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Functional performance of a total ankle replacement: thorough assessment by combining gait and fluoroscopic analyses

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ABSTRACT

Background: A thorough assessment of patients after total ankle replacement during activity of daily living can provide complete evidence of restored function in the overall lower limbs and replaced ankle. This study analyzes how far a possible restoration of physiological mobility in the replaced ankle can also improve the function of the whole locomotor apparatus.

Methods: Twenty patients implanted with an original three-part ankle prosthesis were analyzed 12 months after surgery during stair climbing and descending. Standard gait analysis and motion tracking of the components by three-dimensional fluoroscopic analysis were performed on the same day using an established protocol and technique, respectively.

Findings: Nearly physiological ankle kinematic, kinetic and electromyography patterns were observed in the contralateral side in both motor activities, whereas these patterns were observed only during stair climbing in the operated side. Particularly, the mean ranges of flexion at the replaced ankle were 13° and 17° during stair climbing and descending, respectively. Corresponding 2.1 and 3.1 mm antero/posterior meniscal-to-tibial translations were correlated with flexion between the two metal components ($p<0.05$). In addition, a larger tibiotalar flexion revealed by fluoroscopic analysis resulted in a physiological hip and knee moment.

Interpretation: The local and global functional performances of these patients were satisfactory, especially during stair climbing. These might be associated to the recovery of physiological kinematics at the replaced ankle, as also shown by the consistent antero/posterior motion of the meniscal bearing, according to the original concepts of this ankle replacement design.

1. Introduction

Remarkable developments have been observed recently in the design of total joint replacements. In particular, following advances in computer design and surgical technique, better performances in locomotion in the operated lower limb and improved function in the replaced joints have been claimed. This is especially true for recent total ankle replacement (TAR) designs, which have enhanced considerably ankle joint function (Gougoulias et al., 2010; Guyer and Richardson, 2008), though ankle arthrodesis is still considered to be the treatment of choice for patients at end-stage ankle arthritis (Haddad et al., 2007; Park and Mroczek, 2011). Unfortunately there is a lack of studies assessing, during daily living activities, the efficacy of TAR. A large number of papers have analyzed different TAR designs but using mostly clinical or radiological results (Gougoulias et al., 2009; Stengel et al., 2005), whereas only a few have reported quantitative measurements of joint and lower limb functions in-vivo. A better possible understanding of the ability of current TAR designs to restore both overall lower limb function and physiological ankle motion might be achieved in combined relevant observations during activities.

A few standard gait analyses (GA) on TAR patients have reported lower limb kinematics, kinetics (Brodsky et al., 2011; Piriou et al., 2008; Valderrabano et al., 2007) and also electromyography (EMG) (Doets et al., 2007; Ingrosso et al., 2009) during level walking. The one from the present authors (Ingrosso et al., 2009) showed a good recovery of the range of ankle flexion and EMG activity, which was earlier than any previous TAR design. At intermediate follow-ups, a near-normal gait and improvements in ankle function were reported in patients after TAR (Brodsky et al., 2011; Doets et al., 2007), which were greater than those after ankle arthrodesis according to the previous literature. However, possible long-term benefits of TAR, such as reduced limp and less stress in the adjacent articulations, have not been established yet (Piriou et al., 2008). GA-based techniques allow functional assessments over a large field of view to support analyses of the whole body, i.e. lower limbs, pelvis and also trunk. However, these kinematics and kinetics measurements are affected by considerable artefacts associated with the skin between the external markers and the internal bones (Leardini et al., 2005), resulting in critical uncertainty for

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determining rotations out of the sagittal plane in particular (Della Croce et al., 2005).

Conversely, accurate joint motion in all three anatomical planes can be obtained with high accuracy by tracking, also in-vivo, the prosthesis components by videofluoroscopy, and relevant 2D-to-3D matching techniques, i.e. three-dimensional fluoroscopic analysis (FA). Kinematics in the replaced joints has been analyzed with this technique in a few studies, mainly to understand whether the claims of the specific TAR designs were really true in patients during locomotor activities (Cenni et al., 2012a, 2012b; Komistek et al., 2000; Leszko et al., 2008; Yamaguchi et al., 2011). These studies reported relative motion of the metal components implanted into the bones, but translation of the polyethylene insert has also been analyzed (Cenni et al., 2012b; Leszko et al., 2008). The latter study (Cenni et al., 2012b) showed the coupling between ankle flexion and antero/posterior translation of the insert, and also the extent to which this coupling could restore the natural position and inclination of the axes of joint rotation. However, these measurements are confined to only a single joint, and require time consuming procedures to obtain the results.

These previous studies, performed either with GA or FA, have provided relevant distinguished findings for TAR, though restricted necessarily by the limitations inherent to these techniques. It is expected that a combination of these two analyses can overcome these limitations and hence also provide considerable improvements in the functional evaluation of TAR, as previously achieved in total knee replacement (Catani et al., 2009; Fantozzi et al., 2003). Such thorough assessment would provide a powerful analysis of both the overall lower limb function and replaced ankle motion in these patients, especially during demanding motor tasks. All previous functional studies on TAR patients were performed during level walking and none during stair climbing and descending, where greater kinematic and kinetic changes are expected to differentiate better functional patterns among different designs and patients (Catani et al., 2003).

This comprehensive functional assessment after TAR is particularly relevant for those designs which claim explicitly enhanced restoration of normal joint kinematics. Such an original design was developed (Leardini et al., 2001, 2004) with the aims of re-establishing the natural compatibility between the shape of the articulating surfaces and retained ligaments and guaranteeing full congruence of the components throughout the flexion arc. These were achieved by the special shape of the metal components and a fully conforming and unconstrained meniscal bearing, expected to move forwards and backwards on both metal components during dorsi- and plantar-flexion, respectively. Preliminary clinical and instrumental results from these patients support somehow these claims (Bianchi et al., 2012; Cenni et al., 2012a, 2012b; Giannini et al., 2010, 2011; Ingrosso et al., 2009). In addition to these, the authors were interested in providing more complete evidence of restored function both in the overall lower limbs and the replaced ankle, which can be obtained respectively by standard GA and FA. In particular, the specific goal of the present study was to assess the extent to which a possible restoration of physiological mobility at the replaced ankle can improve function in the whole locomotor apparatus. This seemed to be better revealed in demanding motor activities, such as stair climbing and descending.

