■ FOOT AND ANKLE

Ground-reactive forces after hallux valgus surgery

COMPARISON OF SCARF OSTEOTOMY AND ARTHRODESIS OF THE FIRST METATARSOPHALANGEAL JOINT

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Aims

The purpose of this study was to analyse the biomechanics of walking, through the ground reaction forces (GRF) measured, after first metatarsal osteotomy or metatarsophalangeal joint (MTP) arthrodesis.

Patients and Methods

A total of 19 patients underwent a Scarf osteotomy (50.3 years, standard deviation (SD) 12.3) and 18 underwent an arthrodesis (56.2 years, SD 6.5). Clinical and radiographical data as well as the American Orthopaedic Foot and Ankle Society (AOFAS) scores were determined. GRF were measured using an instrumented treadmill. A two-way model of analysis of variance (ANOVA) was used to determine the effects of surgery on biomechanical parameters of walking, particularly propulsion.

Results

Epidemiological, radiographical and clinical data were comparable in the two groups and better restoration of propulsive function was found after osteotomy as shown by ANOVA (two way: surgery × foot) with a surgery effect on vertical forces ($p < 0.01$) and a foot effect on anteroposterior impulse ($p = 0.01$).

Conclusion

Patients who underwent Scarf osteotomy had a gait pattern similar to that of their non-operated foot, whereas those who underwent arthrodesis of the first (metatarsophalangeal) MTP joint did not totally recover the propulsive forces of the forefoot.

Take home message: The main findings of this study were that after surgical correction for hallux valgus, patients who underwent scarf osteotomy had a gait pattern similar to that of their non-operated foot in terms of forefoot propulsive forces (Fz3, Iy2), whereas those who underwent arthrodesis of the first MTP joint had not.

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During walking, two thirds of plantar pressure occurs under the hallux and the first and second metatarsal heads especially during the late stance phase of gait.[1,2] The ground reaction forces (GRF) generated during walking contribute to shifting the centre of mass and moving the entire body. A greater knowledge of GRF would help in understanding the various musculoskeletal conditions that affect the foot and also could enhance surgical outcomes.

In patients with hallux valgus (HV), foot pressure distribution studies have shown that incomplete load bearing of the hallux and load transfer to the lateral rays of the foot could lead to metatarsalgia.[1,3-6] Moreover, kinematics of the first metatarsophalangeal (MTP) joint are altered in patients with HV because the joint is pronated, leading to reduction in the force-generating capacity of the plantar flexors of the foot. In this situation the hallux loses its propulsive function and the loading parameters in the forefoot are reduced.[7] Grundy et al[8] highlighted the differences in GRF patterns during walking between healthy individuals and those suffering from HV and metatarsalgia. In HV patients, following the first vertical peak force at touch-down, the centre of mass slowly shifts to just in front of the heel. Forces are not transferred forward and then the centre of pressure is only briefly located at the metatarsal heads. Galois et al[9] recorded the GRF after first MTP arthrodesis using a force platform and they found that the propulsive function in both the sagittal and vertical planes was significantly reduced.

Table I. Patients' characteristics, joint mobility, American Orthopaedic Foot and Ankle Society (AOFAS) score and radiographical values before and after surgery

	Osteotomy	Arthrodesis	p-value (*t*-test)
n	19	18	
Women/men	17/2	12/6	
Age (yrs)	50.3 (12.3)	56.2 (6.5)	NS
Mean time after surgery (mths)	10.6 (6.8)	14.1(6.6)	NS
Right/left	10/9	8/10	
Mass (kg)	62.9 (33.9)	76.6 (39.8)	0.007
AOFAS score /100	83.5 (8.8)	76.1 (10.2)	0.02
pain score /40	35.3 (7.0)	33.9 (7.8)	NS
functional score (including MTP movement) /45	33.6 (4.7)	27.6 (3.8)	< 0.001
alignment score /15	14.3 (1.6)	14.6 (1.7)	NS
AOFAS excluding MTP motion /85	78.0 (8.6)	76.1 (10.2)	NS
Mobility of MTP (°)	51.0° (20.0°)	0.0° (0.0°)	< 0.001
Mobility of IP (°)	55.3° (16.5°)	54.7° (11.2°)	NS
Pre-operative M1–M2 angle (°)	11.5° (2.1°)	12.1° (5.5°)	NS
Pre-operative M1–P1 angle (°)	28.0° (9.2°)	27.0° (12.9°)	NS
Pre-operative M1–M5 angle (°)	30.6° (7.6°)	29.1° (5.8°)	NS
Post-operative M1–M2 angle (°)	5.4° (4.1°)	8.7° (2.7°)	0.01
Post-operative M1–P1 angle (°)	10.5° (8°)	13.9° (7.1°)	NS
Post-operative M1–M5 angle (°)	18.6° (6.9°)	24.4° (4.3°)	0.008

