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Short-term Gait Parameters Change in Mild Spastic Cerebral Palsy after Selective Dorsal Rhizotomy Guided by Our Newly-Modified Protocol

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Abstract

Background Selective Dorsal Rhizotomy (SDR) guided by our modified protocol can decrease spasticity in certain muscles. This study aimed to investigate gait parameters changes in cerebral palsy (CP) with focal spasticity after SDR in short-term follow-up.

Methods CP classified as Gross Motor Function Classification System (GMFCS) level □ and □ who underwent SDR were included. Changes of spasticity, gait parameters and gait deviation index (GDI) were retrospectively reviewed.

Results This study contained 26 individuals with 44 affected and 8 intact lower limbs (4 monoplegia, 4 hemiplegia and 18 diplegia). Mean age was 5.7 ± 1.9 years-old and follow-up duration was 9.9 ± 6.6 months. After SDR, average spasticity of 108 target muscles decreased from 2.9 ± 0.8 to 1.8 ± 0.6 in Modified Ashworth Scale (MAS). Kinematic curves changed after the surgery in sagittal and transverse plane in affected sides, further investigation showed improvements in ankle and knee. No changes were found in temporal-spatial parameters except decrease in cadence in affected sides. GDI improved significantly in affected limbs.

Conclusion In short-term follow up, the new-protocol-guiding SDR can lower focal spasticity, GA showed improvements in kinematic parameters and GDI. Longer follow-up duration is needed to clarify the long-term outcome.

Background

Selective dorsal rhizotomy (SDR) is a neurosurgical operation performed at the level of lumbosacral level that could reduce spasticity in lower extremities, and it is usually indicated in cerebral palsy (CP) with generalized spasticity[1]. Certain dorsal rootlets were selected and partially cut to decrease afferent sensory inputs to achieve the effect of muscle tone reduction. The selection of the rootlets seems to be the core of the surgery for the purpose of SDR is to lower spasticity with minimum side effects such as muscle weakness and bladder/bowel dysfunction. Lots of pioneers have done great jobs to improve the selection criteria of dorsal rootlets for better surgical outcome and less sequela. Since Gros introduced electrical stimulation into SDR in 1960s to prevent ventral rootlets damage[2], it’s not until 1976 that Fasano firstly performed the procedure by identifying pathological responses based on intraoperative electromyography (EMG) responses when electrically stimulating dorsal rootlets[3]. Until now, Peacock, Park, Mittal and Browd developed their own selection criteria, and SDR guided by their protocols have been reported to have good surgical outcomes[4–7].

In 2018, single-level approach SDR guided by a newly modified protocol was reported by Xiao and Zhan[8], during which surgeons choose dorsal rootlets mainly depending on the EMG responses of nerve rootlets to single-pulse electrical stimulation[9]. The new-protocol-guiding SDR has the ability to alleviate focal spasticity in what we call "target muscles"[10], and the therapeutic effectiveness of spastic hemiplegic cases has been previously reported, implying its potential to treat mild spastic CP[8]. Although in previous time, to improve gait patterns and moving abilities of CP cases with focal spasticity, rehabilitation, soft-tissue surgeries, or orthotics are frequently preferred[11–14], SDR guided by this new protocol might offer another choice for these cases, mostly Gross Motor Function Classification System (GMFCS) level □ and □. They might be benefited from such SDR procedure after spasticity being reduced.

The current study aims to discuss the short-term gait parameters changes assessed by gait analysis (GA) after SDR guided by our protocol in spastic CP cases classified as GMFCS level □ and □. It might offer subjective clues proving the effectiveness of this procedure other than objective evaluation such as Modified Ashworth Scale (MAS).

Methods And Materials

In this study, we conducted a cohort review in 215 spastic CP cases who treated in Shanghai Children's Hospital from Jul. 2017 to Aug. 2019. The diagnosis of spastic CP was made by our multidisciplinary team composed of physiotherapists, GA specialists and neurosurgeons. During the assessment (done by one single physiotherapist), muscles with elevated tension (MAS ≥ 2) were marked as our "target muscles". Clinical data including demographics, treating methods and relevant evaluation results were taken from the Database of Pediatric Cerebral Palsy in our department. Inclusion criteria for cases included in this current study were listed as follows:

1. Classified as GMFCS level □ or level □;
2. No structural orthopedic deformities or fixed tendon contractures;
3. Underwent SDR procedure guided by our modified protocol;
4. Age at surgery between 3 to 14 years old;
5. Good cognitive ability of children, good support from parents and rehabilitation settings;
6. Had pre-op GA evaluation and at least once post-op GA assessment;
7. Had no extra surgical interventions between GAs other than rehabilitation program;
8. Follow-up at least 1 month or longer.

Based on our protocol described in previous paper, all cases undergone SDR procedure received post-op intensive rehabilitation program. This study reviewed all relevant assessment data including muscle tone (MAS) and GA parameters, putting its focus on the comparisons of gait parameters before and after the SDR procedure.