2. Methods

From all the patients implanted in our Institute with the BOX Ankle (Finsbury Orthopaedics, Leatherhead-Surrey, UK) between February 2006 and February 2009, a group of twenty was enrolled in the present study. These were the first twenty who gave informed consent to participate, according to the relevant procedures approved by the local Ethics Committee. A senior orthopaedic surgeon performed all these TAR. Ten patients were treated on the left side and 10 on the right side; 13 patients were men and 7 women; the average age at the time of surgery was 57.8 years (range, 44–67 years). Thirteen patients were treated for post-traumatic osteoarthritis, 5 for inflammatory arthritis and 2 for primary osteoarthritis. Patients were analyzed at a mean of 12 months postoperatively (range, 7–14 months) by standard GA and FA. For both techniques, data were acquired during barefoot stair climbing and descending twice on the same day: first in the Movement Analysis Laboratory for GA and later in the Radiology Department for the FA, in both using a staircase of three 16-cm-high steps without railings. Clinical assessment was performed using the AOFAS clinical score (maximum value 100) (Kitaoka et al., 1994), both preoperatively and at the time of the two motion analyses. The BOX Ankle prosthesis consists of metal tibial and talar components and a polyethylene meniscal bearing instrumented with three tantalum beads in known positions. Relevant operative techniques have been discussed in detail in previous papers (Giannini et al., 2010; Leardini et al., 2004).

GA data were collected during the whole gait cycle of both legs, i.e. operated and contralateral sides, using a stereophotogrammetric system with eight M2-cameras (Vicon 612, Vicon Motion Capture, Oxford, UK) at a sampling rate of 100 Hz, two dynamometric platforms (Kistler Instruments, Einterthur, Switzerland) and an EMG system (ZeroWire, Aurion, Milan, Italy) at 2000 Hz. An established protocol for lower limb joint kinematics and kinetics was used (Leardini et al., 2007), consistent with ISB recommendations (Wu et al., 2002). Twenty markers were attached to anatomical landmarks on the pelvis and the lower limbs; anatomical landmark calibration via six additional markers, on the two medial epicondyles, medial malleoli, and second metatarsal heads, was performed in a supplementary single static acquisition. Internal joint moments were calculated as the vector product of the position vector of the joint centre and the ground reaction force considering the staircase steps as rigid bodies; for these moments, the relevant anatomical components were taken as those projected in the three axes of the joint coordinate system (Grood and Suntay, 1983). Surface dynamic EMG data were recorded simultaneously (ZeroWire, Aurion, Milan, Italy) from four muscles of each leg: biceps femoris, rectus femoris, gastrocnemius and tibialis anterior. These signals were processed using a specific computer program developed in Matlab (The Mathworks Inc., Natick, MA, USA), to obtain on–off patterns of muscle activity over the gait cycle (Benedetti et al., 2003). In addition, to quantify the amount of co-contraction between on–off patterns of agonist (mA) and antagonist muscles (mB) of knee and ankle joints, an original index, i.e. the trial-index in Eq. (1), was used, similar to that proposed by Doorenbosch and Harlaar (2003). This ranges between 0, total absence of co-contraction, to 1, total presence of co-contraction, and applies to the knee and ankle joints, and the two lower limbs.

$$\text{trial index} = \frac{\sum_{t=1}^{100} |mA - mB|}{\sum_{t=1}^{100} mA + \sum_{t=1}^{100} mB} \tag{1}$$

The co-contraction was also assessed as calculated for each sample of each gait cycle, this being 1 only for On-patterns both in the agonist and antagonist muscles (Fig. 3). A minimum of three trials including each a full right and a full left leg gait cycle were collected at natural speed.

A single fluoroscopic image in up-right posture, with the replaced ankle assumed to be in the neutral joint position, was acquired together with image sequences during stair climbing and descending by means of a standard fluoroscope (digital remote-controlled diagnostic Alpha90SX16, CAT Medical System, Rome, Italy) at 10 Hz. In the sequences, care was taken to position the fluoroscopic field of view to enable collection of the largest possible number of images of the replaced ankle joint. For these tasks, only a part of the stance phase at the staircase, i.e. from flat-foot to heel-off, was collected. At each image collection session, a grid of small tantalum beads, a ruler of known length and a 3D cage with beads in known positions were collected for

Table 1
Mean (standard deviation) of spatial–temporal parameters in the operated and contralateral sides during stair climbing and descending, together with relevant statistical values (in bold significant values).

		Stair climbing			Stair descending		
	Unit	Operated side	Controlateral side	Paired t-test	Operated side	Controlateral side	Paired t-test
Stance	[% gait cycle]	66.4 (5.8)	66.9 (4.3)	0.667	61.4 (4.1)	66.1 (3.6)	**0.000**
Swing	[% gait cycle]	33.6 (5.8)	33.1 (4.3)	0.667	38.6 (4.1)	33.6 (3.6)	**0.000**
Velocity	[cm/s]	32.5 (10.4)	32.4 (8.4)	0.572	44.5 (10.5)	46.6 (14.0)	0.604
Stride length	[cm]	55.6 (15.1)	57.0 (15.4)	0.995	70.0 (11.5)	68.0 (13.1)	0.635

image distortion correction (Fantozzi et al., 2003). Tibial and talar component reference frames were defined onto corresponding CAD models according to the three anatomical directions, that of the insert was defined by using the 3D coordinates of the tantalum beads (Cenni et al., 2012b). According to an established technique (Banks and Hodge, 1996), 3D position and orientation of the three prosthesis components were calculated by a semi-automatic 2D-to-3D matching procedure which achieves the best possible final pose estimation (nominal accuracy 0.5 mm/1.0°) between the projection of the 3D CAD model of the component and the silhouette of this component in the fluoroscopic image. Dorsi/plantar flexion, inversion/eversion and internal/external rotation, in the sagittal, frontal and transverse planes respectively, with respect to the tibia, as well as antero/posterior (A/P) translation of the meniscal and talar components, were all expressed according to the same standard joint convention of GA (Grood and Suntay, 1983). A/P translation was calculated for the centroid of the bead cluster in the reference frame of both the tibial and talar components, normalized with the corresponding position obtained from the image in up-right posture.