Values are presented as mean (standard deviation)
MTP, metatarsophalangeal joint; IP, interphalangeal joint; M, metatarsal; P, phalangeal; NS, not significant

Surgical correction of HV deformity yields good to excellent outcomes in terms of anatomical alignment.[10,11] However, functional weight-bearing of the hallux is not properly restored, no matter which surgical technique is used; osteotomy[2,10,12,13] or arthrodesis.[6] GRF analysis using an instrumented treadmill after HV surgery has not previously been reported. Comparison of the biomechanical effects of various methods of treatment for foot disorders, as advocated by Grundy et al[8] has never been performed.

We hypothesised that GRF are modified, particularly during the push-off phase, in patients who undergo HV surgery. The purpose of this study was to analyse the GRF using an instrumented treadmill following surgery for HV and to compare the results of first metatarsal osteotomy or MTP arthrodesis with the non-operated feet.

Patients and Methods

This was a cross-sectional study. The patients gave their informed consent and the study was approved by the local healthcare facility.

Patients under the age of 65 years who underwent surgical correction for a HV deformity (osteotomy or MTP joint arthrodesis) were included. The surgical technique was determined by the surgeon depending on the patient's history, clinical examination and imaging. Patients were reviewed at a minimum of six months post-operatively and had to be pain-free and able to walk normally without walking aids or assistance.

Patients were excluded from the study if they had undergone previous surgery to their foot. Patients with other symptoms such as pain or discomfort, which affected either the injured or the contralateral lower limb, or who had undergone lower limb or spinal surgery, were also excluded. Patients who had evidence of nonunion, secondary displacement, insufficient correction, or persistent symptomatic malalignment were also excluded from the study.

In all 37 patients were included in this study. A total of 19 patients had undergone a Scarf osteotomy[14] (the osteotomy group), 18 patients had undergone MTP joint arthrodesis[15] and were included in the arthrodesis group Patient characteristics are reported in Table I.

Surgical procedure. A Scarf osteotomy of the first metatarsal was combined with an Akin osteotomy of the first proximal phalanx,[16] which were stabilised using interfragmentary screws. Arthrodesis of the first MTP joint was performed on plane or concave–convex cuts with 10° of valgus and dorsiflexion. Stabilisation for arthrodesis was achieved by means of plates or staples depending on the surgeon's preferences. Weight-bearing was permitted on the first post-operative day with support of a stiff-soled shoe. Normal fitting shoes were allowed six weeks following surgery.

Evaluation procedure. Standard clinical data were collected pre- and post-operatively and at the last follow-up. Pain, function and alignment were assessed using the American Orthopaedic Foot and Ankle Society (AOFAS) Hallux Metatarsophalangeal–Interphalangeal scale.[17] Range of movement at the MTP and interphalangeal joints were measured by a single independent observer using a goniometer. Pre- and post-operative radiographs were measured on

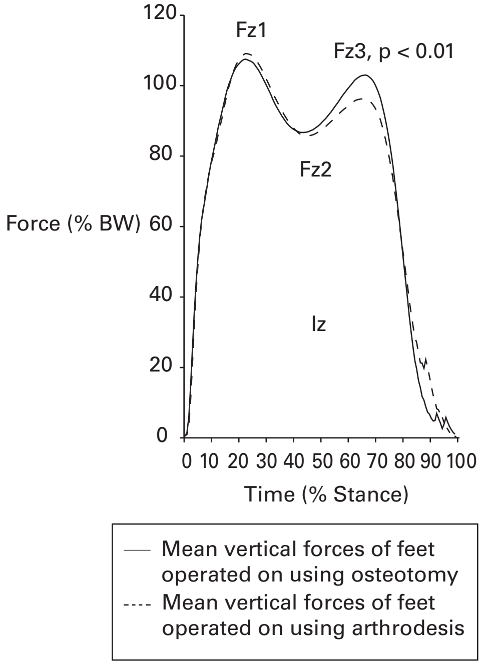

Fig. 1

Graph showing the mean vertical ground reaction forces. Fz, maximum peak force; Iz, impulse, force-time integral; BW, body weight.