Gait Analysis

Cases included in this study all received a comprehensive 3D GA evaluation. Temporal-spatial and kinematic data were collected using a twelve-camera Motion Analysis System (Cortex 8, Motion Analysis Corporation, Santa Rosa, USA). The 3D coordinates of markers were used as inputs to a commercial software program (Visual3D, C-Motion, MD). The Visual 3D program was used to define the joint centers and segment coordinate systems from the 3D marker trajectories, as well as the subsequent rigid body kinematic calculations.

Kinematic curves were statistically compared using the open source 1-dimensional statistical parametric package “SPM1D” offered by Pataky[15]. All Statistical Parametric Mapping (SPM) analyses were conducted in MATLAB (Version 2017, MathWorks Inc., Natick, MA, USA) using the software package downloaded online (www.spm1d.org). Two main types of analyses were used in this paper (SPM T^2 and SPM t tests). Joint vector-fields were constructed by assembling multi-component time series of all subjects, which in detail, kinematic data of three lower joints (hip, knee and ankle) in sagittal, transverse and coronal plane. The post-operational kinematic curves were compared to the pre-op ones using the vector-field (multi-variate) equivalent of the paired t-test, a paired Hotelling’s T^2 test. The same process was used for post hoc comparisons (SPM t tests), taking into consideration of each kinematic data in ankle, knee and hip before and after surgery. Results would be output by MATLAB program.

Changes in kinematic data of ankle, knee and hip were compared to further investigate outcomes of SDR in these ankles (better or worse), including max ankle plantar flexion (PF) angle, max ankle dorsal flexion (DF) angle and ankle DF angle at end of swing phase, average foot progression angle, max knee flexion angle, knee flexion angle at initial contact (IC) and end of swing phase and hip average adduction angle, max hip flexion angle, hip flexion angle at IC and end of swing phase. Temporal-spatial parameters (step width, step length, forward velocity, cadence, total support time, single support time and swing phase time) after surgery were also compared. Gait deviation index (GDI), described by Schwartz and Rozumalski[16], which was calculated to get a new multi-variate measure of overall gait pathology based on a linear combination of 15 gait features (these features were not listed in this article), was used to assess the overall kinematic in each limb after SDR were also compared with pre-op ones.

Statistical analysis

For statistical analyses, MATLAB and commercial statistical software (SPSS, Version 19.0, IBM) were used. As mentioned above, SPM T^2 and SPM t tests in the “SPM1D” package were done to compare the differences between pre-op and post-op kinematic curves in sagittal plane of ankle, knee and hip. Grey bars in the output pictures indicate regions with statistically significant differences. Changes of muscle tension were compared with Mann-Whitney U test, and pre-post comparisons of kinematic and temporal-spatial parameters after SDR were assessed with paired-samples T test. Receiver operating characteristic (ROC) curves were drawn to identify the cut-off point affecting GDI changes after the surgery, and Fisher’s exact test was used for categorical variables (two factors affecting GDI changes: age and follow-up duration). Statistical significance level of $p < 0.05$ was set up for all tests.

Results

A total of 26 individuals (20 boys, 6 girls) were included in this study. The age at surgery ranged from 3.0 to 10.0 with a mean of 5.7 ± 1.9 years old. The duration of post-SDR follow-up was between 1.8 and 31.8

months (9.9 ± 6.6 months). Among these cases, 13 (50.0%) were classified as GMFCS level ▯ and 13 (50.0%) as level ▯. Regarding spastic CP types, one lower limb involved was found in 8 (30.8%) cases, both in 18 (69.2%). Therefore, GA parameters' changes in 44 affected lower extremities in these cases were our priority in the current study. Pre-op GA was performed within 10 days before surgery in all these cases. 26.9% cases went through 2 times post-op GA assessment and 73.1% had only once. No surgical-related complications occurred during the last follow-up except hypersensitivity in 5 cases within 2 weeks after operation (Table 1).

Table 1 Demographic and clinical data of 26 cases included in this study

Characteristics	
Gender (n, %)	
Boy	20 (76.9%)
Girl	6 (23.1%)
Age at surgery, years old (range, mean ± SD)	3.0–10.0 (5.7 ± 1.9)
Spastic CP type (n, %)	
Monoplegia	4 (15.4%)
Diplegia	18 (69.2%)
Hemiplegia	4 (15.4%)
Pre-op GMFCS level (n, %)	
▯	13 (50%)
▯	13 (50%)
Follow-up, months (range, mean ± SD)	1.8–31.8 (9.9 ± 6.6)
Post-op Gait Analysis	
Once	19 (73.1%)
Twice	7 (26.9%)
Surgery-related Complications (n, %)	
Hypersensitivity (≤ 2 weeks)	5 (19.2%)
Urinary/bowel dysfunction	0 (0.0%)

Prominent muscle tone decrease was observed in all 108 target muscles in these 26 cases at the last follow-up, with a mean reduction of 1.1 ± 0.7 grades in MAS (Table 2). Muscle tone of soleus reduced the most (1.3 ± 0.8) among those major muscle groups, with reduction in adductors, hamstrings and gastrocnemii 0.9 ± 0.3, 0.6 ± 0.6 and 1.2 ± 0.6 respectively.

