The use of minimally invasive techniques in multi-level surgery for children with cerebral palsy

PRELIMINARY RESULTS

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This study compares the initial outcomes of minimally invasive techniques for single-event multi-level surgery with conventional single-event multi-level surgery. The minimally invasive techniques included derotation osteotomies using closed corticotomy and fixation with titanium elastic nails and percutaneous lengthening of muscles where possible. A prospective cohort study of two matched groups was undertaken. Ten children with diplegic cerebral palsy with a mean age of ten years six months (7.11 to 13.9) had multi-level minimally invasive surgery and were matched for ambulatory level and compared with ten children with a mean age of 11 years four months (7.9 to 14.4) who had conventional single-event multi-level surgery. Gait kinematics, the Gillette Gait Index, isometric muscle strength and gross motor function were assessed before and 12 months after operation.

The minimally invasive group had significantly reduced operation time and blood loss with a significantly improved time to mobilisation. There were no complications intra-operatively or during hospitalisation in either group. There was significant improvement in gait kinematics and the Gillette Gait Index in both groups with no difference between them. There was a trend to improved muscle strength in the multi-level group. There was no significant difference in gross motor function between the groups.

We consider that minimally invasive single-event multi-level surgery can be achieved safely and effectively with significant advantages over conventional techniques in children with diplegic cerebral palsy.

Single-event multi-level surgery is most commonly performed in ambulant children with spastic diplegic cerebral palsy (CP). It usually involves a combination of bony and soft-tissue procedures to correct complex lower-limb deformities, improve gait and reduce the child's exposure to repeated operations and rehabilitation. Although this surgery is valuable in the care of children with cerebral palsy, post-operative recovery of function is a long and difficult process.

Femoral and tibial derotation osteotomies are often part of conventional multi-level surgery. In the femur, although there is debate about the advantages and disadvantages of proximal (intertrochanteric) or distal (diaphyseal or supracondylar) osteotomy,^{1,2} the results of rotational osteotomy are effective and lasting.³ However, the procedure usually necessitates a period of post-operative immobilisation lasting from 4.5 to 7.6 weeks.^{1,2} Failure of the fixation following early weight-bearing is a potential problem, as well as nonunion, infection and incomplete correction.^{2,4} Open osteotomy involves extensive soft-tissue

dissection and periosteal stripping, which may contribute to these complications. Post-operative pain and immobility resulting from extensive dissection of muscles further compromise pre-existing weakness.

Correction of lower-limb contractures in CP is achieved by muscle-tendon recession or fractional lengthenings. Since muscle-tendon lengthening procedures are known to reduce muscle strength^{5,6} the technique of lengthening at the musculotendinous junction is widely used to minimise loss of strength and accelerate recovery. However, in contrast to animal studies, where loss of strength following a muscle-tendon lengthening recovers completely within six weeks,⁶ there is limited evidence suggesting that recovery of muscle strength in CP following a single lengthening may take up to seven to nine months.^{7,8} Recovery from bony surgery will generally take much longer. The combination of bony and soft-tissue multi-level surgery is associated with slow, prolonged and intensive rehabilitation.^{9,10} Seniorou et al¹¹ recently showed that despite significant improvements in gait one year after multi-level surgery, muscle

Table I. Details of gender, age, weight, Gross Motor Function Classification System level and surgical procedures for all subjects

Patient*	Gender	Age at surgery (y/m)	Weight (kg)	GMFCS [†] level	FDO [‡]	TDO [§]	CLO [¶]	Psoas	Add**	Ham ^{††}	RF ^{‡‡}	Gast ^{§§}	TP ^{¶¶}	Other
MI-SEMLS														
1	M	9.4	24	II	R***		R		R	R	R	R		
2	M	13.9	49	I	L	L	L		L	L	L			
3	M	11.6	32	II	B				R	B	B	B		
4	M	9.7	45	I	B		B		B	B	B	B		
5	M	7.11	24	III	B				B	B	B	B		
6	M	8.5	47	III	B				B	B	B	B		
7	F	11.6	47	II	B		B		B	B	B	B		
8	F	12.2	51	II	B				B	B				
9	M	11.7	37	II	B		B		B	B	B			
10	M	10.8	35	II	B				R	B	B	B	R	
SEMLS														
11	M	9.3	32	II	B		B	B		B	B	B		
12	F	14.4	55	I	B					B		B		
13	M	11.2	34	II	L			B		B	B	B		
14	F	10.3	28	II	B			B		B	B	B		
15	F	11.5	20	III	B		L		L	B		B		
16	F	12.9	32	III	B			B		B		B	B	L Acetabuloplasty
17	M	11.6	52	II	B		B		B	B		B		B Subtalar arthrodesis
18	M	13.11	47	II	R					R		R		R Acetabuloplasty
19	F	11.7	26	II	B		B	B		B	B	B		
20	F	7.9	27	II	R		L			B	B	B	R	