Statistical analysis was performed using the *t*-test for paired samples where variance was comparable, and the Wilcoxon test where the Levene test had given significant results in terms of variance difference. The Pearson product-moment correlation coefficient (R) was also calculated, and here reported in its squared form, i.e. as coefficient of determination (R^2). Corresponding p-values are reported for assessing the significance of these correlations. For each statistical test, p-values <0.05 were considered significant. All calculations were made using the Matlab software tool (The Mathworks Inc., Natick, MA, USA).

3. Results

3.1. Clinical results

Satisfactory clinical results were found after surgery; the mean AOFAS total score increased from 44.1 (standard deviation — SD 18.4, range 20–68) preoperatively to 75.9 (SD 11.0, range 55–92) at the follow-up. In particular, preoperative AOFAS function, pain relief and alignment were 14.2, 25.9 and 6.3 respectively, and became 29.8, 37.1 and 9.0 at the follow-up. The mean clinical range of motion for the ankle complex increased from 19.7° (SD 10.2°, range 0–30) preoperatively to 28.8° (SD 11.3°, range 10–50) at the follow-up.

3.2. Gait analysis

Similar spatial–temporal parameters were observed in the two legs in both tasks, although in the stair descending task a statistically significant lower stance phase duration was observed in the operated side with respect to the contralateral side (Table 1). Kinematic and kinetic parameters for the hip and knee joints showed several differences between the two legs (Table 2). At the hip, a significant nearly 8° greater range of flexion was observed in the operated side with respect to the contralateral one; at the knee, different maximum extension moments in both tasks, maximum abduction moment in climbing, maximum adduction moment in descending, and flexion at maximum flexion moment in climbing were observed. Nearly physiological (Protopapadaki et al., 2007) ankle kinematic and kinetic patterns were observed in the contralateral side in both motor activities (Fig. 1); in the operated side, this was

Table 2
Mean (standard deviation) of the hip and knee joint kinematic and kinetics parameters measured by GA, in the operated and contralateral sides during stair climbing and descending, together with relevant statistical values (in bold significant values).

		Stair climbing				Stair descending			
	Unit	Operated side	Contralateral side	Paired t-test	Wilcoxon test	Operated side	Contralateral side	Paired t-test	Wilcoxon test
Hip kinematics and kinetics									
Range of flexion–extension in stance	[Deg]	57.5 (4.0)	50.3 (7.5)		**0.008**	24.7 (5.3)	17.1 (4.5)	**0.000**	
Flexion at heel contact	[Deg]	63.9 (9.9)	57.8 (7.5)	0.088		18.8 (5.3)	17.1 (4.5)	0.469	
Max extension moment	[% BW*h]	7.5 (1.4)	6.3 (1.1)	**0.011**		3.6 (1.3)	6.9 (6.3)	0.306	
Max flexion moment	[% BW*h]	−1.0 (1.2)	−0.9 (0.7)	0.537		−1.7 (1.0)	−3.2 (2.9)		**0.026**
Max abduction moment	[% BW*h]	5.4 (1.2)	6.1 (1.5)	0.144		5.4 (1.0)	9.2 (5.6)	**0.012**	
Max adduction moment	[% BW*h]	−0.9 (0.4)	−1.0 (0.3)	0.165		−1.5 (1.2)	−2.6 (2.0)		**0.001**
Max extrarotation moment	[% BW*h]	0.6 (0.2)	0.5 (0.3)	0.085		0.5 (0.4)	0.4 (0.3)	0.286	
Max intrarotation moment	[% BW*h]	−0.8 (0.4)	−2.0 (0.6)	**0.000**		−1.4 (0.5)	−1.8 (0.5)	**0.014**	
Flexion angle at max. flexion moment	[Deg]	52.1 (9.8)	50.8 (10.9)	0.317		18.5 (6.3)	20.5 (8.2)	0.288	
Knee kinematics and kinetics									
Range of flexion–extension in stance	[Deg]	55.6 (6.1)	55.6 (4.6)	0.477		79.7 (7.7)	76.4 (5.6)	0.098	
Flexion at heel contact	[Deg]	57.1 (5.5)	59.3 (14.8)	0.419		10.5 (3.5)	8.1 (4.2)	0.399	
Max extension moment	[% BW*h]	1.7 (1.0)	5.3 (1.8)	**0.000**		5.2 (1.8)	7.4 (2.2)	**0.002**	
Max flexion moment	[% BW*h]	−3.4 (1.6)	−3.1 (1.5)		**0.000**	−2.2 (1.3)	−3.6 (2.9)	0.086	
Max abduction moment	[% BW*h]	2.3 (0.7)	3.4 (1.3)	**0.000**		2.7 (0.6)	4.7 (3.9)	0.036	
Max adduction moment	[% BW*h]	−0.8 (0.4)	−1.0 (0.5)		**0.001**	−0.9 (0.5)	−2.0 (1.2)		**0.003**
Max extrarotation moment	[% BW*h]	0.5 (0.2)	0.8 (0.2)	**0.002**		0.9 (0.4)	1.1 (1.1)	0.440	
Max intrarotation moment	[% BW*h]	−0.2 (0.2)	−0.3 (0.2)		**0.005**	−0.4 (0.6)	−0.5 (0.3)		0.766
Flexion angle at max. flexion moment	[Deg]	43.3 (8.4)	54.6 (4.6)		**0.001**	58.3 (14.6)	56.0 (11.3)	0.589	