Table 2 Detail data of muscle tone in target muscles in 26 cases

	Pre-op	**Post-op**	***p* value**
Target muscles (n=108)	2.9 ± 0.8	1.8 ± 0.6	<0.001
Adductors (n=16)	2.4 ± 0.5	1.4 ± 0.5	<0.001
Hamstrings (n=11)	2.3 ± 0.6	1.6 ± 0.4	0.004
Gastrocnemius (n=46)	3.2 ± 0.7	2.0 ± 0.6	<0.001
Soleus (n=35)	2.9 ± 0.81	1.6 ± 0.60	<0.001

Kinematic curves of hip, knee and ankle in three planes were demonstrated in Figure 1, and results of SPM tests were shown in Figure 2. The uppermost panel of Figure 2 showed overall difference in affected sides of sagittal and transverse plane. Significant kinematic differences were found between pre-post comparison at approximately 0-5% (p<0.05), 20-60% (p<0.001) and 95-100% (p<0.05) gait cycle (GC) in affected sagittal plane and 5%-90% (p<0.001) GC in transverse plane. Post hoc t tests revealed that in sagittal plane, the difference locates at 0-5% (p<0.05) and 95%-100% (p<0.05) GC in affected knees and 40%-60% (p<0.01) in affected ankles, while in transverse plane, the difference locates at 5%-90% (p<0.001) GC in affected ankles.

Statistical tests on the extracted scalars were done to figure out the detailed changes of movement in three lower joints. Prominent progress was found in kinematic data at the last follow-up in affected lower limbs of our cases (44 sides, Table 3) in ankle Max PF angle, ankle Max DF angle, knee angle at IC, knee angle at end of swing phase in affected sides. The maximum ankle PF angle decreased from 18.7 ± 11.3° to 14.5 ± 9.9° (p < 0.01), maximum ankle DF angle increased from -1.8 ± 9.5° to 7.7 ± 6.2° (p < 0.001), and the mean PF of the ankle at the end of gait cycles decreased from 11.1 ± 8.9° to 8.9 ± 7.5° (p = 0.05). Improvements were also seen in the mean knee flexion angle at IC and at the end of swing phase, which decreased from 33.3 ± 14.5° to 27.2 ± 11.6° (p < 0.01) and from 35.2 ± 15.0° to 27.8 ± 12.9° (p < 0.001) respectively. No significant changes in kinematics of hip joints involved after SDR were revealed in our cases, as well as kinematic data in intact sides.

Among temporal-spatial parameters, no other changes were found except average cadence in affected sides, which decreased from 119.9 ± 26.5 steps/min to 108.1 ± 24.4 steps/min at the time of last follow-up when compared to pre-op status. Detailed GA data of 44 affected and 8 unaffected sides in 26 cases were shown in Table 3.

Table 3 change of kinematics and temporal-spatial parameters and GDI in all 26 patients in this study

*: positive value means dorsiflexion; negative value means plantarflexion

#: positive value means internal rotation; negative value means external rotation

Characteristics	Pre-op	Post-op	*p* value
Kinematics			
Affected sides (n=44)			
Ankle			
Max PF angle	18.7 ± 11.3	14.5 ± 9.9	0.003
Max DF angle	-1.8 ± 9.5	7.7 ± 6.2	<0.001
*End of swing angle**	-11.1 ± 8.9	-8.9 ± 7.5	0.05
Average foot progression angle#	0.4 ± 5.8	-1.6 ± 6.6	0.263
Knee			
IC angle	33.3 ± 14.5	27.2 ± 11.6	0.001
End of swing angle	35.2 ± 15.0	27.8 ± 12.9	<0.001
Max flexion angle	61.5 ± 11.2	63.0 ± 11.7	0.360
Hip			
IC angle	45.4 ± 7.7	44.3 ± 8.1	0.380
End of swing angle	46.1 ± 7.9	45.0 ± 8.2	0.385
Max flexion angle	48.6 ± 8.1	49.3 ± 8.3	0.585
Average abduction angle	3.0 ± 7.7	5.7 ± 7.9	0.061
Unaffected sides (n=8)			
Ankle			
Max PF angle	17.7 ± 10.6	19.1 ± 8.5	0.731
Max DF angle	9.2 ± 6.2	7.0 ± 3.2	0.217
*End of swing angle**	-8.0 ± 7.3	-8.3 ± 4.7	0.927
Average foot progression angle#	-2.0 ± 4.3	-2.8 ± 3.8	0.212
Knee			
IC angle	13.9 ± 13.0	18.6 ± 12.8	0.379
End of swing angle	16.2 ± 14.2	13.6 ± 8.0	0.592
Max flexion angle	64.5 ± 9.4	63.6 ± 7.2	0.804