* MI-SEMLS, minimally invasive single-event multi-level surgery; SEMLS, single-event multi-level surgery

† GMFCS, gross motor function classification system

‡ FDO, femoral derotation osteotomy;

§ TDO, tibial derotation osteotomy

¶ CLO, calcaneal lengthening osteotomy

** Add, adductor lengthening

†† Ham, hamstring lengthening

‡‡ RF, rectus femoris transfer

§§ Gast, gastrocnemius lengthening

¶¶ TP, tibialis posterior lengthening

*** R, right; L, left; B, bilateral

strength remained significantly less than before operation, and gross motor function returned to pre-operative levels but was not improved by surgery.

In order to achieve the optimum benefit from multi-level surgery, surgical techniques and post-operative rehabilitation need to improve. We have combined new techniques with post-operative strength training to allow early mobilisation and preservation of muscle strength for children with CP. We describe the preliminary results of a pilot study comparing the outcomes of minimally invasive single-event multi-level surgery with conventional multi-level procedures.

Patients and Methods

Ten children with spastic diplegic CP with a mean age of 10.6 years (7.11 to 13.9) had minimally invasive surgery on 18 limbs. They were matched for ambulatory levels I-III using the Gross Motor Functional Classification System (GMFCS)¹² and compared with ten diplegic children who underwent conventional multi-level surgery on 20 limbs (mean age at surgery 11.4 years (7.9 to 14.4) (Table I)). Patients were excluded if they had been treated with botu-

linum toxin or had undergone surgery to the lower limbs in the year before the multi-level procedures.

Both cohorts were recruited prospectively and were sequential. We first studied the multi-level group. Once the minimally invasive techniques were developed and approved for introduction into our unit, we utilised them on all spastic diplegic patients listed for multi-level surgery and continued to collect data prospectively. The first ten patients who underwent minimally-invasive surgery and followed for one year have been matched for gross motor function with ten out of a total cohort of 20 SEMLS patients.

All children in both groups underwent simultaneous bony and soft-tissue procedures by the same surgical team (TNT, AMW). The combination of procedures for each child was decided on pre-operative clinical examination and three-dimensional (3D) gait analysis. In particular, the decision to perform derotation osteotomy was based on the measurement of femoral anteversion¹³ and rotation of the hip on the transverse plane kinematics. When both these measurements were abnormal, derotation osteotomy was recommended.

Standard surgical techniques were used in the conventional multi-level group. Open fractional lengthening at the

Anteroposterior intra-operative radiographs of the right femur during corticotomy and fixation with titanium elastic nails showing a) insertion of the nails, b) closed corticotomy using an osteotome, c) advancement of the nails, d) rotational correction and e) a view of the right hip with the nails advanced into the proximal femur and the reference wire used for anteversion.

musculotendinous junction was undertaken when indicated. Derotation femoral osteotomy was performed at the intertrochanteric level and fixed with an angled blade-plate or at the subtrochanteric level with a straight plate. Tibial osteotomy was carried out at the supramalleolar level and fixed with a plate. Transfer of the rectus femoris to sartorius or gracilis was also undertaken using an open technique. A calcaneal lengthening osteotomy was performed as described by Mosca.¹⁴

In the minimally invasive group, fractional lengthening of musculotendinous units was undertaken using percutaneous techniques. During these procedures, the assistant brought the muscle group to be addressed under stretch. For example, in the case of the hamstrings, the leg would be brought to the position of maximum measurement of the popliteal angle. In this position the surgeon would undertake multiple (usually between two and five) percutaneous transverse incisions (1 mm to 2 mm length) in the musculotendinous area until the position had improved to the desired level (e.g. a popliteal angle of 30° or a plantigrade position of the ankle). In the case of gastrocnemius, a mini-open technique through a 2 cm incision was used to protect the sural nerve and divide the gastrocnemius aponeurosis, while preserving soleus. Transfer of the rectus to gracilis was undertaken using a mini-open technique. Calcaneal osteotomies were fixed with a small fragment AO plate (Synthes Inc., Davos, Switzerland) to achieve immediate stability.