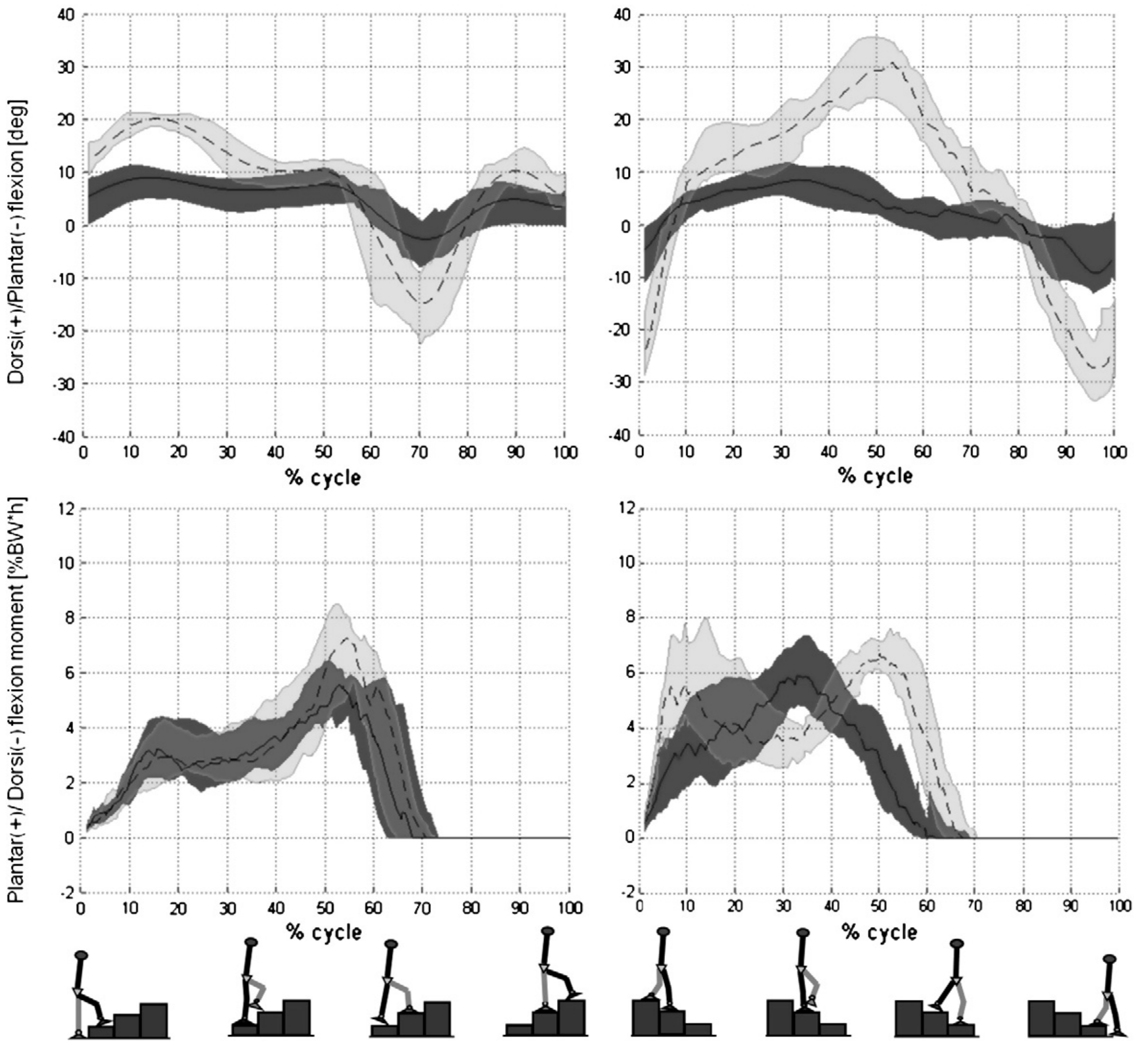

Fig. 1. Ankle flexion (top) and flexion moment (bottom) over the stair cycles from all patients, in the operated (dark gray band) and contralateral (gray band) sides, during stair climbing (left) and descending (right). The bands represent the 25–75 percentile, whereas the solid and dashed lines represent the medians of the operated and contralateral sides, respectively.

true only during stair climbing. In stair descending, much smaller flexion peaks were observed in the operated ankle, and a monophasic flexion moment was also observed, which compares unwell with the biphasic moment of the contralateral ankle. This resulted in a significant smaller range of flexion at the replaced joint and significant differences in other ankle kinematic and kinetic parameters (Table 3).

Table 3
Mean (standard deviation) of the ankle joint kinematic and kinetic parameters measured by GA, in the operated and contralateral side during stair climbing and descending, together with relevant statistical values (in bold significant values).

	Unit	Stair climbing				Stair descending			
		Operated side	Contralateral side	Paired t-test	Wilcoxon test	Operated side	Contralateral side	Paired t-test	Wilcoxon test
Ankle kinematics and kinetics									
Range of flexion–extension in stance	[Deg]	13.4 (5.6)	38.9 (6.7)	**0.000**		16.6 (5.9)	56.2 (11.2)		**0.000**
Flexion at heel contact	[Deg]	5.0 (4.7)	11.6 (5.2)	**0.001**		−6.4 (6.7)	−25.4 (9.1)	**0.000**	
Inversion–eversion ROM	[Deg]	10.3 (3.1)	15.1 (3.6)	**0.000**		12.5 (4.1)	18.0 (4.5)	**0.000**	
Abduction–adduction ROM	[Deg]	10.4 (4.3)	18.7 (7.0)	**0.000**		13.4 (4.6)	18.7 (5.5)	**0.003**	
Max dorsiflexion	[Deg]	9.6 (4.6)	21.2 (2.8)	**0.000**		9.8 (5.4)	30.8 (6.7)	**0.000**	
Max plantarflexion	[Deg]	−3.7 (5.2)	−17.7 (7.5)	**0.000**		−6.7 (6.2)	−25.4 (9.1)	**0.000**	
Max plantarflexion moment	[% BW*h]	6.1 (1.4)	7.8 (1.4)	**0.000**		6.5 (1.4)	8.0 (1.5)	**0.002**	
Max dorsiflexion moment	[% BW*h]	−0.1 (0.2)	−0.2 (0.2)	0.518		−0.4 (0.4)	−0.7 (1.2)	0.324	
Max eversion moment	[% BW*h]	1.1 (0.3)	1.4 (0.5)	0.746		1.6 (0.5)	1.8 (1.1)	0.474	
Max inversion moment	[% BW*h]	−0.1 (0.1)	−0.1 (0.1)	0.954		−0.3 (0.6)	−0.3 (0.3)	0.874	
Max abduction moment	[% BW*h]	1.1 (0.7)	2.0 (0.9)		**0.006**	1.7 (0.6)	2.8 (2.9)		0.275
Max adduction moment	[% BW*h]	−0.3 (0.2)	−0.23 (0.2)	0.936		−0.4 (0.2)	−0.6 (0.5)		0.651
Plantar angle at max plantar moment	[Deg]	6.8 (5.0)	8.2 (4.3)	0.602		10.1 (6.5)	21.8 (10.4)	**0.000**	