Hip			
IC angle	39.7 ± 7.2	40.9 ± 9.1	0.551
End of swing angle	40.0 ± 7.4	40.9 ± 9.1	0.684
Max flexion angle	42.8 ± 8.4	44.2 ± 9.8	0.571
Average abduction angle	3.2 ± 5.1	1.6 ± 3.6	0.100
Temporal-spatial			
Step width (n=26, cm)	14.9 ± 2.9	14.9 ± 3.1	0.942
Affected sides (n=44)			
Step length, cm	29.9 ± 9.4	30.9 ± 8.2	0.828
Forward velocity, cm/s	61.9 ± 24.6	57.8 ± 21.8	0.223
Cadence, steps/min	119.9 ± 26.5	108.1 ± 24.4	0.014
Total support time, %	67.8 ± 6.9	68.3 ± 6.89	0.381
Single support time, %	31.5 ± 6.7	30.7 ± 6.24	0.305
Swing phase time, %	32.2 ± 6.9	31.7 ± 6.9	0.381
Unaffected sides (n=8)			
Step length, cm	36.0 ± 10.5	38.0 ± 10.8	0.645
Forward velocity, cm/s	80.7 ± 20.9	77.1 ± 26.9	0.959
Cadence, steps/min	137.4 ± 12.3	121.7 ± 25.0	0.382
Total support time, %	65.5 ± 3.9	65.8 ± 4.6	0.878
Single support time, %	36.8 ± 2.9	37.3 ± 4.6	0.505
Swing phase time, %	34.5 ± 3.9	34.2 ± 4.6	0.878
GDI			
Affected sides (n=44)	57.9±11.4	62.1±8.9	0.002
Unaffected sides (n=8)	71.1±7.5	73.8±7.6	0.501
Average of both legs	59.9±11.0	63.9±8.9	0.007

(n=26)

GDI score increased in our cases after an average duration of 9.9 months post-op rehabilitation program (Table 3). A mean GDI score increase of 4.0 in both legs was demonstrated in those 26 cases included in the current study ($p < 0.01$). Major GDI improvements were observed in those 44 affected limbs in our cases with a mean score increase of 4.2 which reached statistical significance ($p < 0.01$). Interestingly, with GDI increase in those affected side in 8 hemiplegic cases (68.2 ± 9.8 post-op vs. 67.1 ± 9.3 pre-op), scores were revealed as well a slight improvement in those unaffected lower limbs at the last follow-up (73.8 ± 7.6 post-op vs. 71.1 ± 7.5 pre-op).

Table 4 different factors impacting change of GDI

Characteristics	**Improved GDI**	**Decreased GDI**	***p* value**
Age			
≤6 yrs.	16 (61.5%)	1 (3.8%)	0.034
6 yrs.	5 (19.2%)	4 (15.4%)	
Follow-up time			
≤6 months	5 (19.2%)	4 (15.4%)	0.034
6 months	16 (61.5%)	1 (3.8%)	

Further investigation using ROC curves was conducted to find the cut-off point of categorical variables (age at surgery and duration of post-op rehabilitation program, Figure 3) related to the outcomes in those cases. ROC curve for age showed that sensitivity was 80.0% and specificity was 76.2% if the cut-off point was 6.3 years old (area under curve was 0.738) while ROC curve for rehabilitation duration showed that sensitivity was 81.0% and specificity was 80.0% if the cut-off point was 6.2 months (area under curve was 0.686). Fisher's exact test was used to clarify the significance of these two categorical variables (Table 4). In cases with an increased GDI post-operatively, 61.5% were younger than 6 years old ($p < 0.05$) and 61.5% cases were evaluated 6 months after surgery ($p < 0.05$).

As mentioned above, 7 diplegic cases went through 2 times of GAs during their post-SDR follow-up, therefore, a total of 58 GDIs of those affected limbs in our cases were obtained (44 ΔGDI was obtained from last follow-up GDIs minus pre-op ones, and 14 ΔGDI was obtained from 1st follow-up GDIs minus pre-op ones) and taken into account. GDIs increased by 1.0 ± 7.4 in 18 affected limbs when GA was conducted ≤ 6 months post-SDR. When GA was performed in those cases 6 - 12 months post-op (28 affected lower limbs) and > 12 months post-op (12 affected lower extremities), GDIs improved by 4.5 ± 8.3 and 7.3 ± 8.3, respectively (Figure 4).

Discussion

The newly-modified intra-operative EMG interpretation rhizotomy protocol focuses mainly on the pattern of trigger-EMGs when electrically stimulating those dorsal rootlets[8–10], which is somehow different from the EMG Response Grading System which has been practiced for decades in SDR surgery[5,6].

SDR guided by our protocol has the capability to decrease muscle tone mainly in a certain muscle group, therefore could be safely applied to mild CP cases with focal spasticity.
After the reduction of focal spasticity by SDR, these individuals would have the potential to improve their pathological gait patterns after being through a certain period of post-op rehabilitation program. Among all target muscles identified before SDR in our 26 cases, muscle tone decreased from 2.9 ± 0.8 to 1.8 ± 0.6 grades after the procedure. The reduction of muscle tone in these muscle groups set essential foundations for the post-SDR rehabilitation course.