An innovative technique was used for derotation osteotomy of the femur and tibia, based on closed corticotomy and fixation with the titanium elastic nails (Synthes Inc.). In the femur, a reference anteversion wire was inserted in a neutral position in the femoral neck. The nails were inserted distally and advanced proximally to the isthmus under fluoroscopic control (Fig. 1). At this level, a percutaneous corticotomy was carried out with a drill and osteotome. The nails were advanced across the corticotomy and rotational correction achieved using the anteversion wire

inserted in the femoral neck and measuring its angle with the transcondylar axis at the knee with a goniometer. Following correction of anteversion to 10° to 15°, the nails were advanced further to obtain fixation in the proximal femur. A similar technique was used for the tibia. The tibial nails were inserted antegrade and the fibula left intact.

The immediate post-operative regime for the first three days was identical for both groups, involving bed exercises and continuous epidural infusion followed by oral analgesics as required. Knee immobilisers (gaiters) were used in both groups for three to four days post-operatively and subsequently for up to six months at night. Below-knee casts were used for six weeks in children who underwent gastrocnemius lengthening and/or tibial and calcaneal osteotomies. In patients who had conventional multi-level surgery and long-bone osteotomies with plate fixation, weight-bearing was delayed for up to six weeks depending on the intra-operative assessment of the stability of the fixation. The patients who underwent minimally invasive surgery and had long-bone osteotomies fixed with titanium elastic nails were mobilised from the third day. Both groups used bilateral anterior ground-reaction ankle-foot orthoses for a minimum of six months to aid extension of the knee in the stance phase.

In addition to intensive routine post-operative physiotherapy a strength training programme was started after three months in the minimally invasive group, compared with after six months in the conventional multi-level group. Both groups followed a standardised strengthening protocol three times weekly for six weeks exercising the hip flexors, extensors and abductors, and knee flexors and extensors bilaterally.¹¹

Clinical examination, gait kinematics and temporal parameters, isometric muscle strength and motor function were assessed in all children pre-operatively and 12 months after surgery. Routine radiographs were taken at six and 12 weeks. The operation time, blood loss, time to mobilisation and any complications were recorded.

Table II. Operative details for the two groups

	SEMLS* group Mean (SD)	MI-SEMLS† group Mean (SD)	p-value
Operation time (mins)	229 (66)	165 (26)	0.013
Blood loss (ml)	297 (109)	132 (77)	0.004
Mobilisation (days)	42 (17)	9 (4)	< 0.001

* SEMLS, single-event multi-level surgery

† MI-SEMLS, minimally invasive single-event multi-level surgery

Instrumented 3D gait analysis was performed using a 12-camera Vicon MX40 motion analysis system (Vicon, Oxford, United Kingdom) and a conventional marker set on the pelvis and lower limbs.¹⁵ Subjects walked barefoot, where possible, along a 10 m walkway at their self-selected speed. A minimum of six trials were captured and averaged, and three representative trials were processed using Plug-In-Gait modelling software (Vicon). Velocity, cadence and step length were calculated and normalised according to the method described by Hof.¹⁶

Isometric muscle strength was measured using a combination of fixed and hand-held dynamometry with a digital dynamometer (MIE Medical Research Ltd, Leeds, United Kingdom) in standardised testing positions.¹¹ Five muscle groups were tested in each leg: the hip flexors, extensors and abductors, knee flexors, and knee extensors at 90° and 30° of flexion. The maximum force of three efforts for each muscle group was used in the data analysis and normalised to body mass (Nm/Kg).

Motor function was assessed as the Gross Motor Function Measure (GMFM88) score¹⁷ using the total percentage score for analysis.

The Gillette Gait Index¹⁸ was used to calculate the amount by which a subject's gait deviated from an average normal profile, the deviation being represented as a single number. Routine radiographs were taken at six and 12 weeks after surgery and used to assess union at the site of the osteotomy.