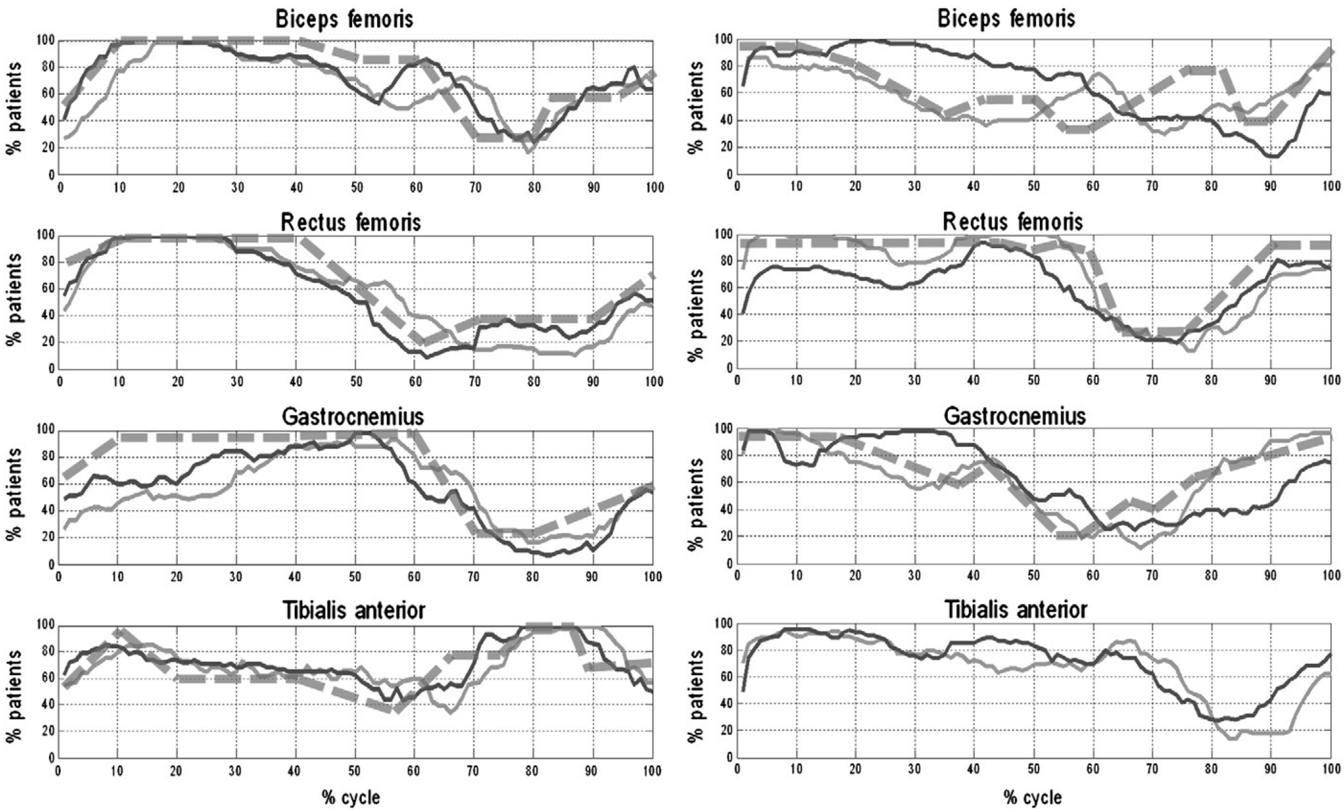

Fig. 2. Patterns of mean muscular activity in the operated (dark gray line) and contralateral (gray line) sides, during stair climbing (left) and descending (right), in the form of on–off muscle timing in percentage over patients, i.e. the percentage at each sample of the gait cycle of patient trials with the muscle activated. This is shown for the biceps femoris, rectus femoris, gastrocnemius and tibialis anterior, and with relevant control data (dashed lines) from a previous paper (Catani et al., 2003) superimposed.

On average over patients, EMG analysis showed similar activation patterns between the two legs (Fig. 2), and also consistency with a control group, from a previous paper during stair climbing and descending (Catani et al., 2003). However, restoration of the alternate activity between tibialis anterior and gastrocnemius was better during stair climbing than it was during stair descending. For the latter, only the contralateral side showed nearly the same patterns of a control group (Catani et al., 2003). This was also reflected in the co-contraction values between agonist and antagonist muscles of thigh and shank, with the largest difference being during mid-stance (Fig. 3). During stair climbing, the mean trail indexes for the knee joints were 0.69 (SD 0.12) in the operated side and 0.65 (SD 0.13) and the contralateral side, whereas for the ankles they were 0.48 (SD 0.21) and 0.49 (SD 0.17), respectively. In stair descending, these indexes for the knee joints became 0.63 (SD 0.21) and 0.62 (SD 0.27), and 0.63 (SD 0.20) and 0.58 (SD 0.16) for the ankles, respectively.

3.3. Fluoroscopic analysis

Consistent and smoothed paths of motion for tibiotalar flexion at the replaced joint and relevant A/P translations of the meniscal bearing were also observed during stair climbing and descending (Fig. 4). The largest range of motion of tibiotalar rotations was found in the sagittal plane, though mobility occurred also in out-sagittal planes, with peaks of about 8° in the frontal and transverse planes. Particularly, during stair climbing and descending, the mean ranges in the replaced joint were 4.0° (SD 2.1°, range 1.1°–7.4°) and 7.8° (SD 3.8°, range 2.5°–17.6°) in flexion, 1.2° (SD 0.8°, range 0.2°–2.9°) and 2.2° (SD 1.9°, range 0.1°–7.6°) in inversion/eversion, and 1.4° (SD 1.3°, range 0.2°–4.8°) and 2.1° (SD 1.9°, range 0.2°–7.5°) in internal/external rotation, respectively. The corresponding A/P translation of the meniscus was 2.1 (SD 1.7, range 0.5–4.5) and 3.1 (SD 1.4, range 0.9–5.2) mm with respect to the tibia, and 2.7 (SD 1.4, range 0.9–5.7) and 4.9 (SD 2.5, range 1.9–10.2) mm with respect to the talar components. Larger tibiotalar flexion was observed in ankles with larger meniscal-to-tibial translation ($p < 0.05$).