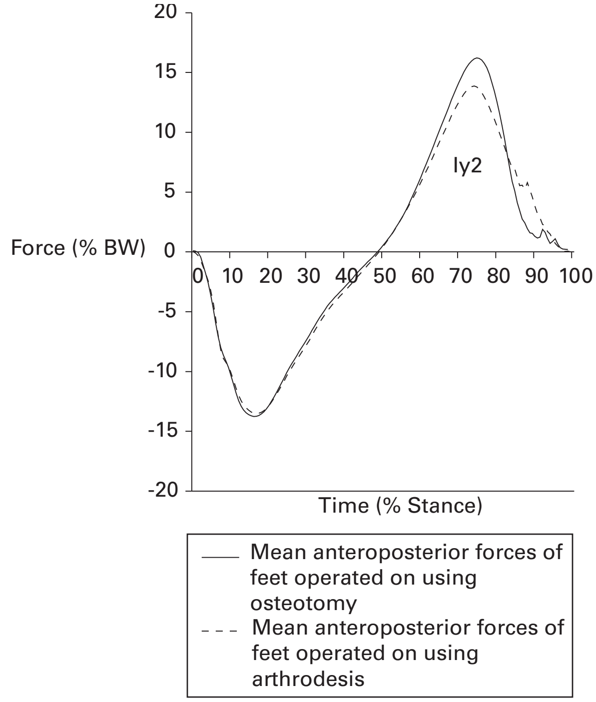

Fig. 2

Graph showing the mean anteroposterior ground reaction forces. Iy, impulse, force-time integral; BW, body weight.

standard weight-bearing anteroposterior views of the forefoot. The angle between the first and second metatarsals (M1–M2), the angle between the first and fifth metatarsals (M1–M5) and the angle between the first metatarsal and first phalanx of the hallux (M1–P1) were measured.

Kinetic and kinematic analyses were performed using a treadmill ergometer (ADAL 3D, HEF-Tecmachine, Andrezieux-Boutheon, France). All measurements were adjusted for body-weight (% BW) to standardise the data and allow comparisons between patients.

A dynamic analysis was conducted with the patients walking on the instrumented treadmill to record the three components of GRF. This was performed with patients walking barefoot and before the data recording began, each patient was given a four minute period to adapt to the treadmill until a comfortable speed of about 4 km/h was reached. This speed was subjectively chosen and corresponded to an easy and comfortable walking speed for the patient. After one minute of rest, the GRF were recorded during a 30-second period, started after a new one-minute adaptation period on the treadmill, without notifying the patient.

In the vertical axis, Fz1 corresponds to the first peak in force during heel strike, Fz2 to the minimum force during ground clearance and unloading of the centre of mass, Fz3 to the maximum force occurring during the propulsive phase and Iz to the overall impulse (force-time integral) in the vertical plane (Fig. 1). The anteroposterior GRF is first a braking force until mid-stance and generates a braking impulse (Iy1); it is followed by a propulsive force generating a propulsive impulse (Iy2) (Fig. 2). Since the forefoot push-off forces are in the vertical plane, the second peak vertical force (Fz3) and the Iy2 acceleration component are in the anteroposterior plane. Ix2 represents the impulse in the transverse axis (Fig. 3).[18]

Statistical analysis. Mean and standard deviation (SD) values were calculated for each variable. The normality of distribution for quantitative values was assessed using skewness and kurtosis coefficients. The operated and non-operated feet of each group (osteotomy and arthrodesis) were compared. A two-way (surgery × foot) analysis of variance (ANOVA) model was used to determine the effects of surgery (osteotomy *versus* arthrodesis) and foot (operated *versus* non-operated) on biomechanical parameters of walking. Significant ANOVA results were followed by unpaired (osteotomy *versus* arthrodesis surgery) and paired (operated *versus* non-operated foot) *t*-tests. Data were analysed using Adisoft software (Adisoft Technologies Pvt, Indore, India). Statistical significance was set at $p \leq 0.05$ for all tests.