Statistical analysis. This was undertaken on 20 limbs in the conventional multi-level and 18 in the minimally invasive group. A paired Students *t*-test was used to assess pre- and post-operative differences within the groups. Differences between the groups were assessed using analysis of covariance. The level of significance was set at $p < 0.05$.

Results

The minimally invasive group had a significantly reduced operation time ($p = 0.013$), less blood loss ($p = 0.004$) and improved time to mobilisation ($p < 0.001$), compared with the conventional multi-level group (Table II). There were no complications intra-operatively or in hospital in either group. In the minimally invasive group, patient 2 developed a transient left trochanteric bursitis and patient 3 developed transient neuropathic pain in the right foot. In the conventional group, there was one failure of fixation requiring revision when patient 20 fell at home five weeks post-

operatively. Otherwise all osteotomies in both groups united within 12 weeks.

Pre-operatively, there were no significant differences in gait kinematics between the groups except for significantly increased knee flexion during stance in the conventional multi-level group ($p = 0.03$). Both groups had significantly improved knee flexion in stance post-operatively and similar significant improvements in sagittal and coronal plane gait parameters. Furthermore, the Gillette Gait Index was significantly improved in both groups ($p < 0.001$). The results are summarised in Table III.

In the conventional group, muscle strength was reduced at 12 months compared with pre-operatively in all lower-limb muscle groups, except for the hip abductors (Fig. 2). This was significant in the knee flexors ($p < 0.001$). In the minimally invasive group there was a significant reduction of knee flexor strength ($p < 0.001$) at 12 months compared with pre-operatively, but improved strength in the hip abductors and knee extensors at 90° and 30°. This was significant in the latter muscle group ($p = 0.01$). When comparing the groups, the minimally invasive group had significantly greater knee flexor strength compared to the conventional group at 12 months post-operatively ($p = 0.048$).

Gross motor function, as measured by the total percentage GMFM, showed no significant change from pre- to post-operative levels either within or between the groups.

Discussion

Improvements in gait following multi-level surgery are well documented,^{9,10,19,20} and compare favourably with deterioration in gait in untreated diplegic children.²¹ In our study, kinematic parameters in the sagittal and coronal planes were shown to be similarly improved by conventional and minimally invasive multi-level surgery. Excessive internal rotation of the hip and foot progression angles were significantly improved by femoral derotation osteotomy with conventional blade-plate fixation or titanium elastic nailing.

The use of titanium elastic nails is well established in the treatment of certain long bone fractures. It is a safe, minimally invasive method, with few complications, avoids injury to the growth-plate, does not require post-operative casts and is associated with short hospital stays and early mobilisation.²² Biomechanical studies have shown that using titanium elastic nails for fixation of the femur has adequate

Table III. Gait, strength and function mean values pre-operatively and 12 months post-operatively