In the current study, we evaluated gait pattern changes in these cases using GA after being through post-op rehabilitation therapy, trying to quantitatively compare their gait patterns (post-op vs. pre-op). It has to be clarified that the normal range of typical developing children was not shown in Fig. 1 owing to the fact that the normal region varied in different age. To begin with the comparisons, we used the open-source SPM1D package (Hotellings T^2 tests) to figure out whether there are differences in three planes during the whole GC, then the post hoc t test could locate the differences into one single joint.

The SPM tests results tell that kinematic curves in intact sides remained unchanged, showing that SDR guided by our protocol left the unaffected limbs alone (or at least no big influences).
Significant differences were found to be in sagittal plane (ankles and knees) and transverse plane (ankles) in affected sides. Further investigation of joint movement angles verifies the improvements in the range of motion. The movement of knee and ankle in sagittal is flexion and extension (DF and PF in ankle) is mainly restricted by spasticity in hamstring, gastrocnemius and soleus. After the reduction of spasticity, it is not difficult to understand the progress in these two joints. While the movement of ankle in transverse plane is a complex one, which might be affected by the muscle tension of adductors and coordination of muscles in calf. With the decrease of muscle tension in adductors, gastrocnemius and soleus, significant change of ankle in this plane appeared. Although the average foot progression angle seems to be unchanged ($p = 0.06$), it might be caused by the restricted number of cases.

Alternation of GDI, a new multi-variate measure of overall gait performance obtained from walking strides to derive a set of mutually independent joint rotation patterns that efficiently describe gait pathology (ranging from 0 to 100. GDI of 100 means that there is no gait pathology) was also used to assess the gait pattern changes in our cases after SDR[16–21]. Results showed general improvements of GDI in those affected sides, resulting into GDI elevation in both sides at the last time of GA assessment after a mean duration of 9.9 months post-SDR rehabilitation therapy. Interestingly, we found that GDI score in unaffected limbs increased along with the affected side in our 8 hemiplegic cases. Similar results were also reported in earlier studies in similar cases when managed with soft-tissue or other orthopedic surgeries[22–24]. The potential explanations for such a phenomenon might be the improvements of gait patterns in affected side after the relief of severe spasticity in these cases making gait patterns in the unaffected limb less pathological compensatory[25].

Age of cases at SDR was found to be highly correlated with the changes of GDI in our retrospective statistical analysis, which was similar to the findings in previous studies[10,26]. Such results might be attributed to the adaptability of gait training, of which younger cases usually have better plasticity for motor control[27,28]. In the meantime, we found that the improvements of GDI are more likely to appear after 6-month post-op rehabilitation program. Further investigation showed that there was a tendency that improvement of GDI would continue as rehabilitation program lasts. Such trend might be attributed to the enhancement of muscle strength, along with the better body control as a result of post-op rehabilitation course, and the commencement of gaiting program in these cases at 6–9 months post-op in our center[8,10]. Such results are comparable with those reported in earlier studies when mild CP cases were managed using other modalities of treatment[29].

Our data showed that post-op rehabilitation course with a mean duration of 9.9 months still could not improve their temporal-spatial gait parameters in our cases. Such results might be related to the post-SDR rehabilitation protocol we are using, based on which, gaiting program would start 6–9 months after SDR in cases with their pre-op GMFCS level □ and □, only when muscle strength in their lower limbs and motor coordination of their body improved reaching a certain degree, making them ready for gait training[8,10]. It usually takes years for a child to mature his gait pattern since he first makes his step on the ground[30]. It remained unclear how long these mild CP cases would spend to reach the maximization of effectiveness of rehabilitation program with regard to their re-shaped gait features after their major spasticity in their lower limbs has been relieved by SDR.

Several limitations exist in the current study. Along with its small sample, time of follow-up was short in our cases. However, this is the first study objectively evaluating outcomes of SDR guided by our newly-modified intra-operative rhizotomy protocol applied in mild spastic CP cases using GA. Studies with larger samples, longer follow-up and better control are expected to validate our EMG interpretation scheme. We hope when it is validated, SDR guided by such a protocol could provide an additional option to those mild spastic CP cases to improve their pathological gait patterns which concern them and their families the most.

Conclusion

SDR guided by the newly-modified rhizotomy protocol was helpful to those mild spastic CP cases with regard to their decreased spasticity. Post-op GA showed major improvements in GDI and kinematic parameters (affected ankles and knees) after the procedure in short-term follow up.

Abbreviations

Selective Dorsal Rhizotomy	SDR
Cerebral Palsy	CP
Gross Motor Function Classification System	GMFCS
Gait Deviation Index	GDI
Modified Ashworth Scale	MAS
Electromyography	EMG
Gait Analysis	GA
Statistical Parametric Mapping	SPM
Receiver Operating Characteristic	ROC
Plantar Flexion	PF
Dorsal Flexion	DF
Initial Contact	IC

Declarations

Ethics approval and consent to participate

This study was approved by the ethical committee of the Institutional Review Board of Shanghai Children's Hospital. Informed written consent was obtained from the parents of each participant. Study procedure was carried out in accordance with the approved guidelines.