3.4. Correlations

In all patients, a similar pattern of ankle flexion in the stance phase was found using the two techniques; in particular, ankle complex rotation in the sagittal plane from GA and tibiotalar flexion between the two metal components from FA showed nearly the same pattern and a similar range, albeit with a biased difference (Fig. 4). In both motor activities, a statistically significant correlation was observed between the range of ankle flexion from GA and FA ($R^2 > 0.25$ and $P = 0.04$ in both cases). In addition, a larger range of ankle flexion from GA was found also in those replaced ankles with larger meniscal-to-talar ($R^2 > 0.22$, $P = 0.05$) and meniscal-to-tibial ($R^2 > 0.15$, $P = 0.10$) translations, although the latter was without statistical significance. In the stair climbing task, a larger range of tibiotalar flexion was revealed by FA in patients with a larger dorsiflexion at foot strike ($R^2 = 0.41$, $P = 0.005$). In addition, a larger tibiotalar flexion measured using FA resulted in a physiological hip and knee moment, i.e. a decrease and an increase in the maximum extension moment found using GA, although only the latter showed statistical significance ($R^2 = 0.22$, $P = 0.05$). No statistically significant correlation was found between flexion ranges at the hip and at the homolateral replaced ankle, though the former was observed larger when the latter was smaller. As for EMG data, a lower co-contraction index was

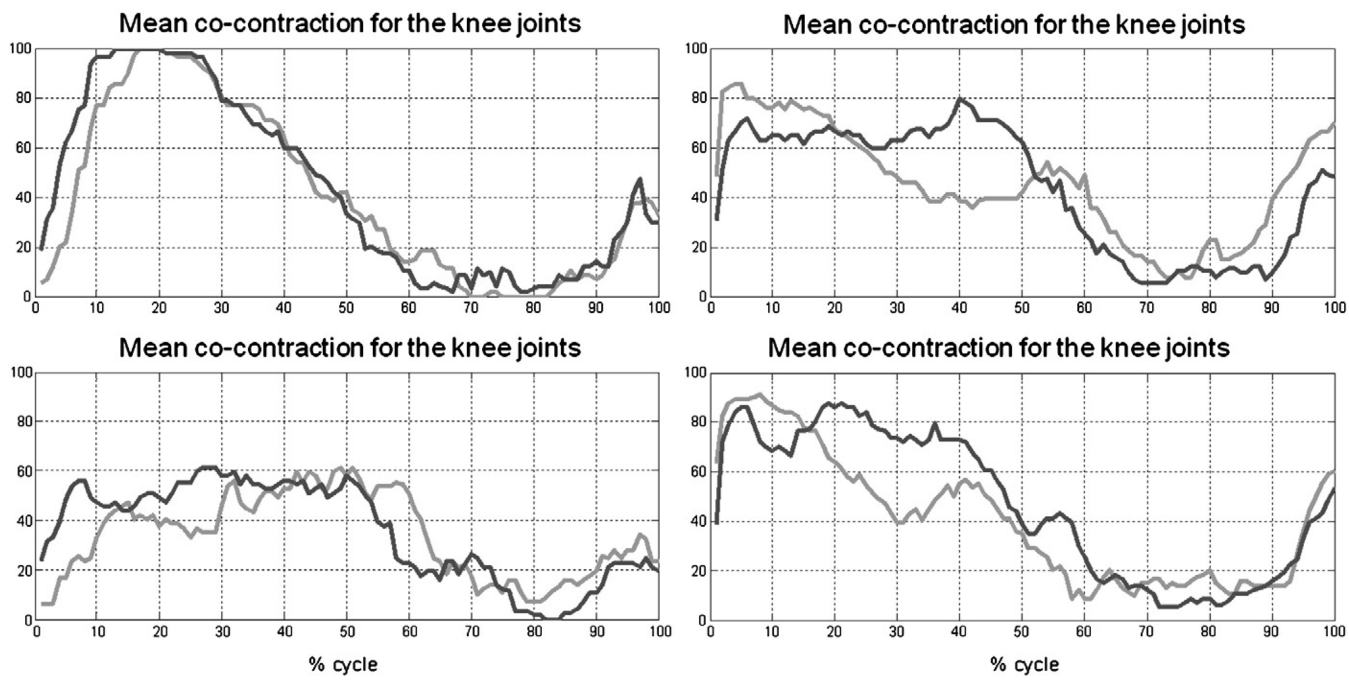

Fig. 3. Patterns of co-contraction muscular activity in the operated (dark gray line) and contralateral (gray line) sides. These were calculated at the knee joint level (top), i.e. biceps femoris and rectus femoris, and at the ankle (bottom), i.e. gastrocnemius and tibialis anterior, at each sample of the gait cycle, during stair climbing (left) and descending (right).

observed in replaced ankles with greater range of flexion found by GA ($R^2 = 0.31$, $P < 0.01$ in both motor activities); this was not true for the contralateral side.

4. Discussion

Recently, TAR is becoming very popular in the treatment of severe ankle arthritis, although clinical and functional results are not as satisfactory as those of total hip and knee replacements. In-depth investigations in-vivo on patients can be very useful to obtain the actual residual function after TAR. In the present study, a cohort of twenty patients treated with an original TAR design was analyzed by combined measurements of standard full body GA together with the modern joint-specific FA. The study revealed first of all the feasibility of this combined approach also for TAR, reported here in the literature for the first time. Furthermore, this combination was able to demonstrate the complex functional recovery in the replaced ankle; particularly, a larger motion was found in those ankles with a larger meniscal translation, according to the original claims of the designers of this TAR (Leardini et al., 2001, 2004). In addition, by looking at the other main joints of the lower limbs, a compensatory larger hip sagittal motion was found in the operated side probably due for the smaller motion at the replaced ankle. Comparisons were made with the contralateral side due to the paucity of relevant control data from the literature and a specific reference to the patients analyzed. The results supported the consistency in patients of this choice for the comparison.