	Healthy (n = 20 legs)	MI-SEMLS group (n = 18 operated limbs)		SEMLS group (n = 20 operated limbs)	
	Mean (sd)	Pre-operative (sd)	Post-operative (sd)	Pre-operative (sd)	Post-operative (sd)
Gait Parameters					
Mean anterior pelvic tilt (°)	9.8 (5.3)	17.88 (3.11)	18.65 (7.49)	15.92 (4.64)	18.97 (9.89)
Mean pelvic obliquity (°)	2.3 (1.6)	6.16 (4.35)	6.64 (2.97)	9.14 (7.47)	7.07 (7.42)
Mean pelvic rotation (°)	5.2 (4.4)	15.81 (10.73)	8.24 (7.43) [†]	15.61 (14.21)	12.37 (16.09)
Maximum hip flexion swing (°)	35.9 (6.3)	49.98 (8.27)	48.22 (8.95)	52.85 (9.37)	50.16 (11.23)
Maximum hip extension (°)	-12.7 (4.6)	6.66 (11.52)	8.12 (12.62)	9.34 (14.14)	8.14 (17.25)
Mean internal hip rotation (°)	-0.7 (5.0)	13.68 (12.45)	0.80 (7.96) [‡]	12.17 (12.84)	1.56 (9.94) [‡]
Maximum knee extensor stance (°)	2.2 (5.4)	22.20 (18.06)	14.29 (13.54) [†]	35.22 (22.92)	21.47 (17.02) [†]
Knee flexion initial contact (°)	5.9 (4.8)	40.58 (11.90)	24.04 (12.43) [‡]	46.42 (17.71)	31.88 (13.18) [‡]
Range knee flexion (°)	60.0 (5.0)	36.69 (15.69)	42.62 (13.76) [*]	31.19 (14.21)	38.46 (12.30) [*]
Maximum knee flexion swing (°)	60.6 (6.3)	58.59 (13.44)	56.64 (10.92)	66.30 (14.15)	59.85 (8.10) [†]
Time maximum knee flexion swing (% cycle)	71.1 (2.0)	82.46 (4.91)	77.56 (4.22) [†]	82.91 (3.82)	79.58 (5.47) [†]
Maximum dorsiflexion stance (°)	14.8 (3.6)	1.23 (17.66)	14.57 (8.30) [†]	13.86 (12.74)	16.94 (6.89)
Maximum dorsiflexion swing (°)	2.4 (1.9)	-8.71 (13.40)	5.01 (7.69) [†]	2.12 (15.30)	9.18 (7.95) [*]
Mean internal foot progression stance (°)	-4.2 (5.1)	13.89 (18.36)	-6.63 (14.85) [‡]	14.73 (13.81)	0.40 (14.51) [‡]
Velocity (% normal)		0.34 (0.09)	0.31 (0.08)	0.28 (0.11)	0.31 (0.12)
Cadence (% normal)		0.56 (0.09)	0.56 (0.09)	0.50 (0.11)	0.52 (0.12)
Step length (% normal)		0.58 (0.09)	0.56 (0.11)	0.55 (0.15)	0.58 (0.14)
Gillette gait index	24.4 (22.4)	421.97 (216.81)	185.71 (115.38) [‡]	391.1 (206.21)	228.08 (175.65) [‡]
Muscle strength (Nm/Kg) (n = 30 legs)					
Knee flexors	1.26 (0.25)	0.86 (0.30)	0.63 (0.40) ^{‡§}	0.90 (0.21)	0.47 (0.22) [‡]
Knee extensors 90°	1.82 (0.37)	1.27 (0.44)	1.29 (0.60)	1.36 (0.54)	1.15 (0.55)
Knee extensors 30°	1.27 (0.17)	0.33 (0.16)	0.43 (0.22) [*]	0.63 (0.53)	0.47 (0.27)
Hip flexors	1.05 (0.19)	0.58 (0.21)	0.54 (0.31)	0.43 (0.20)	0.38 (0.21)
Hip extensors	2.68 (0.51)	2.12 (0.61)	2.00 (0.50)	2.00 (0.58)	1.79 (0.37)
Hip abductors	1.05 (0.29)	0.42 (0.11)	0.46 (0.21)	0.54 (0.21)	0.58 (0.35)
Motor function					
(Total % GMFMD [®] score)		80.41 (9.13)	79.34 (8.74)	82.44 (14.71)	85.06 (13.9)

* indicates significant within-group difference $p \leq 0.05$ † indicates significant within-group difference $p \leq 0.01$ ‡ indicates significant within-group difference $p \leq 0.001$ § indicates significant between-group difference $p \leq 0.05$

¶ GMFMD, Gross Motor Function Measure

stability in all three planes, including rotational stability.²³ There is one report of solid locked nail fixation of femoral osteotomies in skeletally mature adolescents with cerebral palsy by Ferri-de-Barros, Inan and Miller²⁴ but, to our knowledge, titanium elastic nails have not previously been used in this context. By combining minimally invasive multiple soft tissue and bony operations in children with spastic diplegic CP, we found immediate clinical advantages when compared with the conventional multi-level surgery. The operative and therefore the anaesthetic time was significantly reduced. There was significantly less blood loss, thereby reducing the risk of peri-operative anaemia and possible transfusion. Titanium elastic nailing allowed rapid mobilisation in the first post-operative week compared with plate fixation, which required delayed weight-bearing for up to six weeks. These advantages also benefit the resources needed for complex multi-level orthopaedic surgery.