Consent for publication

Written informed consent for publication was obtained from all participants. All parents of the study participants gave written consent for their clinical details along with identifying images to be published in this study.

Availability of data and materials

Data used to support the findings of this study were included within the article.

Competing interests

No financial or non-financial benefits have been received or will be received from any party related directly or indirectly to the subject of this article.

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Authors' contributions

All authors have read and approved the manuscript. JWB conceptualized and designed the study, interpreted the data, and critically revised the manuscript. JSY interpreted the data and revised the manuscript. YY interpreted the data. ZQJ, WM, MR, CF, GY helped designed the study and interpreted the data. XB critically revised the manuscript.

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Figures

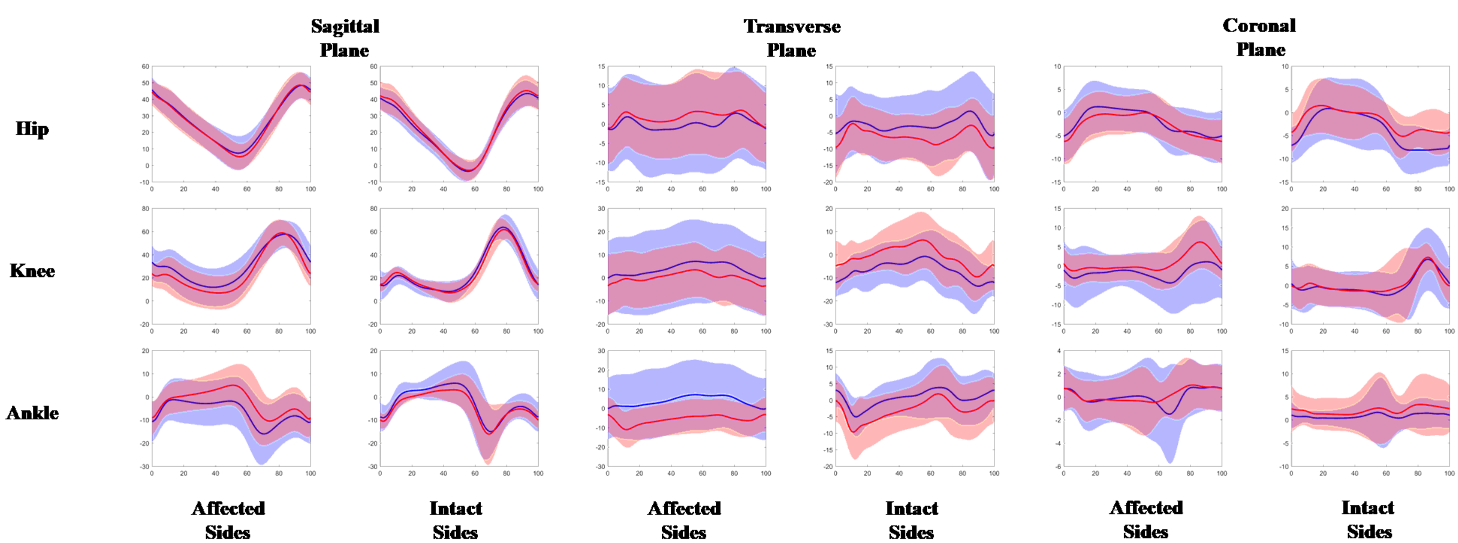

Figure 1

Kinematic curve of hips knees and ankles in sagittal plane, transverse plane and coronal plane in both affected sides and intact sides (mean ± standard deviation). The x axial in each subgraph is gait cycle (%) and y axial is angle degree. Blue: pre-op Red: post-op (last follow-up)