There are however a number of limitations in the present study. Ankle joint kinematics in GA is intended as the gross motion of the entire foot with respect to the shank, and the exact relative motion between the calcaneus, or the talus, and the tibia and fibula is lost. The joint moments were calculated by using the ground reaction force method, which is very suitable for slow gait but increasingly critical for higher velocities and impacts. It is expected therefore that the errors associated with the assumption of null gravitational and inertial factors are amplified when considering stair gait (Whatling et al., 2009). However, the discrepancies among these different methods with respect to progress have not been established, and anyhow not very active patients were analyzed in the present study. We also did not use a control group, but the contralateral leg was used for the measurement comparisons; the function of this leg might be been affected by compensatory mechanisms, but the patterns of joint rotation and moment observed were similar to those on healthy subjects (Protopapadaki et al., 2007). In FA, the images were acquired, and the analysis then performed, only on the replaced ankle joint and for a limited part of the gait cycle; the former for reducing radiation exposure to the patients, the latter due to a fixed position and the small field of view of the fluoroscope. The interval of the stance phase from flat-foot to heel-off was chosen eventually, because it was the largest time period common to all patients analyzed. This also resulted in a small range of flexion for the ankle joint. GA and FA were not recorded simultaneously, although these data acquisitions were performed in very similar conditions, in the same building and at only one hour apart maximum. Post-processing synchronization between the two measuring techniques was easily completed. Finally, it turned out that patients enrolled in the present study had a slightly smaller AOFAS score with respect to that of previous series for the present TAR (Bianchi et al., 2012; Giannini et al., 2010, 2011); the present mean follow-up was however shorter, and therefore further functional progress is expected for the present patients.

To the authors' knowledge, this is the first GA study performed in TAR patients during stair climbing and descending. Despite these very demanding motor activities, traditionally critical for TAR patients, functional assessment by instrumental analysis revealed satisfactory findings. Nearly physiological motion was observed in the main joints by comparison between operated and contralateral lower limbs. This was true for both motor activities, although more normal kinematic and kinetic patterns were found during stair climbing than for stair descending. In fact, in the latter task, a shorter stance phase was found in operated than in the contralateral one (Table 1). However, definitely a smaller range of flexion at the replaced ankle than at the contralateral side was observed in both motor activities (Table 3). This difference is however typical of TAR patients, and can be accounted for many causes, including the frontal scar, the likely soft tissue contractures due to