In the conventional multi-level group two patients underwent Dega²⁵ acetabuloplasty for acetabular dysplasia

without subluxation, which might imply a slower rehabilitation period. However, the two subjects (16 and 18 in Table I) mobilised at 46 and 56 days respectively, and a further six subjects in this group mobilised at between 46 and 64 days. There were three patients in the minimally invasive group with acetabular dysplasia without subluxation. As part of our changing approach we decided not to perform acetabuloplasties as part of minimally invasive surgery. There would be the risk that these hips could subluxate and require additional treatment. However, we believe the advantages of early mobilisation and rehabilitation outweigh this risk.

Percutaneous lengthening at the musculotendinous junction has been used in children with other pathologies to maximise preservation of muscle strength and speed of mobilisation.²⁶ Gordon et al²⁷ concluded that percutaneous lengthening of the medial hamstrings was a useful option in ambulant children with CP undergoing a variety of concomitant operations. They reported significantly

improved knee extension at initial contact, but there was no group with an open hamstring procedure for comparison. We have shown significantly improved knee extension at initial contact and significantly improved maximum knee extension in stance both in the conventional group with open medial hamstring lengthening, and the minimally invasive group who had percutaneous lengthenings.

There was a mild but non-significant trend toward increased anterior pelvic tilt in both groups post-operatively, with a slight increase in hip extension in the conventional group and a slight decrease in hip extension in the minimally invasive group. This difference is likely to be caused by the psoas rather than hamstrings. Our percutaneous hamstring lengthenings were more conservative than the open type and post-operative hamstring strength was almost twice as great in those lengthened percutaneously as in those lengthened by an open technique. However, we did not undertake psoas lengthening in the minimally invasive group as this would have required an open procedure. As the overall value of psoas lengthening remains controversial we felt it was justified not to include this procedure as part of minimally invasive surgery.

The matching of groups with CP is challenging because of the many parameters which can affect gait and function. We chose the GMFCS as it is a validated classification system which reflects the level of function of the individual patients rather than specific parameters of gait. Some differences between groups were to be expected, but the only significant difference in gait kinematics between the two groups before surgery was significantly increased knee flexion during stance in the conventional multi-level group. Although this is a limitation of the study, our indications for multi-level surgery did not change during it. No patient in the conventional group had undergone previous lengthening of the tendo Achillis which may have contributed to increased crouch. We believe that the difference in knee kinematics between the groups was a random effect of the imperfections of the matching procedure.

There was a general trend for improved muscle strength in the minimally invasive group (Fig. 2). Five of the six muscle groups remained weaker than pre-operatively in the conventional multi-level group, whereas three muscle groups had improved strength in the minimally invasive group and the remaining three lost less strength than the conventional group. The hamstrings showed the greatest loss of strength in both groups, despite a cautious technique to avoid over-lengthening. They remained 48% weaker after open lengthening, but only 27% weaker when lengthened percutaneously. The hamstrings appear to be the muscle group most vulnerable to persistent loss of strength after surgery. This is despite prolonged and extensive rehabilitation with an additional resistance strengthening programme to which other lower limb muscles responded well.¹¹ All subjects had derotation femoral osteotomies and both groups had improved

Fig. 2

Chart showing percentage change in muscle strength at 12 months post-operatively in the two groups (SEMLS, single-event multi-level surgery, MI-SEMLS, minimally invasive single-event multi-level surgery).

strength in the hip abductors post-operatively. The correction of internal rotation corrects lever-arm dysfunction and therefore confers a biomechanical advantage on the hip abductors.¹³

Multi-level surgery in CP focuses on the correction of static and dynamic deformity with the aim of improving gait. It is, however, important that children who are straighter and more upright after correction of gait are not made weaker and less functional. Although an initial loss of motor function might be expected, the effect of bony and soft-tissue multi-level surgery on strength and function has not been evaluated specifically by others. Seniorou et al¹¹ showed that motor function significantly deteriorated at six months after conventional multi-level surgery, but recovered by one year. In our study, motor function also returned to pre-operative levels one-year after surgery in both groups. Motor function peaks at about seven years of age in children with CP at GMFCS levels I to III.^{28,29} Thereafter, function remains stable at GMFCS levels I and II, but significantly declines at GMFCS level III.³⁰ Therefore, restoration of function to pre-operative levels, rather than functional improvement, might be viewed as a realistic goal of rehabilitation and a positive outcome.

Our initial findings indicate that multi-level surgery can be achieved safely and effectively using minimally invasive techniques, with the additional benefits of improved muscle strength, faster mobilisation and reduced operative time and blood loss.

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