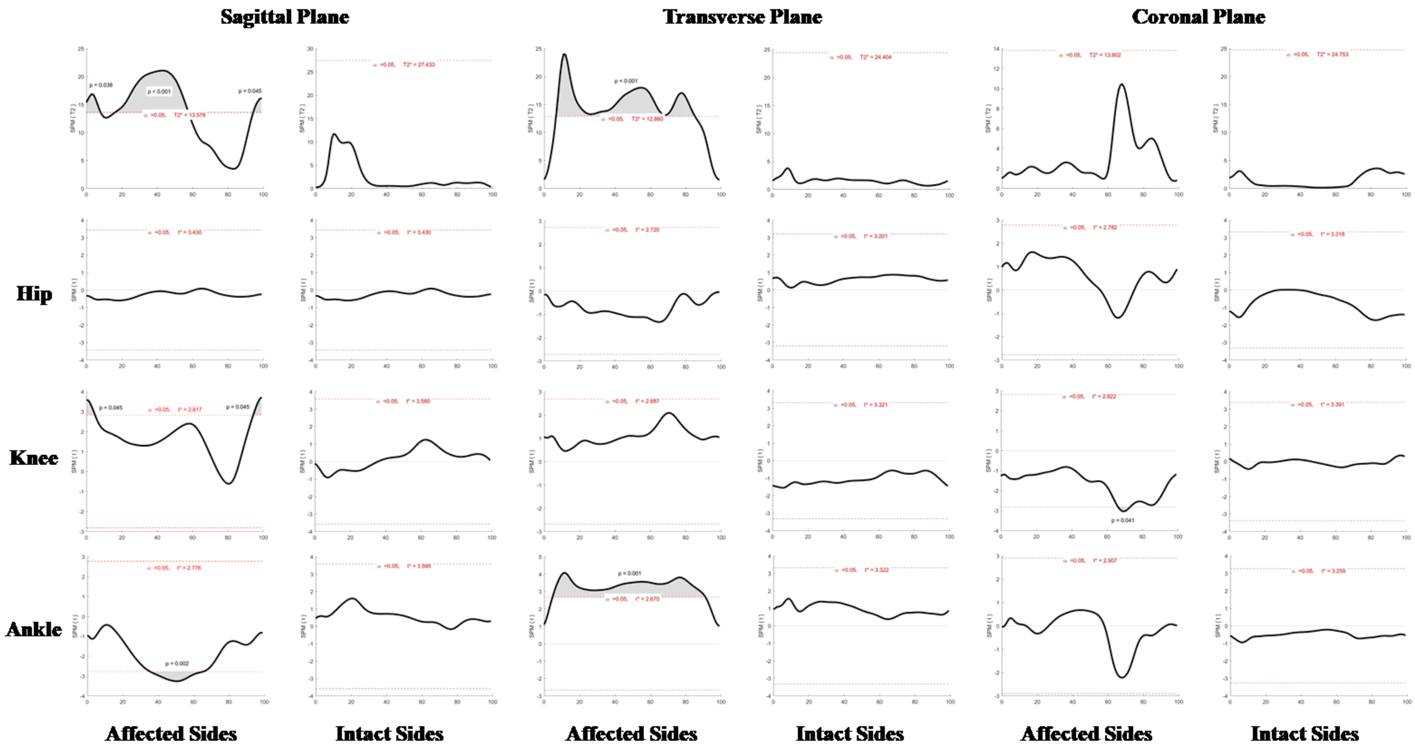

Figure 2

The uppermost panel is the results of SPM {T2} tests in affected sides and intact sides in sagittal plane, transverse plane and coronal plane. The rest three panels are the result of SPM {t} tests of hips knees and ankles in sagittal plane, transverse plane and coronal plane in both affected sides and intact sides. The horizontal dotted line indicates the critical random field theory threshold. Grey bars indicate regions with statistically significant differences with magnitude above the relevance criterion.

