater peak knee extension moments on affected sides resulted during stair ascent and descent during the whole stance phase when compared to control subjects.

4. Discussion

We found decreased values for temporal parameters in the unaffected limbs during stair ascent and descent when compared to the non-operated limb. We believe the reason for this to be that the step length is shortened on the unaffected limb during the first and second rocker on the side that was operated on.

During level walking, the affected limbs showed a different movement pattern with lower hip flexion moments, lower ankle plantarflexion moments, and lower power generation (positive work) during push-off phase. During stair ascent, the affected limbs showed greater knee extension moments, lower ankle plantarflexion moments, and lower power generation (positive work) during the FCN phase. During descent, the affected limbs showed greater knee extension moments, lower ankle plantarflexion moments, and a lower power absorption (negative work) during the WA phase. We speculate that patients with triple arthrodesis or subtalar fusion will strongly limit their ankle function during the FCN phase for stair ascent, the WA phase for stair descent, and the push-off phase for level walking. During level walking, at 30–70% of the stride, a lower hip flexor moment appeared in the limbs with triple arthrodesis. We think that may be due to the ground reaction force acting at a shorter distance from the axis of the hip joint.

We compared our results to Beischer' study [14] for level walking. They analyzed gait patterns for level walking in 13 patients who had undergone unilateral triple or double arthrodesis. They observed that there was a 13% increase in range of flexion of the ipsilateral knee during the third rocker period of stance. In our study, we found a 26% increase during the same period of stance. At the ankle, there was a 53% loss of plantarflexion at toe-off found in Beischer' study. Our results showed a complete loss of plantarflexion at the ankle joint during this period. They also analyzed the ankle kinetic data and identified a 13% reduction in the peak ankle plantarflexion moment and a 45% reduction in mean power generation at the ankle in comparison to the normal side. Similarly, we confirmed the existence of an 87% reduction in peak ankle plantarflexion moment and a 88% reduction in mean power generation at the ankle. We believe that our results confirm those in Beischer' study, that a triple arthrodesis will significantly reduce the push-off function of the operated limb side during level walking.

Fusion of the subtalar joint, talonavicular joint, and calcaneocuboid joint not only limit the sagittal motion but also decrease the motion of inversion and eversion, in the frontal plane. High demand activities of stair ascent and descent are suitable tests of dorsiflexion/plantarflexion angular limitation. The analysis of the inversion/eversion patterns after fusion increase in importance especially during walking on side slopes or on an uneven floor. Therefore, data on the activities of side slope climbing, after triple arthrodesis or subtalar fusion will need a more detailed analysis of foot kinematics.

With our experimental investigation, we have quantified several important clinical observations. Kinematic and kinetic information on level walking and stair ascent and descent for arthrodesis patients provide insight into how triple arthrodesis affects function. The amount of motion remaining in either operated feet or in the more proximal joints has also been quantified. We believe that this is useful for expanding the current body of knowledge after such surgery.

Acknowledgements

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References

[1] Bernau A. Long-term results following Lambrinudi arthrodesis. J Bone Joint Surg Am 1997;59A:473–9.
[2] Drew A. The late results of arthrodesis of the foot. J Bone Joint Surg Br 1951;33B:496–502.
[3] Figgie MP, O'Malley MP, Ranawat C, Inglis AE, Sculco TP. Triple arthrodesis in rheumatoid arthritis. Clin Orthop 1993;292:250–4.
[4] Galindo MJ, Siff SJ, Butler JE, Cain TE. Triple arthrodesis in young children: a salvage procedure after failed releases in severely affected feet. Foot Ankle 1987;7:319–25.
[5] Haritidis JH, Kirkos JM, Provellegios SM, Zachos AD. Long-term results of triple arthrodesis: 42 cases followed for 25 years. Foot Ankle Int 1994;15:548–51.
[6] Ouzounian T. Triple arthrodesis. Foot Ankle Clin 1996;1:133–50.
[7] Sangeorzan BJ, Smith D, Veith R, Hansen ST. Triple arthrodesis using internal fixation in treatment of adult foot disorders. Clin Orthop 1993;294:299–307.
[8] Wukich DK, Bowen JR. A long-term study of triple arthrodesis for correction of pes cavovarus in Charcot–Marie–Tooth disease. J Pediatr Orthop 1989;9:433–7.
[9] Astion DJ, Deland JT, Otis JC, Kenneally S. Motion of the hind foot after simulated arthrodesis. J Bone Joint Surg Am 1997;79A:241–6.
[10] Chen CH, Huang PJ, Chen TB, Cheng YM. Isolated talonavicular arthrodesis for talonavicular arthritis. Foot Ankle Int 2001;22:633–6.
[11] Andriacchi TP, Andersson GBJ, Fermier RW. A study of lower-limb mechanics during stair-climbing. J Bone Joint Surg 1980;62:749–57.
[12] McFadyen BJ, Winter DA. An integrated biomechanical analysis of normal stair ascent and descent. J Biomech 1988;21:733–44.
[13] Duncan JA, Kowalk DL, Vaughan CL. Six degree of freedom joint power in stair climbing. Gait Posture 1997;5:204–10.
[14] Beischer AD, Brodsky JW, Pollo FE, Peereboom J. Functional outcome and gait analysis after triple or double arthrodesis. Foot Ankle Int 1999;20:545–53.
[15] Lin CJ, Guo LY, Su FC, Chou YL, Cherng RJ. Common abnormal kinetic patterns of the knee in gait in spastic diplegia of cerebral palsy. Gait Posture 2000;11:224–32.