Results

Patient characteristics, AOFAS scores and radiographical data are shown in Table I. The AOFAS score was calculated without the 'MTP joint motion of the hallux' item because it was zero in the arthrodesis group.

Spatiotemporal data are shown in Table II. The effect of surgery was evident on stance duration, swing duration as

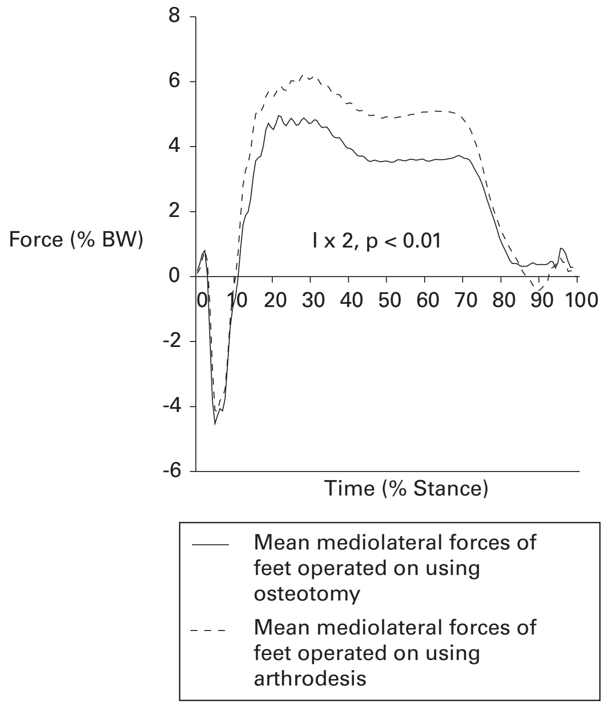

Fig. 3

Graph showing the mean mediolateral ground reaction forces. Ix, impulse, force-time integral; BW, body weight.

well as on single and double duration support. There were statistically significant differences between the osteotomy and arthrodesis groups during the stance duration ($p = 0.005$) single support duration ($p = 0.002$ and double support duration for both the leading and trailing leg ($p = 0.002$ and $p = 0.001$, respectively). In those groups without surgery, there were statistically significant differences in the swing duration ($p = 0.002$) and double support duration for both the leading and trailing legs ($p = 0.001$ and $p= 0.002$, respectively). Although not statistically significant, there was a difference in swing as well as single in-support durations with a 'foot effect' on the group that underwent arthrodesis.The recorded forces and impulses are shown in Table III and the means are illustrated in Figures 1, 2 and 3. A surgery effect was found for the Fz3 ($p < 0.004$) and Ix2 ($p < 0.007$) values. Unpaired *t*-tests with the Fz3 variable found a statistically significant difference between the osteotomy and arthrodesis group for the operated feet ($p < 0.002$) and non-operated feet ($p = 0.01$). Unpaired *t*-tests with the Ix2 variable found a statistically significant difference between the osteotomy and arthrodesis group for the operated feet ($p = 0.03$) and non-operated feet ($p < 0.005$).

A foot effect was found for Iy2, paired *t*-tests indicated a statistically significant difference between the operated feet and non-operated feet in the arthrodesis group ($p = 0.01$). There was a significant interaction between the operated side and type of surgery for the Iy1 parameter.

Discussion

The main findings of this study were that after surgical correction for HV, patients who underwent a Scarf osteotomy had a gait pattern similar to that of their non-operated foot, in terms of forefoot propulsive forces (Fz3, Iy2), whereas those patients who underwent arthrodesis of the first MTP joint, had not.

Although the total impulse in the vertical axis (Iz) did not differ according to the surgical procedure or operated foot, a surgery effect for the Fz3 peak was found. The patients in the arthrodesis group placed less weight on the forefoot at the end of stance, both for the operated and non-operated foot. This result was consistent with the horizontal plane findings of a foot effect for Iy2. Patients in the arthrodesis group seemed to be unable to generate a forward impulse on the operated side, resulting in a reduced ability to propel and accelerate the centre of mass forwards with the operated foot. Our results confirm those of Galois et al[9] who demonstrated a decrease in the propulsive force after arthrodesis of the first MTP joint in the vertical (Fz3) and anteroposterior (Iy2) planes.