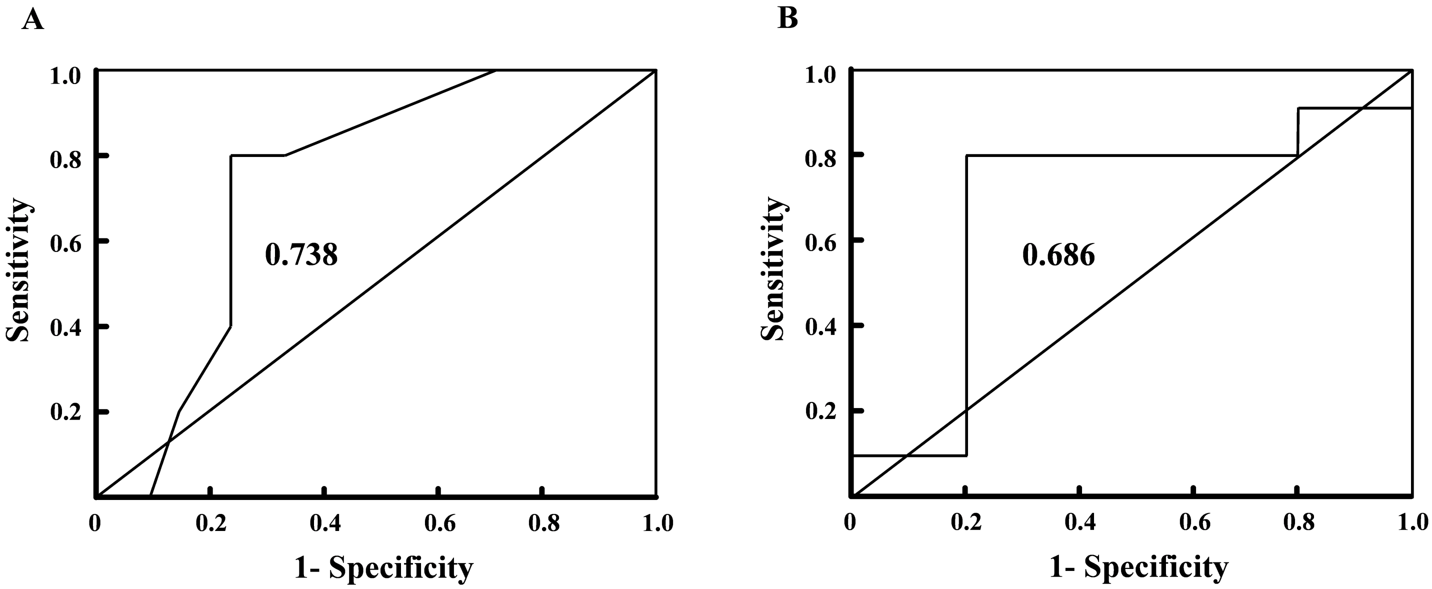

Figure 3

ROC curves (A) ROC curve of age and decreased GDI after SDR in all 26 patients (area under curve: 0.738; CI: 0.536-0.940; cut-off point: 6.3 years old, sensitivity: 80%, specificity: 76.2 %). (B) ROC curve of follow-up duration and increased GDI after SDR in all 26 patients (area under curve: 0.686; CI:0.394-0.978; cut-off point: 6.2 months, sensitivity: 81%, specificity: 80 %).

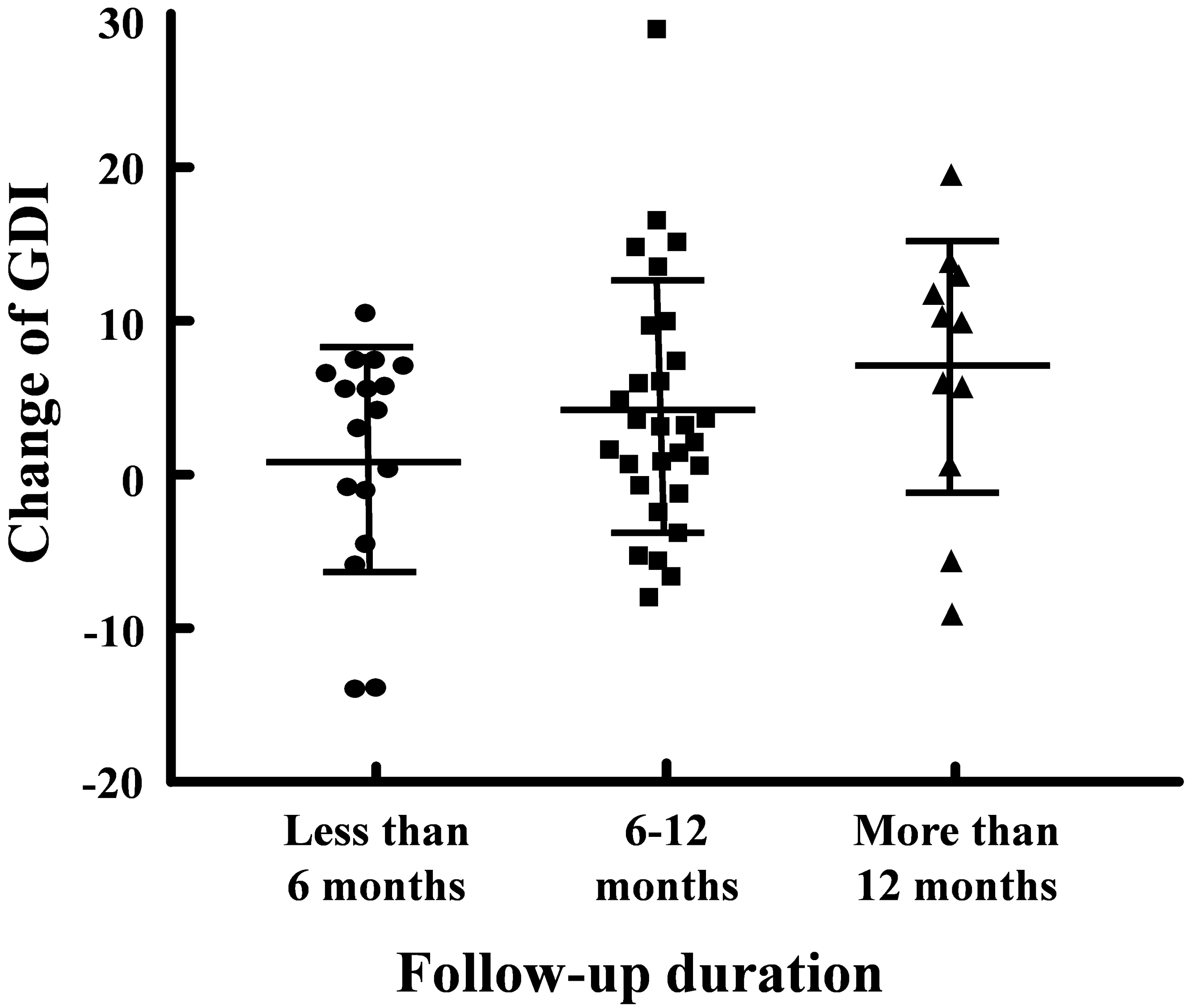

Figure 4

ΔGDI at different follow-up intervals