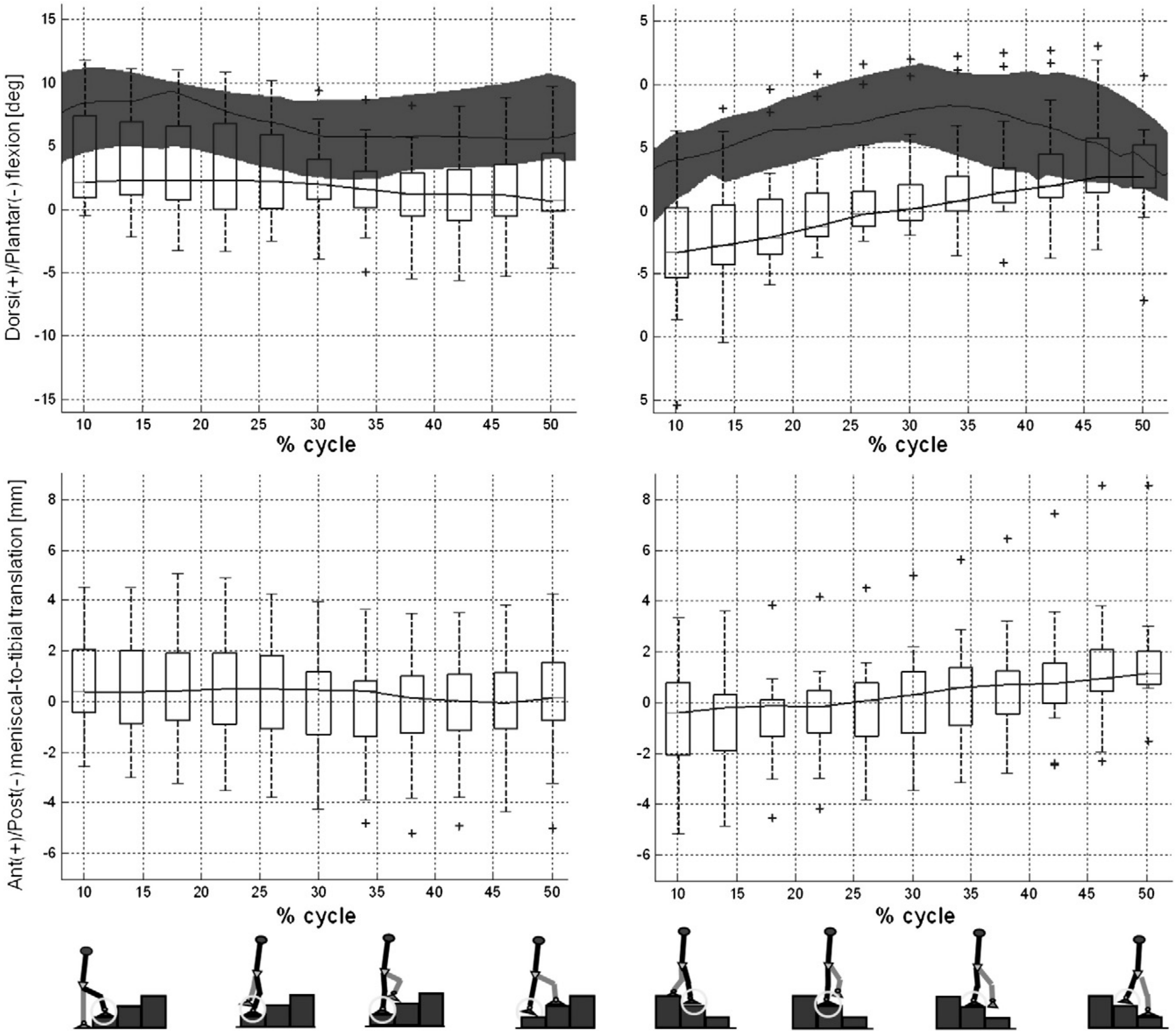

Fig. 4. Dorsi(+)/plantar(−) flexion (top) and antero(+)/posterior(−) A/P meniscal-to-tibial translation (bottom) over a part of the gait cycle, i.e. from flat foot on the stair to toe-off from that stair, during stair climbing (left) and descending (right), are shown as means over all patients measured by FA. In each plot, the boxes have lines at the lower, median, and upper quartile values corresponding to the sampling values of gait cycle; the whisker lines extending from each end of the box show the extent of the rest of the data; outliers are reported beyond the ends of the whiskers. In addition, the corresponding replaced ankle kinematics measured by GA is superimposed with graphical representation as in Fig. 1.

trauma, since 13 out of our 20 patients were affected by post-traumatic osteoarthritis, and the motor tasks here analyzed, more stability than mobility demanding. In addition to these, it is important to emphasize that the clinical range of motion for these patients was much larger, about 29° on average, than that measured during these activities. The fact that these patients do not exploit fully their achievable mobility can be worth for further investigation, but a few observations can be pointed out from the present results. The overall results, including orientation in space of the foot and shank segments, showed that the heel-strike in the replaced ankle occurred with a nearly flat-foot; this must imply a greater stiffness of the joint, and results in the absence of a loading response (Fig. 1). In stair descending, these deductions are also supported by an abnormal ankle flexion moment with a monophasic pattern, unlike the contralateral and physiological ankles (Protopapadaki et al., 2007) which showed two peaks of plantarflexion moment in the early and late stance phase (Fig. 1). Further consistent evidence is shown by EMG, where a prolonged contraction of the gastrocnemius during the mid-stance and a larger co-contraction trial-index were found in replaced ankles with a lower range of dorsiflexion. Conversely, in stair climbing, a nearly physiological pattern of flexion moment and muscle activation was also found in the replaced ankle. Nevertheless, it is important to note that in TAR patients even a small gain for the range of ankle flexion can be valuable for improving the overall lower limbs function.

The GA of the entire lower limbs revealed interesting compensation mechanisms at the hip and knee joints of the operated side. Particularly in the former, there was a larger mean flexion range compared to that of the contralateral, and also a trend for ankles with lower range of motion to be combined with hips with a larger flexion range, although not significant. This compensatory effect seems necessary even in those replaced ankles where a satisfactory flexion range is obtained, i.e. about 13° and 17° in stair climbing and descending respectively, and it is therefore expected to be greater in lower limbs with ankle arthrodesis, as reported in a recent study, although performed during level walking (Hahn et al., 2012). Conversely, the difference between range of flexion in the operated and contralateral sides was found to be very small in the knee joint. Eventually, compensation mechanisms for the replaced ankle might have been experienced at the hip for the kinematic measurements and in the knee for the kinetics. Apparently, an opposite effect can occur in patients with total hip replacement (Lamontagne et al., 2011).

Stiff walking in stair descending was observed somehow also with FA. In fact, rotations in the three anatomical planes between the talar and tibial components were large, although they were smaller than those found in a previous similar study (Cenni et al., 2012b) where, however, another motor task was analyzed. But it is not clear whether the observed range of tibiotalar flexion is the maximum achievable at these replaced ankles, or this limited flexion with respect to the clinical range, about 25°, might be due to the lack of confidence in performing these tasks, especially because these stairs were without railings. Despite the stiff ankle patterns and the limited range of flexion, a considerable A/P translation of the meniscal bearing with respect to the tibia was observed coupled with dorsi- and plantar-flexion, supporting further, during these weightbearing activities, the mathematical model predictions by the designers of this TAR (Leardini et al., 2001) and previous in-vivo measurements (Cenni et al., 2012a, 2012b; Giannini et al., 2010).

Additional valuable information can be obtained by combining the separate observations from the GA- and FA-based measurements. First of all, consistent patterns were found from superimpositions of similar variables from the two techniques, in particular ankle flexion during the stance phase (Fig. 4), where the bias between the curves can be accounted to also for the different reference frames. The different segments analyzed for ankle motion, i.e. the entire foot and talus respectively, were considered, which might also justify the slight time delay between the two patterns, dorsiflexion of the entire foot, measured by GA, occurring probably long before that of the replaced talus, measured by FA, in the same tibial reference frame. It was however found that at least a quarter ($R^2 > 0.25$, see Results) of the variability for the range of flexion of the metal components (from FA) is accounted for the range of flexion in the entire ankle complex (from GA). As expected, the latter was found to be directly correlated also with A/P motion of the meniscal bearing (FA). Interestingly, a larger flexion of the metal components (FA) implied hip and knee extension moments in the operated side more similar to those in the contralateral side, thus a more symmetrical locomotion is obtained. However, all significant correlations here reported account only for a part of the variability, R^2 being found always smaller than 0.41.

In conclusion, the present combined approach for functional assessment enabled the known limitations inherent to the two techniques utilized separately to be overcome and provided synergic information largely beyond what is usually obtained by either technique alone (Fantozzi et al., 2003). GA reports 3D rotations, for a number of joints from both legs and together with ground reaction forces, joint moments and muscle activity, but it is limited by the skin motion artifacts which affects critically any marker position measurement. FA reconstructs joint rotations and translations with high accuracy, for the metal components as well as the polyethylene insert, but these are confined within a single joint. The double picture is particularly important in TAR, where a single small joint is treated to restore joint function and overall normal locomotion patterns. Despite the demanding motor activities here analyzed, the functional results of the present replaced ankles were satisfactory, especially during stair climbing. In addition, we found an increase of hip motion in the operated side, which can possibly have clinic implications. These results might be associated with the recovery of physiological kinematics at the replaced ankle, supported also by the consistent antero/posterior motion of the meniscal bearing, according to the original concepts of this TAR design. All this was achieved at an early follow-up, but should be assessed again at mid- and long-term.

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