The Iy1 parameter reflects the patient's ability to decelerate upon foot strike during the heel strike and mid-stance phases. An interaction between the operated side and the surgery type for the Iy1 parameter was found, however it was not possible to discern where these differences existed. Patients in the osteotomy group had a tendency to decelerate equally with the operated foot and the non-operated foot, while patients in the arthrodesis group had a tendency to decelerate less with the non-operated foot than with the operated foot. The deceleration ability was similar in the operated feet whether they underwent an arthrodesis or an osteotomy, whereas it was reduced in non-operated feet if the contralateral foot had undergone an osteotomy. The non-operated foot in the arthrodesis group may decelerate less because the contralateral operated foot propels less at the same time. These two phases are closely linked, as the start of the non-operated foot's deceleration occurs at the end of the propulsive phase for the operated foot. To preserve the energy of the centre of mass and not brake during this phase, the non-operated foot must decelerate less when the operated foot does not have its full propulsive function. These results confirmed the findings of Galois et al[9] where the gait pattern of the non-fused foot adapted to the fused foot. In our study, the propulsive pattern of the non-operated foot adapted to that of the operated foot in patients with first metatarsal osteotomy or MTP arthrodesis.

We found that there were differences in the mediolateral GRF between the two groups, with a lower Ix2 for the arthrodesis group. During stance, plantar flexor and adductor muscles are major contributors to forward progression and lateral GRF, while abductor muscles contribute to the medial GRF.[19-21] As a consequence, an increase in the propulsive forces produced by the plantar flexors, as shown by the increased Fz3 and Iy2 in osteotomy group, could contribute to increasing the lateral GRF and thereby to reducing Ix2.

Table II. Spatiotemporal data

		Osteotomy		Arthrodesis		p-value (ANOVA)		
Parameters		Operated foot	Non-operated foot	Operated foot	Non-operated foot	Foot	Surgery	F x O
Speed (m.s^{-1})	1.13 (0.03)			1.12 (0)				
Stride duration (s)	1.04 (0.05)			1.04 (0.06)				
Step length (m)	0.59 (0.03)			0.58 (0.03)				
Step frequency (Hz)	1.93 (0.1)			1.97 (0.21)				
Stance duration (% Stride)	61.4 *(1.4)*		61.8 *(1.6)*	62.8 *(1.4)*	62.7 *(2.4)*	0.68	**0.006**	0.58
Swing duration (% Stride)	38.6 *(1.3)*		38.2 *(1.6)*	37.8 *(1.9)*	36.7 *(0.9)*	**0.02**	**0.006**	0.3
Single support duration (% Stride)	38.2 *(1.6)*		38.6 *(1.3)*	36.7 *(0.9)*	37.8 *(1.9)*	**0.02**	**0.006**	0.28
Double support duration – leading leg (% Stride)	11.5 *(1.5)*		11.7 *(1.3)*	12.8 *(0.8)*	12.9 *(0.6)*	0.46	**0.001**	0.58
Double support duration – trailing leg (% Stride)	11.7 *(1.3)*		11.5 *(1.5)*	12.9 *(0.6)*	12.8 *(0.8)*	0.46	**0.001**	0.58

Values are presented as mean (standard deviation)
A two-way (surgery × foot) analysis of variance (ANOVA) with repeated measures was performed; p-values represent the main effects of surgery (S: osteotomy*vs* arthrodesis) and foot (F: operated *vs* non-operated)
Bolding indicates statistical significance

Table III. Ground reactions forces in the osteotomy and arthrodesis groups

	Osteotomy		Arthrodesis		p-value (ANOVA)		
Parameters	Operated foot	Non-operated foot	Operated foot	Non-operated foot	Foot	Surgery	F x S
Fz1	106.32 (4.74)	106.50 (5.48)	108.10 (5.93)	107.89 (5.57)	0.98	0.36	0.74
Fz2	82.02 (4.07)	82.41 (4.03)	82.29 (2.70)	82.43 (2.60)	0.36	0.90	0.66
Fz3	102.92 (7.16)	103.02 (8.21)	96.51 (3.84)	97.07 (4.89)	0.51	0.004	0.65
Iz	51.81 (3.30)	52.16 (3.51)	51.60 (2.87)	52.34 (3.18)	0.09	0.99	0.52
Iy1	-3.00 (0.55)	-3.12 (0.48)	-3.02 (0.38)	-2.86 (0.47)	0.71	0.39	0.04
Iy2	2.29 (0.40)	2.30 (0.51)	2.12 (0.38)	2.29 (0.36)	0.048	0.51	0.08
Ix2	1.32 (0.76)	1.25 (0.66)	1.94 (0.85)	2.02 (0.88)	0.94	0.007	0.44

Values are presented as mean (standard deviation)
A two-way (surgery × foot) analysis of variance (ANOVA) with repeated measures was performed; p-values represent the main effects of surgery (S: osteotomy*vs* arthrodesis) and foot (F: operated *vs* non-operated). Forces are expressed as a percentage of body weight (% BW) and impulses are in % BW×s
ANOVA, analysis of variance

Our study demonstrated preservation of the forefoot push-off force after a Scarf osteotomy without localising the application point or distribution pattern of the centres of pressure. According to Bruening et al[18] propulsion (including Fz3 and Iy2) was related to the forefoot (down the midtarsal joint). However, hallux loading after osteotomy was probably not restored as had been demonstrated in previous studies.[6,13] Kernozeck and Sterriker[12] and Kernozeck, Roehrs and McGarvey[22] analysed foot pressure distribution after a hallux chevron osteotomy by dividing the foot into seven areas. They found that there were no changes in the hind-foot, mid-foot or medial forefoot loading patterns. However they observed that greater and prolonged loading occurred in the central and lateral areas of the forefoot as well as in the fifth toe at the expense of the hallux, in which post-surgical loading was not restored. Jones et al[10] reported similar foot pressure data with decreased peak force under the first metatarsal head after a Scarf osteotomy and increased stress beneath the fourth and fifth metatarsal heads.

In light of these results and the published data, the propulsive forces appeared to be better maintained after osteotomy than after arthrodesis but were associated with lateral transfer of the centre of pressure to the forefoot. There might be a higher risk of transfer metatarsalgia after osteotomy than after arthrodesis due to these two synergistic effects. Any metatarsalgia should be addressed during the osteotomy to prevent the occurrence or deterioration of lateral metatarsalgia and an isolated hallux osteotomy to correct lateral static impairment should be avoided.

The strengths of this study relate to the use of a treadmill ergometer for GRF measurement during many consecutive steps.[23] The ADAL treadmill makes it possible to measure a large number of consecutive steps for each lower limb independently, decreasing the variability of the resulting data.

There are limitations with this study. The groups were not matched and it was a retrospective cross-sectional study. The surgeon determined the surgical technique the patient and groups could be different in terms of aetiology. Also there was no independent control group, with the non-operated feet being used as the control. Since the healthy foot is influenced by the abnormal foot, it was useful to compare the recovery in the contralateral healthy foot after surgery rather than with a group of healthy patients. In addition walking on a treadmill could alter the gait pattern particularly in older patients. Because the duration and relative share of the different phases of the gait cycle vary with walking speed,[24] a speed was 4 km/h was chosen for all patients in order to harmonise the comparisons and not introduce a confounding factor. The main limitation of using GRF as an outcome measure is that it provides an overall picture of the foot-floor interaction, but it is not specific to any given joint.

In conclusion, this study compared the biomechanics of walking following a Scarf osteotomy with patients who underwent a first MTP joint arthrodesis. We found that following arthrodesis, forefoot propulsion was not totally restored, but it was restored after Scarf osteotomy resulting in the gait pattern in the operated foot being similar to that of the non-operated foot.

Author contributions:
R. Ballas: First author, Conception and design of the study, Data collection, Data analysis, Interpretation of data, Writing the paper, Corresponding author.
P. Edouard: Second author, Substantial contributions to the conception and design of the project, interpretation of data, Drafting and revising of the manuscript, Final approval of the version to be published.
R. Philippot: Performed surgeries.
F. Farizon: Performed surgeries.
F. Delangle: Performed surgeries.
N. Peyrot: Data collection, Data analysis, Writing the paper.

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